

A comparative simulative study to determine controller schemes of static var compensator (svc) for stability of power system

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Received: 28 February 2025, Revised: 28 June 2025, Accepted: 30 June 2025, Published: 01 July 2025

KEY WORDS

Power System
Static Var Compensator
FACTS
Fuzzy Logic
Proportional Integration (PI)

ABSTRACT

A key challenge in ensuring and maintaining power system stability is the rapid management of power transients. These voltage fluctuations arise from various causes, such as sudden load changes or network faults, which, if not addressed quickly, can lead to cascading failures or even system blackouts. The Static Var Compensator (SVC) is used to mitigate the effects of power transients through the targeted use of Flexible Alternating Current Transmission System (FACTS) devices. The SVC is crucial in dynamic voltage support and reactive power compensation, making it an ideal candidate for stabilizing transient conditions. The research explores the effectiveness of various control strategies, including Proportional Integration (PI) controllers, Fuzzy Logic Controllers (FLCs), and a hybrid PI-FLC approach. The study aims to identify the most efficient scheme for enhancing SVC performance under transient conditions by comparing these control methodologies. These controllers are pivotal in modulating the SVC's reactive power output, determining how swiftly and accurately it can counteract voltage deviations. The insights gained from this investigation can inform the design of more resilient power systems that maintain stability in the face of unpredictable disturbances.

1. Introduction

Power system operation involves the transmission of electrical energy to meet the required demand. Stability in a power system refers to its ability to return to a normal, steady-state condition within the shortest possible time after a transient fault or disturbance [1-3]. This stability is contingent on the post-disturbance behaviour of synchronous machines, making it a significant challenge in power system operation. Increasing electricity demand necessitates new installations, interconnections, or higher-capacity generation units [4, 5]. Power system instability leads to asynchronous oscillations in a three-phase system, adversely affecting its performance [4]. Stability disturbances can arise from load changes, short

circuits, line faults, and switching events [5]. Among these, three-phase faults are the most common and can cause maximum acceleration of connected machines [6, 7]. To address this challenge, early researchers delved into the potential of employing series compensation for transmission lines [8]. In [9], R.E. Marbury et al. introduced the concept of incorporating a series capacitor within the line. The aim was to enhance voltage by interleaving negative reactance. The author in [10] also explores various approaches to implementing series capacitors, providing a comprehensive discussion. To improve the transient stability of a multi-machine system, a Flexible AC Transmission Systems (FACTS) device is proposed [11]. FACTS devices (Static Var Compensators

(SVC), Thyristor Controlled Reactor (TCR), etc.), known for effectively controlling power flow, damping oscillations, and improving the controllability and transfer capability of power networks, contribute significantly to the transient stability of a system [12-14]. SVC works analogously to an impedance in parallel with the load, actively regulating the voltage magnitude at the point of common coupling (PCC) through the absorption or generation of reactive power [15]. SVC incorporates harmonic filters to maintain voltage variations within acceptable limits [16]. A thyristor-controlled reactor (TCR) with capacity adjustments through a dynamic control system is employed for reactive power control [17].

In [18], the utilization of SVC to diminish power system losses is outlined. The findings indicate that implementing reactive power compensation through SVC to determine the optimal reactive capacity substantially reduced power losses by up to 32% in a 330 kV power system. In [19], a method for optimizing power flow to enhance the voltage profile in a power system is introduced, employing SVC. The study designs and analyses SVC topology to enhance the voltage profile [20], mitigate losses, and dampen oscillations. The research demonstrates that effective control of SVC, coupled with injecting reactive power into the network, can enhance the voltage profile and minimize power losses. Based on these studies, an SVC is employed in the current study that would help enhance the transient stability of a power system.

Utilizing SVCs with an additional controller can mitigate fluctuations and enhance overall system stability. In [21], the investigation focused on utilizing an optimal Proportional-Integral (PI) controller design for SVC, employing genetic algorithms. The study explored this approach and provided practical demonstrations of its application. In [22], the enhancement of Single Machine Infinite Bus power system stability is achieved through the optimal design of an SVC. The author specifically employed the SVC to improve the angle stability of a synchronous generator. In [23], the model of an SVC is introduced, and a Proportional Integral Differential (PID) controller is implemented as an auxiliary control mechanism. The primary objective is to enhance power system stability and voltage regulation. In [24], PID and Lead-Lag (LL) controllers are considered, incorporating associated time delays. The study utilizes a differential evolution algorithm to determine the optimal parameters for these controllers, contributing to improving power system stability. Although PI controllers have improved system stability to some extent and their design is simple [25],

their main limitation is that their function is inappropriate when the system's operating conditions are wide-ranging with large disruptions [26-28].

A fuzzy logic approach is another emerging method to address intricate problems in systems characterized by complex natural behaviour [29]. A notable advantage of fuzzy logic control lies in its robustness against system parameter variations and operating conditions changes [30-32]. Fuzzy controllers demonstrate sensitivity to substantial variations in system parameters and nonlinear factors, adapting swiftly to changes. Consequently, fuzzy controllers are proposed to overcome the shortcomings of classical controllers and mathematical analytical methods that lack adequate control mechanisms against alterations in system conditions [33]. An adjustable-gain fuzzy control technique is proposed in [34] to enhance the stability of the five-machine power system. Fuzzy control is applied to the SVC in [10] to mitigate low-frequency oscillations in the three-machine power system and minimize generator rotor speed fluctuations. In [35], fuzzy control is applied to the SVC to manage system attenuation in a two-area, 3-machines power system, specifically focusing on reducing low-frequency oscillations. Similarly, in [36], fuzzy control is employed for the SVC to dampen low-frequency oscillations in a 3-machine power system and alleviate rotor speed oscillations in the generators.

