

Power System Stability Enhancement by Simultaneous Tuning of Fuzzy PSS and Fuzzy based STATCOM Controllers Including Wind Farm

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ABSTRACT

Modern power systems, particularly those integrated with wind energy, increasingly rely on both Power System Stabilizers (PSS) and Flexible AC Transmission System (FACTS) devices to suppress oscillations. This study proposes a fuzzy rule-based control approach for managing STATCOM operation under both steady-state and transient conditions, replacing traditional PI controllers for AC line voltage and DC-link voltage regulation. To further improve damping, a Fuzzy Power System Stabilizer (FPSS) is applied to all generators. A genetic algorithm is used to optimally coordinate the fuzzy-based STATCOM and FPSS controllers. Comparative simulations highlight the superior transient stability achieved with the proposed method over conventional PI control in a four-machine wind-integrated power system.

I. Introduction

Initially, power systems were designed as isolated networks, where local generation served local loads and were managed by independent utilities. While this setup was adequate in the early stages, growing environmental concerns and energy demands have recently driven governments and planners to promote alternative, cleaner energy sources—chiefly renewable energies like wind power. The power transfer capacity of long-distance transmission lines is primarily constrained by large-signal stability limitations. Economic considerations, including substantial infrastructure costs and potential revenue from increased power delivery, drive the exploration of technically viable solutions to enhance stability margins. Concurrently, significant research focuses on optimizing transmission systems to operate near their thermal limits. Advances in power electronics have profoundly impacted the energy sector, particularly through the development of Flexible AC Transmission Systems (FACTS) - made possible by modern power electronic devices that enable dynamic grid control capabilities. The Static Synchronous Compensator (STATCOM) is a shunt-type FACTS device used to regulate voltage levels at its connection point within the power grid. By adjusting the reactive power injected into the system and the active power absorbed from it, the STATCOM effectively controls both line voltage and its internal DC bus voltage [1]. Additionally, the use of Power System Stabilizers (PSS) has become essential for enhancing dynamic stability. However, integrating these devices increases system nonlinearity, making control more complex.

In recent years, many studies have proposed designing STATCOM PID controllers using linear control techniques, where system equations are linearized at a specific operating point and the PI controllers are tuned accordingly to achieve optimal performance [2, 3]. However, a major drawback of these controllers is that their parameters are often set through trial-and-error, making them less effective when operating conditions vary. In contrast, nonlinear

adaptive controllers offer robust performance across a broader range of operating scenarios but involve more complex structures and are harder to implement. Additionally, they require an accurate mathematical model of the system to be effective [4–8]. Artificial intelligence-based controllers present a promising alternative to overcome these challenges [9, 17], particularly with the application of expert systems in control design [9]. Neural network controllers have also been implemented in STATCOM configurations [10–12], alongside other artificial intelligence methods such as fuzzy logic controllers (FLCs) [13, 14]. FLCs are nonlinear controllers that typically do not require an explicit mathematical model of the system to function. In recent years, numerous studies have explored the application of FLCs in power systems. However, the performance of an FLC largely depends on proper tuning of its design parameters. Some works have focused on designing fuzzy-based power system stabilizers (FPSS) for enhancing transient stability [15], while others have implemented FLCs specifically for the AC voltage regulation component of STATCOM systems [16]. A common limitation in these studies is the use of a large number of fuzzy rules, with each controller designed using distinct rule sets. This complexity often leads to slower response times in FLCs. Power system stabilizer (PSS) design has incorporated various advanced control techniques to enhance performance, including artificial neural networks (ANN) [17], fuzzy logic control (FLC) [18], H_∞ control [19], linear matrix inequality (LMI) approaches [20], and μ -synthesis methods [21]. However, the large-scale, complex nature of power systems makes linearized modeling particularly challenging. Consequently, while online adaptive controllers prove difficult to implement in these time-varying systems, fixed-parameter controllers remain more practical and advantageous for operational implementation. This study aimed to design, simulate, and compare a PID controller, a lead-lag compensator, and a fuzzy logic controller within a STATCOM configuration for enhancing transient stability. The proposed fuzzy controllers replace the PI regulators for both the AC line voltage and the DC link voltage in the STATCOM, as well as the conventional PSS. A key advantage of the proposed method is the reduced number of fuzzy rules, which simplifies implementation and enhances computational efficiency—especially since all FLCs in the STATCOM and PSS share the same rule base. To improve design precision, coordination among all FLCs within the STATCOM is ensured. Simulation results confirm that the simultaneous tuning of the fuzzy controllers significantly enhances overall system stability.

