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Adaptive Fuzzy Logic Control of SVC for Enhanced Transient Stability in Multi-Machine Power Systems

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***Abstract*—This paper focuses on enhancing power system transient stability using a Static VAR Compensator (SVC) controlled by an Adaptive Fuzzy Logic Controller (AFLC). The SVC provides dynamic reactive power support to regulate voltage during disturbances such as faults and load changes. The fuzzy logic controller improves system performance by handling nonlinearities and uncertainties without requiring an exact mathematical model. Simulation results in MATLAB/Simulink show that the proposed AFLC-based SVC effectively reduces voltage fluctuations, minimizes oscillations, and improves overall system stability compared to conventional methods.**

***Index Terms*—Adaptive fuzzy logic control, Static VAR compensator (SVC), transient stability, multi-machine power systems, Flexible AC Transmission Systems (FACTS).**

I. Introduction

The escalating intricacy and demands imposed on contemporary power systems, in conjunction with the incorporation of renewable energy sources and nonlinear loads, have rendered system stability an imperative consideration for the dependable operation of these systems. Among the numerous concerns regarding stability, transient stability—the power system's capability to uphold synchronism following considerable disturbances such as faults, rapid load fluctuations, or generator breakdowns—continues to be one of the most daunting challenges in multi-machine power systems. The inability to maintain transient stability can precipitate cascading failures and extensive blackouts, highlighting the need for resilient and adaptive control methodologies [1].

Flexible AC Transmission Systems (FACTS) devices have emerged as effective tools to improve the stability and controllability of the power system. Among these, the Static VAR Compensator (SVC) plays a significant role in regulating reactive power, improving voltage profiles, and damping power oscillations. By dynamically controlling susceptance, SVC can effectively support system stability under disturbed conditions and influence multiple generators when optimally placed in a multi-machine network. [2]

Conventionally, SVCs are controlled using linear controllers such as proportional–integral (PI) regulators. However, due to the highly nonlinear, time-varying, and uncertain nature of power systems, these controllers often fail to provide satisfactory performance under severe disturbances. To overcome these limitations, intelligent control techniques such as fuzzy logic controllers (FLCs) have been widely explored. FLCs offer advantages such as robustness, model-free design, and the ability to handle system nonlinearities effectively. [3]

Subsequently, researchers introduced fuzzy logic-based control strategies for SVC. For instance, studies have shown that fuzzy logic controllers using inputs such as generator speed deviation and power variations can effectively regulate reactive power and improve transient stability in both single-machine infinite bus (SMIB) and multi-machine systems. These approaches demonstrated superior robustness compared to fixed-parameter controllers. [4]

The research showed that SVC operations with fuzzy control create better damping results while decreasing fault-related oscillations. The comparison showed that fuzzy-controlled SVC systems achieved better performance results than traditional PI controllers in maintaining rotor angle stability and controlling terminal voltage and damping active power oscillations.

The development of adaptive fuzzy control strategies for multi-machine systems needs to progress because current methods fail to handle both system disturbances and non-linear behavior. The research gap gets filled through this study which presents an adaptive fuzzy logic-based SVC controller that improves transient stability in complex power networks.

II. Design of SVC based Adaptive Fuzzy Logic Controller

A. Fuzzy Logic Controller for SVC

Fuzzy logic enables scientists to create formal systems which express all uncertainties that arise from their complete global understanding of a complex nonlinear system. The method needs to follow three essential stages which include fuzzification and inference rule development and defuzzification [5]. The Mamdani type is employed in this work, and

the main objective is to place an adaptive FLC in the SVC to enhance the transient stability.

The FLC input variables were selected from the error and its change signals which measured the difference between the reference voltage and the actual voltage. The fuzzy circuit uses the susceptance (B) signal as its output signal. The fuzzification of the inputs membership functions of the error and change in error are shown in Figures 1 and 2.