Furthermore, in [37], a Neuro-Fuzzy logic is utilized for the optimal design of the SVC, aiming to mitigate damping in low-frequency oscillations within the context of a two-area, 4-machines power system. Fuzzy logic controllers are proficient in managing uncertainties and variations; however, their effectiveness may be limited when precision and responsiveness are crucial in dynamic systems [38]. Additionally, these controllers might encounter difficulties ensuring system stability, particularly in scenarios marked by large disturbances [39]. These issues can be addressed by combining fuzzy and classical controllers, which allows enhanced tuning and adjustment and improves precision in controlling systems with dynamic behaviour [40, 41].

This study emphasizes the consideration of transient stability, which plays a crucial role in maintaining and synchronizing the acceleration of a machine when subjected to transient disturbances. A hybrid PI-Fuzzy-based control strategy is proposed for a three-bus system with an SVC in the middle of the transmission line. System performance evaluation is done by observing the rotor angle and fault current by generating a single phase to ground fault. To verify the

effectiveness of the proposed control strategy, the system is tested at 20% loading, 40% loading, and also for the worst-case scenario, i.e., 100% loading condition, and the proposed control strategy is compared with PI controller and Fuzzy controllers under these loading conditions. Moreover, sensitivity analysis is carried out to check the robustness of each controller. The MATLAB Simulink results have validated that the proposed control strategy can ensure a fast transient response with minimum overshoot/undershoot for rotor angle and load current compared to other controllers.

2. Methodology

This study focuses on a power system represented in the block diagram shown in Fig 1. The detailed system as shown in Fig 2, comprises two synchronous machines connected to a turbine and a regulator that manages the generated power. Machine 1 has a capacity of 1000 MVA, while Machine 2 has a capacity of 5000 MVA. The system operates as a three-bus configuration, with a Static VAR Compensator (SVC) positioned in the middle of the transmission line to ensure stability. Additionally, two step-up transformers with identical parameters are incorporated into the power system.

A single line-to-ground fault is simulated using the fault block depicted in the schematic diagram to investigate stability issues. Various controllers are tested in the SVC block, starting with conventional controllers such as Proportional-Integral (PI) controllers. These traditional controllers—namely Proportional (P), Integral (I), Proportional-Integral (PI), Proportional-Derivative (PD), and Proportional-Integral-Derivative (PID)—are popular in industries and power systems due to their simple design and ease of implementation.

A meter measures various parameters, including deviations in rotor angle, output power, and voltages of the respective machines and the line and voltages at all three buses. The implemented MATLAB Simulink model is illustrated in Fig 2. Initially, the load is resistive (R), and the fault is introduced for one second, specifically between $t = 5$ and 5.1 s, by configuring the fault block accordingly. The proportional and integral gains for the PI controller are tuned to achieve the desired outcomes.

With advancements in control techniques, artificial neural networks have become increasingly significant for enhancing stability in power systems, especially in terms of minimizing response time. In this study, an intelligent controller based on fuzzy logic is implemented with the SVC to restore stability quickly

following a fault. The system is subjected to the same type of fault for the same duration as the *PI* controller, and various performance evaluation parameters are recorded.

Researchers are exploring hybrid or cascaded controllers, such as PI-PD and PID-fuzzy controllers, recognizing that each controller has its strengths and weaknesses. We tested the system with a hybrid PI-fuzzy controller to assess the simultaneous performance of the two controllers. The results obtained with this controller were the most favourable. A comprehensive analysis was conducted to measure and compare several parameters, along with a sensitivity analysis to evaluate the robustness of each controller. Subsequently, the results from the different controllers were compared.

