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Fuzzy Logic Control and Genetic Algorithm Optimization: A Powerful Combination for Title Enhanced Power System Stability in Peerdawd Gas Power Station-KRD

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Abstract

The ever-growing demand for electricity necessitates innovative approaches to power system control. Traditional methods often struggle to handle the complexities of modern grids. This study explores the potential of Fuzzy Logic Control (FLC) and Genetic Algorithms (GAs) for optimizing Power System Stabilizer (PSS) settings at the Peerdawd Gas Power Station (PPGS) under normal load conditions (80% power factor). FLC excels at mimicking human decision-making in uncertain situations, making it ideal for power systems with fluctuating loads. GAs, inspired by natural selection, efficiently searches for optimal solutions in complex problems. By combining these techniques, we can effectively fine-tune PSS2B parameters, leading to significant improvements. This study utilizes MATLAB Simulink to compare the performance of FLC and GA-based optimization with traditional methods. Key power system parameters are monitored, including voltage terminal (VT), rotor speed (ωm), active and reactive power output (Peo and Qeo), alongside transient response characteristics like damping ratio (ζ), overshoot (%MP), settling time (ts), peak time (tp), natural frequency (ωn), and damping frequency (ωd). Optimizing PSS2B parameters using FLC and GAs is expected to demonstrably reduce power oscillations, minimize overshoot, and accelerate system stability restoration.

Keywords: *transient stability, damping ratio (ξ), settling time (ts), maximum overshoot (MP%), FLC, GA, fuzzy power system stabilizer (FPSS2B), fuzzy genetic power system stabilizer (FGAPSS2B), Peerdawod Power Gas station (PPGS).*

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1 Introduction

Electric power systems are characterized as nonlinear systems that can experience a broad range of transient conditions. These conditions can cause low-frequency variations in speed, which can result in oscillations in power. Power control systems are therefore needed in order to continuously maintain a balance between the electrical power generated and the variation in load demand, all the while preserving the voltage and oscillation level for power transmission lines. Since the occurrence of disruption in power systems suddenly causes major changes in loads or the disconnection and connection of some network elements, this causes a change in the power given by generators or taken by motors in the system where the disruption occurred. Any change in the power output causes a deviation in the rotor position of the generators in the system. This can cause some generators to accelerate and others to brake. With the advent of automatic voltage regulators (AVRs) in the late 1950s, the installation of automatic voltage regulators on power generation units became common. However, the high performance of these voltage regulators caused an instability phenomenon in the electric power system. Most of these problems are accompanied by low-voltage oscillations of interconnected electric power systems, especially irregular models. The magnetic effect and low-voltage oscillation may last for a long time [1], [2], [3]. To achieve fast system damping to improve dynamic performance, a control signal can be used to add to the excitation system or the automatic control system of the generating unit. Power system stabilizers (PSSs), which are the least expensive among damping controllers and have different types (CPSS, PIPSS, and PIDPSS), have been widely applied to suppress low-voltage oscillations and enhance dynamic system stability. The reliable performance of (PSSs) in power system stability is attributed to providing the excitation system with a helping signal [4], [5]. The main components of the power system stabilizer (PSS) allow for the damping of electromechanical oscillations while producing electrical torque components in phase with the generator's rotor speed deviation. One way to model a generic (PSS) is as a non-linear system with a

1. **Stabilizer Gain (K_{PSS}):** It is determining the extent of damping the stabilizer imposes.
2. **Wash-out Term:** The purpose of these high-pass filters is to remove low frequencies from the speed deviation signal so that the PSS can only react to variations in speed.
3. **Phase Compensation:** These days, they are used to adjust for phase lags between the excitation voltage and the electrical torque of the synchronous machine. The lead-lag compensation is represented by a cascade of two or more first-order lead-lag transfer functions.
4. **Output Limiter:** To keep the (PSS) from opposing the (AVR’s) action, its output must be restricted. As seen in Figure 1, the PSS must give more feedback when the signal deviation rises above the desired value than it does when the deviation falls below the desired value [6], [7], [8], [9].

