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Evaluation of Distance Relay Behavior under Faults in Two-Machine Systems with Fuzzy-PI Based Series STATCOM

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Abstract

The growing energy demand, coupled with constraints on expanding transmission infrastructure, poses significant challenges to the sustainable operation of power systems. Flexible AC Transmission Systems (FACTS), particularly Static Synchronous Compensators (STATCOMs), offer an effective solution for enhancing system stability and voltage control. This study designs and implements fuzzy-logic-based and hybrid fuzzy-PI controllers for STATCOM to improve transient stability in a two-machine power system. Simulations conducted in MATLAB/SIMULINK compare the performance of these controllers with a conventional Proportional-Integral (PI) controller. The results demonstrate that the proposed controllers not only enhance voltage stability but also outperform the traditional PI controller in damping transient oscillations. Additionally, this study investigates the impact of STATCOM on distance relay operation, revealing that STATCOM alters the apparent impedance observed by the relay, thus affecting its protective behavior. Consequently, careful consideration of interactions between FACTS devices and protection systems is critical for ensuring the reliable operation of modern power networks.

Keywords: Power systems, Flexible ac transmission systems devices, Static synchronous compensator, Fuzzy controller, Transient stability, Distance relay.

1 | Introduction

The continuous growth of electricity demand, coupled with the inherent physical, economic, and environmental constraints on expanding transmission infrastructure, has become one of the most critical challenges in the reliable and efficient operation of modern power systems [1]. Intensive loadings and the associated stresses can significantly endanger system stability, particularly under severe disturbances. To address these challenges, Flexible AC Transmission Systems (FACTS) have been introduced as an effective solution. By exploiting advancements in power electronic technologies, FACTS devices enhance the

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controllability of transmission networks and enable more efficient utilization of existing line capacity without compromising stability margins [2].

Among FACTS technologies, shunt compensators such as the Static Var Compensator (SVC) and the Static Synchronous Compensator (STATCOM) play a pivotal role in voltage regulation and reactive power support [3]. In particular, STATCOM demonstrates superior dynamic performance compared to conventional compensators, owing to its fast response and capability to both inject and absorb reactive power. By regulating terminal voltages, STATCOM significantly improves transient stability and enhances system reliability [4]. Despite these advantages, integrating FACTS devices introduces new challenges for protection schemes, particularly for distance relays. Distance relays operate based on apparent impedance measurements to detect and isolate faults. However, in the presence of FACTS devices, relay-observed impedance values can be distorted, potentially leading to misoperation or delayed fault clearance [5]. This interaction reduces the reliability of protection systems, underscoring the need to analyze FACTS relay coordination to ensure secure system operation [6].

Over the past few decades, extensive research has been conducted on the application of FACTS devices to enhance power system stability. Classical controllers such as Proportional-Integral (PI) regulators have been widely employed due to their simplicity and ease of implementation [7]. Nevertheless, their performance deteriorates under nonlinear operating conditions, parameter variations, and dynamic disturbances. To overcome these limitations, advanced strategies such as fuzzy logic control and hybrid fuzzy–PI control have been proposed. These methods, with their adaptive capabilities and robustness against uncertainties, offer effective alternatives to traditional controllers [8], [9]. Motivated by these considerations, the present study focuses on the design and implementation of fuzzy and hybrid fuzzy–PI controllers for STATCOM in a two-machine power system. The primary objective is to evaluate their impact on transient stability enhancement and to compare their performance with that of the conventional PI controller. Furthermore, the effect of STATCOM on distance relay operation is analyzed to identify potential protection challenges and propose reliable coordination strategies between FACTS devices and protective schemes.

A review of prior works highlights the evolving role of FACTS in modern power systems. Early research primarily concentrated on SVC applications, which demonstrated notable improvements in voltage profile regulation and transmission capacity enhancement [10]. However, their relatively slow response and dependency on system conditions emphasized the need for more advanced devices. The introduction of STATCOM, a new generation of shunt controllers, marked a significant advancement in reactive power compensation and voltage stability control [11]. With its fast response and adaptability under varying load conditions, STATCOM has been shown to outperform SVC in improving transient stability and mitigating oscillations.

Nevertheless, designing efficient controllers remains a key challenge for maximizing STATCOM performance. While classical PI controllers provide satisfactory performance under linear and steady-state conditions, their limitations in nonlinear and dynamic operating conditions have motivated the adoption of intelligent and adaptive approaches [12]. Fuzzy logic control, in particular, has been recognized for its capability to handle uncertainties and deliver smoother responses. Several studies have demonstrated that fuzzy and hybrid fuzzy–PI controllers can significantly improve transient stability compared to traditional methods [13]. Additionally, the interaction between FACTS devices and protection systems, particularly distance relays, has attracted increasing attention. STATCOM can alter the apparent impedance seen by distance relays, potentially leading to incorrect fault detection or delayed tripping [14]. Recent investigations emphasize that proper coordination between FACTS devices and relay settings is crucial for ensuring reliable protection in modern power systems [15].

In summary, although FACTS devices—especially STATCOM—play a crucial role in enhancing power system stability, challenges remain in developing advanced control strategies and understanding their impact on protection schemes. The present work addresses these issues by proposing fuzzy and hybrid fuzzy–PI controllers for STATCOM, evaluating their effectiveness in improving transient stability, and analyzing their influence on distance relay operation.

2 | Methodology

2.1 | Development of a Fuzzy Logic Controller for the Operation of a STATCOM

In this section, a fuzzy logic controller with two inputs—generator frequency (ω) and its derivative ($d\omega/dt$)—and a single output, α (Alpha), is designed. The main advantage of the fuzzy controller is that it does not require precise information about the system. The Mamdani fuzzy model and if–then rules are employed for inference within the controller. Each input is associated with a corresponding fuzzy variable, and the inputs are fuzzified using appropriate membership functions. The output is then computed using the Center of Area (COA) method. Moreover, suitable membership functions for the output variables are also defined [16].

The membership functions for the input variables, namely ω and $d\omega/dt$, are illustrated in *Figs. 1* and *3*, respectively.