II. Multimachine Power System Being Studied

Figure (1) illustrates the studied power system configuration, featuring a four-machine network with a wind park at bus 8 and a STATCOM at bus 11. The wind generation connects to the 230 kV transmission system via dual 69 kV parallel lines. This modified two-area system, designed to analyze low-frequency electromechanical oscillations in interconnected grids [23], incorporates FACTS devices for inter-area oscillation damping. Capacitor banks at buses 7 and 8 are adjusted to 200 MVAR and 180 MVAR respectively, working in conjunction with the STATCOM to maintain voltage profiles near 1 p.u. All simulations are implemented in MATLAB.

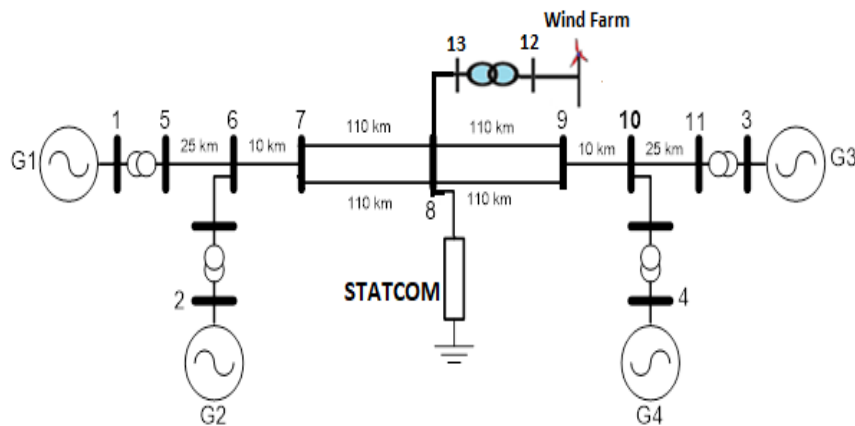


Figure 1. Four-machine power system with Wind farm installed with STATCOM

III. STATCOM & PSS structure

III.1. Statcom Structure

Initially, the STATCOM is controlled using conventional PI regulators. The d-axis and q-axis voltage deviations, calculated as the difference between the actual and reference values of the AC line voltage (ΔV) and the DC bus voltage (ΔV_{dc}), are processed by two PI controllers to produce control signals Δe_d and Δe_q (as shown in Figure (2)). These signals are then used to determine the modulation index and phase shift of the inverter output in the PWM module [19]. As previously stated, the STATCOM employs two PI controllers, resulting in four gain parameters to be optimized.

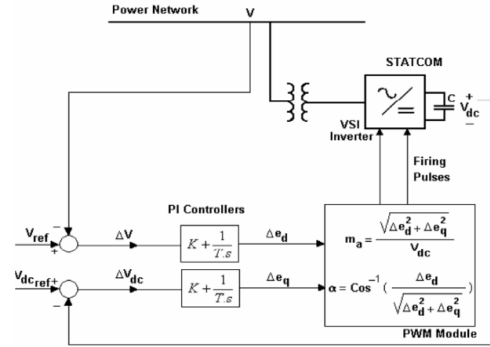


Figure 2. Statcom internal control structure [24].

III.2. PSS System Structure

The parameters of the STATCOM PI controllers (as described in Section 3-1) and the Power System Stabilizer (PSS) are simultaneously fine-tuned at a specific operating point using a Genetic Algorithm (GA). A three-phase fault is introduced into the power system, and the PI and PSS parameters are selected to ensure stable and satisfactory dynamic performance based on time-domain responses. The PSS used in the analyzed system is of second order. Figure (3) illustrates the conventional structure of the PSS in a four-machine system. When the washout filter with time constant T_m is bypassed, the second-order PSS presents five tunable parameters: K_{PSS} , T_1 , T_2 , T_3 , and T_4 . Consequently, the total number of parameters requiring coordination for both the PI controllers in the STATCOM and the PSS amounts to nine.

