

(RESEARCH ARTICLE)



TECHNIQUES FOR DISCRETE MITIGATION AND CONTROL IN FOUR AREA SYSTEM WITH DFIG SYSTEM

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ABSTRACT

Integrating large-scale wind power into current power systems presents serious stability concerns as the use of renewable energy increases worldwide. This study assesses discrete-time Power System Stabilizers (PSS) deployed to a four-area interconnected network connected to a Doubly Fed Induction Generator (DFIG) wind farm in order to mitigate low-frequency oscillations. We evaluated conventional controllers, namely Delta-Omega ($\Delta\omega$), Delta-P (ΔP_a), and Multi-Band (MB-PSS4B), versus an intelligent Fuzzy Logic-based stabilizer (FL-PSS) under extreme fault situations using a MATLAB/Simulink framework.

The findings demonstrate that the Fuzzy Logic controller performs noticeably better than conventional fixed-parameter solutions, providing far more robust damping for oscillations in rotor angle and speed. The FL-PSS provides a useful and reliable digital control solution for contemporary power systems with a significant penetration of renewable energy due to its remarkable performance in discrete time.

Keywords: Power system stability, DFIG, Power System Stabilizer, Fuzzy Logic Control, Discrete-time control, Multi-area system.

1 INTRODUCTION

Modern electrical grids, because of the large number of interconnected control areas, have become highly complicated systems. The structural complexity of these grids has led to considerable operational difficulties, particularly in the areas of dynamic stability and reliability. This situation has become even more complicated as a result of the greater integration of renewable energy sources, especially wind energy. The Doubly Fed Induction Generator (DFIG) has become a widely used wind generation technology since it offers efficient energy capture, has a power converter rating on a partial scale, and provides flexibility in terms of variable-speed operation.

The incorporation of Doubly Fed Induction Generator (DFIG) units into a multi-area power grid leads to particular operating problems which require precise stabilization. In a four-area network, where the grid is divided into four separate regional control areas, the power supply has to work in close coordination with demand in order to maintain a constant frequency, voltage profile, and synchronism. Since DFIG units operate asynchronously and provide

considerably less rotational inertia than conventional synchronous generators, their inclusion increases the system's vulnerability to severe frequency variations and short-term instability.

To maintain system stability during extreme disturbance events, power grid operators employ a mix of automatic controls and safety measures:

- Automatic Generation Control (AGC): by constantly varying the output of the generators in different areas, it addresses any shifts in the balance and keeps the grid frequency at a constant level.
- The Governor and Droop controls enable an immediate primary frequency response by altering the output of the generator immediately when there are changes in demand.
- Static VAR compensators and excitation systems continuously inject or absorb reactive power in order to keep the voltage within the safe operating limits, thus controlling the local voltage stability.
- Under-Frequency Load Shedding (UFLS): It functions as an emergency backup to avoid total grid outages by disconnecting non-essential electrical loads when the frequency drops below safe limits.

Power System Stabilizers (PSS) are one of the techniques which are necessary for reducing low-frequency electromechanical oscillations. Although conventional linear, single-band PSS designs perform well at certain operating points they have difficulties when the conditions of the system change. In order to overcome these limitations, the present study examines the performance of advanced Multi-Band PSS and intelligent Fuzzy Logic-based PSS controllers in both the continuous-time and discrete-time domains.

The rest of the manuscript is structured as follows: in Section 2 the mathematical modelling of the test system is set out in full. Section 3 deals with the architecture and design of the various controllers under evaluation. The simulation results are given in Section 4 together with a detailed analysis of system performance. Section 5 then concludes by summarising the main findings of the study.