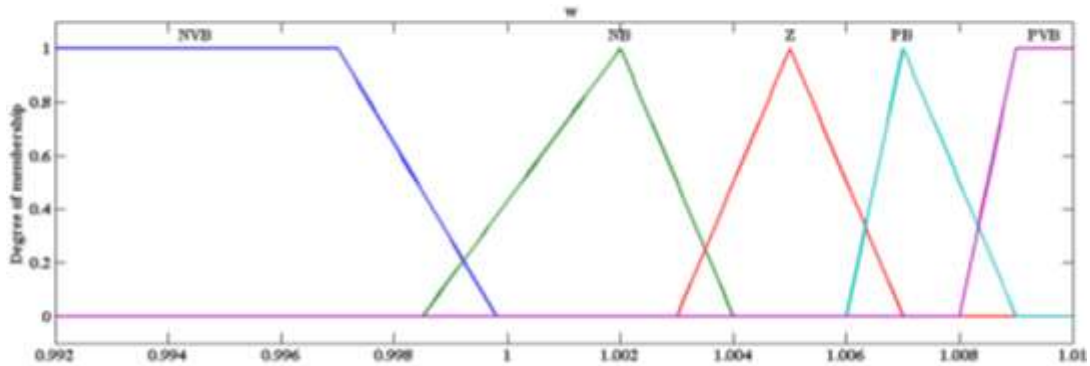

Fig. 1. Input membership function for the variable ω.

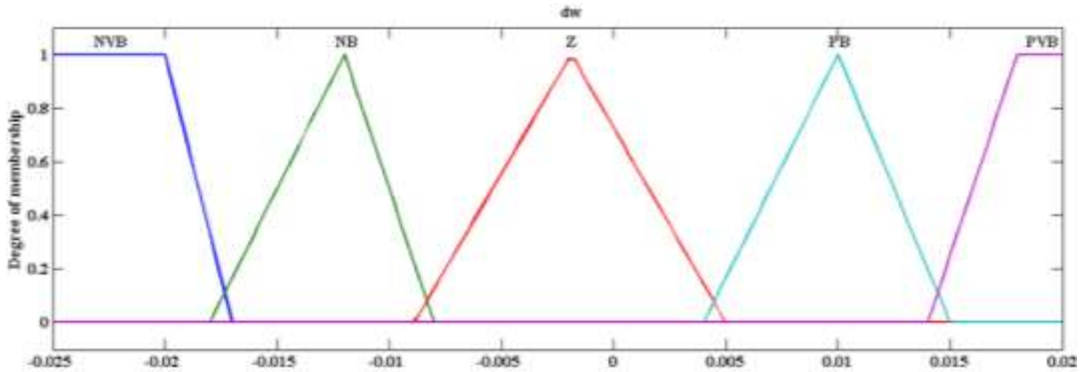

Fig. 2. Input membership function for the variable dω/dt.

The appropriate range for each interval and the number of membership functions can be defined based on system configuration and experimental testing. The membership functions for $d\omega/dt$ are symmetric, whereas their definitions differ from those of ω. This difference is due to the rotor speed behavior and can be determined from simulation results. *Fig. 4* illustrates the output membership functions of the α angle for the voltage-source converter, which are used to construct the aggregated output of the controller from the motor's fuzzy outputs. The proposed defuzzification method for this purpose is the COA technique [17].

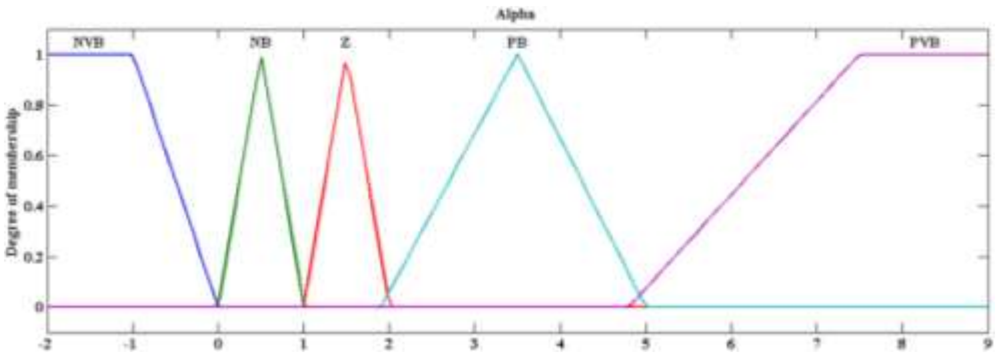

Fig. 3. Output membership function for the variable α.

Table 1 is designed according to the rules defined for the fuzzy controller installed on the STATCOM in a two-machine system. The logic of these rules can be easily extracted. For example:

I. R1: If ω is Positive Big (PB) and dω/dt is Positive Very Big (PVB), then the firing angle α is PB.

II. R2: If both ω and dω/dt are PB, then the firing angle α is also PB.

Table 1. Rule base of the fuzzy controller based on the variable ω.

ω / dω/dt	**NVB**	**NB**	**Z**	**PB**	**PVB**
NVB	NB	NB	NB	NB	NB
NB	NB	NB	NB	NB	NB
Z	NB	NB	Z	PB	PB
PB	PB	PB	PB	PB	PB
PVB	PB	PB	PB	PB	PB

When the system frequency is high and increasing rapidly, the mechanical input power of the generators exceeds the electrical output power, placing the system in a critical condition. Under such circumstances, the series compensator must inject a large capacitive current into the network; hence, the firing angle α should be chosen small to increase the transferable line power on which the series compensator is installed and to enhance transient stability [18]. Other operating conditions can be analyzed and evaluated similarly.

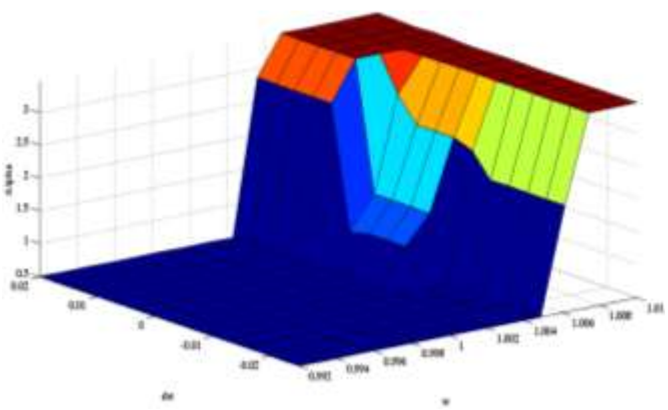

Fig. 4. Fuzzy system behavior in the frequency control mode.

2.2| Fuzzy-PI Controller

The PI controller is one of the most widely used controllers in industrial applications. Commonly referred to as the PI controller in industry, it consists of two components: the Proportional (P) and the Integral (I) parts.