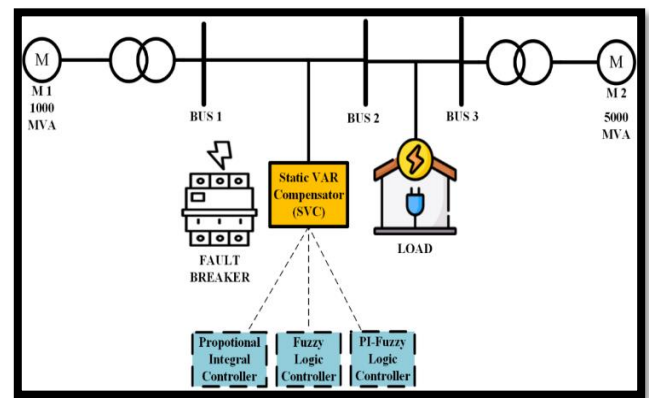


Fig. 1. Block Diagram of power system with SVC

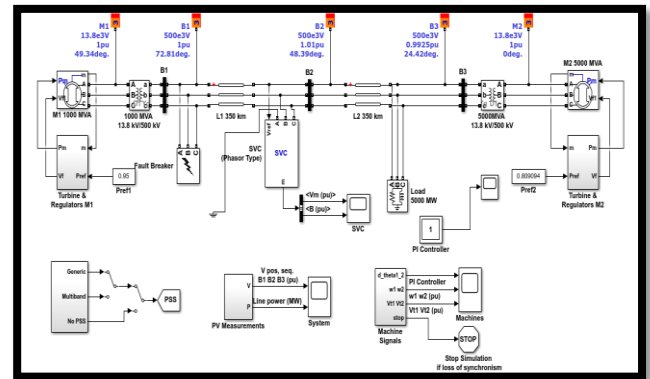


Fig. 2. MATLAB Simulink model for simulation

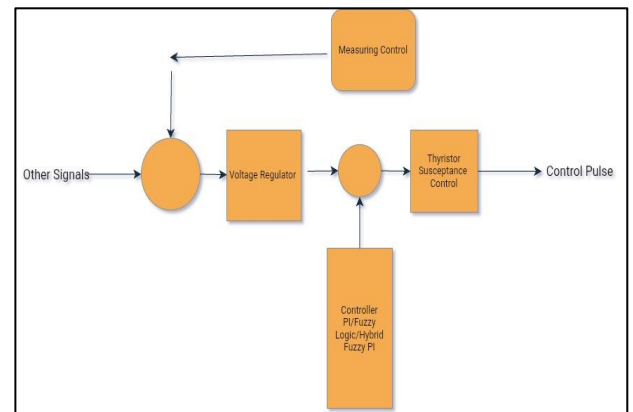


Fig. 3. Block Diagram of SVC with Control Schemes

3. Results and Discussion

Various parameters such as line voltage at $B1$, $B2$, $B3$, line power, rotor angle, and load current are noted for the system by generating the fault at a time instant of 5 s. The simulation is run for 30 s so that we can observe the time the controller takes to stabilize the output. The fault duration is one second. The system is tested at 20% loading, 40% loading, and the worst-case scenario, i.e., 100% loading condition.

At first, the change in bus voltages represented per unit (p.u.) and change in line power in MW is observed when the fault is generated. The results are shown in Fig. 4. It can be seen from the results that during the fault, the voltage undershoots to a value of 0.5 p.u. and then overshoots to 1.255 p.u. from a nominal value of 1 p.u. The behaviour of line power is observed (Fig. 4) in transient state power undershoots to 450 MW and then overshoots to 1450 MW from a nominal value of around 800 to 1000 MW.

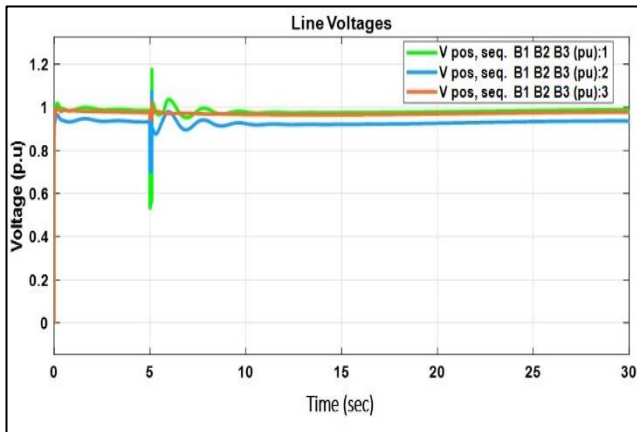


Fig. 4. Bus voltages concerning time results

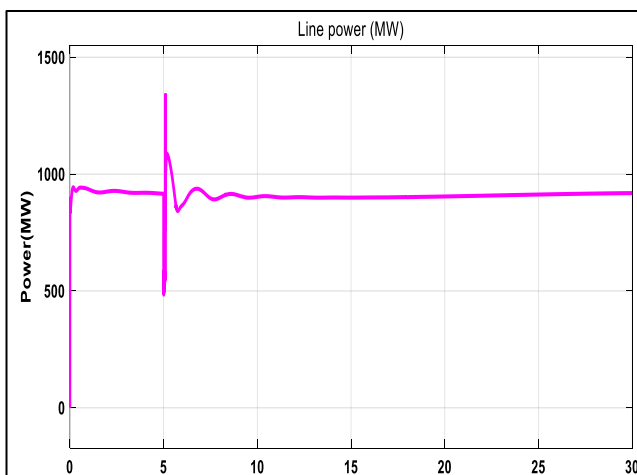


Fig. 5. Line power results

3.1 Results with 20% Loading using PI

The system's response is evaluated by implementing a Proportional-Integral (PI) controller within the static var Compensator (SVC). The efficacy of this

controller is assessed during fault conditions by monitoring two pivotal parameters: the rotor angle and the load current. The results of this analysis are depicted in Fig. 6(a) and 6(b) under a loading condition of 20%.

In normal operating circumstances, the rotor angle is maintained at a stable value of approximately 10° . However, upon the occurrence of a fault, there is an immediate and significant increase in the rotor angle, which surges to 57° . This deviation is concerning, as prolonged exposure to such an elevated rotor angle may lead to substantial system damage. A drop to -20.01° is observed, which could precipitate a complete system shutdown. Fortunately, implementing the PI controller ensures a rapid recovery, restoring steady-state operation within 14 s.

Fig. 6(b) further illustrates the dynamic behaviour of the load current. Initially, the load current peaks at 5,200 A and stabilizes at a steady-state value of 2,000 A, achieving this equilibrium in a noteworthy time frame of 12 s. This swift recovery highlights the effectiveness of the PI controller in managing the system's response during critical fault conditions. As previously outlined, the system's response is evaluated by implementing a Proportional-Integral controller within the static var Compensator. The efficacy of this controller is assessed during fault conditions by monitoring two pivotal parameters: the rotor angle and the load current. The results of this analysis are depicted in Fig. 6(a) and 6(b) under a loading condition of 20%.

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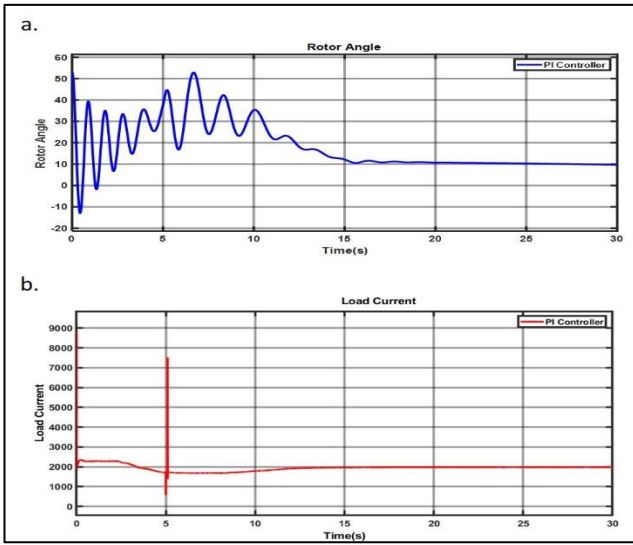