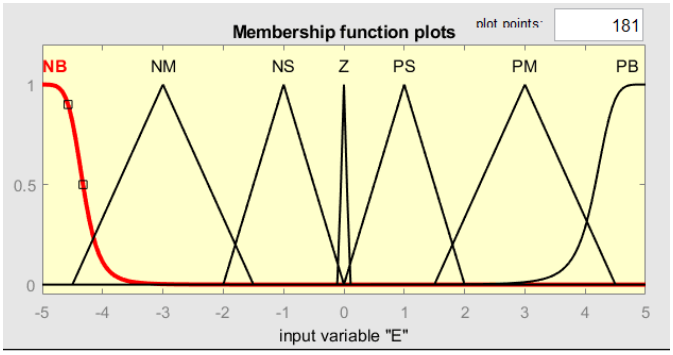


Fig. 1. Input membership function of the error

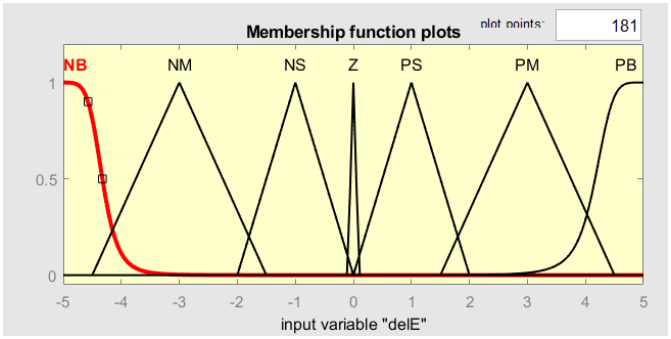


Fig. 2. Input membership function of the change in error

The fuzzy rules are defined through simulation and real world experience to improve system performance. Mamdani's fuzzy inference approach, proposed with forty-nine rules, was used in this processing stage. The table in Table 1 presents the rule set through its tabular format, while Figure 3 shows the output membership function for susceptance B.

TABLE I
FUZZY LOGIC RULE BASE FOR SVC CONTROL

E \ ΔE	NB	NM	NS	Z	PS	PM	PB
NB	PB	PM	PS	Z	NS	NS	NS
NM	PM	PM	PS	Z	NS	NS	NS
NS	PS	PS	PS	Z	Z	Z	Z
Z	Z	Z	Z	Z	Z	Z	Z
PS	Z	Z	Z	Z	NS	NS	NS
PM	PS	PS	PS	Z	NS	NM	NM
PB	PS	PS	PS	Z	NS	NM	NB

The abbreviations (NB, NM, NS, Z, etc.) describe the magnitude and polarity of the variables. All three variables (*E*, Δ*E*, and *D*) are mapped using the following seven standard linguistic terms: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), and Positive Big (PB). By using seven distinct membership functions, the controller is designed to provide highly granular, smooth, and sensitive responses to both minor oscillations and severe transient faults.

