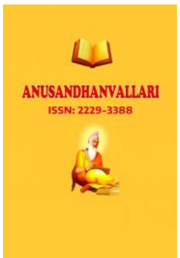

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Comparative Performance Analysis of PI and Fuzzy Logic Controlled UPFC Under Single Line-to-Ground Fault Conditions

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Abstract: Electric power systems form the backbone of industrial and economic development. With the continuous growth in global electricity demand, the large-scale generation and transmission of power to residential and industrial consumers have become increasingly critical. Ensuring flexible, efficient, and reliable operation of modern power networks remains a significant challenge, particularly under heavily loaded and faulted conditions. Flexible AC Transmission System (FACTS) devices offer an effective solution by enhancing power flow control, improving system stability, and increasing transmission capacity utilization.

This work presents a comparative performance analysis of the Unified Power Flow Controller (UPFC) under a single line-to-ground (S-L-G) fault condition. The study demonstrates that the Fuzzy Logic Controller (FLC) outperforms the conventional Proportional–Integral (PI) controller in terms of transient stability enhancement, oscillation damping, and faster system recovery. A detailed multi-machine power system model subjected to various fault scenarios is developed and simulated using MATLAB to validate the effectiveness of the proposed control strategies.

Keywords— UPFC, STATCOM, SSSC,PI controller

I. Introduction

Earth fault conditions, comparing PI and PI-based Fuzzy Logic Controllers and A 0.5-second LG fault at Bus-5 is simulated, with system responses voltage, reactive power, rotor angle, speed deviation, and active power. This research examines the performance of UPFC during various faults conditions specifically focusing on its ability to maintain active and reactive power in a transmission line under Line to Ground Fault conditions. The study also explores the UPFC's effectiveness in damping oscillations and enhancing transient stability. In this research we have compared ability of UPFC for damping oscillations working on PI controller, FLC controller Improvement of power system oscillations is observed in the reactive power, active power output from generator-2 and generator1are observed.

II. Literature Review

The L-G fault is applied for a particular duration to examine the improvement in parameters. Similarly results are also validated using lab prototype hardware A novel AC voltage sag and swell compensator using a three-phase hybrid transformer with a buck–boost matrix-reactance chopper to stabilize the power quality in distribution networks. A novel AC voltage sag and swell compensator using a three-phase hybrid transformer with a buck–boost matrix-reactance chopper has also been reported to improve power quality in distribution networks [1]. Other studies show that well-tuned PSS controllers significantly enhance transient response, oscillation damping, and system robustness compared to conventional stabilizers, emphasizing the need for multi-objective tuning techniques under varying load conditions [2].

Comparative studies on harmonic mitigation indicate that PI controllers perform well under steady-state linear conditions but show slower response and higher overshoot under nonlinear and rapidly changing loads. In contrast, Fuzzy Logic Controllers provide better adaptability, reduced overshoot, shorter settling time, and effective harmonic suppression, making them more suitable for modern power systems with nonlinear loads [3–4]. Active power filters are also shown to improve power quality by eliminating current harmonics and compensating reactive power, with shunt active filters offering faster dynamic response than passive filters [6].

Other research demonstrates that devices like SSSC can control line impedance and power flow effectively by injecting controllable series voltage during disturbances [7]. Fuzzy-based UPFC controllers further improve robustness and control precision under nonlinear and uncertain conditions, overcoming the limitations of conventional PI controllers [8–9]. Intelligent control approaches such as Model Predictive Control combined with Bacterial Foraging Optimization have shown superior performance in regulating power flow, mitigating voltage fluctuations, and enhancing transient stability [10]. Similarly, coordinated control of series and shunt converters in UPFC significantly improves dynamic response and reduces harmonic distortion [11].

Studies also confirm that SSSC and UPFC devices enhance voltage regulation, reduce congestion, and stabilize active and reactive power exchanges, especially under renewable energy integration [12–13]. Neural network-based controllers outperform traditional methods by offering faster response, better handling of nonlinearities, and improved damping during transient disturbances [14]. Intelligent control strategies further optimize reactive power support and voltage regulation, improving power transfer capability [15–16].

Optimal placement of UPFC using sensitivity analysis and optimization techniques yields maximum improvement in voltage stability margin, congestion relief, and loss reduction [17–20]. Integration of energy storage systems such as super capacitors and batteries with FACTS devices enhances transient response, voltage support, and frequency regulation [21–25]. Neural network-based predictive control methods have also shown superior performance over conventional PI controllers in regulating power flow efficiently [26].