The proportional component adjusts the controller output in proportion to the error's magnitude, while the integral component eliminates steady-state deviation [18]. The overall structure of the PI controller in MATLAB, both in continuous and discrete forms, is illustrated in *Figs. 5* and *6*.

These controllers are typically tuned with fixed parameters, and their response may not be sufficiently fast or effective when the control design parameters vary. To overcome this limitation, various approaches have been proposed, among which the Fuzzy-PI controller stands out as a prominent example. In this relation, the reference values correspond to the Fuzzy-PI controller [19]. The overall configuration of the Fuzzy-PI controller for voltage and current regulation is depicted in *Figs. 7* and *8*.

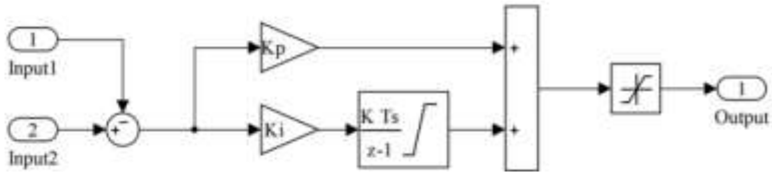

Fig. 5. Discrete PI controller.

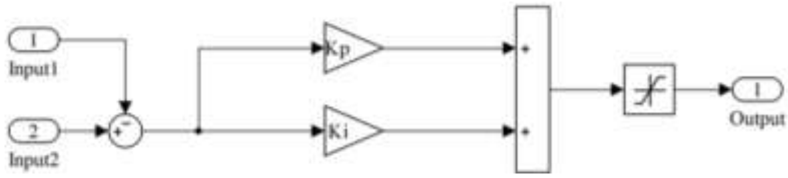

Fig. 6. Discrete PI controller.

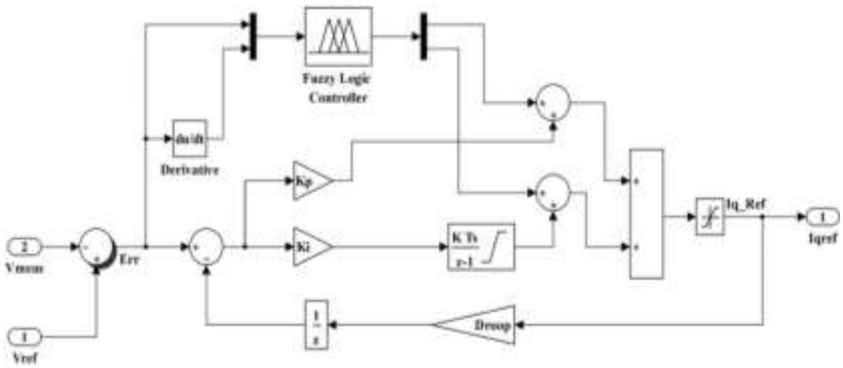

Fig. 7. Fuzzy-PI controller design for voltage regulation.

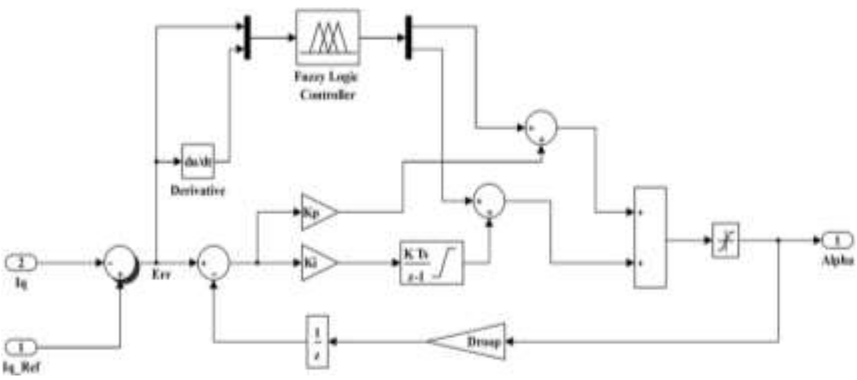

Fig. 8. Fuzzy-PI controller design for current regulation.

The error and its variations are used as numerical values of the actual system. Five fuzzy sets—Negative-Very Big (NVB), Negative-Big (NB), Zero (Z), Positive-Big (PB), and Positive-Very Big (PVB)—are selected to convert these numerical values into fuzzy variables. The membership functions of the input and output variables for the voltage and current controllers are illustrated in *Figs. 9* to *16*.

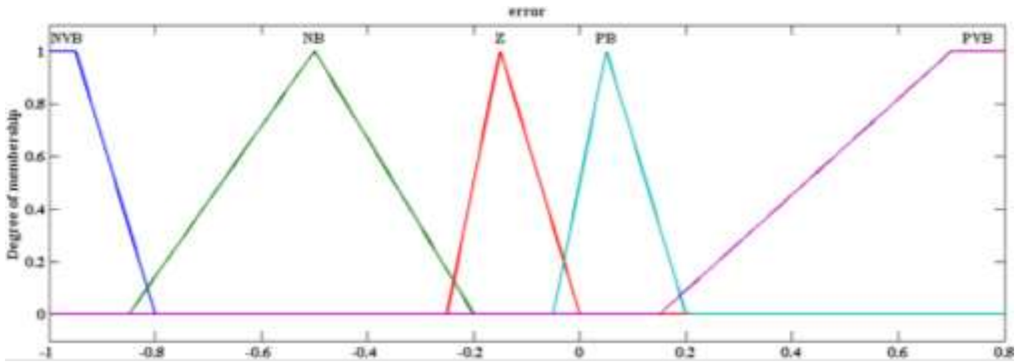

Fig. 9. Input membership function for the error (voltage regulator).

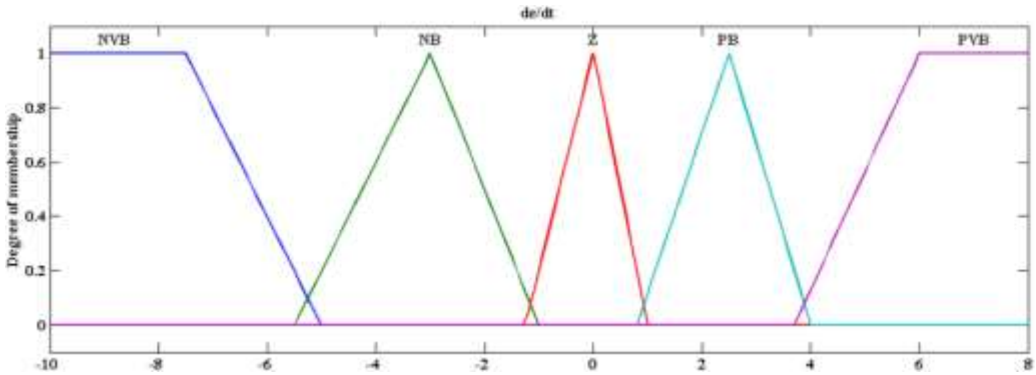

Fig. 10. Input membership function for de/dt (voltage regulator).