2 MATHEMATICAL MODELING OF THE TEST NETWORK

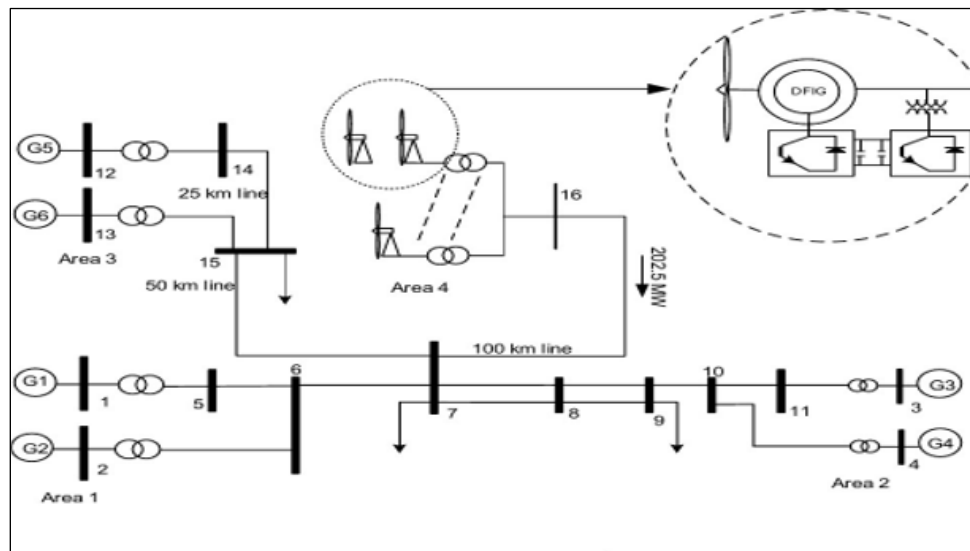


Figure 1: Six-machine, four-area DFIG system

To carry out an organized performance evaluation, a typical test network was developed using the MATLAB/Simulink environment. The system is based on a 230 kV, 50 Hz transmission network which has a considerable short-circuit capacity of 5500 MVA. Generator-1 is assigned the role of the swing bus and the network includes six synchronous machines located over four interconnected areas. The total installed capacity of all the generating units, including the renewable ones, is 5409 MW.

A specialized 100-kilometer transmission line connects the wind-based generation, which is located in Area-1, to bus 15. With 135 identical turbines rated at 1.5 MW apiece, the wind farm has a total wind capacity of 202.5 MW. With this arrangement, Area-1's wind penetration level is about 25%. The entire wind farm is modelled as a single equivalent lumped DFIG model for computing efficiency and modelling tractability. This aggregated form offers adequate integrity for transient stability tests and has been extensively validated in the literature. The corresponding model's per-unit

parameters match those of a single 1.5 MW DFIG, with the farm's base power and collective inertia represented by the proper scaling.

The post-fault oscillatory period, which usually lasts a few seconds, is the simulation horizon. A concentrated investigation of the damping properties offered by the individual stabilizers is made possible by this targeted timeframe.

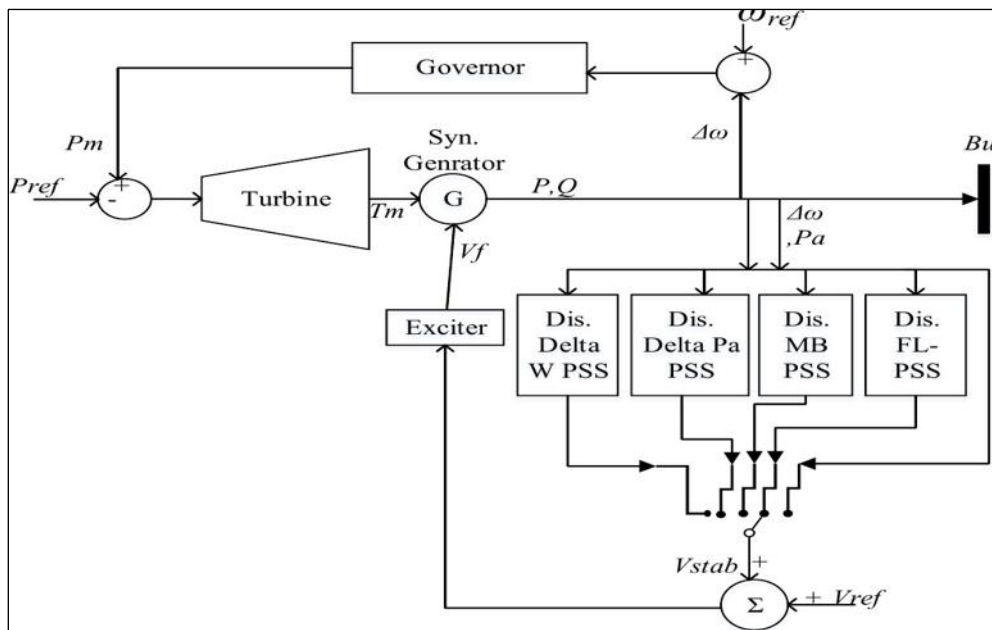


Figure 2. Systematic SLD of a discrete-time PSS-connected machine.

3 CONTROL ARCHITECTURES AND DESIGN

The operating concepts and design concerns for the four different stabilizer types included in this comparative analysis are described in detail in this section.