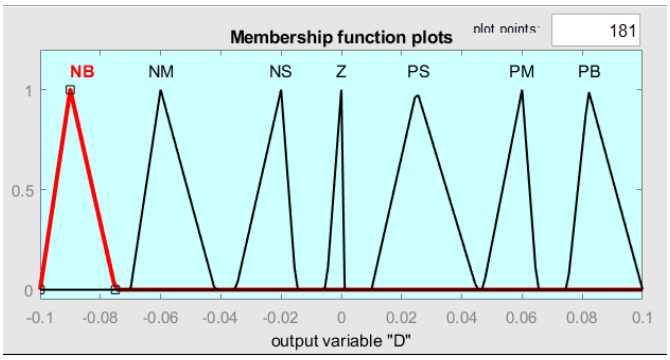


Fig. 3. Output membership function

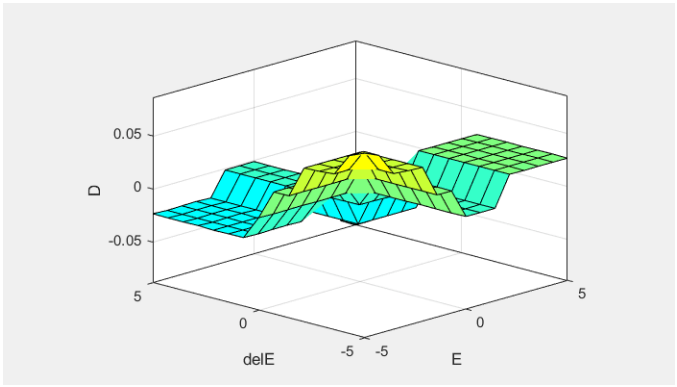


Fig. 4. Input-Output mapping of fuzzy inference system

The final stage is defuzzification, which requires converting the resulting fuzzy susceptance (B) into a number. As a result, the process gains its true susceptibility. Figure 4 displays the fuzzy inference system output 3D surface.

B. Adaptive Fuzzy Logic Controller

The proposed adaptive fuzzy logic controller uses time-dependent membership functions together with time-dependent linear mappings. The error (or) deviation function serves as performance measure to assess the system which uses time-dependent parameters for the fuzzy controllers. The literature provides multiple training methods which researchers use to change fuzzy controller settings [6], [7]. This paper implements an adaptive fuzzy method which operates based on the output error (or) deviation of the system [8]. The selected method proves to be efficient while maintaining simplicity of implementation.

The figure 5 shows how an adaptive Mamdani fuzzy logic controller (FLC) controls transient stability in power systems.

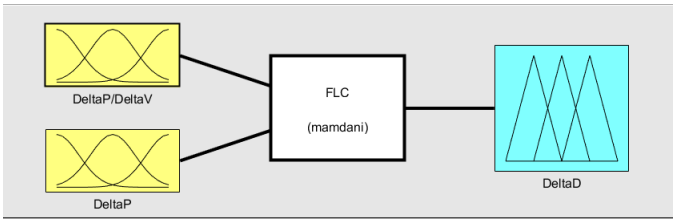


Fig. 5. Architecture of the adaptive fuzzy logic controller

The system processes two input variables which are power deviation (ΔD) and the power sensitivity to voltage changes ($\Delta D/\Delta V$) through fuzzy membership functions that define linguistic terms (e.g., low, medium, high). The AFLC processes these fuzzified inputs through a rule base and inference mechanism to identify the correct control action. The controller generates an output ΔD (control signal or change in damping/susceptance) which uses membership functions to represent the value before it undergoes defuzzification into a precise value. The controller uses this structure to make decisions because it allows them to adapt to different conditions which occur in the system.

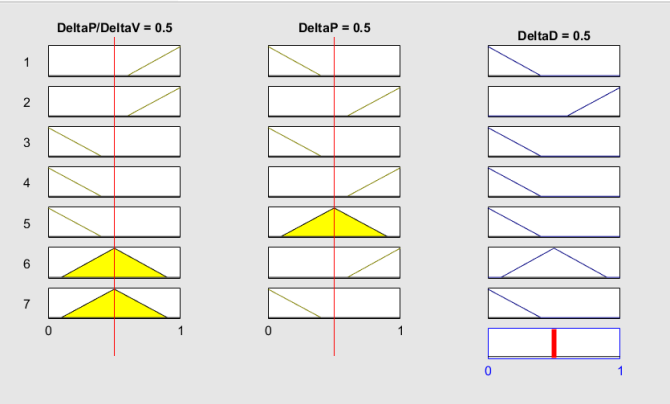


Fig. 6. Adaptive fuzzy rule base

The figure 6 depicts the fuzzy inference rule viewer of the proposed adaptive Fuzzy Logic Controller (AFLC) which combines two input variables $\Delta P/\Delta V$ and ΔP and produces one output variable ΔD through evaluation of both inputs at 0.5. The system comprises seven fuzzy rules which show each rule through one row display while the yellow-highlighted membership functions which display the degree of activation for that rule show the input conditions. The rules exhibit strong activation at the specified operating point which shows $\Delta P/\Delta V$ = 0.5 and ΔP = 0.5 because the triangular membership functions appear in the input columns. The DeltaD column shows an aggregated output which creates a precise output value that the red vertical line shows at around 0.5 and which the defuzzification process generated.