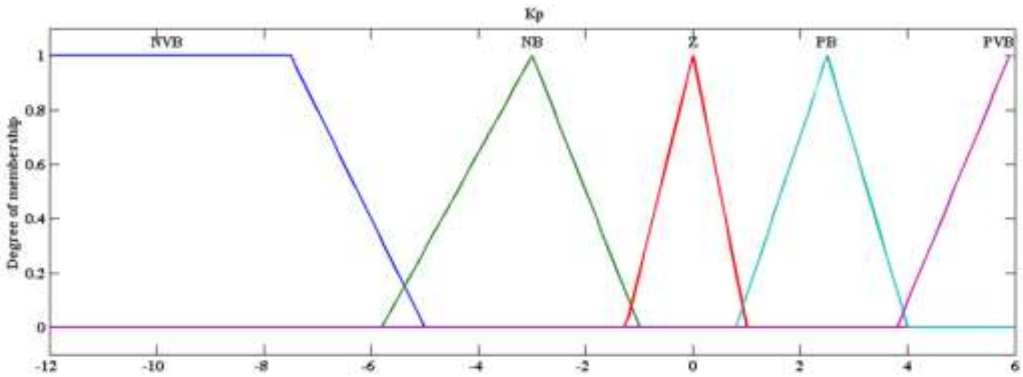

Fig. 11. Output membership function for K_p (voltage regulator).

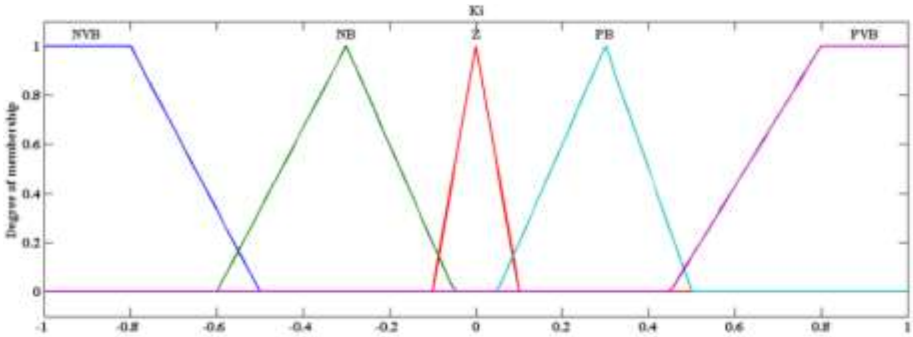

Fig. 12. Output membership function for K_i (voltage regulator).

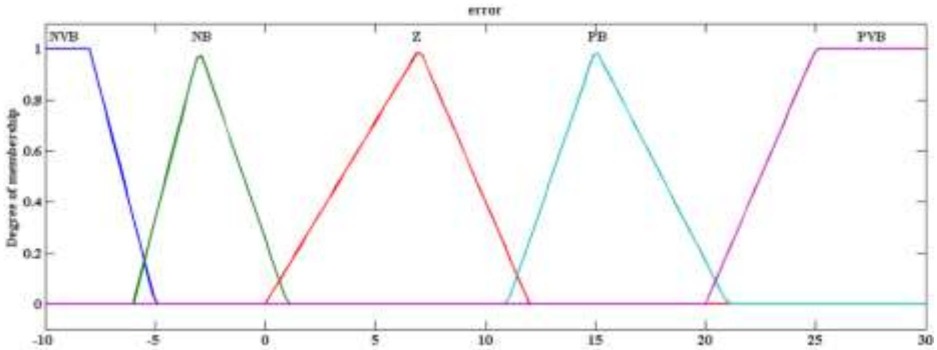

Fig. 13. Input membership function for error (current regulator).

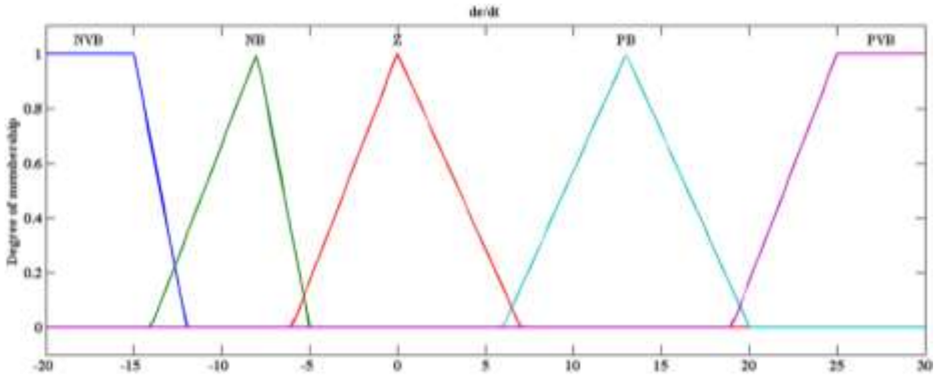

Fig. 14. Input membership function for de/dt (current regulator).

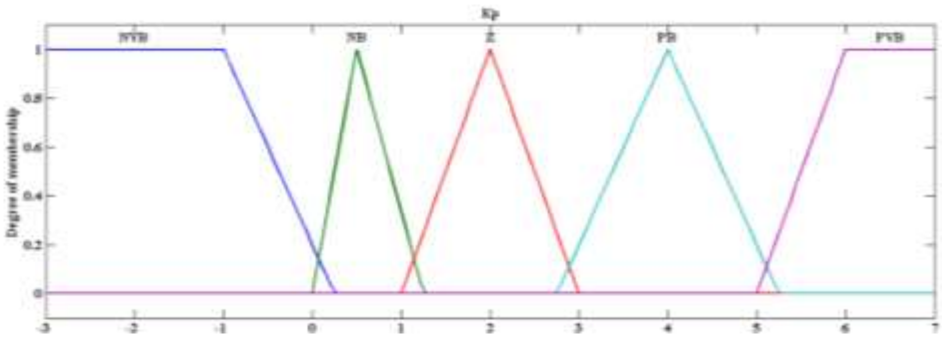

Fig. 15. Output membership function for K_P (current regulator).

