

Renewable Energy Integration for Enhanced Power System Stability Under Large Disturbances

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Received: 4 September 2026

Accepted for publication: 30 September 2026

Published: 12 October 2026

Abstract— The Large-Scale integration of renewable energy sources fundamentally alters the dynamic behavior of modern power systems, presenting both critical challenges and unprecedented opportunities for stability enhancement. This paper investigates the dual-edged impact of wind power, via Doubly-Fed Induction Generators, and solar photovoltaic systems on power system stability during severe contingencies. While the inherent intermittency of these sources characterized by fluctuating wind speeds and partial shading of PV arrays introduces significant operational uncertainties, their advanced power electronic interfaces offer a pathway for intelligent grid support. This work proposes a novel control framework that leverages the fast-acting reactive power capability of DFIGs and the active power modulation of solar PV inverters to provide synthetic inertia and voltage support, thereby improving the system's transient stability. Concurrently, a small-signal stability analysis is conducted using eigenvalue and modal decomposition techniques to evaluate the impact of these RESs on the system's damping characteristics and oscillatory modes. The efficacy of the proposed strategy is validated through time-domain simulations on a modified IEEE test system. Results demonstrate a marked improvement in rotor angle stability and critical fault clearing time, alongside enhanced damping of inter-area oscillations. This research establishes that, when equipped with suitable grid-forming controls, renewable energy sources are not merely a source of instability but a crucial asset for bolstering overall grid resilience against large disturbances.

Keywords— Transient stability, small signal stability, power system wind-solar integration.

I. INTRODUCTION

The global energy landscape is undergoing an unprecedented transformation, driven by the urgent need to decarbonize electricity generation and mitigate climate change [1]. This transition has catalyzed the massive integration of renewable energy sources (RESs), particularly wind and solar photovoltaic (PV) systems, into modern power grids [2],[3]. However, this paradigm shift fundamentally alters the dynamic behavior of power systems, as conventional synchronous generators with their inherent inertia and damping characteristics are progressively replaced by inverter-based resources (IBRs) with fundamentally different operational properties [4], [5]. The power injected from Doubly-Fed Induction Generators (DFIGs) in wind farms and solar panels (SPs) into the power system introduces new dynamics that challenge traditional stability paradigms [6], [7].

The inherent intermittency of renewable sources characterized by fluctuating wind speeds and partial shading conditions in PV arrays introduces significant operational uncertainties that complicate power system stability management [8],[9],[10]. These variable generation patterns, combined with the reduced system inertia resulting from power-electronic decoupling, pose critical challenges to both transient stability during large disturbances and small-signal stability under normal operating conditions [11]. The problem is further exacerbated as power systems approach high RES penetration levels, where conventional stability assessment and control methodologies become inadequate [12]. Extensive research has addressed the stability challenges associated with RES integration. Sheikh Ali et al. [13] Comprehensively surveyed stability assessment techniques under high RES penetration, categorizing methodologies into model-based, optimization-based, and AI-based approaches. [14] Critically reviewed grid-forming (GFM) converter capabilities for low-inertia systems,

highlighting their potential for transient stability enhancement through voltage and frequency regulation. [15] Examined dual-axis excited synchronous generators as an alternative for improved stability in modern energy systems.

Regarding DFIG contributions, virtual inertia control strategies have been proposed to partially compensate for reduced system inertia [16]. However, the effectiveness of these approaches during severe contingencies remains limited without comprehensive control frameworks. For solar PV systems, research has focused on reactive power capability and fault-ride-through (FRT) requirements [17]. Recent studies have explored energy-storage-based GFM converters for grid support during disturbances [18],[19] Analyzed technical obstacles in large-scale RES integration, emphasizing the need for coordinated control strategies. The impact of RESs on small-signal stability has been investigated through eigenvalue analysis, revealing that high RES penetration can significantly alter system oscillatory modes [9].

This research addresses the following questions: (1) how can the fast-acting reactive power capability of DFIGs and the active power modulation of solar PV inverters be coordinated to enhance transient stability during severe contingencies?, (2) What is the impact of RES on the small-signal stability characteristics, particularly damping of inter-area oscillations?, (3) Can RESs, when equipped with suitable grid-forming controls, transform from stability challenges to stability assets?.