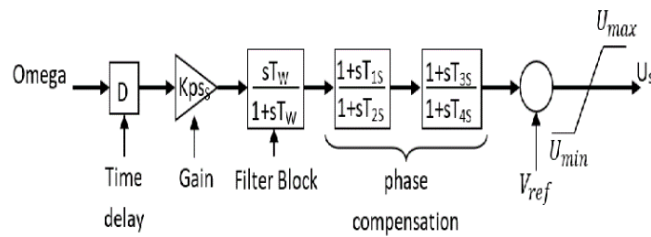


Figure 3. Standard Power System Stabilizer Architecture

IV. Simultaneous design Fuzzy based PSS and STATCOM

Due to the STATCOM and PSS performance in power system stability, they have to be tuned simultaneously so that one performance does not affect another response. In this section, the FLC structure is introduced first and then applied in PSS and STATCOM. Because all the FLC inputs are with error and also employed rules are based on the error and the change in the error: (all controllers have same and similar rules) an advantage proposed by FLC is since FLCs structure and rules is similar so FLCs tuning has become so easy that has been converted to an optimization problem.

IV.1. Fuzzy controller structure

In the above-mentioned fuzzy controller, it uses three gains in input and output of FLCs. Some papers don't use these three gains and only have optimized fuzzy sets [24]. Other papers only have used some gains and then don't optimize fuzzy sets. This paper, in addition to fuzzy sets optimization using an intelligence algorithm, plans to use three proportional gains as such that all these gains optimized together. Figure (4) presents the unified fuzzy logic controller architecture implemented for both PSS and STATCOM control systems.

In designing a FLC scaling factors have the most influence on FLC optimal performance. Scaling factors function is to normalize the variables to the $[-1, 1]$ interval. Equation (1) shows scaling factors limits for FLCs.

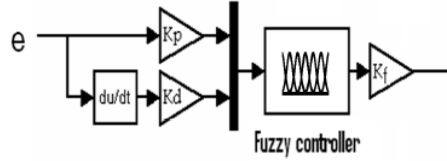


Figure 4. Proposed Fuzzy logic controller structure

$$\begin{aligned} 0 \leq K_{pi} &\leq 2 \\ 0 \leq K_{di} &\leq 2 \quad i = 1,2,3 \\ 0 \leq K_{fi} &\leq 150 \end{aligned} \quad (1)$$

Index 1 corresponds to the AC voltage fuzzy regulator, Index 2 to the DC voltage fuzzy regulator, and Index 3 to the fuzzy power system stabilizer (FPSS). These limit values were determined through extensive simulation studies.

IV.2. Selecting the suitable configuration of the FSTATCOM

As previously stated, two fuzzy logic controllers (FLCs) are employed in place of conventional PI controllers within the STATCOM system. The FLC responsible for AC voltage regulation takes two inputs: the line voltage deviation $\Delta V(t)$ and its rate of change $\Delta E(t) = \Delta V(t) - \Delta V(t-1)$. For DC voltage regulation, the corresponding FLC receives the DC link voltage error and the change in that error as inputs.

IV.3. Selecting the suitable configuration of the FPSS

In most papers on the shaft speed, bus frequency and real power are commonly used input as signals to the PSS. Among these signals, the shaft speed is very easy to measure and is found to be quite effective. In this paper, speed deviation of the synchronous machine and its derivative are chosen as inputs to the FPSS. Gains K_{p3}, K_{d3}, K_{f3} are used to scale the input-output variables of the FPSS. Gaussian Membership Function (MF) is used in the design of FPSS and STATCOM Fuzzy Controller. The study employs Gaussian membership functions (MFs) for all fuzzy logic controllers due to their fewer tuning parameters (mean and variance) compared to triangular MFs. This selection effectively reduces the optimization problem dimensionality.

