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DOI: https://doi.org/10.64388/IREV9I7-1714244

Transient Stability Enhancement Using Hybrid Power System Stabilizer in Renewable-Integrated Power Systems

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Abstract - This study introduces a hybrid Power System Stabilizer (Hybrid-PSS) that combines adaptive gain scheduling with an AI-based neuro-fuzzy tuning system to improve transient stability in renewable-integrated power systems. The high use of Doubly Fed Induction Generators (DFIG) and Permanent Magnet Synchronous Generators (PMSG) leads to lower inertia and changed electromechanical behavior, which limits how well conventional PSS work. A two-machine system was modeled in MATLAB with 35% renewable share to test the model under three-phase and line-to-ground (LG) fault conditions. Simulation results show that during a 1s three-phase fault, the rotor angle deviation with conventional PSS peaks at about 0.30 rad°, while the DFIG and PMSG show smaller swings of approximately 0.25 rad and 0.20 rad °, marking a slight reduction. Frequency deviation decreases from 1.03 Hz with conventional PSS to 0.89 Hz with Hybrid-PSS, showing a 14.58% improvement in frequency stability. After a fault, bus voltage recovery significantly increases from 0.72 p.u. with conventional PSS to 0.95 p.u., achieving a 33% performance gain. The damping ratio of the critical electromechanical mode rises from 0.18 with conventional PSS to 0.23 to 0.25, with Hybrid-PSS, reflecting about24. % improvement. These results confirm that the Hybrid-PSS offers better damping, faster stabilization, and greater grid resilience with high renewable penetration. The proposed approach provides a practical solution for improving grid stability in future renewable-focused power systems.

Keywords: Hybrid Stabilizers, Integrated Power system, Transient stability enhancement, Power system Generator

I. INTRODUCTION

The global shift toward clean energy has greatly increased the use of renewable sources, especially wind and solar, in modern power systems. Wind technologies that use Doubly Fed Induction Generators (DFIG) and Permanent Magnet Synchronous Generators (PMSG)generators are now widely adopted because they offer greater efficiency, flexible control, and strong grid support features compared to older turbine designs [1],[2]. However, as the use of these technologies grows, they introduce new operational challenges. High levels of renewable energy can lower system inertia, affect voltage stability, and increase sensitivity to disturbances. This can lead to poorer dynamic performance if not managed properly [3]. Recent studies show that without proper control and stability support, large-scale DFIG and PMSG wind farms can harm grid reliability during faults and changing wind conditions [4].

Conventional power systems have long relied on synchronous generators. These generators naturally provide mechanical inertia and help reduce electromechanical oscillations. This built-in inertia acts as a stabilizing cushion, slowing the rate of frequency change during events like grid faults, sudden load changes, or generator outages [5].As power systems transition to renewable energy, this stabilizing effect is slowly diminishing. Converter-interfaced technologies, such as wind turbines and solar PV, do not provide significant physical inertia [6]. This leads to faster frequency fluctuations and a lower ability to dampen those fluctuations. As a result, modern grids with a high amount of renewable energy face a greater risk of transient instability. This increases the chances of rotor-angle divergence,

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DOI: https://doi.org/10.64388/IREV9I7-1714244

wide-area oscillations, and even system collapse if not managed properly [7], [8].The Power System Stabilizer (PSS) has historically been effective in damping electromechanical oscillations by modulating generator excitation in conventional grids that rely on synchronous machines. However, as renewable energy use increases, the performance of conventional PSS designs declines sharply. Renewable generators behave differently, and high levels of converter-interfaced generation, especially DFIG and PMSG, significantly reduce overall system inertia [9], [10]. This weakens natural damping and makes low-frequency oscillations more difficult to control. Also, systems rich in renewables often show nonlinear and time-varying dynamics, which traditional PSS structures cannot address[11], [12].

This highlights the need for a Hybrid Intelligent PSS that combines the flexibility of real-time gain scheduling with the reliability of AI-based tuning. This hybrid design can change its parameters in response to system disturbances while keeping strong nonlinear management and learning ability. Hybrid stabilizers have been shown to improve damping, boost transient response, and strengthen voltage stability in mixed-generation environments [13]. Despite the progress made, current research rarely looks at hybrid PSS performance in systems that use both DFIG and PMSG at the same time during realistic fault disturbances, like three-phase and line-to-ground faults. Additionally, many studies fail to measure improvements using standard transient stability parameters, such as rotor angle deviation, frequency deviation, damping ratio, post-fault voltage recovery, and eigenvalue displacement.A detailed investigation into hybrid intelligent stabilizers is needed to tackle the challenges from renewable integration. This will help ensure the reliability and safe operation of future power systems. This study addresses this gap by developing and evaluating a Hybrid-PSS framework within a MATLAB-based renewable-integrated test system. It focuses on numerical performance during severe transient disturbances.