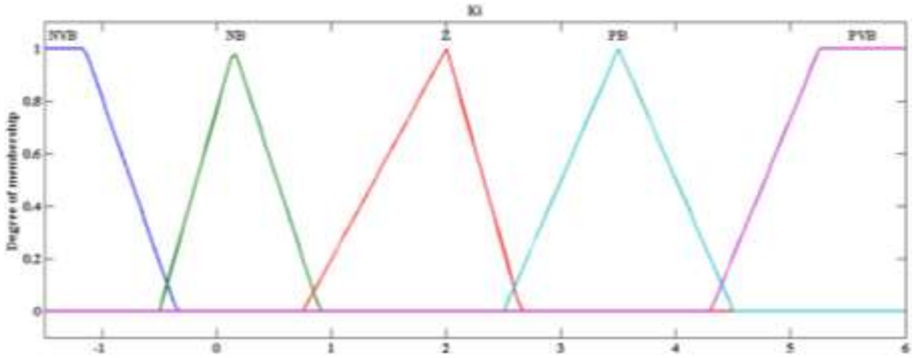

Fig. 16. Output membership function for K_i (current regulator).

Tables 2 and *3* are constructed according to the rules for the Fuzzy-PI controller applied to series compensation in the two-machine system.

Table 2. Rule base for the fuzzy controller based on K_p.

e De/dt	NVB	NB	Z	PB	PVB
NVB	NB	NB	NB	PB	Z
NB	NB	NB	Z	Z	PB
Z	NB	NB	Z	PB	PB
PVB	NB	NB	Z	PB	PB
PB	Z	NB	PB	PB	PB

Table 3. Rule base for the fuzzy controller based on K_i.

e De/dt	NVB	NB	Z	PB	PVB
NVB	Z	NB	NB	NB	Z
NB	Z	NB	NB	Z	Z
Z	Z	Z	Z	PB	Z
PVB	Z	Z	PB	PB	Z
PB	Z	PB	PB	PB	Z

To achieve maximum performance, the fuzzy rules are determined based on experimental results and system simulations. In deriving the rules for Kp and Ki, the following considerations are taken:

I. For large values of e and de/dt, a high gain is required.

II. For very large values of e and de/dt, a set including zero is considered to prevent control saturation, while for small values of e, a large gain is assigned to reduce the steady-state error [20].

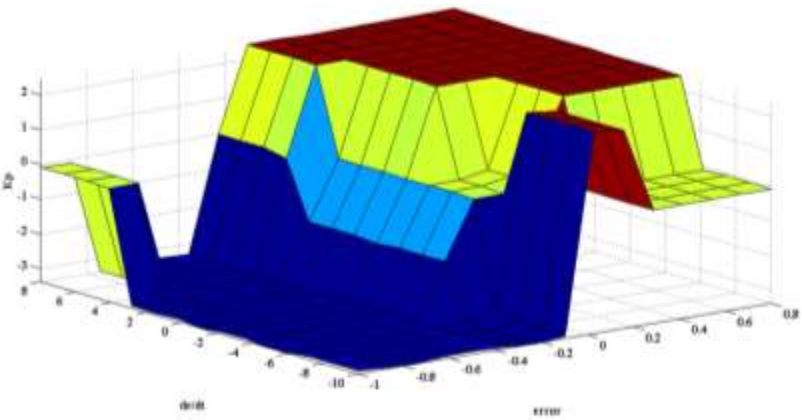

Fig. 17. Fuzzy system for the voltage regulator mode.

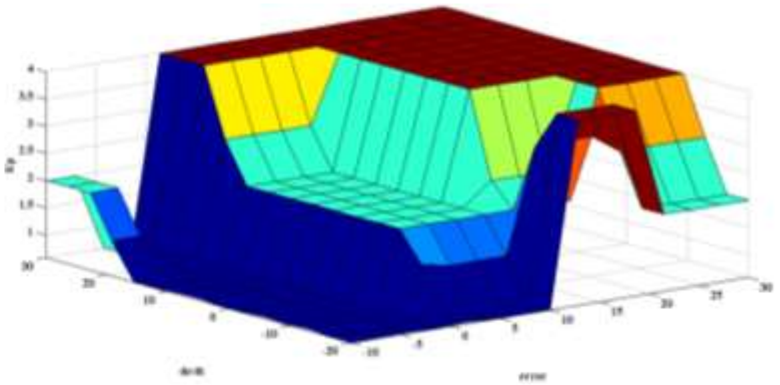

Fig. 18. Fuzzy system for the current regulator mode.

2.3 | Simulation and Data Analysis

In this study, to assess the impact of STATCOM on the performance of distance relays in transmission lines, a 500 kV transmission system was modeled using MATLAB Simulink. The STATCOM was installed at the midpoint of the line to analyze its compensating effects on line voltage and current accurately. Various fault scenarios, including single-, two-, and three-phase faults at different locations along the line, were applied, and the relay's apparent impedance was calculated for each to determine its protective zones. Simulation results indicated that the presence of a STATCOM can affect the reach, tripping time, and distance relay accuracy. Based on the obtained data, new rules for setting protective zones were developed to ensure correct relay operation under various system conditions. The model's validity and the proposed rules were verified by comparing results with reference data and previous studies, demonstrating that this approach can serve as a practical and scientific guide for protecting transmission lines equipped with STATCOM.

2.4 | Test System

A power plant with a 1000 MW generator is connected to a load center via a 500 kV transmission line that is 700 km long. The load center is modeled as a 5000 MW resistive load. This load is supplied by the 1000 MW power plant and a local generation unit of 5000 MW, as shown in *Fig. 18*.

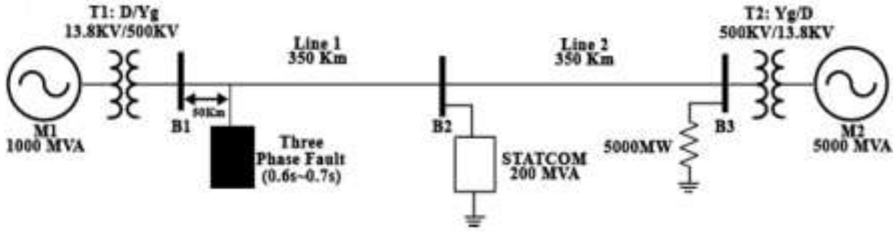

Fig. 19. Single-line diagram of the two-area system.