This study proposes a novel control framework that leverages the fast-acting reactive power capability of DFIGs and the active power modulation of solar PV inverters to provide synthetic inertia and voltage support. Concurrently, small-signal stability analysis is conducted using eigenvalue and modal decomposition techniques to evaluate the impact of these RESs on system damping characteristics and oscillatory modes. The efficacy of the proposed strategy is validated through time-domain simulations on a modified IEEE test system.

The primary aim is to establish that RESs can be crucial assets for bolstering grid resilience against large disturbances. Key contributions include: (1) a comprehensive control framework for coordinated DFIG and PV inverter support; (2) systematic small-signal stability assessment of RES-integrated systems; and (3) demonstration of improved rotor angle stability and critical fault clearing time.

The remainder of this paper is structured as follows: In section 2, reviews the transient stability, and small signal model respectively of the standard system of three areas interconnected with a parallel integration RES view as enhancing the stability of electric power systems. Section 3 comprehensively characterizes the key operational features of wind and solar energy systems. In section 4 shows the simulation results and discussions. Finally, the paper concludes by summarizing the key findings.

II. THREE AREAS FOR INTERCONNECTED POWER SYSTEM WITH INTEGRATED RES MODEL

Renewable energy integration with three-area of the three synchronous generators (SG) and nine bus network in a steady state operating condition have great potential for

damping power system electromechanical oscillations. In The case study Schematic Diagram of the Three-area machine System interconnected with, shown As in Fig [1].

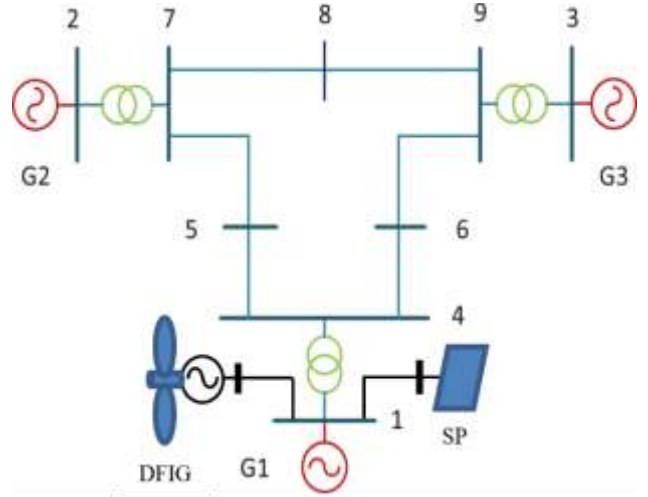


Fig. 1. Three SG and 9bus Architecture with integrated RES

A. Simplified Transient Model of Synchronous Machine

In transient stability studies, generators with their controls and dynamic loads are usually described by a set of differential equations (DE), represented in time-domain as follow.

1) Electrical Equation

$$T'_{doi} \frac{dE'_{qi}}{dt} = -E'_{qi} + E_{fd} - (X_{di} - X'_{di})I_{di} \quad (1)$$

$$T'_{qoi} \frac{dE'_{di}}{dt} = -E'_{di} - (X_{qi} - X'_{qi})I_{qi} \quad (2)$$

2) Mechanical Equation

$$\frac{d\delta_i}{dt} = \omega_i - \omega_s \quad (3)$$

$$\frac{2H_i}{\omega_s} \frac{d\omega_i}{dt} = T_{Mi} - P_{ei} - T_D \quad (4)$$

Where: ($i = 1, \dots, n = 4$) number of synchronous machines

3) Static Exciter Differential Equation

The differential equations governing the operation of the excitation system is given by:

$$T_a \frac{dE_{fd}}{dt} = -E_{fd} + k_a(V_{ref} - V_t + V_s) \quad (5)$$

B. Simplified Small-Signal Model of the Power System

In addition to the assumptions made in the transient model, the following assumption is also made here. The damper winding (q-axis) dynamics are neglected since T'_{q0} is small compared to T'_{d0} . Hence, $T'_{q0} = 0$, therefore, the linearization of the DEs around operating point given by the system of first-order equations $\dot{x} = f(A, x, B, u, t)$, the state-space variables denote the deviations from the equilibrium state, The model is written as follows:

$$\begin{bmatrix} \Delta \dot{\delta} \\ \Delta \dot{\omega} \\ \Delta \dot{E}'_q \\ \Delta \dot{E}'_{fd} \end{bmatrix} = \begin{bmatrix} 0 & \omega_s & 0 & 0 \\ -\frac{K_1}{2J} & -\frac{K_D}{2J} & -\frac{K_2}{2J} & 0 \\ -\frac{K_3}{T'_{do}} & 0 & -\frac{K_4}{T'_{do}} & \frac{1}{T'_{do}} \\ -\frac{K_5 K_a}{T_a} & 0 & -\frac{K_6 K_a}{T_a} & -\frac{1}{T_a} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta \omega \\ \Delta E'_q \\ \Delta E'_{fd} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{2J} \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} T_M \\ V_{ref} \end{bmatrix} \quad (6)$$

