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Modelling and Simulation for the Performance Analysis of Integrated Power Flow Controllers

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Abstract— The increasing complexity of modern power systems, driven by growing load demand and high penetration of renewable energy sources, necessitates advanced control devices for efficient power flow management and voltage stability enhancement. The Integrated Power Flow Controller (IPFC), a versatile member of the Flexible AC Transmission Systems (FACTS) family, offers simultaneous control of multiple transmission lines, making it a promising solution for improving system performance. This study focuses on the modelling and simulation of the IPFC for performance analysis in interconnected power systems. A detailed mathematical model of the IPFC is developed based on voltage source converter (VSC) principles and implemented in a simulation environment such as MATLAB/Simulink. The model incorporates key control strategies to regulate active and reactive power flow, maintain voltage profile, and enhance system stability under varying load and fault conditions. Simulation results demonstrate the effectiveness of the IPFC in improving voltage regulation, reducing power losses, and mitigating transmission congestion. The dynamic response analysis highlights the capability of the IPFC to provide fast and stable control during transient disturbances. Comparative evaluation with conventional FACTS devices further establishes the superior performance of the IPFC in multi-line power flow control. Overall, the study confirms that accurate modelling and simulation of IPFC are essential for understanding its operational characteristics and optimizing its application in modern power systems, thereby contributing to enhanced reliability, efficiency, and large-scale grid integration.

Keywords: - Integrated Power Flow Controller (IPFC), Flexible AC Transmission Systems (FACTS), Modelling and Simulation, Voltage Source Converter (VSC), Power Flow Control, Voltage Stability

I. INTRODUCTION

Modern power systems are becoming increasingly complex due to the rapid growth in electricity demand, expansion of interconnected networks, and large-scale integration of renewable energy sources such as wind and solar. These developments introduce significant challenges in maintaining voltage stability, controlling power flow, and ensuring reliable system operation. Conventional transmission systems often face issues such as line congestion, uneven load distribution, voltage fluctuations, and increased power losses. Therefore, advanced control devices are required to enhance the flexibility and performance of power networks [1, 2].

Flexible AC Transmission Systems (FACTS) technology has emerged as an effective solution to address these challenges by providing fast and dynamic control of key system parameters such as voltage, impedance, and phase angle. Among the various FACTS devices, the Integrated Power Flow Controller (IPFC) is one of the most advanced and versatile controllers. Unlike traditional FACTS devices that operate on a single transmission line, the IPFC is capable of controlling multiple transmission lines simultaneously, making it highly suitable for complex and heavily loaded power systems [3].

The IPFC is based on the concept of multiple Voltage Source Converters (VSCs) connected in series with different transmission lines and linked through a common DC bus. This configuration allows coordinated control of active and reactive power flows across multiple lines. By injecting controllable series voltages, the IPFC can regulate power flow, improve voltage profile, reduce transmission congestion, and enhance overall system stability. Its ability to transfer real power between lines through the common DC link provides a significant advantage over other FACTS devices [4].

To evaluate the effectiveness and performance of the IPFC, accurate modelling and simulation are essential. Mathematical modelling helps in understanding the dynamic behavior of the device, while simulation tools such as MATLAB/Simulink enable analysis under various operating conditions, including steady-state, transient disturbances, and fault scenarios. Through simulation studies, key performance parameters such as voltage regulation, power flow control, transient stability, and system response can be analyzed in detail [5, 6].

This study focuses on the modelling and simulation of the Integrated Power Flow Controller for performance analysis in modern power systems. It aims to investigate the operational characteristics of the IPFC, evaluate its impact on system stability and efficiency, and demonstrate its effectiveness in improving power flow management and voltage profile under different system conditions. The outcomes of this work contribute to the development of more reliable, efficient, and flexible power transmission systems [7].