Fig. 6. (a) Rotor angle at 20% load condition using PI; (b) Rotor angle & Load current I at 20% load condition using PI

3.2 Results with 40 per cent Loading using PI

Now, the load is altered 40% from its nominal value, and the system is observed under fault conditions from 5-5.1 s. The results are shown in Fig. 7. The maximum overshoot of the rotor angle is 52.5° , and at that time, the value of the current is 4812 A, the maximum undershoot of the rotor is -05.03° , and the load current is 3165 A. The steady-state time of the rotor is 13 s, and the steady-state time of current is 8.75 s. The angle where the rotor comes to a steady state is 30.2° , and the value where the current is at a steady state is 4002 A. It can be seen from the results that PI, being the conventional controller, still causes the system to reach a stable value.

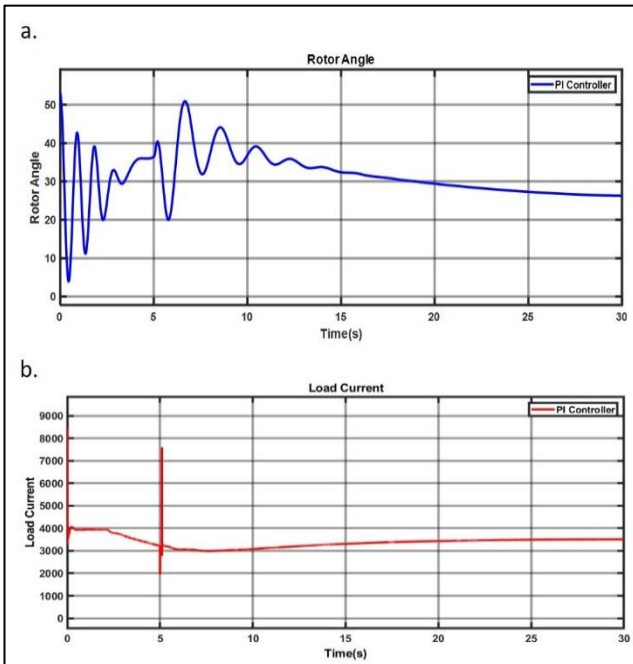


Fig. 7. (a) Rotor angle at 40% load condition using PI; (b) Load current at 40% load condition using PI

3.3 Results with 70% Loading using PI

Fig. 8 shows the rotor angle and load current concerning time (s) at fault condition from 5-5.1 when the load is 70% of its nominal value. Using the PI controller, the steady state for the rotor angle is reached within 16 s, and the steady state value of the current is reached after 25 s. Maximum overshoot in the rotor angle is observed to be 52.3° , and at that time from Fig. 8(b), the value of current reaches 8006 A, the maximum undershoot of rotor angle is 18.05° , and the load current at that instant is 6232 A.

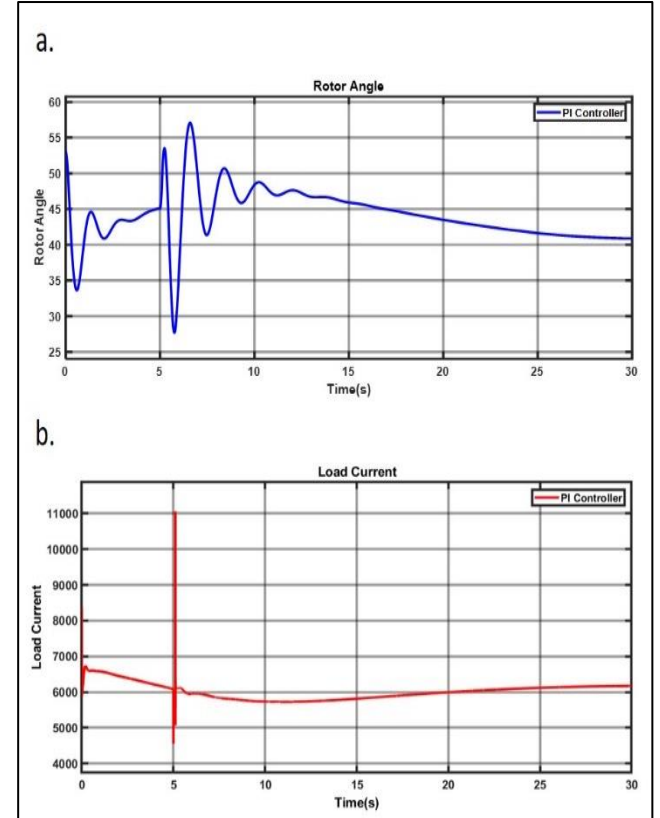


Fig. 8. (a) Rotor angle at 70% load condition using PI; (b) Rotor angle & Load current at 70% load condition using PI

3.4 Results with 100% Loading using PI

Now, the load is altered 100% from its nominal value, which is considered a worst-case scenario. The system is again observed under fault conditions from 5-5.1 s. The results are shown in Fig. 9(a) and 9(b). The maximum overshoot of the rotor angle is 78.2° , and at that time, the current value is 10282 A, the maximum undershoot of the rotor is 21.02° , and the load current is 9038 A. The steady-state time of the rotor is 13.5 s, and the steady-state time of the current is 25.2 s. The angle where the rotor comes to a steady state is 52.55° , and the value where the load current is at a steady state is 9386 A (Fig. 8(b)).