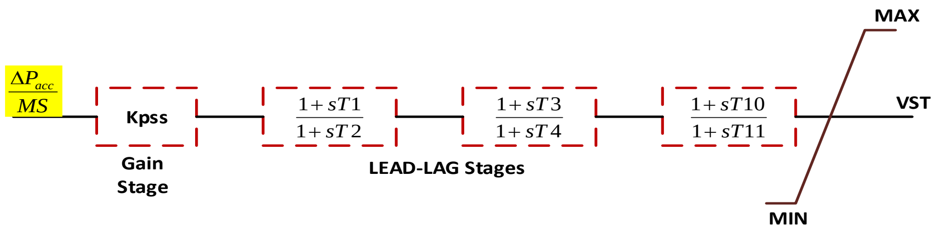

Figure 1. Stabilizing parts of PSS of PSS2B model.

The PSS2B operates on the basis of the phase compensation technique, and the effectiveness of its oscillation damping mechanism is contingent upon the appropriate adjustment of compensator parameters (the Time Constants values and PSS gain, correspondingly, "T1, T2, T3, T4, T10, T11, and K_{PSS}") [9], [10], [11]. Despite the existence of various structures of power system stabilizers, most power system stations still prefer the traditional power system stabilizer (PSS) of the fixed lead-lag type compensated for phase difference. This may be due to the easy and direct tuning and the lack of stability guarantee for some of the other diverse or modified structural methods [12]. Accordingly, the power system stability system plays an important role in the stability of synchronous generators, especially when they are exposed to a specific fault, or when there is no general change in power, or when they stabilize in a new operating mode without losing the synchronization feature. In general, two types of stability must be ensured for power systems: steady-state stability, which is defined as the ability of the system to return to its normal operating state when the system is exposed to a small disturbance. Therefore, research that deals with this type of stability must include the analysis of linear equations in the static space. The second type of stability is called transient stability, which aims to return the system to its normal state when it is exposed to a large disturbance such as single-phase, two-phase, or three-phase faults, which cause a decrease in the terminal voltage of the generator in addition to a decrease in the ability to transmit the power generated from it. As for the dynamic stability of power systems, it represents the stability of the system until the change in the load angle of the generator (δ) stops in the shortest possible time and not only when the fault is disconnected. When the generator is exposed to a variable dynamic load, it causes a change in the voltage angle and the rotor angle as shown in Figure 2 [1], [13].

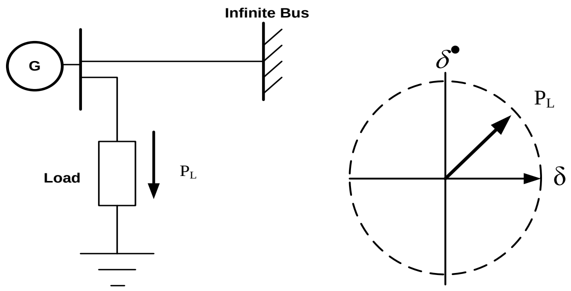

Figure 2. Load contribution to damping of a single-machine infinite bus (SIMB) system.

In order to enhance power system stability in the case of a fault, a fuzzy-PID-based STATCOM is recommended in [14]. To develop the controllers, the MATLAB/SIMULINK environment is utilized. The simulation results amply illustrated the Fuzzy-PID-based controller's efficacy on the power system in the event of a fault. The design of (PSS) and (STATCOM) controllers that will more successfully reduce power system fluctuations can be achieved by coordinating and optimizing fuzzy controllers, as examined in this article [15]. The designed fuzzy controller is used in place of the