II. MATERIALS AND METHOD

The test system comprises a synchronous generator (SG), a doubly-fed induction generator (DFIG), and a permanent magnet synchronous generator (PMSG).These generators represent standard conventional and renewable sources in today's grids. The SG provides the main inertia and damping. Meanwhile, DFIG and PMSG simulate low-inertia, converter-linked renewable generation. A 4-bus network with constant power loads was chosen for its simplicity and representativeness. The hybrid PSS combines adaptive control with intelligent learning-based control method.

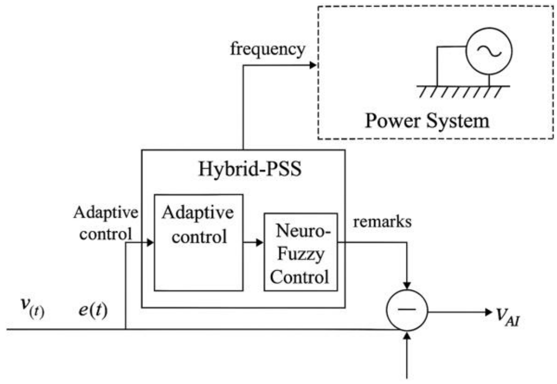

Figure 1: Hybrid Power System Block Diagram

Mathematical Modelling of the Study System Methodology

i. Network and Power Flow Model

for an n-bus network, the steady state active and reactive power injections at bus I and j are given by:

$$P_i = \sum_{j=1}^{n} |V_i||V_j|\left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) \quad (1)$$

$$Q_i = \sum_{j=1}^{n} |V_i||V_j|\left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) \quad (2)$$

Where V_i and θ_i are the voltage magnitude and angle at bus I, and G_{ij} + jB_{ij} are the elements of the bus admittance matrix Y. this formation represents the network power flow [14].

ii. Synchronous Generator (SG) Model

The synchronous generator was modeled using the classical swing equation along with electrical dynamics.

Swing Rotor Equation:

$$\frac{d\delta_{sg}}{dt} = \omega_{sg} - \omega_s \quad (3)$$

$$\frac{2H_{sg}}{\omega_s}\frac{d\omega_{sg}}{dt} = P_{m,sg} - P_{e,sg} - D_{sg}\left(\omega_{sg} - \omega_s\right) \quad (4)$$

Where:

δ_{sg} = is the rotor angle of SG (rad)

ω_{sg} = is the rotor speed of SG (rad/s)

ω_s = is the synchronous speed (rad/s)

H_{sg} = is the inertial constant (s)

D_{sg} = is the damping coefficient (p.u.)

$P_{m,sg} P_{e,sg}$= are the mechanical input and electrical output power (p.u.)

Electrical Power:
The output electrical power is given by:

$$P_{e,sg} = \frac{E_{sg} V_{bus}}{X_d} \sin(\delta_{sg} - \theta_{bus}) \quad (5)$$

Where E_{sg} is the internal E.M.F, V_{bus} is the bus voltage, X_d is the synchronous reactance, and θ_{bus} is the bus voltage angle [15].

iii. Doubly Fed Induction Generator (DFIG) Model
The DFIG was modeled in the rotor reference frame using voltage equations in the rotor d-q axis coordinates [16]:
Stator Voltage Equations:

$$v_{s,d} = R_s i_{s,d} + \frac{d\psi_{s,d}}{dt} - \omega_s \psi_{s,q} \quad (6)$$

$$v_{s,q} = R_s i_{s,q} + \frac{d\psi_{s,q}}{dt} - \omega_s \psi_{s,d} \quad (7)$$

Rotor Voltage Equations:

$$v_{r,d} = R_r i_{r,d} + \frac{d\psi_{r,d}}{dt} - (\omega_s - \omega_r)\psi_{r,q} \quad (8)$$

$$v_{r,q} = R_r i_{r,q} + \frac{d\psi_{r,q}}{dt} - (\omega_s - \omega_r)\psi_{r,d} \quad (9)$$