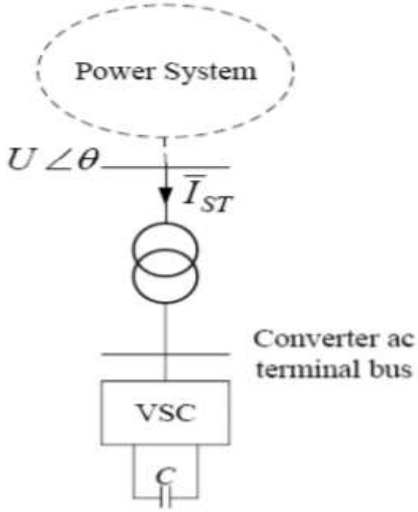

Figure 1: Line diagram of STATCOM

II. VOLTAGE STABILITY AND ITS CLASSIFICATION

Voltage stability refers to the ability of the power system to maintain steady voltages at all the buses in the system after being subjected to a disturbance from a given initial operating point. It depends on the ability of the power system to maintain/restore equilibrium between the load demand and supply. Instability appears in the form of a progressive fall or rise of voltage of some buses. A possible consequence of voltage instability is the loss of load in a particular area, tripping of lines and/or other elements by their protections, leading to cascading outages. This could give way to loss of synchronism of some generators [5]. Voltage collapse is the process wherein, a sequence of events accompanying voltage instability lead to a black-out or abnormally low voltages in major parts of the power system. At low voltages, the stable operation may continue after the transformer tap changers reach their boost limits with intentional and /or unintentional tripping of some loads. The remaining load is voltage sensitive and it so happens that the connected demand at normal voltage is not met [6]. So, if the post disturbance equilibrium voltages are below acceptable limits, a voltage collapse, partial or total blackout is bound to occur.

The time scale for the course of events that develop into a collapse varies from few seconds to several tens of minutes. Accordingly, voltage stability is classified into four categories [7].

Large disturbance voltage stability: It refers to the ability of the system to maintain steady voltages following occurrence of large disturbances like system faults, loss of generation or circuit contingencies. This ability is determined by the system load characteristics and interaction of both continuous and discrete controls and protections. To analyze the large disturbance voltage stability, the system dynamics for the entire time frame of disturbance need to be captured. A suitable model of the system needs to be framed and a compressive analysis needs to be carried out so as to get a lucid picture of stability. The period of study may be from a few seconds to tens of minutes [8].

Small disturbance voltage stability: This type of stability concerns the ability of the system to maintain steady acceptable voltages, when subjected to small disturbances such as gradual changes in the system load. It is called the small disturbance or steady state voltage stability. Such small disturbances on the system can be analyzed by linearizing around the pre-disturbance operating point. Steady state voltage stability analysis aids in getting a qualitative picture of the system; i.e. how much stressed the system is, or how close the system is to the point of instability. This form of stability is influenced by the system load characteristics, continuous and discrete controls at a given instant of time. The basic methods that contribute to the small disturbance stability are essentially of steady state nature. So, the static voltage stability analysis is effectively used to estimate the stability margins. The time span of disturbance in a power system, that may cause a potential voltage instability problem, can be classified as short-term and long-term. Short term Voltage Stability-Automatic voltage regulators, excitation systems, turbine and governor dynamics fall in this short-term time scale, which is typically of the order of a few seconds. Induction motors, electronically operated loads and HVDC interconnections also fall in this category. The analysis requires solution of appropriate system differential equations. If the system is stable, the short-term disturbance dies out and the system enters into slow long-term dynamics [9].

Long term Voltage Stability- The long term time frame is of the order of a few minutes to tens of minutes. Components operating in this time frame are transformer tap changers, thermostatically controlled loads and generator current limiters. The analysis requires long term dynamics system simulation [10].

III. PROPOSED METHODOLOGY

A 100-Mvar STATCOM regulates voltage on a three-bus 500-kV system. The 48-pulse STATCOM uses a Voltage-Sourced Converter (VSC) built of four 12-pulse three-level GTO inverters. Look inside the STATCOM block to see how the VSC inverter is built. The four sets of three-phase voltages obtained at the output of the four three-level inverters are applied to the secondary windings of four phase-shifting transformers (-15 deg., -7.5 deg., 7.5 deg., +7.5 deg. phase shifts). The fundamental components of voltages obtained on the 500 kV sides of the transformers are added in phase by the serial connection of primary windings. Please refer to the "power_48pulsegtoconverter" example to get details on the operation of the VSC.