This model has two inputs and four state-space variables. The inputs are mechanical torque ΔT_m and rotor excitation winding voltage $\Delta E'_{fd}$ deviations, the state space variables are rotor angle $\Delta \delta(t)$, rotor speed $\Delta \omega(t)$.

C. Wind Turbine Characteristic

Wind power-generating systems are one of the clean energy sources, with variable speed and constant frequency being the most widely utilized in DFIGs, which is made up of a wind turbine, a gearbox, an induction motor, and control modules[20]. The power coefficient $C_p(\lambda, \beta)$ represents the efficiency which the turbine converts wind kinetic energy into mechanical energy. It depends on the tip-speed ratio λ , which defines the relationship between the wind speed and the rotational speed of the turbine blades, as well as the pitch-angle β of the blades. The expression used to identify $C_p(\lambda, \beta)$ for a particular wind turbine [21] is given by (7).

$$C_p = 0.5176 \left(\frac{116}{\lambda_i} - 0.4\beta - 5 \right) \exp \left(-\frac{21}{\lambda_i} \right) + 0.0068\lambda \quad (7)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (8)$$

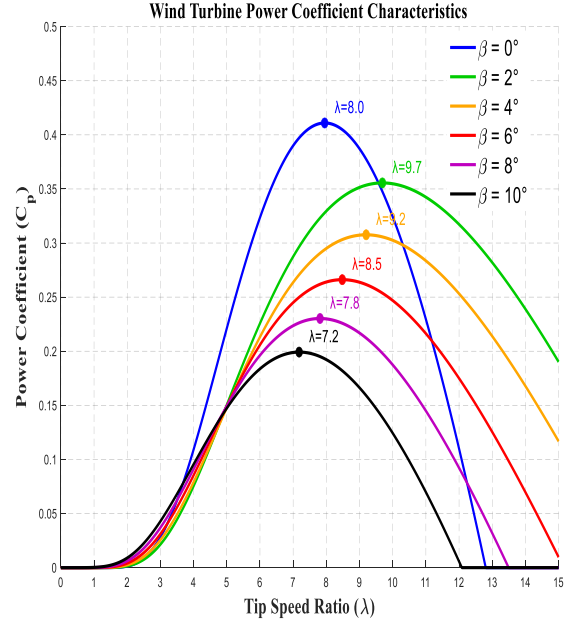


Fig. 2. Wind Turbine Power Coefficient Characteristics (C_p) vs. tip speed ratio (λ) for various pitch angles (β).

Figure 2. Shows how the power coefficient C_p varies with the tip-speed ratio λ for different blade pitch angles, each curve exhibits a distinct peak, corresponding to the maximum power achievable at the optimal λ for that specific pitch angle.