3.1 Classical Power System Stabilizer (CPSS)

The traditional PSS, which is a key element of synchronous generator control, is primarily employed in order to reduce low-frequency rotor oscillations. The CPSS injects an auxiliary stabilising signal into the Automatic Voltage Regulator (AVR) loop. This extra signal produces an additional damping torque on the rotor shaft by changing the generator's excitation level. As inputs to the CPSS either the rotor speed deviation (delta omega) or the accelerating power ($P_a = P_m - P_e$) are generally used. The internal circuit consists of a series of lead-lag compensators which, after a washout filter has eliminated the steady-state bias, add the required phase advance. The stabilising voltage (V_{stab}) is the output of the chain.

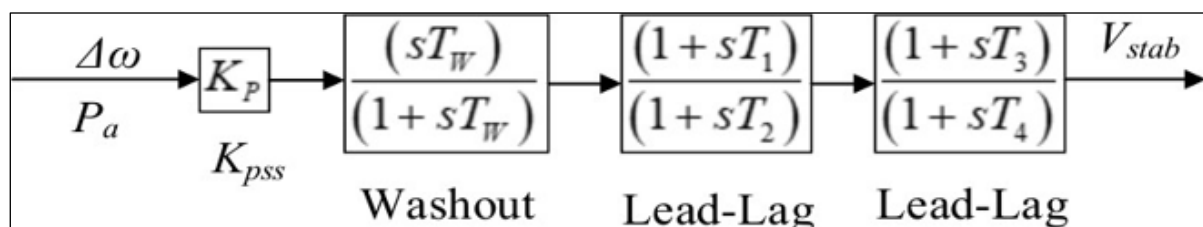


Figure 3: Conventional PSS (CPSS).

3.2 Multi-Band Power System Stabilizer (MB-PSS4B)

The MB-PSS4B is a sophisticated stabiliser designed to deal with oscillations over a wider frequency range. Instead of focusing on a single frequency band like the CPSS, it employs parallel filter paths, each tuned to a different frequency range—usually low (for inter-area modes), intermediate (for local plant modes), and high (for torsional modes). The multi-channel arrangement enables independent gain to be set for each band and thus ensures effective damping for several oscillatory modes without them interfering with one another. Because of this, the MB-PSS4B offers outstanding adaptability and versatility when applied to highly interconnected systems.

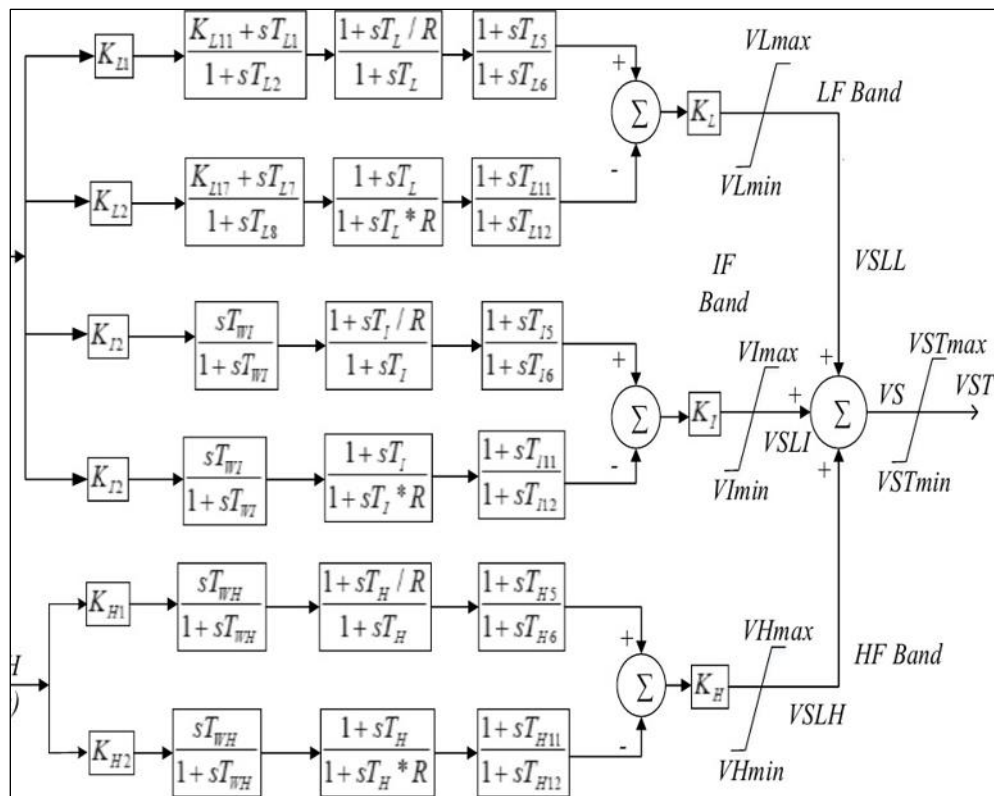


Figure 4: Multi-Band PSS4B.