Based on these findings, the work suggests developing intelligent FACTS controllers using a hybrid PI–Fuzzy Logic control method.. A comparative evaluation of different controller designs is included to highlight performance differences. Simulations result are verified through prototype hardware model.

III. METHODOLOGY

The figure 1 shows basic diagram of UPFC connected between sending and receiving end.

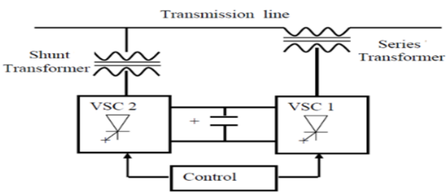

Figure 1 Unified power flow controller

The UPFC consists of two voltage source converters (VSCs) connected back-to-back through a common DC link capacitor: One converter is connected in shunt (STATCOM). The other is connected in series (SSSC). The shunt converter maintains the DC link voltage and provides reactive power support, while the series converter injects a controllable voltage in magnitude and phase into the transmission line. This allows independent control of: Active power flow Reactive power flow Bus voltage

Figure 2 presents the overall structure of the UPFC and highlights its major components. The setup includes two converters: Converter-1, which serves as the shunt converter, and Converter-2, which operates as the series

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converter. A PI-based control system is used to regulate both the STATCOM for shunt compensation and the SSSC for series control. The architecture also contains a measurement unit and a settings block for defining control parameters.

Figure 3 shows the representation of UPFC, which consists of two VSCs connected to the transmission line: in shunt through the shunt transformer and in series through the series transformer, both sharing the common DC link capacitor. The shunt converter deals with bus voltage control, supplies or absorbs reactive power, and also supplies the active power needs for the series converter.

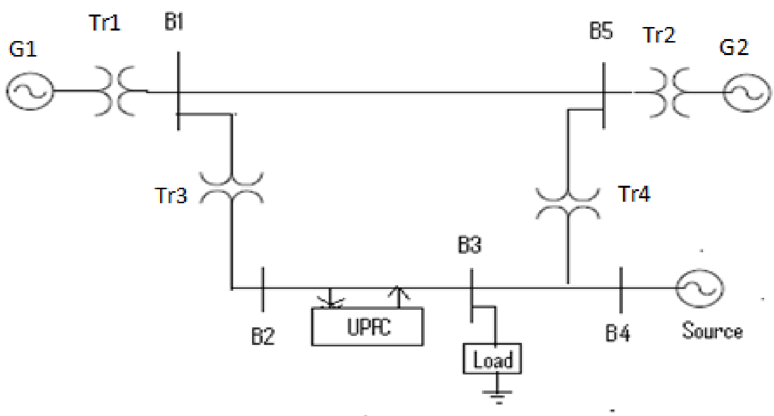

Figure 3 Structure of 2-machines 5-bus system

The equipment's ratings are as follows:

Generators: Each generator operates at 13.8 kV with a capacity of 1000 MVA.

Rotor Type: Salient pole. Mechanical Input: 0.5 per unit (P.U).

Connections: On the Generator Side: Delta/Star configuration.

On the Main Network Side: Star/Star configuration.

Voltage Ratings: Generator Side: 230 kV. Main Network Side: 500 kV.

Transmission Lines: Lines: Three lines, labelled L1, L2, and L3.

Each Line Length: 50 kilometers. Measurement Blocks:

Base Voltage: 230 kV. Load: Type: Load is connected at bus 2 Power Consumption: 200 MW.UPFC based on PI controller with 1000 KVAR capacity

System Consideration

The various conditions are taken into consideration are as follows:

CASE 1 : Multimachine system without fault.

CASE 2 : Multimachine system with single line to ground(S-L-G) fault without UPFC.