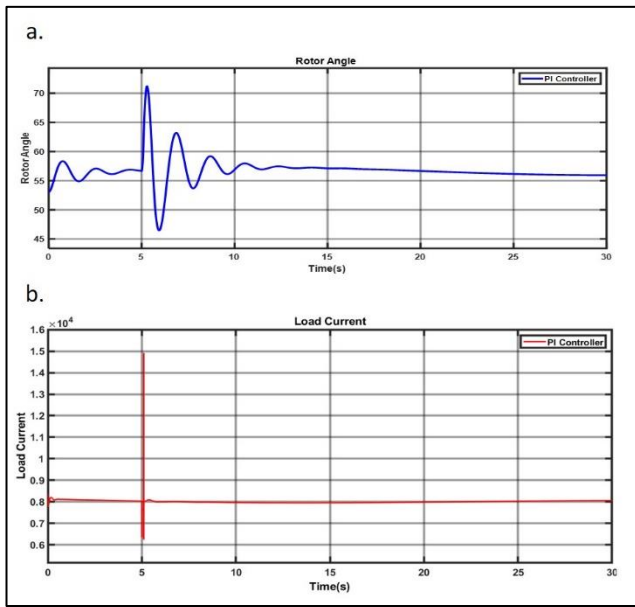


Fig. 9. (a) Rotor angle at 100% load condition using PI3
Load current at 100% load condition using PI

3.5 Results with 20% Loading using FLC

The SIMULINK model planned in the previous chapter is simulated under fault conditions, and a 1-phase to an earth fault is created in the system. The results when the loading was 20% of the full load are shown in Fig. 10(a) and (b). It can be seen that the maximum overshoot of the rotor angle is 53° , and at that time, the value of the current is 2002 A. The maximum undershoot at the rotor angle is -11.05° , and it is 1428 A for load current. The steady state for the rotor angle is reached in 18.8 s, and the steady-state time for the load current is 13.2 s. At a steady state, the rotor angle becomes 9.2° , and the steady-state value of current is 1500 A, as shown in Figure 10 (b).

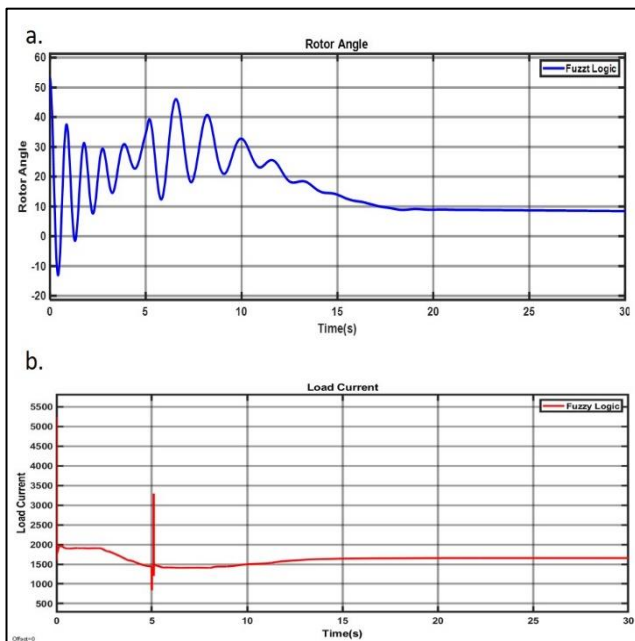


Fig. 10 (a) Rotor angle at 20% loading using FLC; **(b)** Load current at 20% loading using FLC.

3.6 Results with 40% loading using FLC

Now, the load is altered by 40% from its nominal value, and the system is observed under fault conditions from 5-5.1 s in Figure 11. The maximum overshoot of the rotor angle is 53.5° , and at that time, the value of the current is 3917 A, the maximum undershoot of the rotor angle is 04.02° , and the load current is 2906 A. The steady-state time of the rotor is 22.3 s, and the steady-state time of the current is 9.98 s. The angle where the rotor comes to a steady state is 27.2° , and the value where the current is at a steady state is 3306 A in Fig. 11(b).

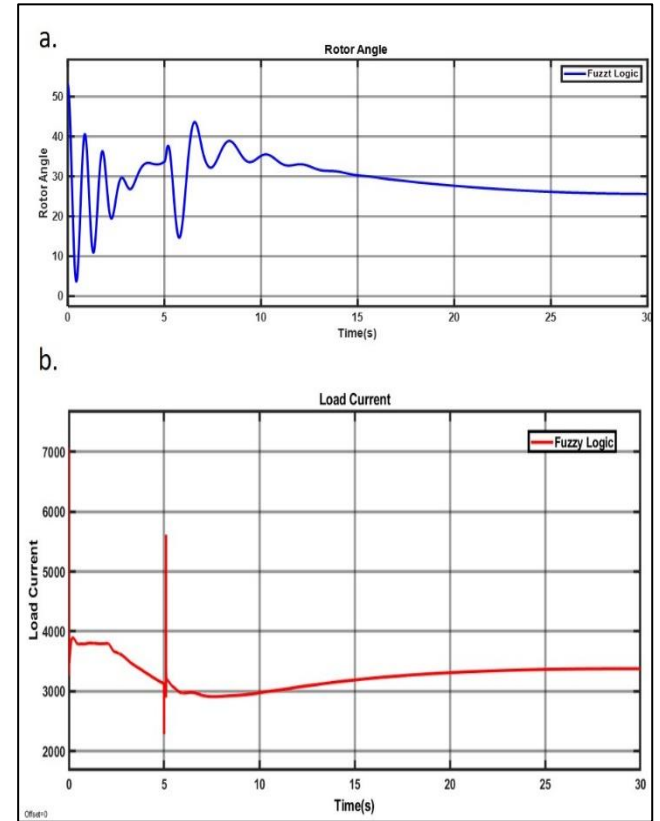


Fig. 1.1 (a) Rotor angle at 40% loading using FLC;
(b) Load current at 40% loading using FLC.