3.3 Fuzzy Logic-Based Power System Stabilizer (FL-PSS)

Instead of relying on traditional linear control, the FL-PSS introduces a new approach by applying rule-based fuzzy inference to find appropriate stabilizing measures. Its architecture employs predefined membership functions (for example, Negative Large, Zero, Positive Large) in order to convert the precise input data—usually the speed deviation ($\Delta\omega$) and its derivative (acceleration)—into linguistic variables. The correct fuzzy set for the output is obtained from a rule base that is derived from expert control knowledge. This imprecise conclusion is then turned into a definite stabilising signal through a defuzzification process. The FL-PSS provides excellent damping even under substantial disturbances and is particularly good at handling system nonlinearities and uncertainties.

3.4 Discrete-Time Implementation

In order to enable their practical implementation on digital hardware, all continuous-time stabilizers are discretized by means of suitable transformation methods, among which Tustin's bilinear transformation and the Zero-Order Hold (ZOH) equivalency are the most popular. Although the discretization process introduces only small approximation errors, it still provides considerable advantages regarding programmability, repeatability, and resistance to the ageing of analogue components. The research in question evaluates all the stabilizers in both continuous and discrete time.

4 SIMULATION RESULTS AND DISCUSSION

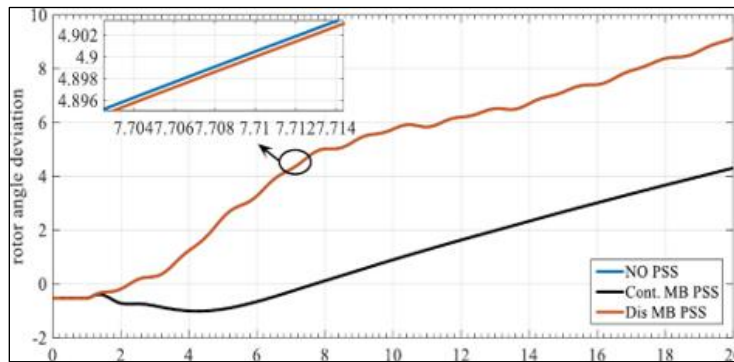
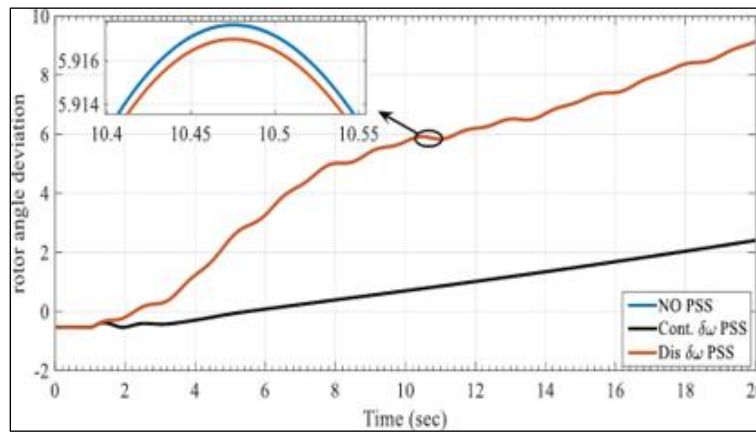
A simulation study was carried out in order to evaluate the transient response of the four-area system incorporating the DFIG. A transmission line suffered a serious three-phase line-to-ground fault at the moment when t was 1 second, and the fault was cleared after 12 cycles. The following configurations are used to capture and analyze the dynamic reactions of Generator-1: (a) No PSS; (b) Delta Omega PSS; (c) Delta Pa PSS; (d) MB-PSS4B; (e) FL-PSS (Discrete); and (f) FL-PSS (Continuous).

4.1 Rotor Angle Deviation Analysis

A direct measure of synchronism stability is the rotor angle deviation. Poor stability is indicated by the uncontrolled system's critically high peak deviation of 0.85 radians with prolonged oscillations, as Table 1 illustrates. By offering moderate dampening, conventional PSSs lower the peak deviation to between 0.58 and 0.62 radians. With a high of 0.45 radians, the MB-PSS4B exhibits enhanced performance. With a peak variation of just 0.32 radians and a settling time of 1.6 seconds, the continuous version of the FL-PSS setups notably produces the best results. The discrete version comes next, demonstrating that digital implementation is feasible.