The 3D control surface representation in figure 7 shows how an adaptive fuzzy logic controller (AFLC) system uses its output variable ΔD to control two input variables ΔP and $\Delta P/\Delta V$. The surface shows the fuzzy controller rule base because it functions as a visual representation. The surface area displays all possible fuzzy inference results which function according to predefined linguistic rules. The controller creates continuous output changes through its adaptive control system which responds to different operating conditions instead of using fixed linear gains which are characteristic of standard PI controllers.

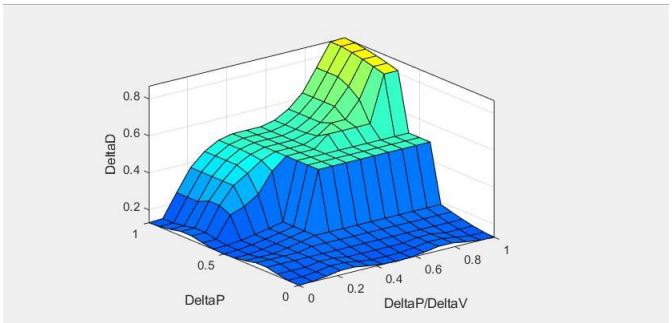


Fig. 7. Input-Output Mapping of Adaptive fuzzy inference system

The surface demonstrates that controller output remains low during steady-state conditions because small changes in ΔP and $\Delta P/\Delta V$. The surface raises up when disturbances increase because higher ΔP and $\Delta P/\Delta V$ values require stronger control actions to maintain system stability. The plateau regions suggest saturation or bounded control effort to prevent excessive compensation. The fuzzy controller achieves better transient stability than traditional control methods be-cause its nonlinear adaptive behavior enables faster oscillation damping and enhanced system stability during large distur-bances.

III. Modelling of the Test System

The employed test power system with an SVC has the following characteristics, as depicted in the single-line diagram shown in Figure 8. The study employed detailed SVC controller models together with thyristor-based static VAR compensator systems. The test system MATLAB simulink

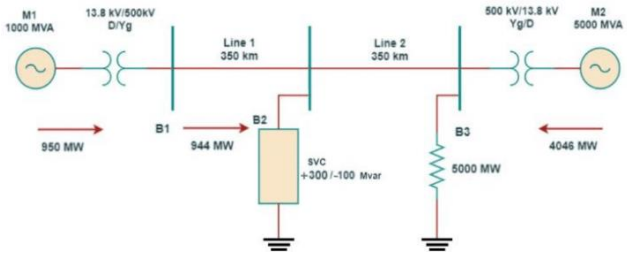


Fig. 8. Single-line diagram of a 2-machine 3-bus system

model shown in Figure 9. The 5000 MW resistive load of the system receives power from a remote source which operates at 1000 MVA and a local generating source which operates at 5000 MVA. The production rates of M1 and M2 reach 950

MW and 4046 MW respectively. The system operates with a controlled load flow of 944 MW which the line carries at its maximum impedance loading capacity of 977 MW [9].

The SVC which operates at the midpoint of the transmission line delivers optimal voltage control and reactive power handling through its capability to maintain balanced power flow during both regular operations and emergency situations.

The SVC system comprises one 109MVAR thyristor controller reactor bank TCR and three 94MVAR thyristor switched capacitor banks (TSC1, TSC2, TSC3) and a 200kV/30kV 333MVA coupling transformer. The secondary reactive power may be continuously varied from zero to 282 MVAR capacitive at 11kV side in 94MVAR steps by turning on and off the TSCs. The TCR system provides phase control which enables operation between zero and 109MVAR inductive power.