3.7 Results with 70% Loading using FLC

Figures 12(a) and (b) show the rotor angle and load current concerning time (sec) at fault condition from 5-5.1 when the load is 70% of its nominal value. Using the FLC controller, the steady state for the rotor angle is reached within 20.2 s, and the steady state value of the current is reached after 22.5 s. The maximum overshoot in the rotor angle is 53.08° ; at that time, the current value reaches 6409 A. The maximum undershoot of the rotor angle is 28.73° , and the load current at that instant is 5407 A. Fig. 12(a) and 12(b) show steady-state values of rotor angle and load current are 20.2° and 22.5 A, respectively.

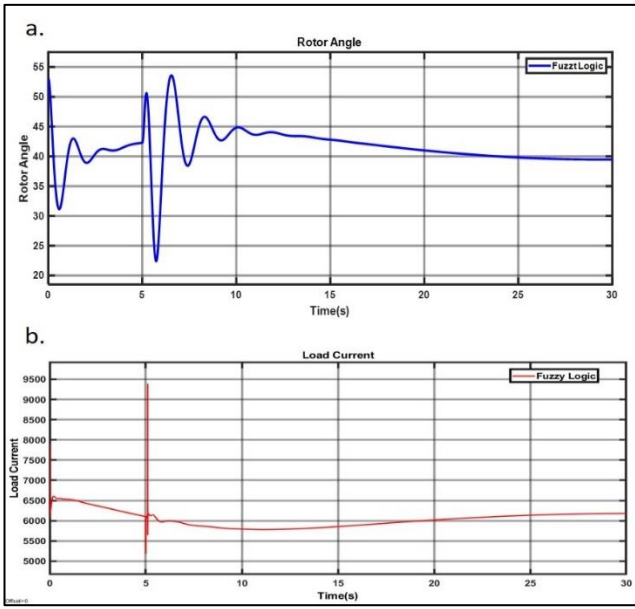


Fig. 12. (a) Rotor angle at 70% loading using FLC; **(b)** Load current at 70% loading using FLC

3.8 Results with 100% Loading using FLC

Now, the load is altered 100% from its nominal value, which is considered a worst-case scenario. The system is again observed under fault conditions from 5-5.1 s. Fig. 13(a) and 13(b) show the maximum overshoot of the rotor angle is 67.00° , and at that time, the value of current is 8168 A, the maximum undershoot of the rotor is 36.0° , and the load current is 7257 A. The steady-state time of the rotor is 13.8 s, and the steady-state time of the current is 08.07 s. The angle where the rotor comes to a steady state is 53.5° , and the value where the load current at a steady state is 8000 A, as in Fig. 13(a) and 13(b).

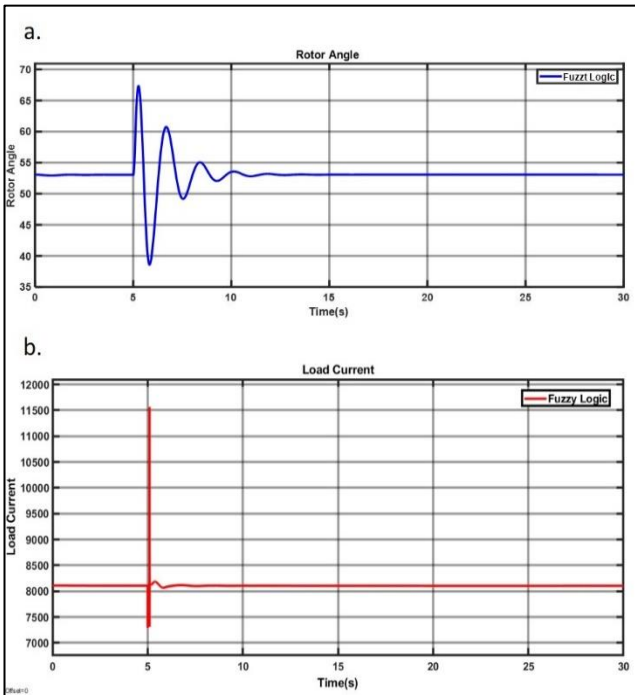


Fig. 13. (a) Rotor angle at 100% loading using FLC; **(b)** Load current at 100% loading using FLC.

3.9 Results with 20% loading using Hybrid PI- FLC

As mentioned earlier, cascaded controllers provide better results in every aspect, so a hybrid PI-Fuzzy Logic Controller is created in this study to take advantage of the benefits of both intelligent and classical control methods. Under typical circumstances, the PI controller guarantees quick reaction and simple implementation, while the fuzzy logic controller improves the system's flexibility in dealing with of nonlinearities and changes in parameters. The fuzzy controller dynamically adjusts the control action based on error and error change, while the PI controller controls the overall error correction in this cascaded implementation of the hybrid controller. System performance is evaluated by observing the rotor angle and fault current generated by generating a single-phase to-ground fault by implementing the PI-FUZZY controller in SVC.

Results in Fig. 14(a) and 14(b) are obtained for the 20% loading condition. It can be seen that during normal operation, the rotor angle is around 10° . A significant change in rotor angle is observed as soon as the fault occurs. It overshoots to a value of 53.2° . If this situation persists for longer, it can damage the system. Moreover, the value also collapses -13.00° which can cause a complete shutdown. Because of the presence of the PI-FUZZY controller, the steady state is recovered within 21.5 s. Similarly, the load current has been raised to a value of 1962 A and also dropped to a value of 1432 A, but due to controller action, it reaches a steady state value of 1600 A in 12.5 s (as in Fig. 14(b)).