Table 1: Performance of Rotor Angle Deviation

Stabilizer Type	Peak Angle Deviation (rad)	Settling Time (s)
No PSS	0.85	> 5.0
Delta Omega PSS	0.62	4.2
Delta Pa PSS	0.58	3.8
MB-PSS4B	0.45	2.9
FL-PSS (Discrete)	0.38	2.1
FL-PSS (Continuous)	0.32	1.6

**Figure 5: Rotor Angle Deviation both without PSS and with continuous and discontinuous MB-PSS.****Figure 6: Rotor Angle Deviation both with and without Delta Omega PSS, both continuous and discontinuous.**

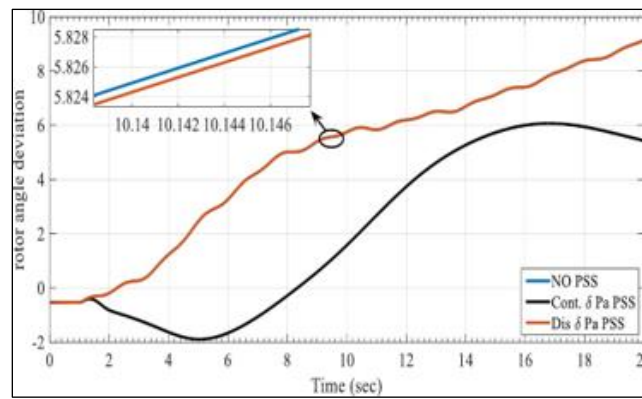


Figure 7: Rotor Angle Deviation both with and without PSS and with continuous and discontinuous Delta Pa PSS.

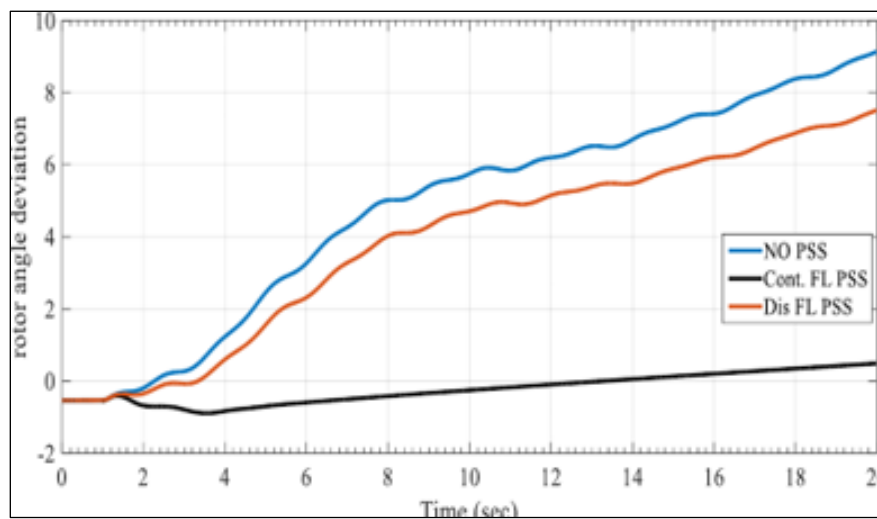


Figure 8: Rotor Angle Deviation both with and without fuzzy-logic PSS, both continuous and discontinuous.

4.2 Rotor Speed Deviation Analysis

The system's capacity to quickly recover from a disruption is reflected in the rotor speed deviation. A similar pattern may be seen in the results, which are shown in Table 2. The highest speed variance in the no-PSS scenario is 0.040 p.u., and the settling period is too long. The MB-PSS4B achieves a smaller deviation of 0.019 p.u., whereas the traditional PSSs limit the variance to about 0.025-0.028 p.u. The FL-PSS (continuous) settles in 1.4 seconds and attains the lowest variation of 0.012 p.u. Once more, the discrete-time FL-PSS performs admirably, settling in 1.8 seconds.