(STATCOM) AC voltage regulator. In addition, each machine has a fuzzy power system stabilizer (FPSS) installed to offer extra damping. SALBA, or Self-Adaptive Learning Bat Algorithm, makes it easier for FPSS and FSTATCOM (Fuzzy Based STATCOM) to coordinate in two stages. The fuzzy sets of membership functions (MFs) and scaling factors will be first adjusted using a performance index as a reference. In order to show the effectiveness of the proposed scheme, the coordinated optimized (FPSS) and FSTATCOM are compared with conventional design techniques such as proportional-integral controller-based STATCOM (PISTATCOM) and conventional PSS (CPSS). In [16], the effects of uncertainties are investigated for a multi-machine power system with a high wind farm penetration rate. It is believed that the transmission system, generating unit uncertainties, and demands are the three primary sources of uncertainty. Therefore, a novel optimized type II fuzzy power system stabilizer (PSS) is proposed to lower uncertainty and increase the power system dynamic stability margin. Through the use of the integral of square error until settling and the figure of demerit as desired functions, a multi-objective particle swarm optimization algorithm optimizes the proposed stabilizer's membership. A comprehensive overview of a novel control scheme that considers synchrophasors and Power System Stabilizers in conjunction with an optimized Load Frequency Control loop to address undamped local and wide-area oscillatory problems is given in [17]. Consequently, a Robust Fuzzy PSS utilizing local signals is examined first. Also examined is an Inter-Area PSS based on a high-sampling rate phasor measurement unit. In fact, efficient energy management process monitoring will benefit from the use of time-synchronized measurements as control input signals. Consequently, an alternative mixed-PSS configuration that combines remote and local control inputs is proposed. The performance of these PSSs is evaluated in conjunction with a tuned PI-based load frequency control design under a range of operating conditions. Results obtained with a modified IEEE 9-Bus test system. In [18], a novel fuzzy logic controller is introduced as a power system stabilizer with the goal of enhancing stability and the dynamic response of the power system during malfunctioning conditions. It is contrasted with both multi-brand and traditional power system stabilizers. The generator excitation system is supplemented with a power system stabilizer to improve damping during low-frequency oscillations. Fuzzy logic controllers use the synchronous machine's acceleration and rotor speed deviation as inputs to increase power system stability. This paper, is a study of using the data resulting from the genetic algorithm to train and test the Fuzzy network, leading to the application of the adaptive fuzzy inference system to improve the dynamic stability of a realistic mathematical model for the (FGAPSS2B) power system stability system, and the excitation system of the generator (excitation system) of the Peerdawd Gas Power Station (PPGS), and the effectiveness and stability strength of the design was verified by comparison with the Power System Stabilizer with real value parameters (FPSS2B) that exists through the implementation of computer simulation of the studied station model during fault with normal load condition.

2 Genetic Algorithm and Fuzzy Logic CONTROL for Optimum PSS2B Parameters

The (GA) algorithm adjusts the PSS parameters by carrying out genetic operations on individuals of a population, such as crossover, variation, and inversion. The (GA) optimization process involves minimizing an objective function, such as the Integral of the Time weighted Absolute Error (ITAE) of the rotor speed of the generator. By applying the GA to optimize PSS parameters, the stability and damping of power systems can be enhanced [19], [20], [21], [22], [23]. The multi-objective optimization function for (PSS2B) can be expressed as follows:

$$minJ_{T1,T2,T3,T4,T5,T6,Kpss} = W_{VT}J1 + W_{\omega}J2 + W_{ts}J3 \quad (1)$$

Where the individual functions J1, J2, and J3 represent the sum of square error between the desired and real value for the Terminal Voltage of exciter (V_T), The rotor speed (ω_m), and settling time(t_s) and (WV_T, $W\omega$, and Wt_s) represent the weights assigned to each objective function. These weights are used to achieve a balance between the different objectives being optimized. The parameters of (PSS2B) would be specified in the (GA) and within constraint limits as follows:

$$T1_{min} < T1 < T1_{max}$$

The Procedures of Genetic Algorithm for GAPSS2B are:

- The starting point for genetic algorithms is a population of potential solutions to problems.
- Potential solutions are assessed based on how well they can resolve specific cases; only the most effective ones endure and build upon one another to generate even more potential solutions.
- A population of patterns in a genetic algorithm model, like the one we're using for this project (GAPSS2B), stands in for potential solutions to a problem (T1, T2, T3, T4, T10, T11, K_{PSS}).
- This population of patterns "evolves" as the algorithm cycles, utilizing processes that resemble natural selection, reproduction, and mutation. Figure 3 of the flowchart below illustrates how a genetic algorithm operates.