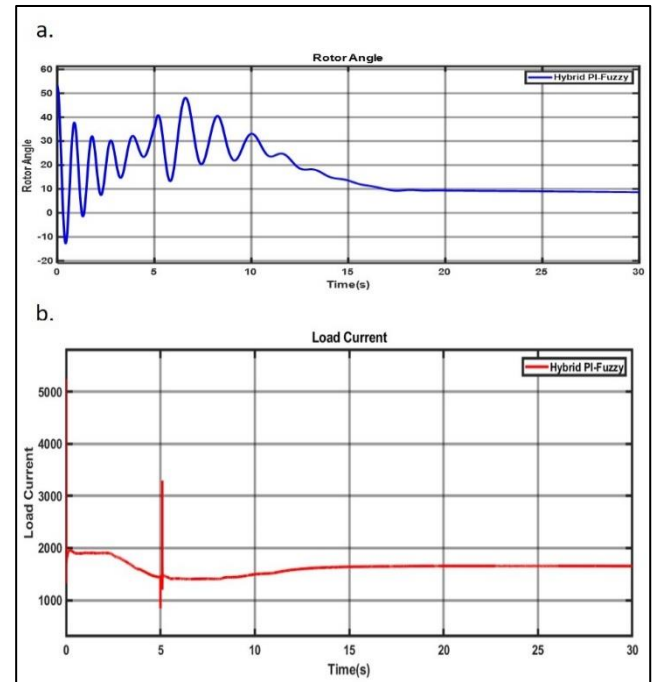


Fig. 14. (a) Rotor angle at 20% load condition using hybrid PI- FLC; **(b)** Load current at 20% load condition using hybrid PI- FLC

3.10 Results with 40% loading using Hybrid PI- FLC

Now, the load is altered 40% from its nominal value, and the system is observed under fault conditions from 5-5.1 s. As shown in Fig. 15(a) and 15(b), the maximum overshoot of the rotor angle is 52.6° , and at that time, the value of current is 3090 A, the maximum undershoot of the rotor is 1.05° , and the load current is 1432 A. The steady-state time of the rotor is 20 s, and the steady-state time of the current is 19.5 s. In Fig. 14(a), the angle where the rotor comes to a steady state is 30.4° , and the value where the current at a steady state is 3287 A.

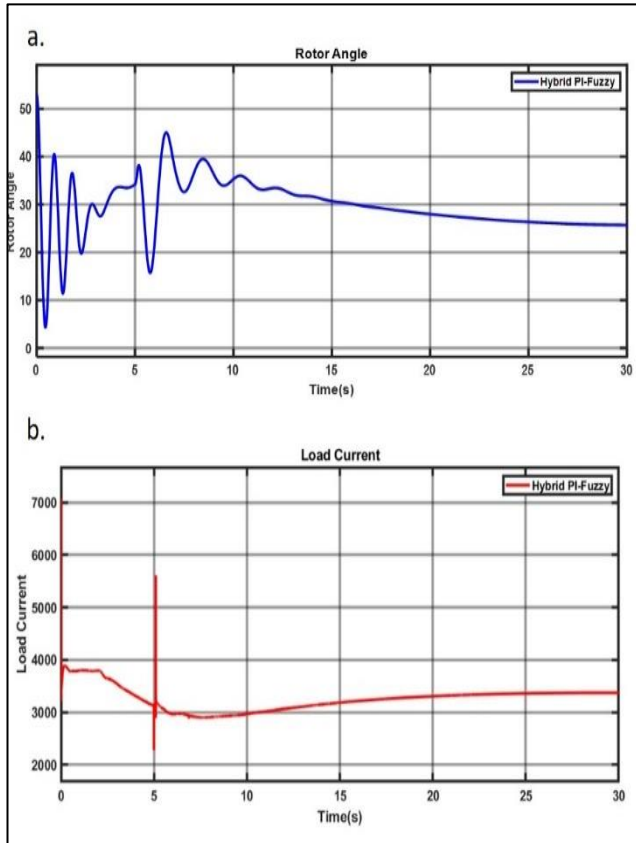


Fig. 15. (a) Rotor angle at 40% load condition using hybrid PI- FLC; **(b)** Load current at 40% load condition using hybrid PI- FLC

3.11 Results with 70% loading using Hybrid PI- FLC

Fig. 16(a) and 16(b) show the rotor angle and load current concerning time (s) at fault condition from 5-5.1 when the load is 70% of its nominal value. Using the FLC controller, the steady state for the rotor angle is reached within 20.7 s, and the steady state value of the current is reached after 9.5 s. The maximum overshoot in the rotor angle is 52.0° ; at that time, the current value reaches 6253 A. The maximum undershoot of the rotor angle is 19.07° , and the load current at that instant is 4878 A. The steady-state values of rotor angle and load current are 38.4° and 5720 A, respectively, as shown in Fig. 16(b).

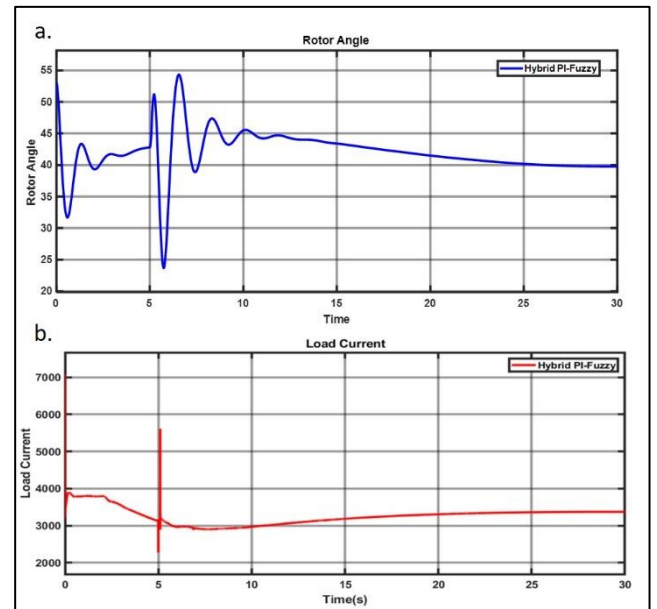


Fig. 16. (a) Rotor angle at 70% load condition using hybrid PI- FLC; **(b)** Load current at 70% load condition using hybrid PI- FLC