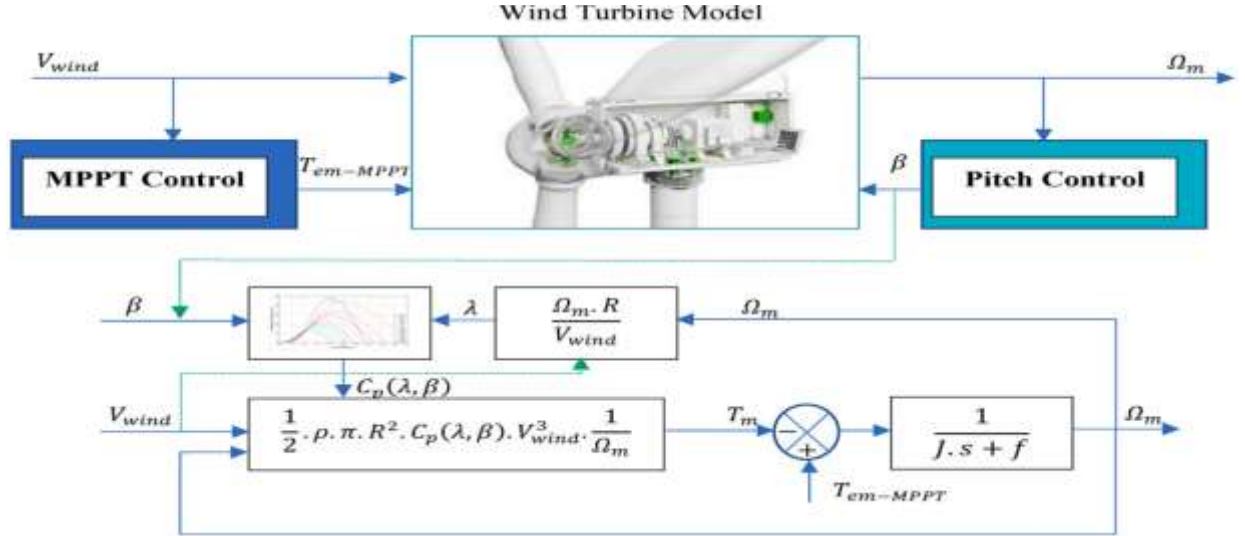


Fig. 3. Simplified Schematic block diagram of the variable-speed wind energy conversion system (WECS) integrating MPPT and pitch angle (β) control architectures.

TABLE I. WIND TURBINE POWER COEFFICIENT (C_p) CHARACTERISTICS MULTIPLE PITCH ANGLES

Calculating $C_p(\lambda, \beta)$ for multiple pitch angles ($\beta = 0^\circ$ To 10°)		
$\beta = 0^\circ$	$\lambda_{opt} = 7.95$	$C_{p_max} = 0.4110$
$\beta = 2^\circ$	$\lambda_{opt} = 9.69$	$C_{p_max} = 0.3556$
$\beta = 4^\circ$	$\lambda_{opt} = 9.20$	$C_{p_max} = 0.3076$
$\beta = 6^\circ$	$\lambda_{opt} = 8.48$	$C_{p_max} = 0.2661$
$\beta = 8^\circ$	$\lambda_{opt} = 7.81$	$C_{p_max} = 0.2303$
$\beta = 10^\circ$	$\lambda_{opt} = 7.18$	$C_{p_max} = 0.1992$

D. Solar panel Generator Characteristic

The mathematical equation for plotting I-V and P-V curves characteristic is given by (9).

$$I_{sc} = I_{ph} - I_{d1} \left[\exp \left(\frac{I_{sc} R_s}{n_1 N_s V_{th}} \right) - 1 \right] - I_{d2} \left[\exp \left(\frac{I_{sc} R_s}{n_2 N_s V_{th}} \right) - 1 \right] - \frac{V_{tl} + I_{sc} R_s}{R_{sh}} \quad (9)$$

This one is an equivalent circuit of a practical PV cell, in many literatures it is also termed as a seventh parameter model ($I_{ph}, I_{d1}, I_{d2}, I_{sh}, R_s, R_{oc}, V_{oc}$). For the maximum power point ($I = V_{mp}, V = V_{mp}$), For the short circuit current ($I = I_{sc}, V = 0$) [1],[22].

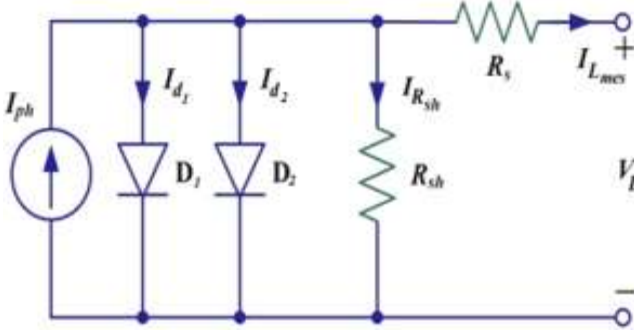


Fig. 4. Equivalent Circuit of the Two-Diode PV Model

Figure 4. Shows an equivalent circuit diagram of a double-diode model, used to describe the behavior of PV cells characteristic, figure includes a current source, which depends on solar irradiance and cell temperature, a diode in which the inverse saturation current depends on the operating temperature, a series resistor, and a shunt resistor, considering the resistive load, which mathematically expressed as (9).