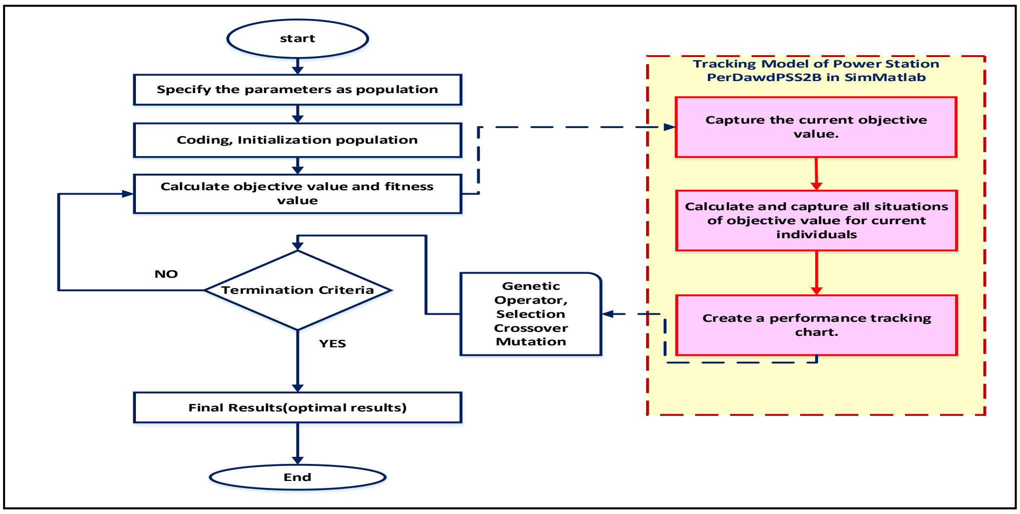

Figure 3. Flowchart of Genetic Algorithm.

Fuzzy rules use fuzzy inference to infer the rule's outcome from the information provided as rule input. It is also known as approximate or fuzzy reasoning. The Fuzzy Inference System (FIS) finds application in various domains, including computer vision, expert systems, data classification, automatic control, and decision analysis. As a result, it goes by various names, including fuzzy logic controllers, fuzzy modeling, fuzzy associative memory, fuzzy expert systems, and fuzzy rule-based systems.

"IF.....THEN" statements are used by FIS to create the required decision rules. The most widely used fuzzy methodology is the Mamdani fuzzy inference method. It was suggested by Ebrahim Mamdani in 1975 [24], [25], [26]. This paper applies fuzzy logic control theory to improve the power system stabilizer's (PSS2B) performance during normal load (power factor of 80%) conditions. The three-phase fault lasts for five seconds. The system's stability is predicted to increase by adding a fuzzy controller using MATLAB 2020a SIMULINK in parallel with the (PSS2B) in the real case study model of the Peerdawd Gas Power Station (PPGS) as shown in Figure 4. The fuzzy controller's input is divided into seven membership functions representing the input signal to the (PSS2B) (accelerating powers of the generator (P_{acc})) within the range of (0 to 0.105), denoted by (EL, VL, L, N, H, VH, EH). Similarly, the output of the fuzzy set is divided into seven membership functions representing the output signal from the (PSS2B) to the excitation system within the range of (0 to 0.09), labeled as (EL, VL, L, N, H, VH, EH), as depicted in the accompanying rule Table 2 and Figures (5 and 6). The synchronous generator of Peerdawod Gas power station (PPGS) is represented by the Sixth-Order model comprising of the electromechanical swing equation and the generator internal voltage equation, the full set of six differential equations describing the generator and the air-gap power of the generator can be calculated as [27], [28], [29], [30], [31]:

$$P_e = \left(E''_d I_d + E''_q I_q\right) + (X''_d - X''_d) I_d I_q. \tag{2}$$

$$2H\Delta\dot{\omega} = P_m - P_e. \tag{3}$$

$$\dot{\delta} = \Delta\omega. \tag{4}$$

$$T'_{do}\dot{V}'_q = E_f - V'_q + I_d(X_d - X'_d). \tag{5}$$

$$T'_{qo}\dot{V}'_d = -V'_q + I_d\left(X_q - X'_q\right). \tag{6}$$

$$T''_{do}\dot{V}''_q = V'_q - V''_q + I_d(X'_d - X''_d). \tag{7}$$

$$T''_{qo}\dot{V}''_d = V'_d - V''_d + I_q\left(X'_q - X''_q\right). \tag{8}$$

Table 1: Generator Model Variable Definitions

Variables	**Units**	**Definitions**
P_e	Pu	Synchronous output active power
P_m	Pu	Synchronous mechanical power
δ	Rad	Angle of q-axis with respect to system reference
V_q V_d	Pu	d- and q-axes synchronous voltage
E_f	Pu	Equivalent excitation voltage
X_d, X_q	Pu	d- and q-axes synchronous reactance
X'_d, X'_q	Pu	d- and q-axes transient reactance
X''_d, X''_q	Pu	d- and q-axes sub-transient reactance
T'_{do}, T'_{qo}	Sec	d- and q-axes transient open circuit time constant
T''_{do}, T''_{qo}	Sec	d- and q-axes sub-transient open circuit time constant

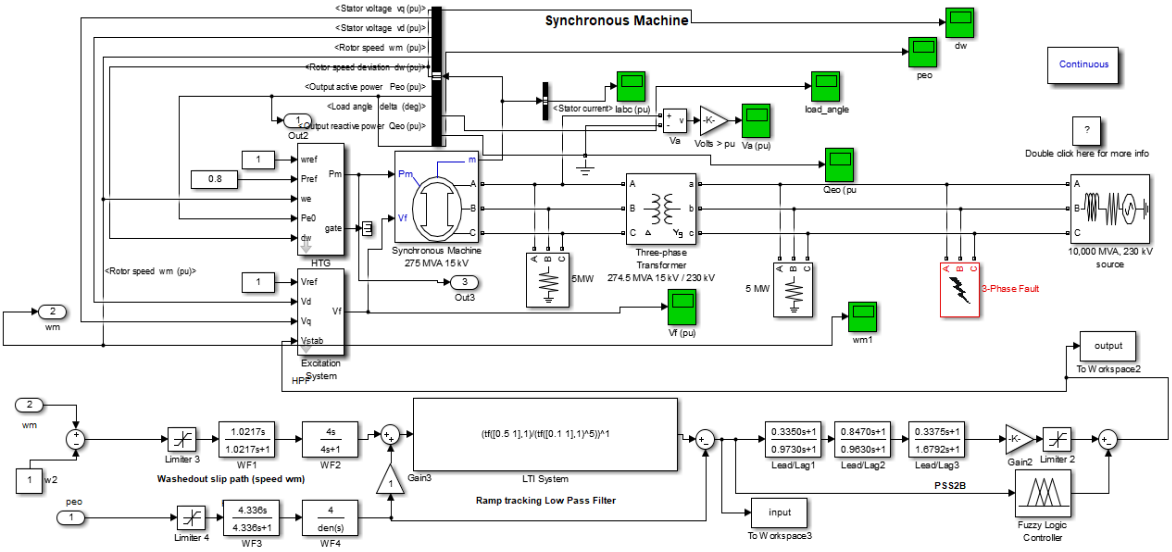

Figure 4. Model of a practical power system, Generator, Exciter, and FGAPSS2B in Matlab/Simulink.

Table 2: Fuzzy Rules.