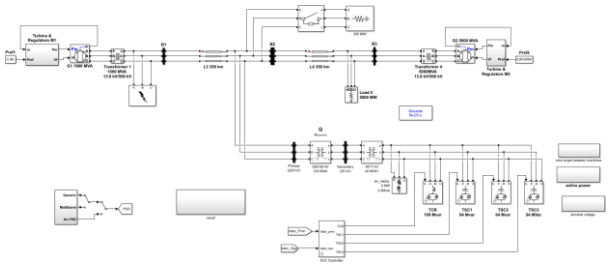


Fig. 9. MATLAB-SIMULINK tested power system

IV. RESULTS

The simulation results which were produced during testing the 3-bus system with two machine power system were shown in this section. The fault occurs between Bus bar 1 and Bus bar 2 for synchronous machine 1 which is located in the area shown in Figure 9. The system was tested using a three line short circuit fault case. The three phase fault block in MATLAB Simulink enables users to create these faults.

The team tested the faults on three distinct system configurations. The first scenario is a system with the typical SVC based on a PI controller, the second scenario is the system with the SVC based on an FLC and the third scenario is the system based on the proposed adaptive fuzzy logic controller.

The presented figures 10 and 11 illustrates the transient response of a generator's rotor angle over a five-second simulation period, comparing the efficacy of three distinct control architectures: a Proportional-Integral (PI) controller, a Fuzzy Logic Controller (FLC), and an Adaptive Fuzzy Logic Controller (AFLC).

After the system experiences its first disturbance it settles down to operate at an angle of approximately 60 degrees. The conventional PI controller red trace demonstrates the least favorable dynamic response because it reaches a first-swing peak angle of 82.0608 degrees and shows extended lightly

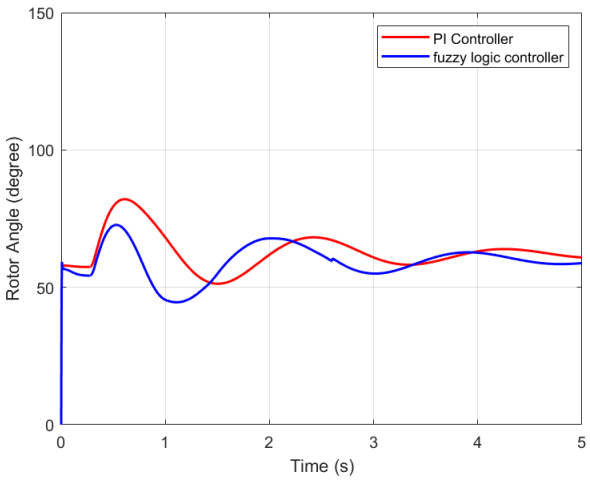


Fig. 10. Difference in Rotor angle of Synchronous Machine 1: PI vs FLC

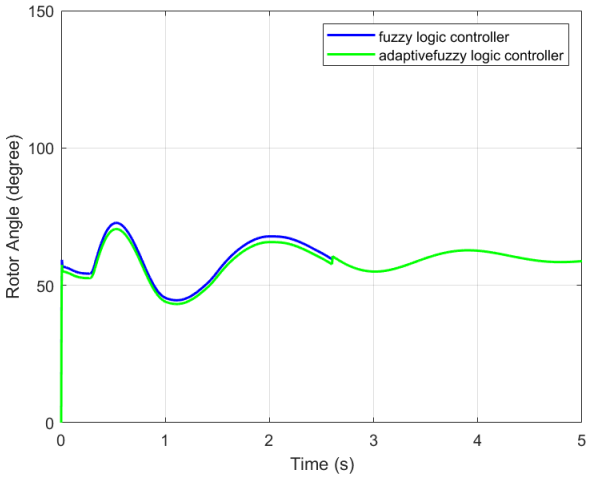


Fig. 11. Difference in Rotor angle of Synchronous Machine 1: FLC vs AFLC

damped oscillations. The implementation of fuzzy logic system decreases the instability problem. The standard FLC blue trace limits the peak angle to 72.5397 degrees while it speeds up the process of damping subsequent swings. The AFLC green trace provides the best transient performance because it lowers the peak angle to 69.8000 degrees. The AFLC system provides a 46.51 percent reduction in maximum overshoot when compared to the PI controller. The AFLC system achieved a 7.90 percent enhancement over standard FLC systems. The proposed AFLC system demonstrates improved ability to handle non-linear electromechanical oscillations through its enhanced capacity to stabilize these systems.