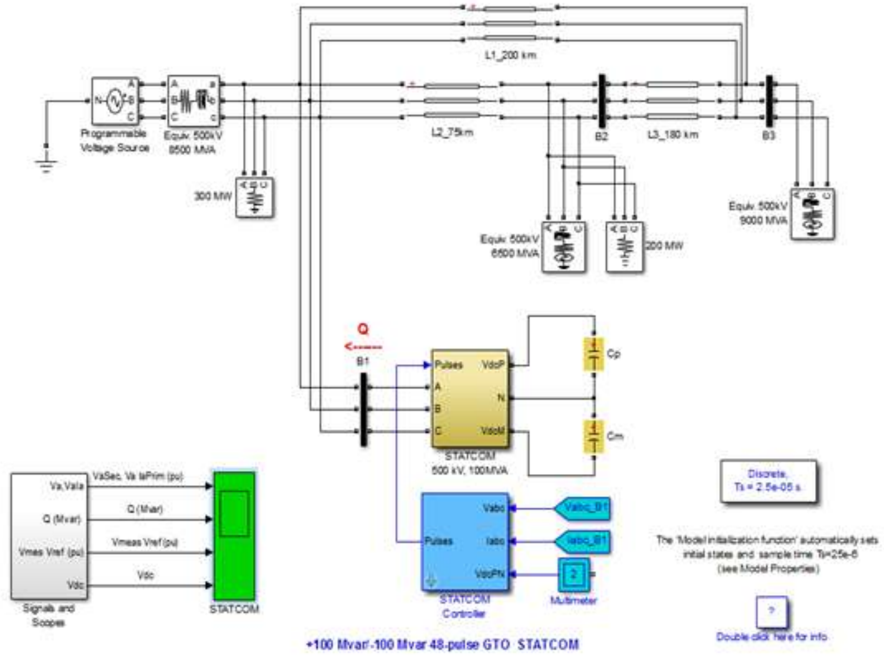

Figure 2: Simulink Model of STATCOM

During steady-state operation the STATCOM control system keeps the fundamental component of the VSC voltage in phase with the system voltage. If the voltage generated by the VSC is higher (or lower) than the system voltage, the STATCOM generates (or absorbs) reactive power. The amount of reactive power depends on the VSC voltage magnitude and on the transformer leakage reactance. The fundamental component of VSC voltage is controlled by varying the DC bus voltage.

The diagram represents an IEEE 14-bus test system single-line diagram, which is widely used to study power system operation and stability. It consists of multiple buses (numbered nodes), generators, loads, and transmission lines interconnected to form a network. In this system, buses act as connection points where power is either injected (from generators) or drawn (by loads). The generators are shown at specific buses (such as bus 1 and bus 2), supplying electrical power into the network, while several buses are connected to loads that consume this power.

The transmission lines interconnect the buses, enabling power flow across the system. These lines are represented by straight connections between buses and may include transformers, such as the three-winding transformer equivalent shown on the right side of the diagram. This transformer helps in voltage level adjustment and efficient power transfer between different sections of the network. Some buses also include shunt elements like synchronous condensers, which are used for reactive power compensation and voltage regulation.

Figure 3: Output Waveform of the STATCOM

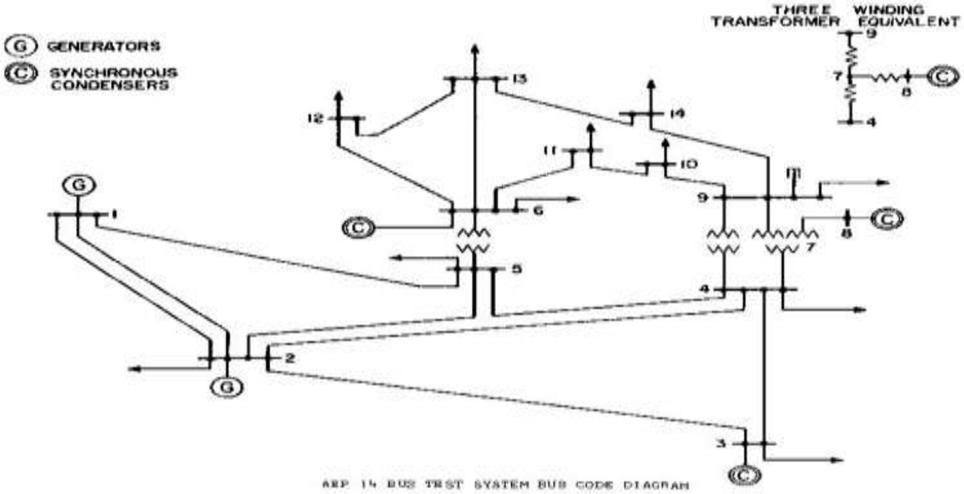

Figure 4: Flow Chart of IEEE 14 Bus Systems

The system includes multiple paths for power flow, which enhances reliability and flexibility. Power generated at the generator buses travels through transmission lines and transformers to reach load buses. Circuit breakers and switches (indicated near bus connections) allow control and protection of the system by isolating faults or managing power flow. Overall, this diagram illustrates how a moderately complex power grid operates, balancing generation, transmission, and consumption while maintaining voltage stability and system reliability.