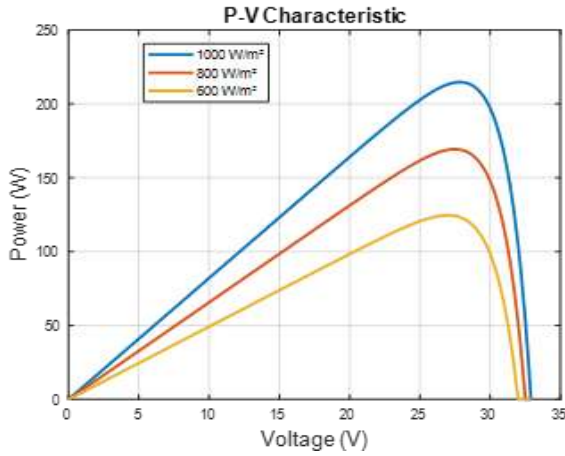


Fig. 5. P (V) characteristics by varying irradiance at T= 25°C

Figure 5. Describes P-V characteristics of double diode model for The P-V curves of a PV module at different irradiance values for normal conditions ($T=25^\circ$). We can locate its peak (maximum power point) with respective voltages for varying irradiance. And it is being observed that as irradiance increases output power also increases and reaches nominal power point at Standard temperature condition (STC).

III. RESULT SIMULATION AND DISCUSSION

A. Simulation of Interconnected Power Systems without Integrated Renewable Energy

The comprehensive nonlinear Simulink model of a synchronous generator and interconnected power system,

With detail of differential algebraic equation for transient stability in (d, q) transformations, excitation control loops, and the fundamental algebraic equations for network. This time-domain framework serves as the foundational plant model for assessing transient stability prior to linearization.

1) Transient Stability Simulation

A power system transient stability simulation model consists of a series of differential equations derived from dynamic models ($\delta_i, \omega_i, \dot{E}'_q, \dot{E}_{fd}$), along with a set of algebraic equations that reflect the power system network.

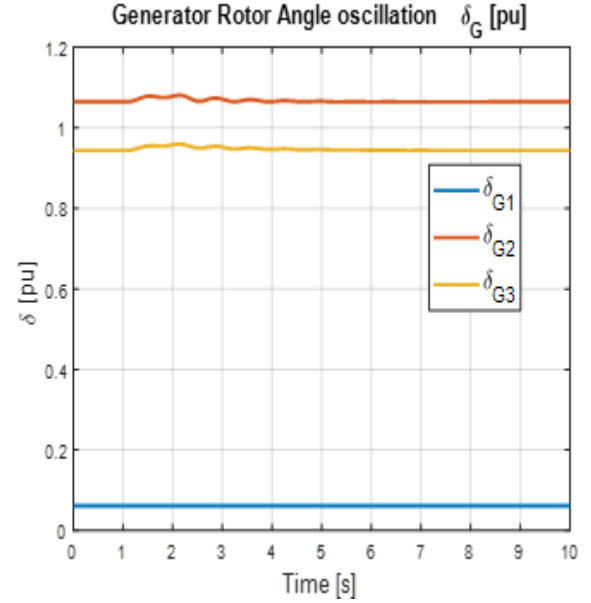


Fig. 6. Generator rotor angle oscillation

Figure 6 shows the rotor angle deviations ($\delta_1, \delta_2, \delta_3$) of the three machines, relative to the center of inertia (COI). The angles are oscillating due to the fault, but the system is stable as the oscillations are damped.

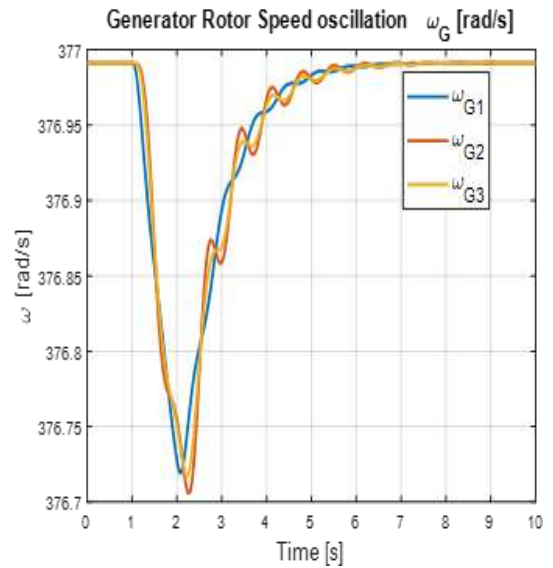


Fig. 7. Generator rotor speed oscillation

Figure 7 represents generator rotor speed deviations ($\omega_{G1}, \omega_{G2}, \omega_{G3}$) of the three machines, the speeds are

oscillating due to the fault, which has been cleared at time ($t=4s$), but the system is stable as the oscillations are damped. ω_G remains constant at 376 rad/s while the stays at 377 rad/s indicating no speed deviation, the machines are oscillating together indicating a coherent response.