Table 2: Performance of Rotor Speed Deviation

Stabilizer Type	Peak Speed Deviation (p.u.)	Settling Time (s)
No PSS	0.040	> 5.0
Delta Omega PSS	0.028	4.0
Delta Pa PSS	0.025	3.5
MB-PSS4B	0.019	2.6
FL-PSS (Discrete)	0.015	1.8
FL-PSS (Continuous)	0.012	1.4

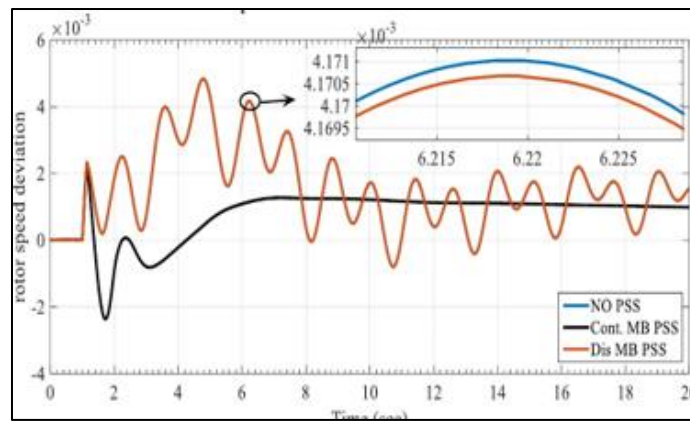


Figure 9: Rotor Speed Deviation without PSS and with continuous and discontinuous MB-PSS.

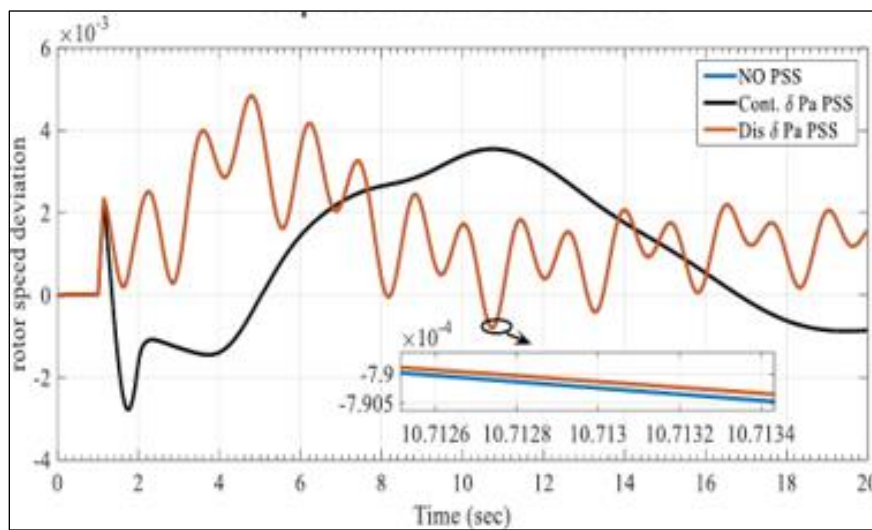


Figure 10: Rotor Speed Variation both with and without PSS and with continuous and discrete Delta Pa PSS.

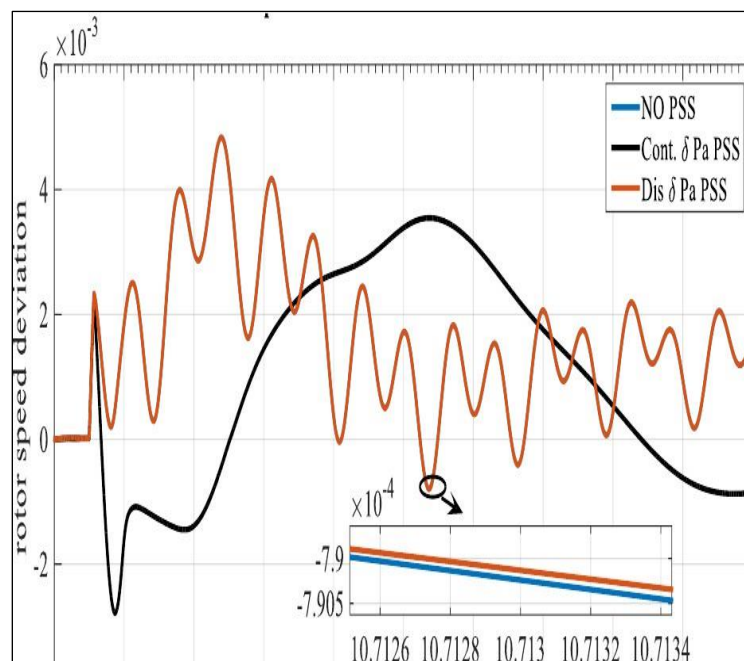


Figure 11: Comparison of Rotor Speed Deviation for Delta Pa PSS.