The load flow in this system is conducted with a generation of 950 MW, resulting in the 1000 MW unit producing 4046 MW. The transmission line carries 944 MW, which is close to the SIL. To maintain system stability after a fault, a 200 MVA STATCOM is connected in parallel at the midpoint of the transmission line. Its placement at the midpoint significantly enhances the system's power transfer capability.

Subsequently, two proposed controllers, the Fuzzy and Fuzzy-PI controllers, are integrated into the system. To evaluate the performance and effectiveness of these controllers in improving STATCOM operation, a three-phase fault is applied between Bus 1 and Bus 2 At a distance of 50 km from Bus 1, the system response is recorded.

The simulation results of this scenario are compared with the system performance without STATCOM and with a conventional PI-based STATCOM to quantitatively and qualitatively assess the impact of the proposed controllers on transient stability and system performance. The models are equipped with STATCOM controllers based on PI, Fuzzy, and Fuzzy-PI, respectively. Machines M1 and M2 represent hydroelectric power plants with 1000 MW and 5000 MW generators, both equipped with hydraulic turbines and governors (HTG), excitation systems, and power system stabilizers. The turbines and regulators of both machines are included in the model, which is interconnected via a 500 kV, 700 km transmission line. A 5000-MW resistive load is connected to the side of machine M2, and a 200-MVA GTO-based STATCOM is installed at the midpoint of the line. The specifications and details of the equipment used in the MATLAB/SIMULINK model are presented comprehensively in *Table 4*.

Table 4. Power system component parameters for the two-machine system.

Parameter	Value	Description
M1	1000 MVA	Hydroelectric generator 1
M2	5000 MVA	Hydroelectric generator 2
V	13.8 kV	Generator voltage
f	60 Hz	System frequency
Xd	1.305 p.u	Synchronous direct-axis reactance
Xd'	0.296 p.u	Transient direct-axis reactance
Xd''	0.252 p.u	Subtransient direct-axis reactance
Xq	0.474 p.u	Quadrature-axis reactance
Xq''	0.243 p.u	Subtransient quadrature-axis reactance
Xl	0.18 p.u	Line reactance
H	3.7 s	Generator inertia constant
T1	1000 MVA	Transformer 1 rating
T2	5000 MVA	Transformer 2 rating
α	13.8 / 500 kV	Transformer turns ratio
Rm = Lm	500 Ω	Equivalent resistance and inductance
R1	0.01755 Ω	Line phase resistance
R0	0.2758 Ω	Line zero-sequence resistance
L1	0.8737 mH	Line phase inductance

Table 4. Continued.

Parameter	Value	Description
L0	3.22 mH	Line zero-sequence inductance
C1	13.33 nF	Shunt capacitor 1
C2	8.297 nF	Shunt capacitor 2
STATCOM	200 MVA	STATCOM rating
V	500 kV	STATCOM voltage
Vref	1 V	STATCOM reference voltage
Ts	20×10^{-6} s	Sampling time
Cp = Cm	5000×10^{-6} nF	Control capacitors

2.5 | System without STATCOM (under Fault Conditions)

By applying a three-phase fault for 0.1 seconds within the time interval of 0.6 to 0.7 s, as shown in *Figs 19* and *20*, the dynamic response of the system without STATCOM diverges toward infinity, indicating system instability. This behavior demonstrates the system's inability to maintain transient stability under severe three-phase fault conditions. Specifically, as illustrated in *Fig. 19*, the rotor angle deviation continuously increases and exhibits a diverging trend, indicating the loss of transient stability. Furthermore, the results in *Fig. 20* show that the load angle exhibits severe, undamped oscillations after the fault and does not return to its initial equilibrium value. Overall, these results confirm that the two-machine system without STATCOM cannot recover its stable operating state and loses synchronism during three-phase faults.

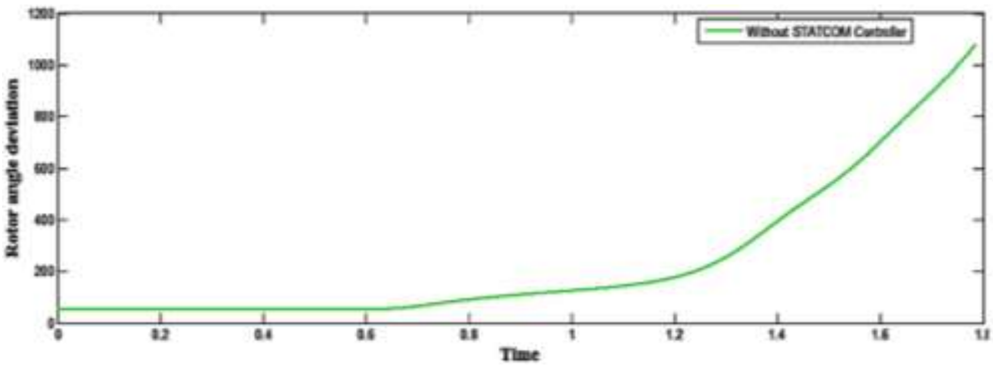

Fig. 20. Rotor angle deviation.

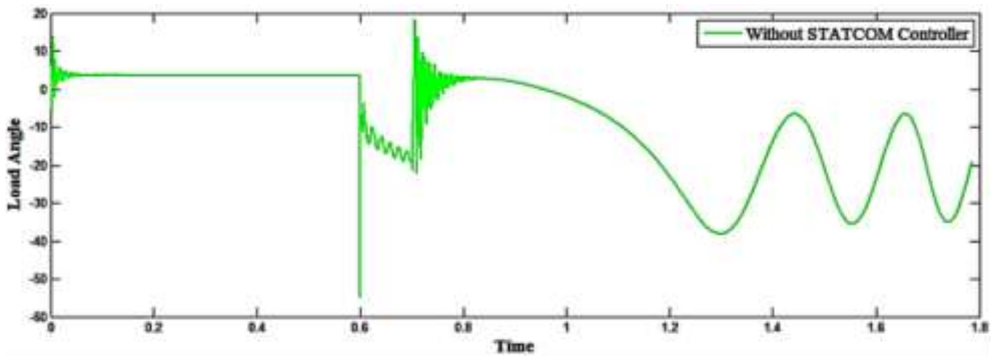

Fig. 21. Load angle.

2.6 | System with PI-Based STATCOM (under Relay Operation)

In the studied system, a PI-based STATCOM was connected to the network, and a 0.1-second fault was applied. As illustrated in *Figs. 21* and *22*, the system returns to a stable state after clearing the fault, demonstrating the PI controller's effectiveness in enhancing transient stability. Moreover, the dynamic responses of various STATCOM parameters during and after the fault are presented in *Figs. 21* to *22*, effectively illustrating the device's control behavior under transient conditions.