IV. SIMULATION RESULT

The diagram represents a control system model for generating switching pulses using a three-phase Phase-Locked Loop (PLL) and modulation technique, typically implemented in a simulation environment like MATLAB/Simulink. The system begins with a three-phase voltage input (Vabc), which is fed into a discrete 3-phase PLL block. This PLL synchronizes with the grid voltage and extracts the phase angle (ωt), ensuring that the control system operates in alignment with the supply frequency. The output of the PLL is then used to generate sine and cosine signals, which serve as reference waveforms for further processing.

These reference signals are passed through trigonometric function blocks to produce synchronized sinusoidal signals. Constants are used to define amplitude or scaling factors, and these signals are multiplied using product blocks to shape the reference signals appropriately. Meanwhile, another part of the system processes a variable input, which is passed through a gain block and a fuzzy logic controller. The fuzzy controller helps in dynamically adjusting the control signal based on system conditions, improving performance such as stability or response time.

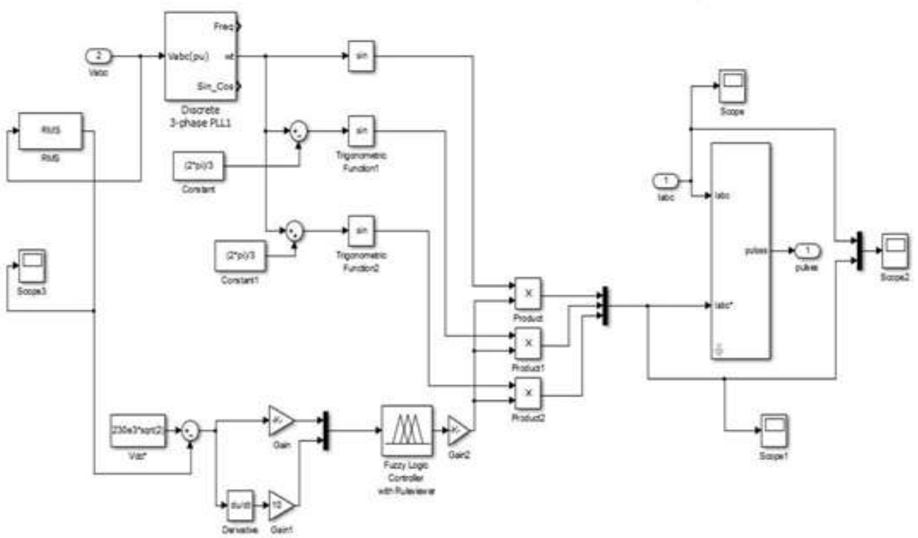

Figure 5: Control scheme of FLC based STATCOM

The processed signals are then combined and compared within a modulation block, where pulse-width modulation (PWM) or a similar switching strategy is applied. This block generates switching pulses based on the comparison between reference signals and a carrier waveform. The output pulses are used to control power electronic switches (such as inverters). Scopes are connected at different points in the system to monitor signals like reference waveforms, PLL output, and generated pulses for analysis.
Overall, the diagram demonstrates a closed-loop control approach where synchronization (via PLL), intelligent control (via fuzzy logic), and modulation (via PWM) are integrated to produce precise switching signals for power electronic applications.