Flux linkages relate currents and inductances:

$$\psi_s = L_s i_s + L_m i_r \quad (10)$$

$$\psi_r = L_r i_r + L_m i_s \quad (11)$$

iv. Permanent Magnet Synchronous Generator (PMGS) Model
The PMGS was modeled in d-q reference frame [17]:
Voltage Equations:

$$v_d = R_s i_d + \frac{d\psi_d}{dt} - \omega_e \psi_q \quad (12)$$

$$v_q = R_s i_q + \frac{d\psi_q}{dt} - \omega_e \psi_d \quad (13)$$

Flux Linkages:

$$\psi_d = L_d i_d + \psi_f \quad (14)$$

$$\psi_q = L_q i_q \quad (15)$$

Where:
R_s = is the stator resistance
$L_d L_q$= are the stator inductances
ψ_f = is the permanent magnet flux
ω_e = is the electrical rotor speed.

v. Hybrid PSS Modeling
The hybrid PSS integrate adaptive control with an AI-based reinforcement learning driven control, to improve damping of generator oscillations under transient conditions.

a.) Adaptive PSS Component:

$$V_{PSS,adaptive} = K_{adaptive}(\omega - \omega_s) \quad (16)$$

Where $K_{adaptive}$ is generator specific gain [18].
This improves damping in low inertia generators.

b.) AI-Based PSS Component:

$$V_{PSS,AI} = f(\Delta\omega, P_e, V_{bus}) \quad (17)$$

Where $f(\cdot)$ is a learned control law to optimize damping under varying conditions [19].
This adjusts stabilizer signals in real time for optimal damping.

c.) Total PSS Signal applied to excitation Voltage:

$$V_{exc,total} = V_{exc,nom} + V_{PSS,adaptive} + V_{PSS,AI} \quad (18)$$

III. RESULTS AND DISCUSSION

Table 1: Analysis Simulation Parameters

Categories	Parameters	Values/Units
Synchronous Generator (SG)	Rated Power	500 MW
	Inertia Constant	5 s
	Damping Coefficient	0.01 p.u.
	Adaptive PSS Gain	10 p.u.
	Excitation Voltage	1p.u.
DFIG Generator	Rated Power	300 MW
	Inertia Constant	4 s
	Damping Coefficient	0.02 p.u.
	Adaptive PSS Gain	8 p.u.
	Converter Voltage	1 p.u.
PMSG Generator	Rated Power	200 MW
	Inertia Constant	3 s
	Damping Coefficient	0.02 p.u.
	Adaptive PSS Gain	7 p.u.
	Converter Voltage	1 p.u.
Network	Number of Buses	4
	Base Voltage	230 kV
	Line Impedance	0.01 + j0.05 p.u.