2) Small Signal Stability Simulation

The stability of the operating point of a dynamic system to small disturbances is termed small signal stability, to test small signal stability of the system's dynamic equations are linearized about a steady state operating point to get a linear set of state equations ($\Delta\dot{x}_i, \Delta\dot{\omega}_i, \Delta\dot{E}'_q, \Delta\dot{E}_{fd}$).

$$\begin{cases} \Delta\dot{x} = A\Delta x + B\Delta u \\ \Delta y = C\Delta x + D\Delta u \end{cases} \quad (09)$$

Where $\Delta x_{(n,1)}$ Represent space vector, $A_{(n,n)}$ represent state space matrix, $B_{(n,p)}$ represent input matrix for control vector, $\Delta U_{(p,1)}$ represent control vector, $\Delta Y_{(q,n)}$ represent output vector, $C_{(q,n)}$ represent output matrix, and $D_{(q,p)}$ represent a feed-forward matrix.

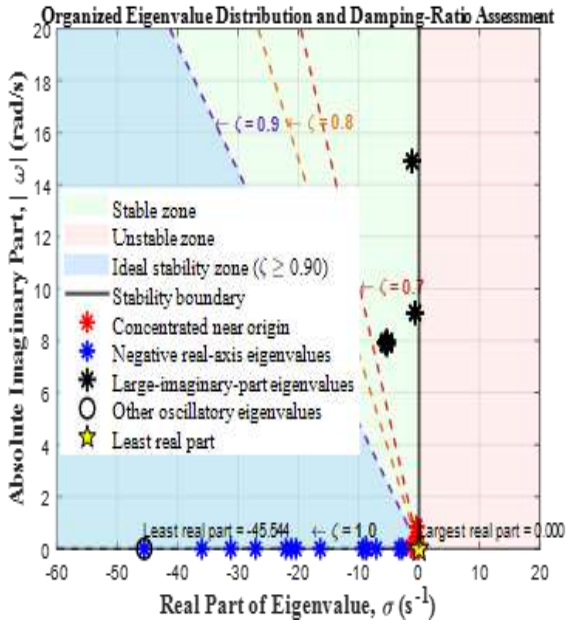


Fig. 8. System's eigenvalues without integrated RES

The most common way to visualize the eigenvalues is by plotting them in the complex plane where, complex eigenvalues are always composed of conjugate pairs represented as: $\lambda_i = \sigma_i + j\omega_i$ which can be described as the real part represents the damping of the system oscillation mode, while the imaginary part represents the frequency of the system oscillation. The frequency of oscillation can be expressed as:

$$f_i = \frac{\omega_i}{2\pi},$$

The damping ratio is defined as:

$$\xi_i = \frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}},$$

It represents the attenuation characteristic of the oscillation amplitude.

TABLE II. POWER SYSTEM EIGENVALUE ANALYSIS

Power System Eigenvalue Analysis	
Total number of eigenvalues	33
Number of stable eigenvalues	32
Number of unstable eigenvalues	1
Least real part	-45.544291
Largest real part	0.000000
Ideal damping-ratio limit	0.90
Minimum damping ratio	-1.000000
Minimum damping coefficient	-0.000000
Overall stability result	unstable

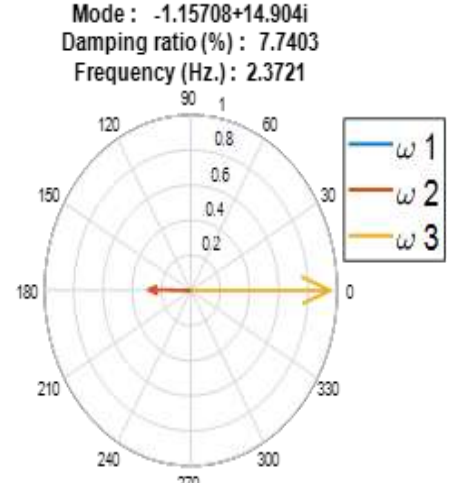


Fig. 9. Generator's speed mode shape

Figure 9 depicts the inter-area and local-mode shapes of the studied system, The inter-area mode shape demonstrates that machines 2, located in Area 2 with frequency 0.2Hz, swing in the opposite direction with respect to generator 3, which are located in Area 3 with frequency 0.8Hz. Because the magnitude of mode shape is higher for Area 3, they have a greater effect on the inter-area mode than the generators in Area 2.