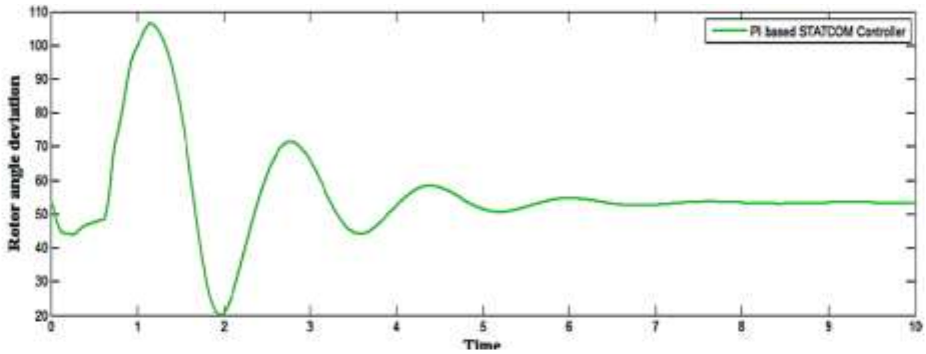

Fig. 22. Rotor angle deviation versus time.

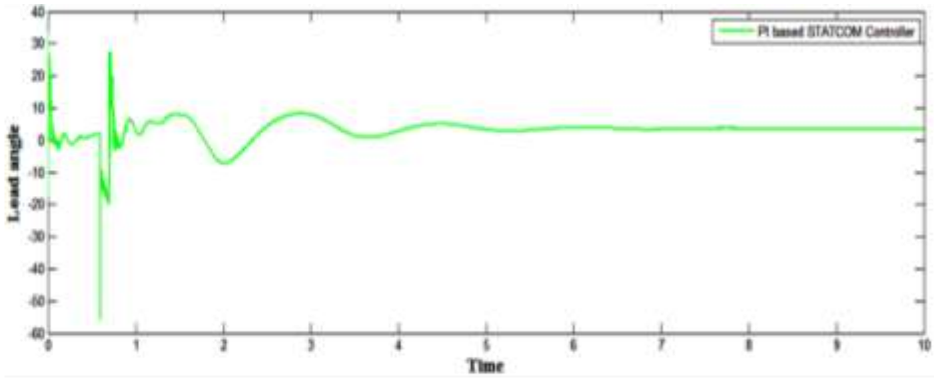

Fig. 23. Load angle versus time.

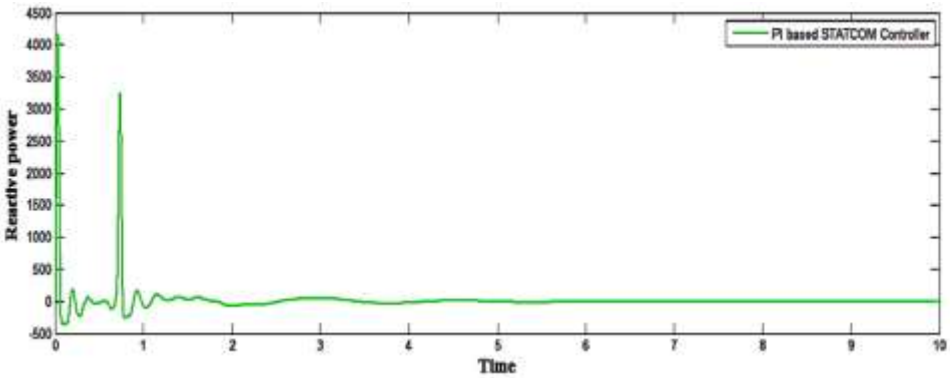

Fig. 24. Reactive power.

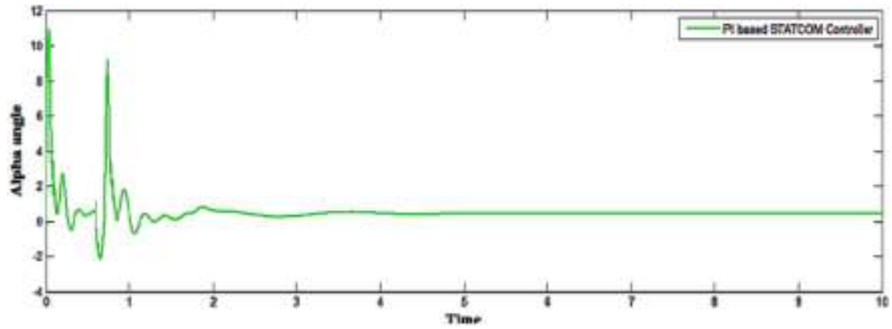

Fig. 25. firing angle α.

2.7 | System with Fuzzy-PI-Based STATCOM (Under Relay Operation)

A Fuzzy-PI-based STATCOM is now installed in the system, and a 0.1-second fault occurs. The system's dynamic responses under fault conditions are presented in the following figures.

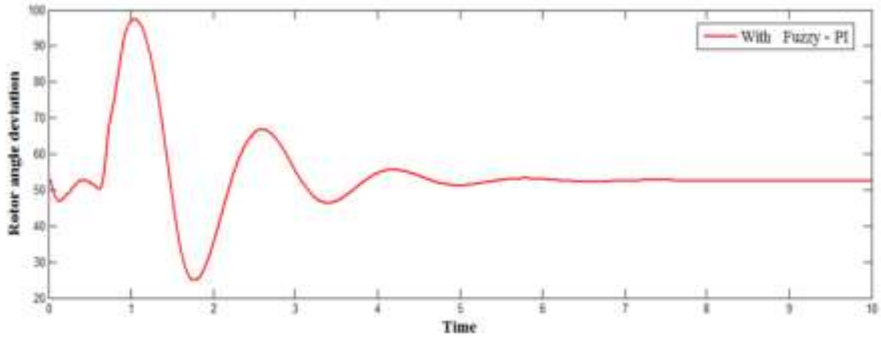

Fig. 26. Rotor angle deviation.