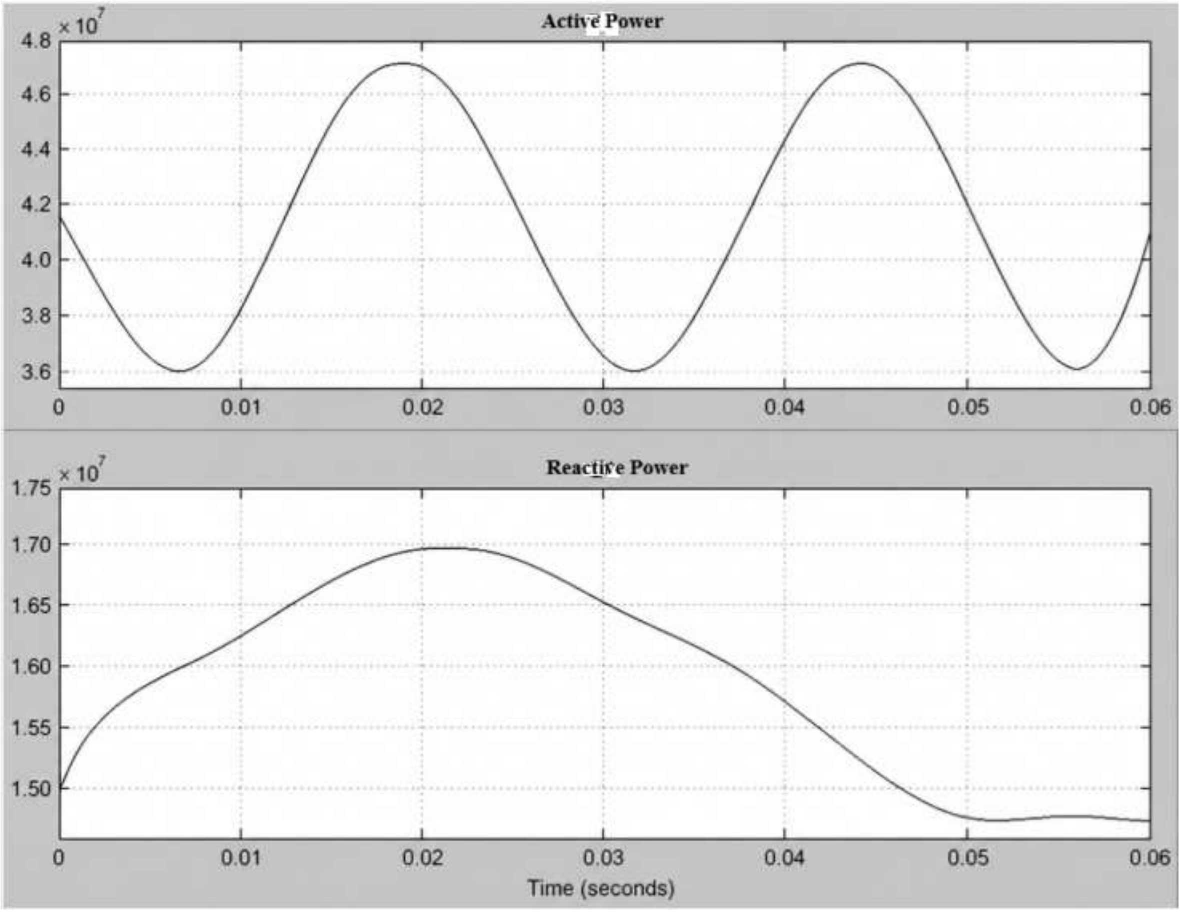

Figure 6: Simulation Result of Active and Reactive Power of IEEE 14-bus System with FLC based STATCOM

The figure shows the variation of active power and reactive power with respect to time in a power system. In the upper plot, the active power exhibits a smooth oscillatory behavior, varying between approximately 3.6×10^7 W and 4.7×10^7 W over the time interval of 0 to 0.06 seconds. This oscillation indicates that the real power delivered to the load is not constant but fluctuates periodically, which is typical in AC systems due to dynamic operating conditions, switching actions, or control system responses. The waveform appears stable and repetitive, suggesting that the system is operating under steady-state conditions with small power oscillations rather than experiencing instability.

In the lower plot, the reactive power shows a different trend. Initially, it increases from about 1.5×10^7 VAR to a peak near 1.7×10^7 VAR around 0.02 seconds, after which it gradually decreases and stabilizes close to 1.48×10^7 VAR. This behavior indicates a transient response where reactive power demand rises and then settles as the system reaches equilibrium. Reactive power is mainly associated with voltage control and magnetic energy storage in inductive and capacitive elements, so this trend suggests that the system is adjusting its voltage profile before stabilizing.

Overall, the combined observation of both plots indicates that the system maintains a stable operation. While active power continues to oscillate due to the inherent nature of AC power transfer, the reactive power settles over time, showing that voltage and reactive compensation mechanisms (such as controllers or compensators) are effectively regulating the system.