IV.4. Rule base

Fuzzy rules constitute the fundamental component of Fuzzy Logic Controllers (FLCs), defining the relationship between fuzzy input and output variables. In a system with two control variables—error (e) and its rate of change (Δe)—each described by seven linguistic terms, the rule base results in a 7×7 decision table. The control strategy relies on a series of *if-then* rules, such as: *if the error is Negative Big (NB) and the change in error is Negative Medium (NM), then the control adjustment (c) is Positive Big (PB)*. These rules are established through system tuning and experimental analysis. Figure 7 illustrates the membership functions for both inputs and the output, while Figure 10 presents the rule surface, demonstrating a smooth transition in control signals. A smaller number of rules tends to enhance the responsiveness of the FLC. The rule base is summarized in Table I, and the fuzzy knowledge was developed based on expert operator insights [25]. Notably, the FLC design employs symmetrical Gaussian membership functions, distributed across seven fuzzy sets. The study replaces the STATCOM's conventional PI controllers (line voltage and DC-link voltage) with two fuzzy logic controllers (FLCs). To enhance

system damping, a fuzzy power system stabilizer (FPSS) is implemented on each machine, resulting in three FLCs total. Each FLC requires three scaling factors, creating nine parameters for initial tuning. With three genes representing each scaling factor, the chromosome length becomes 27. This approach enables simultaneous optimization of all scaling factors, formulating the FPSS-FSTATCOM coordination as an optimization problem. Table II presents the genetic algorithm parameters used for scaling factor tuning. The selection of an appropriate fitness function can utilize time-domain performance metrics such as settling time or overshoot. In this study, we employ the integral of absolute error (IAE) as an evaluation criterion, considering either rotor speed deviations or angular differences among synchronous machines. This method specifically targets the reduction of peak amplitudes in residual oscillations following disturbances, even when the total error integral remains minimal.

Table I. Fuzzy Logic Controller rule base

$\Delta e/e$	NVB	NB	NM	NS	Z	PS	PM	PB	PVB
NVB	PVB	PVB	PVB	PB	PM	PM	PS	Z	Z
NB	PVB	PVB	PB	PM	PS	PS	PS	Z	Z
NM	PVB	PB	PM	PS	PS	Z	Z	Z	NS
NS	PB	PM	PM	PS	PS	Z	Z	NS	NS
Z	PM	PM	PS	Z	Z	Z	NS	NS	NM
PS	PM	PS	PS	Z	NS	NS	NM	NM	NB
PM	PS	PS	Z	NS	NS	NM	NB	NB	NB
PB	PS	Z	Z	NS	NM	NM	NB	NVB	NVB
PVB	Z	Z	NS	NM	NM	NB	NB	NVB	NVB

Table II. GA parameters in scaling factors tuning stage

Variable number	9
Gene number for each variable	3
Chromosome length	27
Population size	54
Generation number	50

To enhance damping performance over time, we introduce a time-weighted component by multiplying oscillation values by the time variable (t). The specific formulation applied to the four-machine system is presented in Equation (2).

$$\min J = \int_0^{t_{sim}} t \left(\sum_{i=1}^4 |\Delta \omega_i| \right) dt \quad (2)$$

In the defined objective function t_{sim} represents the simulation duration while $\Delta \omega_i$ denotes the speed deviation of the i -th generator. The choice of time interval significantly impacts the optimization process: shorter intervals reduce the objective function's sensitivity to subsequent changes (particularly oscillation damping related to dynamic stability), while longer intervals require more extensive simulation time

V. The proposed algorithm flowchart

Figure (5) shows the proposed algorithm flowchart in designing the STATCOM and PSS fuzzy control system. In the meantime, by application of GA, PI controllers parameters and fuzzy sets membership functions.