B. Simulation of interconnected Power Systems with Integrated Renewable Energy

In this case implements a MATLAB/Simulink model of a modified architecture integrating renewable energy sources (RES) and network dynamics, equipped with PI regulators for active solar and reactive wind power control loops, to evaluate time-domain responses.

1) Transient stability simulation

The fault significantly affected the generator dynamics particularly the rotor angle and rotor speed response, leading to large deviations in the generators rotor angles δ_r , and rotor speed ω_r . as depicted in Figures (10 and 11). Consequently, the dynamic responses of the generators improved, and stability observed. However, the rotor angle deviation less than 0.2 Hz is recorded at the G1, while the increasing of rotor speed deviation more than nominal speed 377 [rd/s] around 382.2[rd/s] indicating that the network generators remained unstable even after the fault, despite sufficient

active and reactive power injection from the renewable energy system and classical PI controller unable.

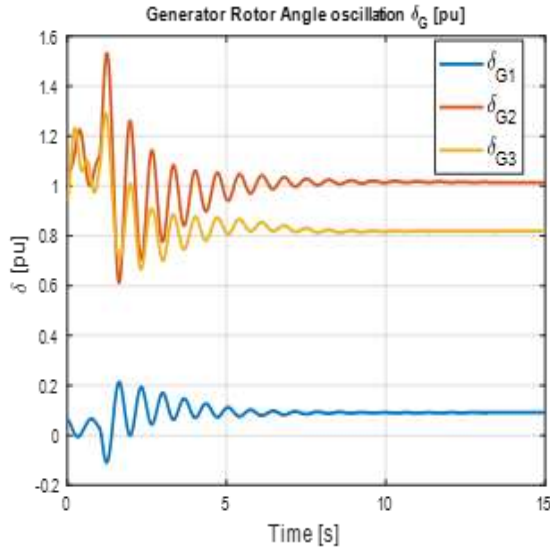


Fig. 10. Generator rotor angle oscillation

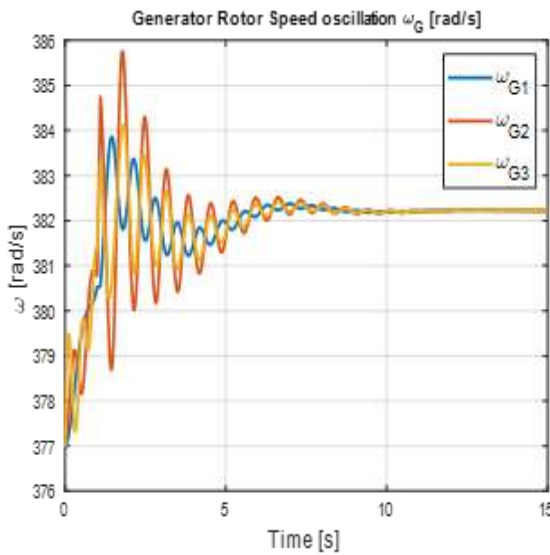


Fig. 11. Generator rotor speed oscillation

2) Small signal stability simulation

In this section implements the linearized differential equations of a small-signal model of synchronous machine, integrated with algebraic equation solvers, to conduct comprehensive eigenvalue analysis, and examine the coherent interaction oscillation generators between each other, across local-area, inter-area, and wide area modes representation under generators-side fault disturbances.

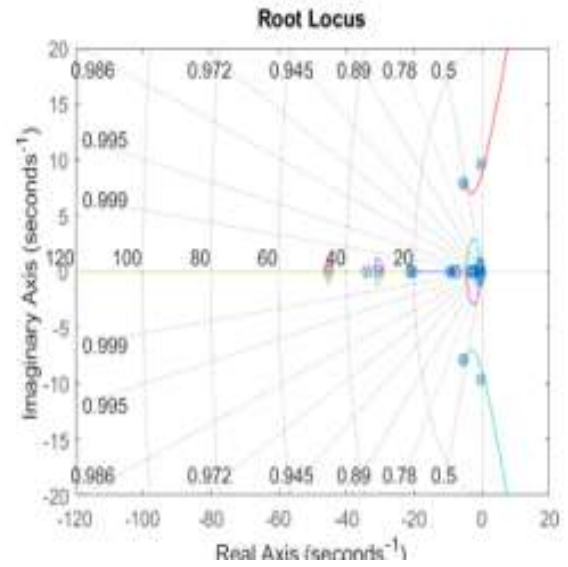


Fig. 12. System's root locus (eigenvalues)

Figure 12 shows Root Locus complex poles with damping ratios (ζ) from 0.4 to 0.999, all lying far from the imaginary axis indicating well-damped or over-damped oscillatory modes.