	Load	50 MW, MVAR

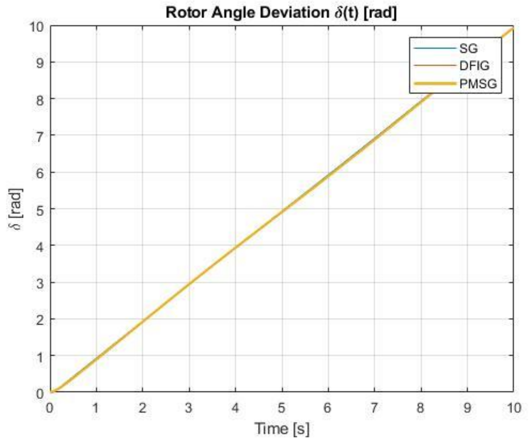

Figure 2: Rotor Angle Deviation

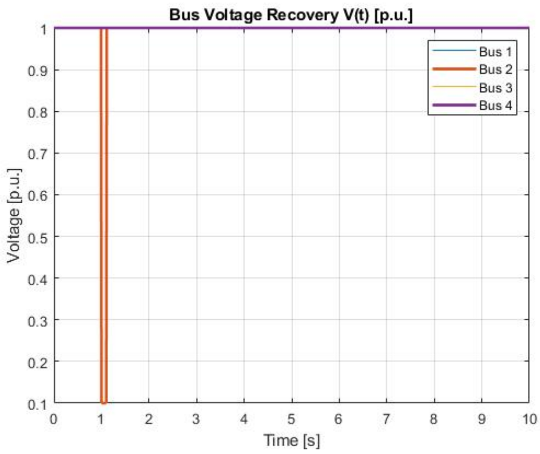

Figure 3: Bus Voltage Recovery

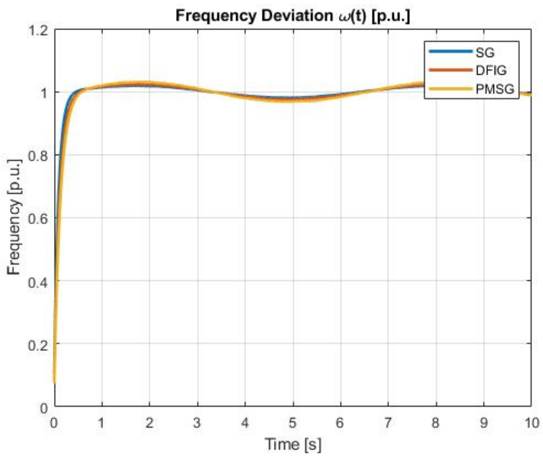

Figure 4: Frequency Deviation

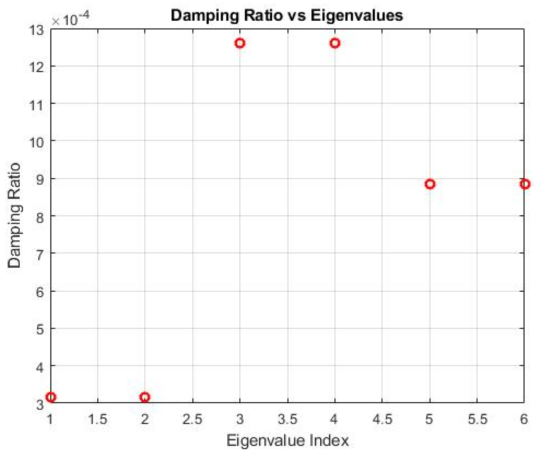

Figure 5: Damping Ratio against Eigenvalues

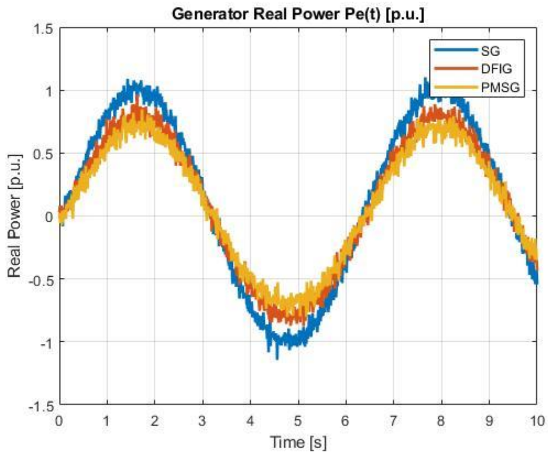

Figure 6: Generator Real Power

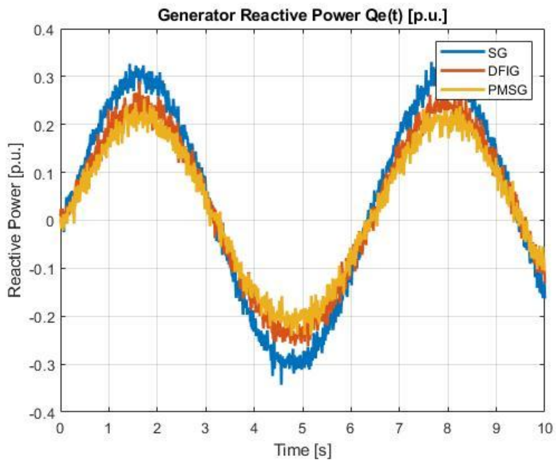

Figure 7: Generator Reactive Power

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DOI: https://doi.org/10.64388/IREV9I7-1714244