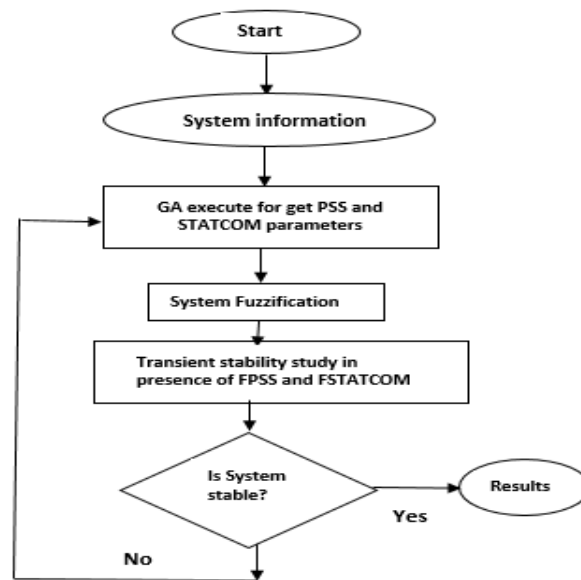


Figure 5. Proposed algorithm flowchart

VI. Simulation results

Figure 1 displays the studied four-machine system integrated with a wind farm. The test configuration comprises two identical areas connected via twin 230 kV, 220 km transmission lines.

VI.1. Preliminary information – system parameters determination

The system model utilizes the slack bus as the reference for load flow calculations. A 200 MVar STATCOM is installed at bus 8, strategically positioned at the midpoint of the transmission line. The study examines a severe three-phase ground fault scenario occurring at 0.1 seconds on one of the parallel transmission lines adjacent to bus 8. The fault condition persists for 200 milliseconds (from 0.1 to 0.3 seconds), with subsequent line isolation occurring after a 70-millisecond clearing time. Table III presents the optimized proportional-integral control parameters for both the STATCOM and Power System Stabilizer (PSS) systems.

Table III. Proportional – integral parameters of STATCOM and PSS after optimization

Parameters		Parameters	
Kp_Vac_SH	3.574	T1	0.3706
Ki_Vac_SH	530	T2	0.0001
Kp_Vdc_SH	0.0001	T3	0.303
Ki_Vdc_SH	0.002	T4	4.475
KPSS	89.5	-	-

VI.2. Membership Function

In this part for the optimized membership functions related to FLCs input errors will be shown as an example (Fig. 6). As it can be seen, fuzzy sets average and variance changed which resulted in assigning the best value membership degree to FLCs input errors.

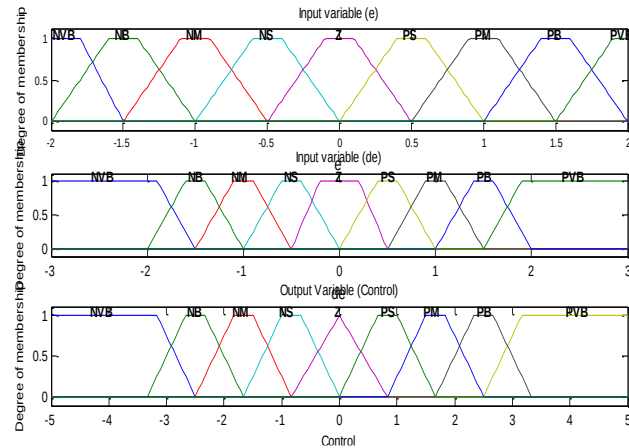


Figure 6. membership functions

VI.3. Results and discussions

1) Simulation without controller

Figure (7) show four generators speed in presence of wind farm without the proposed controller. The generators speed in this case oscillations damping is less. It can be seen Effect of this damping in generators angle different.

Figure (8) illustrates the comparative transient response of generator rotor angles, showing significantly improved oscillation damping when using the proposed controller compared to the uncontrolled system.