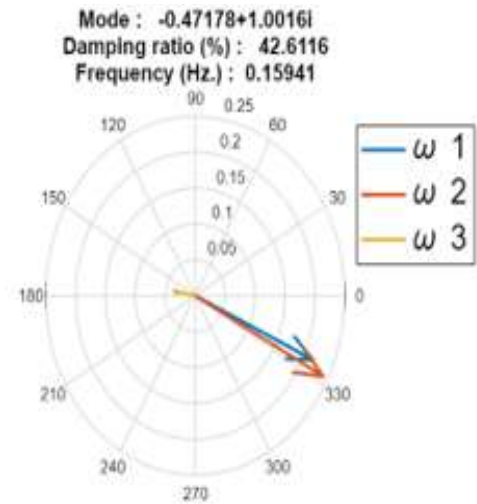


Fig. 13. Generator mode shape

Figure 13 depicts one inter-area mode shape 1 shows that area 1 generator G1 and area 2 generator G2 oscillates against Area 3 generator G3, with G1 and G2 playing a significant role. Mode shape 1 and 2 shows that area 1 generator G1 and Area 2 generators G2 oscillate coherently against Generator G3 in Area 3 with high participation factor.

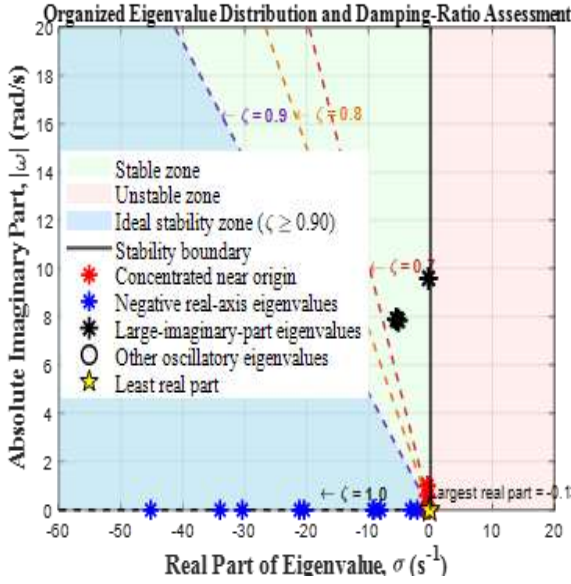


Fig. 14. System's eigenvalues with integrated RES

Figure 14 shows the distribution of eigenvalues in s-plane, where we can observe that eigenvalues concentrated near the origin represent slow, and weakly damped modes, eigenvalues distributed along the negative real axis correspond to non-oscillatory modes with relatively high damping ratios, eigenvalues with large imaginary parts represent high-frequency electromechanical or control-related oscillations.

TABLE III. POWER SYSTEM EIGENVALUE ANALYSIS

Power System Eigenvalue Analysis with Integrated RES	
Total number of eigenvalues	25
Number of stable eigenvalues	25
Number of unstable eigenvalues	0
Least real part	-185.640263
Largest real part	-0.134414
Ideal damping-ratio limit	0.90
Minimum damping ratio	0.032959
Minimum damping coefficient	0.134414
Overall stability result	Stable

IV. CONCLUSION

This study confirms that the strategic integration of renewable energy sources, specifically wind and solar PV systems, presents a crucial challenge for stability interconnected modern power system during large disturbances as shown in fig 10, and fig 11, while wind and solar energy introduce new dynamic complexities impacting rotor angle, rotor speed oscillation, and small-signal stability as evidenced by representing the eigenvalue fig 8, and fig 12, where increasing damping coefficient less than 0.5 and 15Hz on imaginary axis.

In addition, this work insight into the result of simulation we can conclude that the power system with renewable energy integration has best result on small signal stability than without. Whereas Overcoming eigenvalue-related stability issues in RES integrated with interconnected power system, provide enhanced damping and stability, for all eigenvalues in system stability region.

For future work, machine-learning techniques will be investigated for eigenvalue classification, while deep reinforcement learning will be employed to control modern interconnected power systems and enhance their transient stability.

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