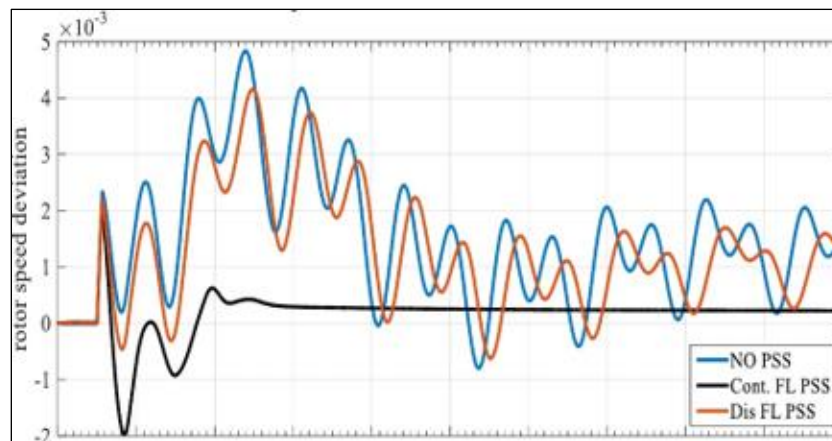


Figure 12: Rotor Speed Deviation using discrete and continuous fuzzy-logic PSS.

4.3 Comparative Performance Ranking

Table 3 establishes a qualitative ranking of the stabilizers based on the cumulative simulation results. From best to worst, the performance is ranked as follows: Continuous FL-PSS > Discrete FL-PSS > MB-PSS4B > Delta Pa PSS > Delta Omega PSS > No PSS.

Table 3: Ranking of Overall Damping Performance

Stabilizer Type	Damping Quality	Rank
No PSS	Very Poor	6th
Delta Omega PSS	Moderate	5th
Delta Pa PSS	Moderate	4th
MB-PSS4B	Good	3rd
FL-PSS (Discrete)	Very Good	2nd
FL-PSS (Continuous)	Excellent	1st

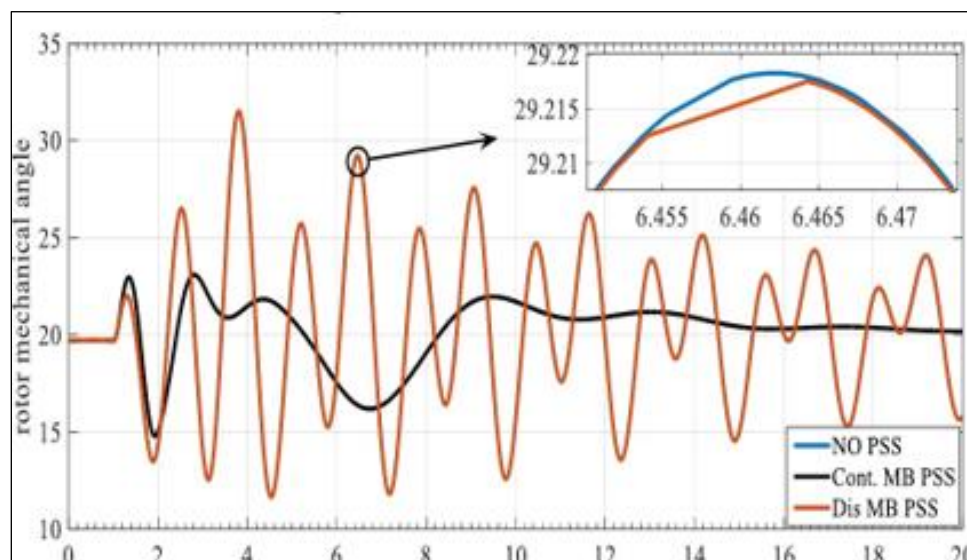


Figure 13: Rotor Mechanical Angle using both discrete and continuous MB-PSS

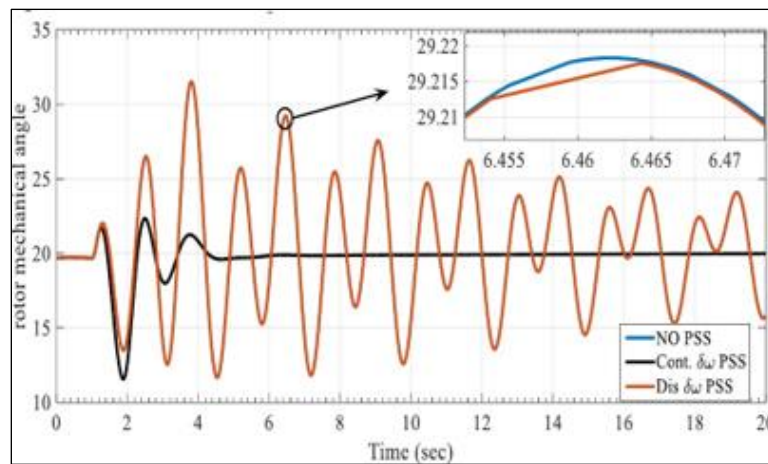


Figure 14: Rotor Mechanical Angle using both discrete and continuous Delta Omega PSS.