3.12 Results with 100% loading using Hybrid PI- FLC

Now, the load is altered 100% from its nominal value, which is considered a worst-case scenario. The system is again observed under fault conditions from 5-5.1 s. The results are shown in Fig. 17(a) and 17(b). The maximum overshoot of the rotor angle is 67.8° , and at that time, the value of the current is 8180 A, the maximum undershoot of the rotor is 37.07° , and the load current is 7248 A. The steady-state time of the rotor is 9.5 s, and the steady-state time of the current is 6.3 s. The angle where the rotor comes to a steady state is 52.2° , and from Fig. 17(b), the value where load current at a steady state is 8120 A.

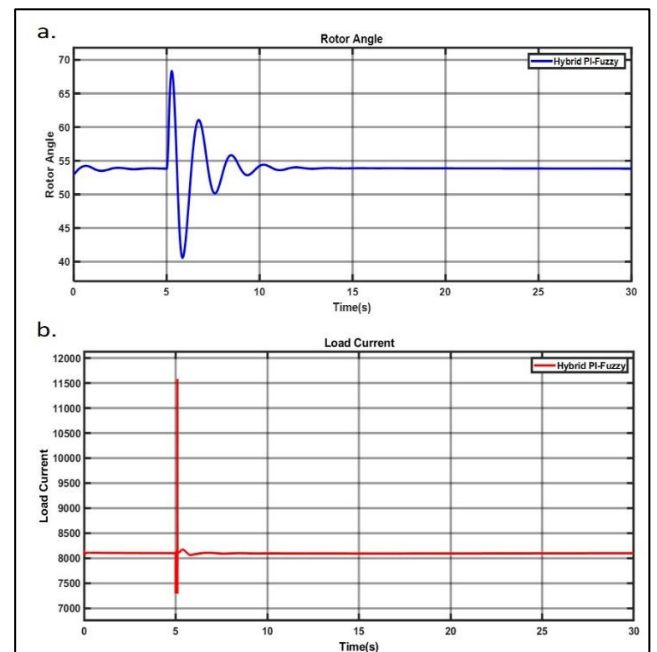


Fig. 17. (a) Rotor angle at 100% load condition using hybrid PI- FLC; **(b)** Load current at 100% load condition using hybrid PI- FLC

4. Conclusion

The stability of the power grid is a crucial parameter for the distribution of sustainable Energy. This study helps in determining different controllers for SVC to increase stability. Three controllers were simulated, including PI, Fuzzy Logic, and a combination of PI and Fuzzy logic. Bus-bar system was simulated on multiple loading conditions to test the performances of these controllers. The PI controller gave the rotor angle of 30° with a load current of 4000 A. This rotor angle for the fuzzy logic controller was 27°, and the load current decreased to 3306A. Similarly, using a combination of PI-Fuzzy controllers, this rotor angle was 30 by dropping load current to 3200 A.

With the increase in loading to 70%, the PI controller showed a rotor angle of 38° and a load current of 6854 A. For the Fuzzy controller and PI-Fuzzy controller, the rotor angle was 39° and 37°, while the load current was 5782 A and 5700 A, respectively. A similar trend was observed with 100% loading, showing the PI-Fuzzy controller with the lowest load current of 8000, while the PI and Fuzzy controllers resulted in higher currents of 9389 A and 8100 A, respectively.

From the results of PI and FLC, we concluded that the performance of an FLC is better than the PI; however, it is expensive practically, but here, our main emphasis is system stability as FLC takes less time to achieve stability than the PI and has negligible oscillations. Moreover, the load current decreases significantly using FLC, which is the main factor in achieving stability. However, the hybrid combination of Fuzzy Logic and PI controller showed the best results. As the steady-state time for the results of rotor angle and load, the current is 9.5 s and 6.3 s, respectively, for the PI-Fuzzy Hybrid controller when subjected to 100% loading. In contrast, for the same scenario when the PI controller is employed, the steady-state time is 13.5 s for rotor angle results and 25.2 s for load current and for the fuzzy controller, the steady-state time was 13.8 s and 8.7 s for rotor angle and load current respectively which is still very high as compare to PI-Fuzzy hybrid controller. A comparison Tables 1 & 2 are given below which include the key performance metrics of implemented controllers under 100% loading condition. So, by comparing all these three controllers under observation and considering several factors, it is concluded that Fuzzy Logic showed better results than the PI controller. At the same time, a combination of PI and fuzzy logic ended up better among all controllers for stability in all respects.

Table 1

Performance Comparison of Rotor Angle at 100% of Loading

Parameters	Rotor Angle		
	PI	Fuzzy	Hybrid
	Control	Logic	Fuzzy PI
		Control	Control
Maximum Overshoot	78.2°	67°	67.82°
Maximum Undershoot	21.2°	36°	37.7°
Steady State Time(s)	13.5	13.8	9.5
Steady State Value	52.55°	53.5°	52.2°

Table 2

Performance Comparison of Load Current at 100% Loading

Parameters	Load Current		
	PI	Fuzzy	Hybrid
	Control	Logic	Fuzzy PI
		Control	Control
Maximum Overshoot	10282 A	8168 A	8180 A
Maximum Undershoot	9038.2 A	7257 A	7248 A
Steady State Time(s)	25.2	8.7	6.3
Steady State Value	9386 A	8000 A	8120A

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