CASE 3: Multimachine system with UPFC based on PI controller

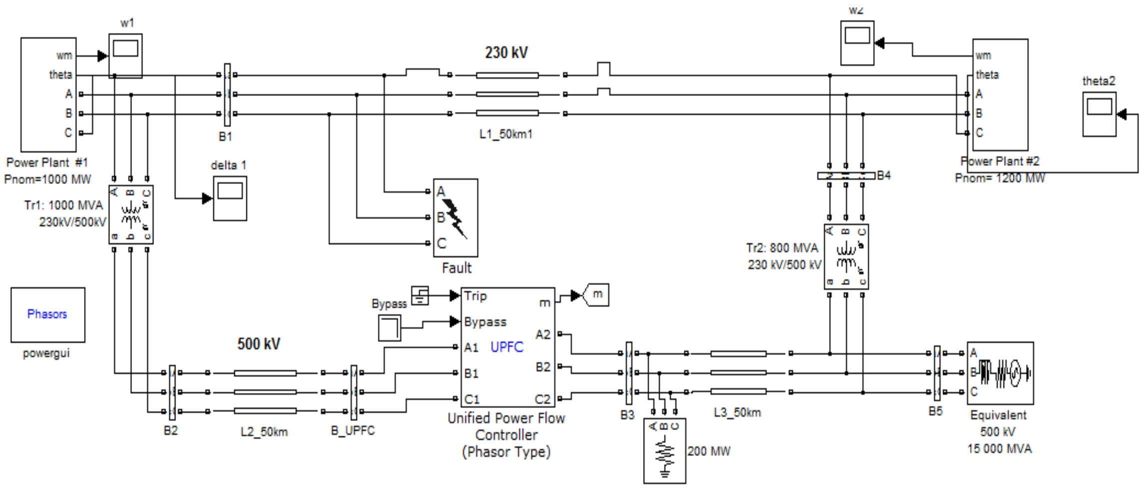

Figure 4 System model

IV RESULT

Figure 5 illustrate the dynamic behavior of active power at five different buses during and after a disturbance, highlighting the system response under two different control conditions. In both cases, a fault is applied at around 2 seconds, which causes a sudden and sharp deviation in active power at all buses. This disturbance leads to large oscillations, particularly noticeable at Bus 5, which shows the highest peak deviation, indicating that it is most sensitive to the fault. Immediately after the fault, all buses experience severe fluctuations, reflecting the loss of system balance and transient instability. Overall, the comparison shows that the second case provides superior dynamic performance. It reduces peak overshoot, minimizes oscillation amplitude, and shortens settling time for all buses. These improvements confirm that the enhanced control method significantly strengthens system stability during disturbances. The results prove that advanced control strategies, when applied to power flow controllers such as UPFC, can effectively mitigate the adverse effects of faults, improve damping of power oscillations, and ensure faster restoration of normal operating conditions, thereby increasing the reliability and security of the power system

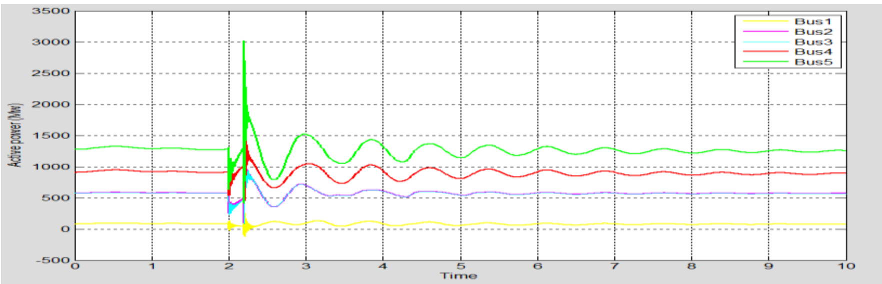

Figure 5 Active power (MW) without UPFC with S-L-G fault

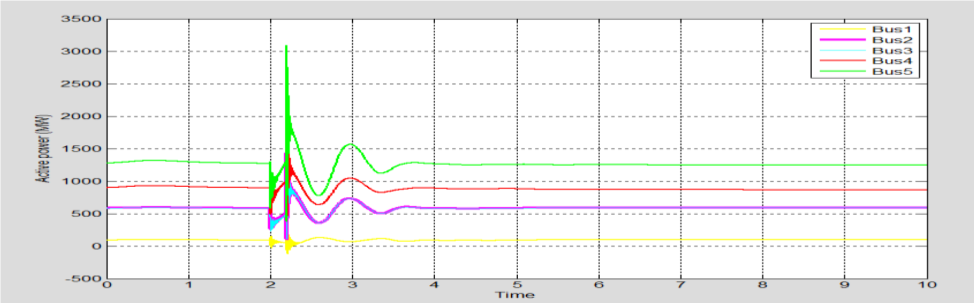

Figure 6 Active power with PI based UPFC with S-L-G fault

Table 1 Active Power

Parameter	with out UPFC	with PI based UPFC
Control scheme	PI-based UPFC	PI-based UPFC (improved response)
Fault type	Single Line-to-Ground (S-L-G) fault	Single Line-to-Ground (S-L-G) fault
Fault location	Bus-5	Bus-5
Fault inception time	≈ 2 s	≈ 2 s
Peak active power deviation (Bus-5)	Very high (≈ 3000 MW)	Slightly reduced peak (≈ 2800–2900 MW)
Active power oscillation magnitude	Moderate	Lower
Post-fault oscillations	Present, damped	Better damped