If the input signal of the PSS2B (P_{acc}) is:	Then output signal of the PSS2B to Excitation is:
signal (P_{acc}) : EL LV L N H VH EH	Excitation: EL LV L N H VH EH

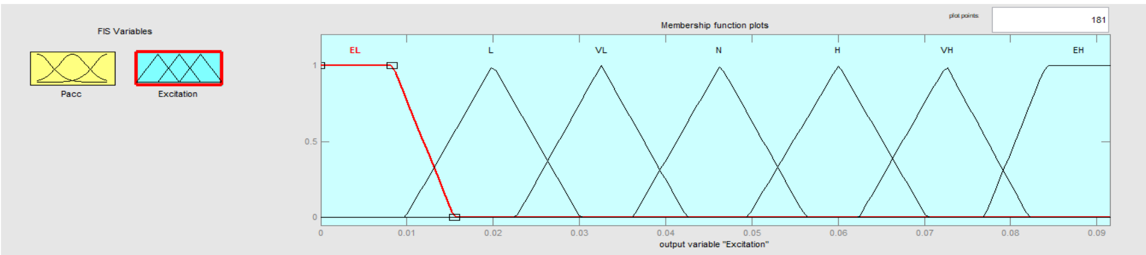

Figure.5. Fuzzy input membership (P_{acc}).

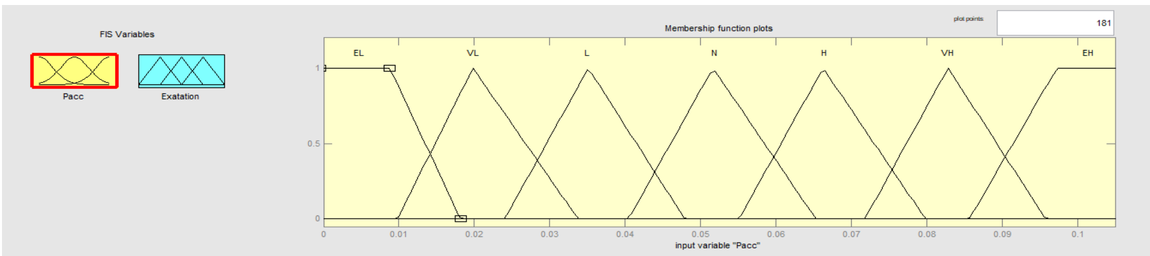

Figure 6. Fuzzy output membership (Excitation).

3 Simulation and Results

The model of the actual case study has been run using MATLAB Simulink. Then the power system coefficients (voltage terminal (V_T), rotor speed (ω_m), active power (P_{eo}), and reactive power (Q_{eo}) in pu) are analyzed and compared in this study regarding the PSS2B's performance and the affected of the load conditions in three cases: In the baseline scenario, the power system stabilizer (PSS2B) is implemented using real parameter values, The second using fuzzy logic control in conjunction with the PSS2B's real parameter values denoted by (FPSS2B) and. The third case explores the optimization of (PSS2B) parameters using Genetic Algorithms and fuzzy logic control (FGAPSS2B), the three cases demonstrate together and compare them under different load conditions each examined separately. And also noted the transient parameters (damping ratio (ζ), maximum overshoot (%MP), Settling Time (t_s), Peak Time (t_p), natural frequency (ω_n), and Damping Frequency (ω_d) of the power system parameters (Voltage Terminal (V_T), rotor speed (ω_m), output active power (P_{eo}), and reactive power (Q_{eo}) in pu) during fault three-phase fault 5 sec, as shown in Figures (7-10) and the Tables (3 and 4) below.