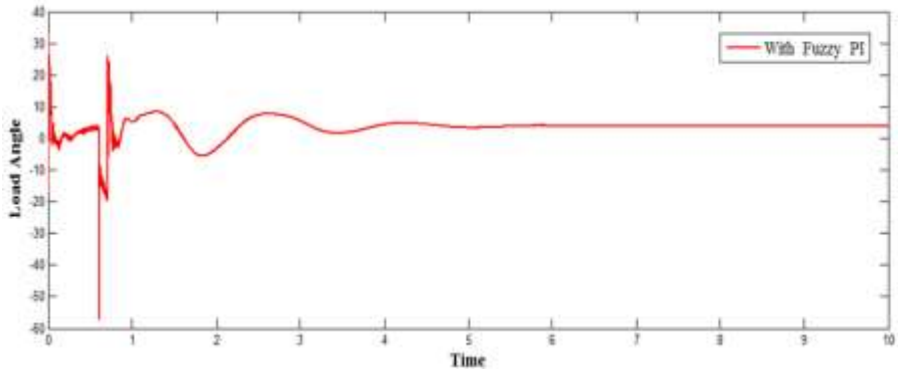

Fig. 27. Load angle.

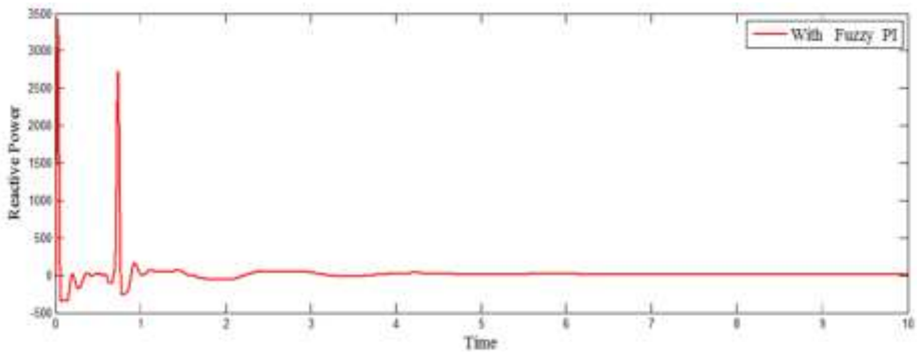

Fig. 28. Reactive power.

2.8 | Comparison between Fuzzy-Based and PI-Based STATCOM Systems (Under Relay Operation)

In the two-machine system equipped with STATCOM, a comparative analysis between PI-based and Fuzzy-PI-based controllers under fault conditions reveals notable differences in transient performance. As shown in *Figs 28 to 30*. For the PI controller, the rotor angle deviation exhibits oscillations that gradually decay toward equilibrium after the fault. In contrast, the load angle undergoes moderate oscillations that require several cycles to stabilize. In contrast, the Fuzzy-PI controller significantly reduces both the amplitude and duration of oscillations in rotor and load angles, enabling the system to return to a stable operating state more rapidly. This enhanced performance is attributed to the adaptive adjustment of the proportional (Kp) and integral (Ki) gains by the fuzzy logic mechanism, which allows the controller to respond more effectively to dynamic variations. Overall, the Fuzzy-PI controller demonstrates superior capability in improving transient stability, minimizing oscillation peaks, and reducing the risk of loss of synchronism compared to the conventional PI controller.

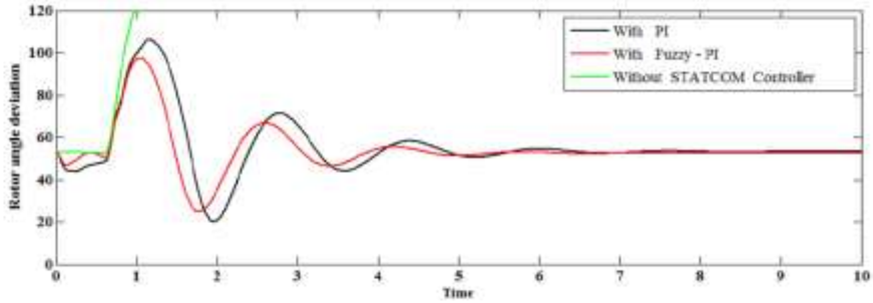

Fig. 29. Rotor angle deviation.

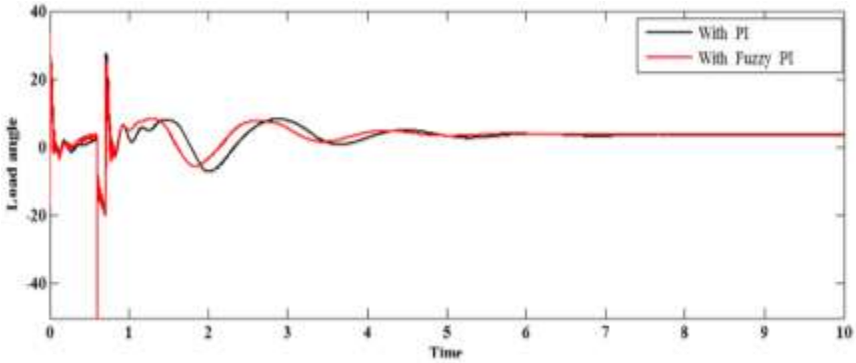

Fig. 30. Load angle.

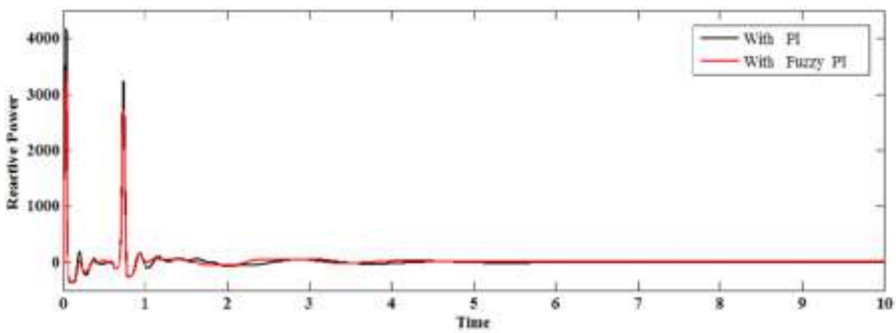

Fig. 31. Reactive power.

3 | Conclusion

In this study, the performance of two intelligent controllers, Fuzzy and Fuzzy-PI, for STATCOM in a two-machine power system was investigated. Simulation results demonstrated that, compared with the conventional PI controller, both proposed controllers significantly enhance transient stability and damping performance. Among them, the Fuzzy-PI controller provided superior dynamic response, ensuring faster recovery and improved system robustness under severe fault conditions. These findings confirm the effectiveness of intelligent control strategies in improving power system stability and reliability.

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