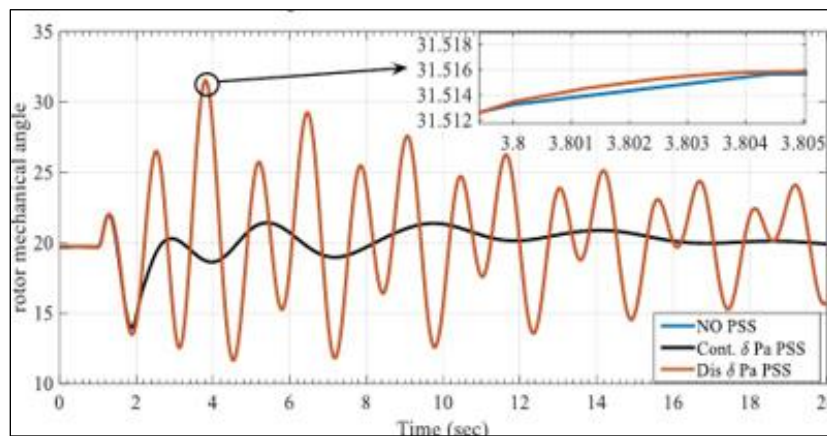


Figure 15: Rotor Mechanical Angle with both discrete and continuous Delta Pa PSS.

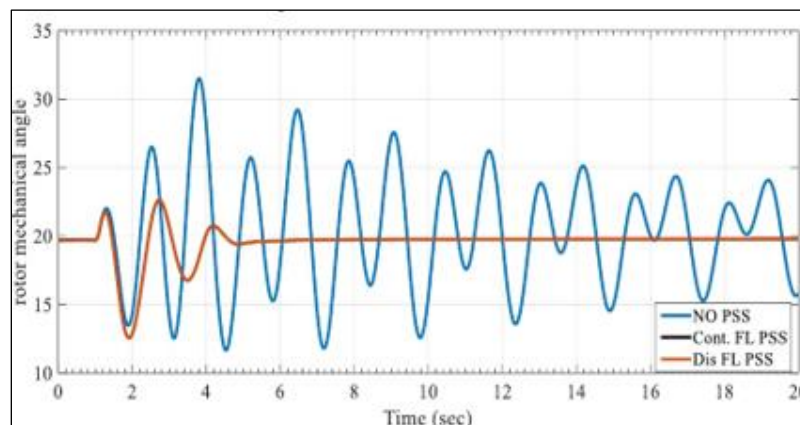


Figure 16: Rotor Mechanical Angle using discrete and continuous fuzzy-logic PSS.

5 CONCLUSIONS

The study includes a thorough comparative analysis of discrete-time stabilisers for a four-area power system which has been integrated with DFIG. The fuzzy logic-based stabilisers and the conventional stabilisers (Delta Omega, Delta Pa, MB-PSS4B) were subjected to extensive testing in a severe fault situation.

The following is a summary of the main findings:

Stabilizer Requirement: Any stabilizer greatly improves dynamic performance as compared to an uncontrolled system.
2. Conventional Performance: Because of its multi-frequency dampening capacity, the Multi - Band PSS4B performs

better among conventional designs than the more straightforward Delta-based stabilizers. 3. Fuzzy Logic Superiority: With the lowest peak deviations and quickest settling times for both rotor angle and speed, the FL-PSS continuously provides the highest damping performance. 4. Discrete-Time Feasibility: With only a slight compromise in comparison to its continuous version, the discrete-time FL-PSS maintains a considerable performance advantage over traditional stabilizers. It is hence very appropriate for contemporary digital control applications. 5. Hierarchy of Performance: The final effectiveness ranking is determined to be: Continuous FL-PSS > Discrete FL-PSS > MB-PSS4B > Delta Pa PSS > Delta Omega PSS > No PSS.

In order to improve the fuzzy stabilizer's membership functions and rule bases and possibly achieve even better performance under a variety of operating settings, future research could concentrate on including adaptive or optimization methods (such Particle Swarm Optimization).

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

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