3.1. Transient State of FGAPSS2B During Fault at Normal Load

It is clear from examining the normal load condition during faults and the addition of a parallel fuzzy logic controller with (PSS2B) in two scenarios: (one with PSS2B parameters tuned by Genetic Algorithms (FGAPSS2B), and the other with its real parameters value without Genetic Algorithm tuning (FPSS2B)), that the fuzzy logic controller's inclusion enhances PSS2B's performance during faults and pre-fault transient states. It dampens vibrations, serves as a filter, allows (PSS2B) to react to faults quickly, and speeds up the process of returning to stable conditions. When the fuzzy logic controller and genetic algorithm approach are combined (FGAPSS2B), PSS2B performs at its best, and this improvement is particularly noteworthy. Furthermore, the Reactive Power (Q_{eo}) that is not further absorbed during pre-fault transient periods is greatly decreased in the presence of the fuzzy logic controller, especially in the case of (FGAPSS2B). The Voltage terminal (V_T) also stays close to 1 per unit. Additionally, in comparison to scenarios without the fuzzy logic controller, the transient state parameters (damping ratio (ζ), maximum overshoot (%MP), damped natural frequency (ω_d), un-damped natural frequency (ω_n), peak time (t_p), terminal voltage peak (V_{TP}), and settling time (t_s)) show their optimal values, with the settling time (t_s) being significantly shorter. These results show that the fuzzy logic controller, when used in conjunction with the genetic algorithm (FGAPSS2B), improves the system's performance and maintains its stability both before and after faults. This is demonstrated in the following tables and figures, which show how the power system coefficients (Terminal voltage V_T, rotor speed ω_m, active power P_{eo}, and reactive power Q_{eo}) behave under normal load conditions and during faults shown the Figures (7-10) and the Tables (3 and 4) below.

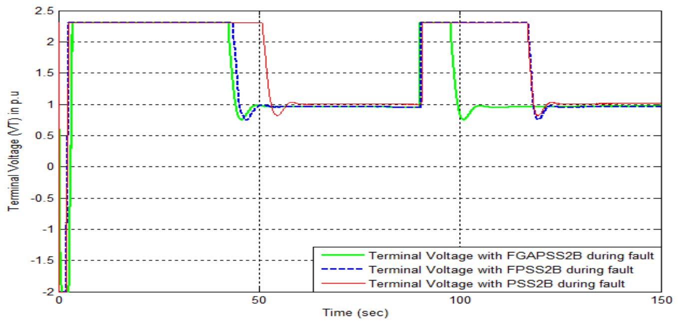

Figure 7. (V_T) in pu during fault at normal load.

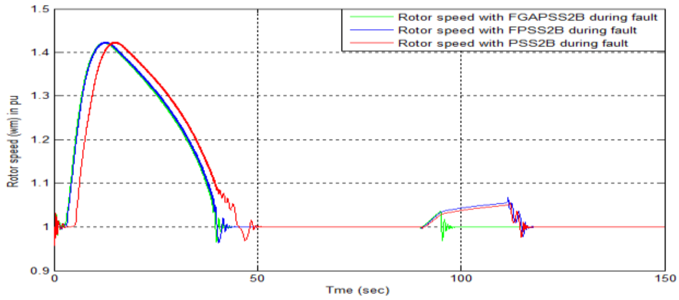

Figure 8. (ω_m) in pu during fault at normal load.

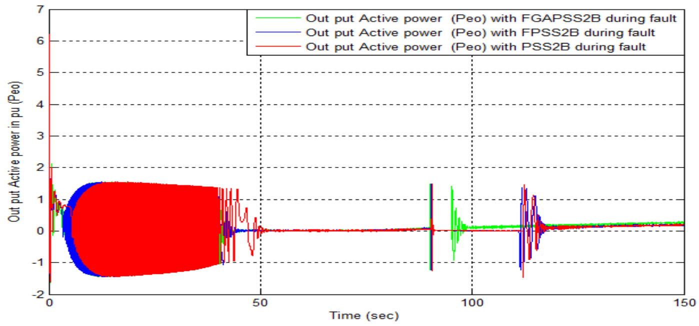

Figure 9. (P_{eo}) in pu during fault at normal load.