The terminal voltage response curves presented in the figures 12 and 13 demonstrate the progressive performance improvement from a conventional PI Controller to a Fuzzy Logic Controller (FLC) and ultimately to an Adaptive Fuzzy

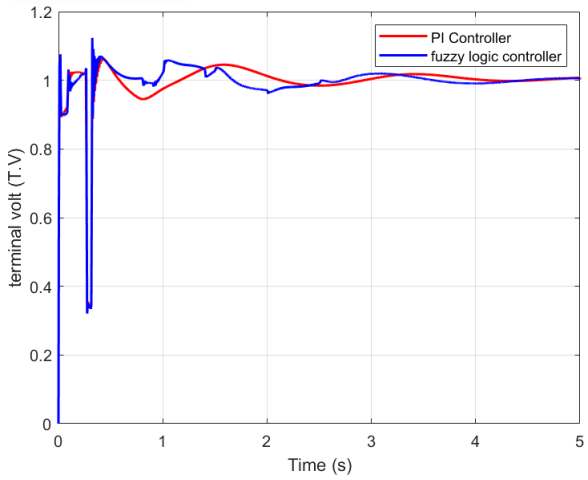


Fig. 12. Terminal Voltage: PI vs FLC.

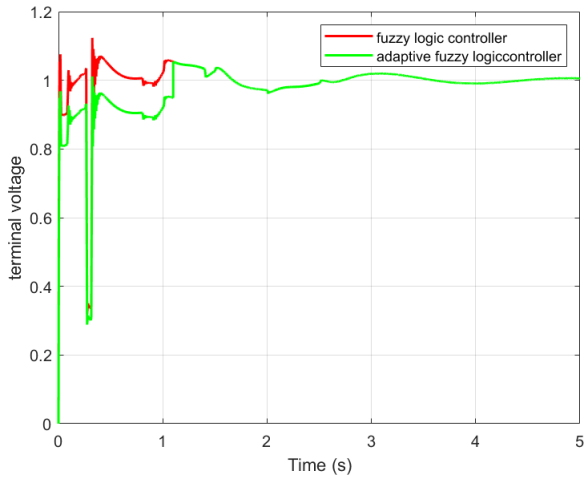


Fig. 13. Terminal Voltage: FLC vs AFLC

Logic Controller (AFLC) under a disturbance condition applied to a synchronous machine. The PI controller in Image 12 demonstrates slow voltage recovery because it takes more than 2 seconds to reach the nominal value of 1.0 p.u. while the FLC reaches its settling point faster and shows less steady-state error which demonstrates that rule-based intelligent control systems perform better than standard linear control systems.

The AFLC provides better performance than standard FLC because it produces a smoother response after disturbances while reaching the reference voltage of 1.0 p.u. within 2 to 2.5 seconds while the FLC shows extended oscillations until 3 seconds. The AFLC undergoes a larger initial voltage drop of around 0.3 p.u. during the transient phase because its adaptive gain adjustment mechanism reacts to sudden disturbances.

It achieves quicker recovery and reaches stability with less overshoot and smaller oscillation patterns when compared to the FLC. The AFLC control system adapts its membership functions and rule parameters according to system operating conditions which results in better dynamic voltage regulation and improved system performance. The AFLC control strategy stands out as the most effective solution among three evaluated methods for synchronous machine excitation control.

The figures 14 and 15 show how a synchronous machine responds to active power during a disturbance, while testing three control systems, which include a PI Controller, Fuzzy Logic Controller (FLC), and Adaptive Fuzzy Logic Controller (AFLC) over a period of 5 seconds. The PI controller and the FLC both show an initial transient spike, which reaches 800 W at time t = 0.3 seconds, and then they proceed to produce substantial power fluctuations.