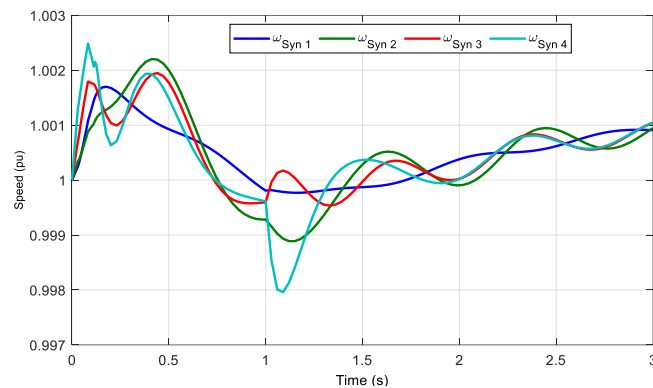


Figure 7. Generators Speed without the proposed controllers

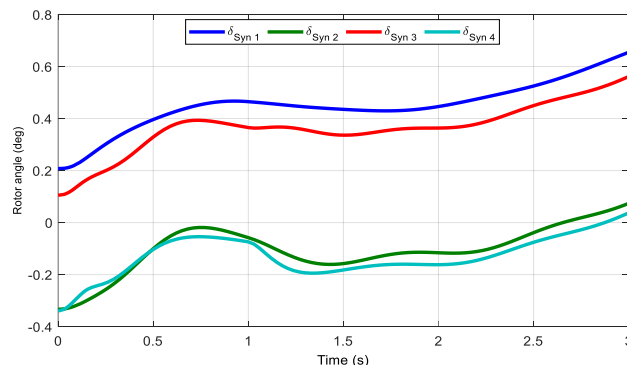


Figure 8. Difference of generators angle without the proposed controllers

2) Simulation with controller

Figure (9) shows the difference of generators angle in the case of integrated the proposed controller. It can also be seen that in the case of optimized parameters and fuzzy sets, not only transient stability but also dynamic stability is improved significantly.

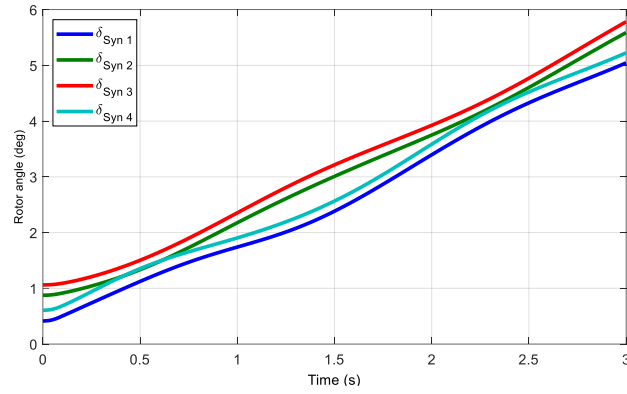


Figure 9. Difference of generators angle with the proposed controllers

In this case, the figure (10) presents the generators speed with the proposed controllers. It is seen that dynamic and transient stability in controlled system by fuzzy controllers is better.

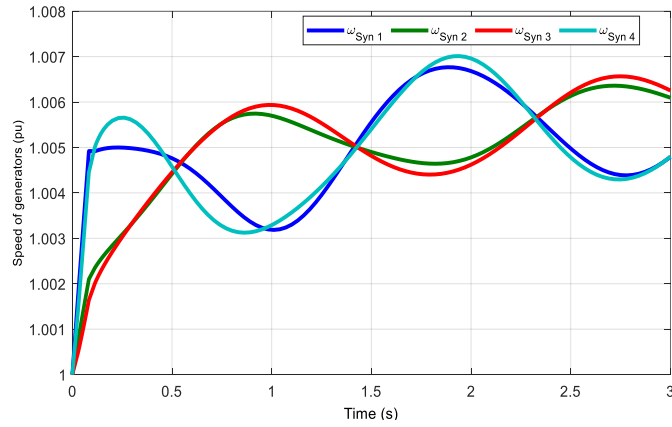


Figure 10. Generators Speed with the proposed controllers

VII. Conclusion

In this paper, fuzzy logic-based controllers were designed to replace the conventional PI controllers for the line voltage and DC-link voltage regulation in the STATCOM. To enhance damping performance, a Fuzzy Power System Stabilizer (FPSS) was implemented on all machines within the studied power system. Optimal coordination between the FSTATCOM and FPSS was achieved using a Genetic Algorithm (GA). The key simulation findings can be summarized as follows:

1. The proposed controller demonstrates significantly improved dynamic and transient stability, outperforming traditional control methods.
2. The application of fuzzy control rules introduces greater flexibility into the control system, enabling more robust adaptation to grid disturbances.
3. In the meantime, a genetic algorithm was used for set optimization. Simulation results showed that applying the genetic algorithm at each stage further improved the system's performance and responsiveness.

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