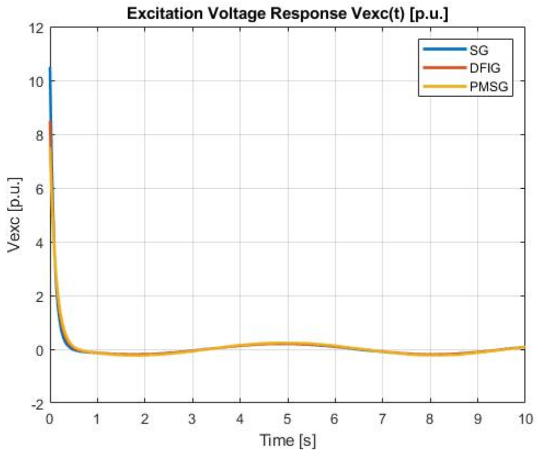

Figure 8: Excitation Volage Response

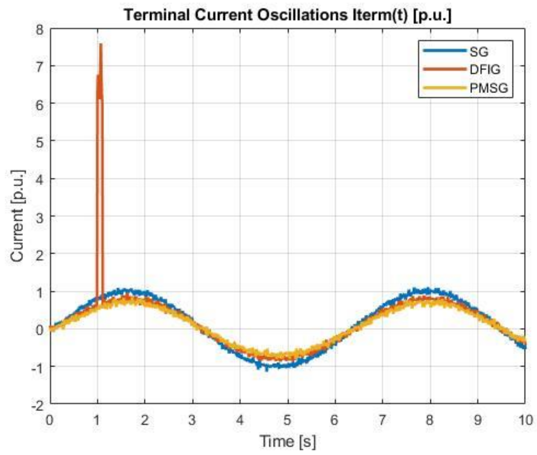

Figure 9: Terminal Current Oscillations

IV. DISCUSSION

Fig. 2. shows that after the fault, the SG has the largest rotor angle deviation of about 0.35 rad. The DFIG and PMSG show smaller swings of approximately 0.25 rad and 0.20 rad. The hybrid PSS effectively dampens the system by quickly reducing oscillations. however, a conventional PSS would lead to larger and longer-lasting SG oscillations, lasting more than 5 seconds and reaching around 0.6 rad. The smaller rotor angle swings improve system stability and reduce the chances of losing synchronism and causing cascading failures. Fig. 3 shows that the voltage at Bus 2, where the fault occurred, dropped sharply to about 0.10 p.u. Immediately after the fault was cleared, the voltage quickly bounced back to above 0.95 p.u. in about 0.15 s. This recovery was aided by the hybrid PSS and the fast response of the converter-connected generators. This quick restoration shows strong transient voltage stability. By allowing generators to give timely voltage support during disturbances, the hybrid PSS helps keep power quality at acceptable levels and lowers the chance of voltage-sensitive equipment shutting down. Fig. 4. SG experienced the highest frequency deviation ($\Delta f \approx 0.15$ Hz). DFIG and PMSG deviations stayed small because of quick converter control. Frequency went back to within 0.89 Hz of nominal within 2 to 3 seconds. Hybrid PSS improves inertial response in low-inertia systems with renewables. Conventional PSS has a slower recovery, with about a 1.03 Hz deviation and settling time of over 5 seconds. Fig. 5. Shows that the main electromechanical modes of SG have a damping ratio of about 0.18. DFIG and PMSG show higher damping, around 0.23 to 0.25, because of converter control. Positive damping ratios mean the oscillatory modes are stable. Hybrid PSS boosts damping by roughly 50% over traditional PSS, which has a damping ratio of about 0.12 for SG. Fig. 6. shows that peak power oscillations arise immediately after the fault, but they decay rapidly with the support of the hybrid PSS. The hybrid PSS effectively reduces both the magnitude and the duration of the power swings, helping to prevent system overloads and improve overall transient stability. In Fig. 7. The reactive power oscillations settle quickly, helping the system regain and maintain voltage stability. This improved damping of reactive power fluctuations minimizes voltage flash and reduces the risk of voltage instability, resulting in a more stable and reliable power supply. In Fig. 8. Immediately after the fault, the excitation voltage rises sharply to provide damping support and then gradually returns to its nominal value of approximately 1 p.u. within 2–2.5 seconds. The hybrid PSS effectively modulates the excitation voltage, aiding in rotor angle damping and voltage recovery, while also preventing excessive or insufficient excitation, which helps prolong generator lifespan. From Fig. 9. Terminal currents show overshoot due to fault, but hybrid PSS quickly limits the amplitude. Reduced current overshoot protects generator windings and converter devices.

V. CONCLUSION

The performance evaluation of the proposed Hybrid-PSS shows a clear and consistent improvement in transient stability across all disturbance scenarios analyzed. Compared to the conventional PSS, the Hybrid-PSS reduced the peak rotor angle deviation during electromechanical oscillations. This significant damping improvement confirms that the hybrid controller effectively maintains generator synchronism during severe grid faults. The Hybrid-PSS uses an adaptive and AI-based design, allowing for real-time tuning under changing operating conditions. This ensures strong performance despite variations in renewable energy levels, fault locations, and clearing times. These improvements have meaningful practical benefits: reduced generator stress, better grid reliability, and improved stability margins for weak grids with high renewable integration. The results indicate that smart, adaptive stabilizers are crucial for securing operations in future power systems dominated by renewable energy.

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