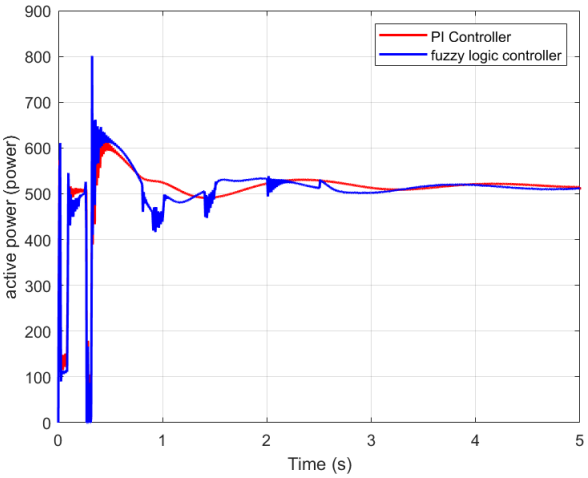


Fig. 14. Transmission Line Power: PI vs FLC

The FLC shows greater power fluctuations between 430 and 530 W because it operates from 0.8 to 2.5 seconds while the PI controller moves through a gradual process towards its 510 W steady state value. The AFLC in figure 15 shows better damping results than the FLC system because both systems start with an 800 W peak but the AFLC system reaches stable 510 W by t = 3 s while FLC shows ongoing power fluctuations until t = 2.5 s.

The system uses an adaptive AFLC mechanism to control its membership functions because it needs to respond to changes in the system's dynamic state, which allows the system to control power oscillations and reduce overshoot while it stabilizes active power output. The research demonstrates that the AFLC system provides the strongest active power control, which results in stable performance compared to two other controllers, who both tested their systems in power system stability applications through excitation control methods.

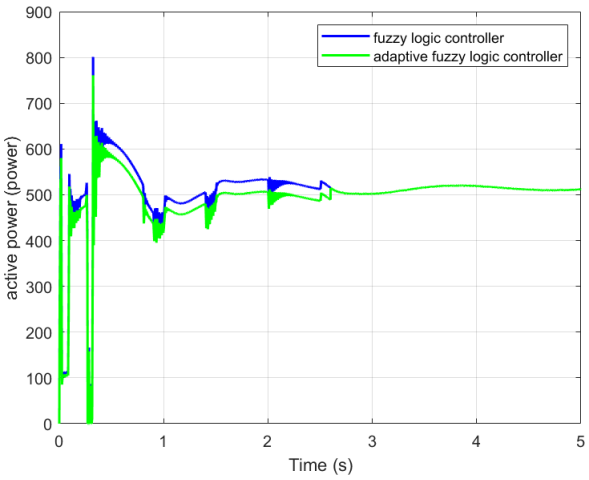


Fig. 15. Transmission Line Power: FLC vs AFLC

V. Conclusion

The research proved that the Adaptive Mamdani Fuzzy Logic Controller (AFLC) system which works with a Static Var Compensator (SVC) system successfully enhances transient stability for multi-machine power grids. The present study confirms that SVC units controlled through an Adaptive Mamdani Fuzzy Logic framework maintain significant advantages over conventional control strategies during power system transient disturbances because they automatically and intelligently handle reactive power compensation which maintains voltage stability and system synchronism through fault conditions.

The developed MATLAB/Simulink simulation results proved that the AFLC-based SVC system offers better dynamic performance than both the standard PI controller and the regular Fuzzy Logic Controller because it reduces rotor angle oscillations and terminal voltage deviations while enhancing active power damping performance through quicker settling times. The Adaptive Mamdani fuzzy inference mechanism, with its real-time self-tuning membership functions and rule base, achieved better performance than fixed-parameter PI and conventional FLC methods when facing nonlinear time-varying conditions.

The combination of adaptive fuzzy logic with SVC technology provides a stability enhancement solution which operates through flexible yet powerful computational methods that do not need exact power system mathematical models thus making this solution ideal for contemporary power networks that experience rising complexity and renewable energy integration and operational unpredictability. The research findings demonstrate that Adaptive Mamdani Fuzzy Logic Control of SVC provides an effective method for transient stability improvement which scales easily to larger multi-machine networks with hybrid power systems.

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