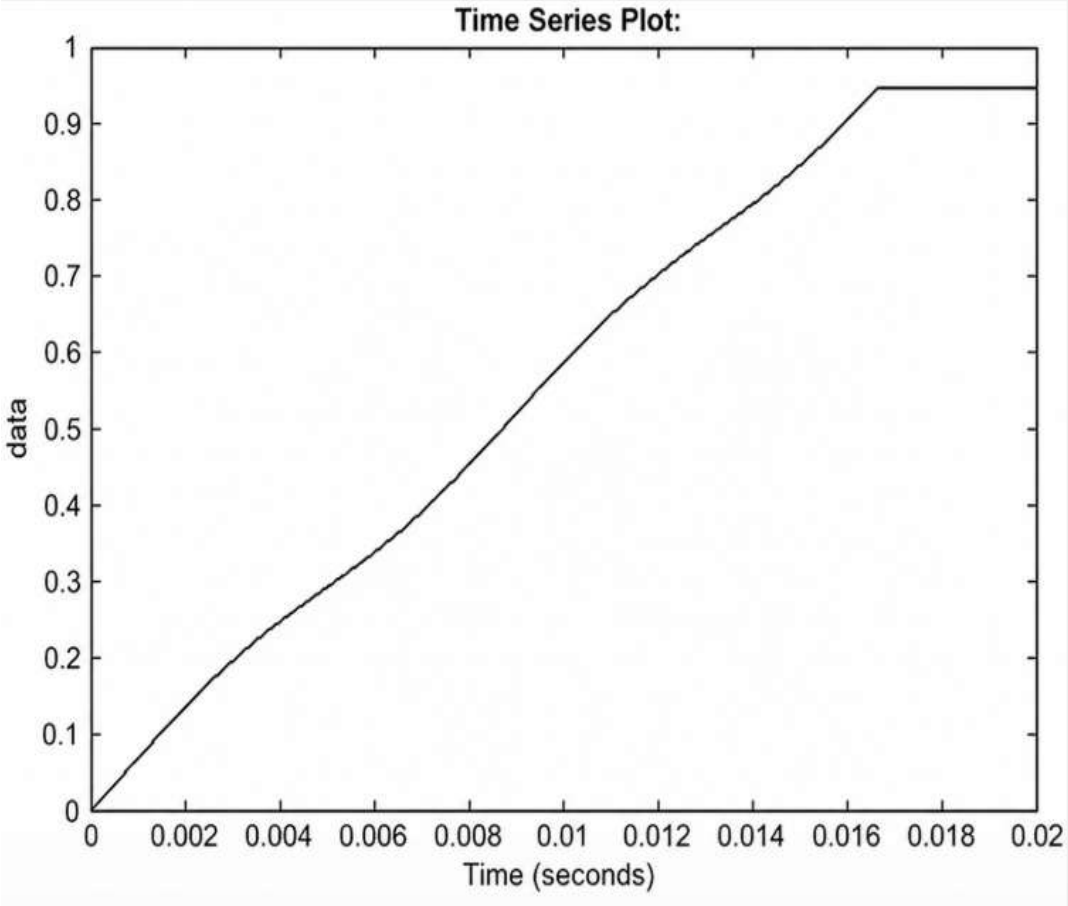

Figure 7: Voltage v/s Time Plot of IEEE 14-bus System with FLC based STATCOM

V. CONCLUSION

The modelling and simulation study of the Integrated Power Flow Controller (IPFC) demonstrates its significant capability in enhancing the performance of modern power systems. By enabling simultaneous control of multiple transmission lines, the IPFC effectively regulates both active and reactive power flow, leading to improved voltage profiles, reduced transmission congestion, and better utilization of existing network infrastructure.

The developed model, based on voltage source converter principles, provides a clear understanding of the operational behavior of the IPFC under various conditions. Simulation results confirm that the IPFC offers fast dynamic response, efficient power flow control, and enhanced system stability during both steady-state and transient conditions, including disturbances and faults. Compared to conventional FACTS devices, the IPFC shows superior performance in multi-line coordination and overall system efficiency.

Furthermore, the study highlights the importance of accurate modelling and advanced control strategies in maximizing the benefits of IPFC implementation. With the increasing integration of renewable energy sources and the growing complexity of power networks, devices like IPFC play a crucial role in maintaining system reliability and stability.
In conclusion, the IPFC is a highly effective and flexible solution for modern power system challenges. Future work may focus on optimized placement, cost-effective implementation, and integration with intelligent control techniques such as artificial intelligence and machine learning to further enhance its performance and applicability in smart grid environments.

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