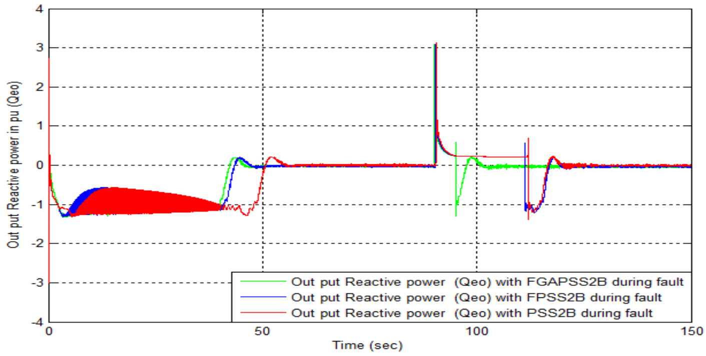

Figure 10. (Q_{eo}) in pu during fault at normal load.

Table 3: (V_T) Characteristic of Transient Conditions During Fault at 80% P.F (Normal Load).

parameters value	PSS2B	FPSS2B	FGAPSS2B
damping ratio (ζ)	0.0640	0.1010	0.095
maximum overshoot (%MP)	1.2232	1.375	1.35
un-damped natural frequency (ω_n) in sec	148.2041	146.73	146.68
Damped natural frequency (ω_d)	147.9002	145.98	146.006
peak time (t_p) in sec.	0.0212	0.0215	0.0215
Voltage terminal peak (V_{TP})	2.3050	2.3050	2.3050
settling time (t_s) in sec.	104.1001	109.11	102.87

Table 4: (ω_m) Characteristic of Transient Conditions During Fault at 80% P.F (Normal Load).

parameters value	PSS2B	FPSS2B	FGAPSS2B
damping ratio (ζ)	0.2636	0.263	0.2612
maximum overshoot (%MP)	0.4239	0.423	0.423
un-damped natural frequency (ω_n) in sec	0.2226	0.2515	0.2612
Damped natural frequency (ω_d)	0.2148	0.0322	0.2519
peak time (t_p) in sec.	14.6286	12.49	12.47
rotor speed peak (ω_{mp})	1.4238	1.423	1.4231
settling time (t_s) in sec.	98.4322	104.433	98.164

4 Conclusion

This work explores the potential synergistic application of a Genetic Algorithm (GA)-optimized Power System Stabilizer (PSS) and a Fuzzy Logic Controller (FLC) to improve the dynamic performance of the Peerdawd Gas Power Station (PPGS).

GA-Based Parameter Tuning: The initial phase involved employing a GA to optimize the lead-lag parameters (T1, T2, T3, T4, T10, T11, K_{PSS}) of the conventional PSS2B under nominal load conditions. This optimization resulted in a demonstrably improved fault response from the PSS2B.

FLC Integration and Comparative Analysis: Subsequently, an FLC was strategically integrated in parallel with the PSS2B to evaluate its efficacy in further augmenting system stability. Two configurations were assessed:

- **FLC with Untuned PSS2B:** The FLC was introduced prior to GA optimization of the PSS2B parameters. This configuration exhibited no statistically significant improvement in fault response compared to the standalone PSS2B. However, when combined with the GA-tuned PSS2B (FGAPSS2B), it demonstrated marginally better performance under light load conditions.
- **FLC with GA-tuned PSS2B (FGAPSS2B):** In this configuration, the FLC was implemented subsequent to GA optimization of the PSS2B parameters. This combined approach (FGAPSS2B) yielded the most significant performance enhancements. FGAPSS2B effectively dampened power system oscillations, ensured rapid response to fault events, and minimized the duration of transient states both during and following faults, particularly under nominal and high-load scenarios.

Critical Parameter Identification: The investigation identified the KPSS parameter as the most influential factor governing the performance of the PSS2B. Even minor adjustments to KPSS demonstrably impacted system stability across various load conditions.

In conclusion, this study underscores the effectiveness of combining FLC with a GA-tuned PSS2B. By leveraging the complementary strengths of these techniques, the proposed approach achieves superior fault response and demonstrably enhances overall power system stability.

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