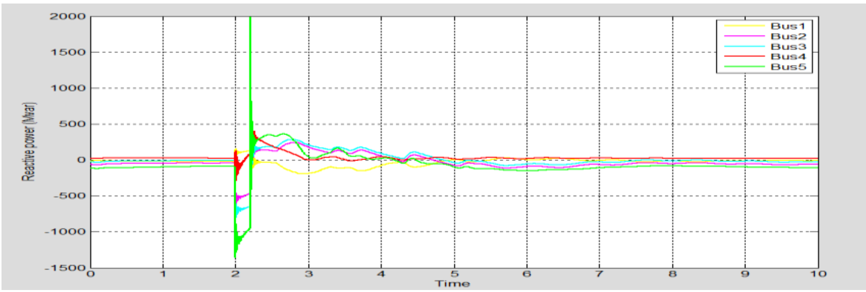

Figure 7 Reactive power (Mvar) with time (without UPFC with S-L-G fault)

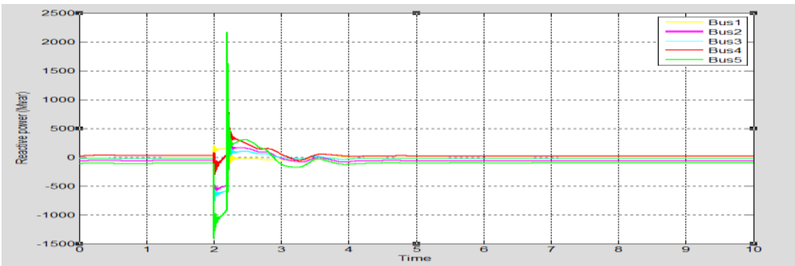

Figure 8 Reactive power (Mvar) with time (with UPFC with S-L-G fault)

Table 2 Reactive Power

Type of faults	without UPFC	with UPFC
Fault type	Single Line-to-Ground (L–G) fault	Single Line-to-Ground (L–G) fault
Fault location	Bus-5	Bus-5
Fault inception time	≈ 2 s	≈ 2 s
Maximum reactive power deviation (Bus-5)	Very high (≈ −1500 kVAr)	Reduced (≈ −1200 kVAr)
Reactive power oscillations	High-amplitude oscillations	Lower-amplitude oscillations
Dominant bus affected	Bus-5	Bus-5
Damping characteristic	Moderately damped	Well damped
Settling time	≈ 5–6 s	≈ 3.5–4 s

From table 1 it is clear that there is Larger oscillation amplitudes Slightly longer settling time Reactive power ripples persist until about 5–6 s when UPFC absent in the system With UPFC there is Lower peak overshoot Oscillations are more damped System settles faster, around 3.5–4 s

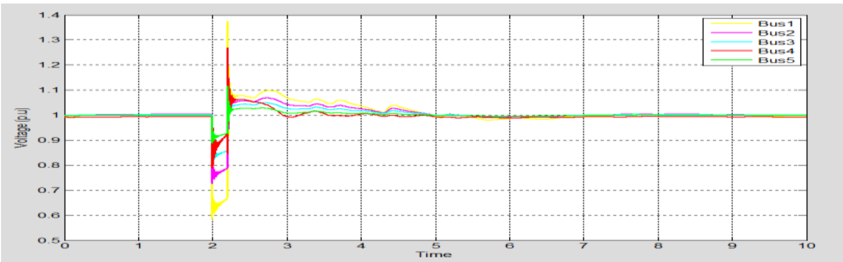

Figure 9 Voltages with time (without UPFC with S-L-G fault)

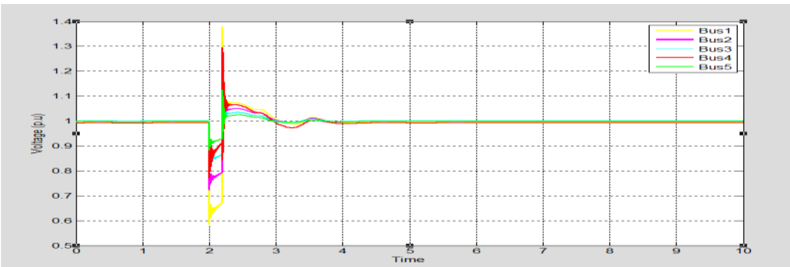

Figure 10 Voltages with time with UPFC with S-L-G fault)

V Conclusion

The inclusion of the UPFC significantly enhances system damping when compared to the uncompensated power system. While the PI controller improves overall stability, its performance degrades under nonlinear operating conditions and severe disturbances. In contrast, the Fuzzy Logic Controller (FLC) adapts more effectively to system variations, resulting in a noticeable reduction in oscillations and improved transient performance.

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