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The Effect of Cirata PV Power Plant Integration on Small-Signal Stability in the 500 kV Jawa-Bali System

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ABSTRAK

Integrasi pembangkit berbasis renewable energy resources (RES) dapat mempengaruhi kestabilan sistem ketika sistem mengalami gangguan kecil. Penelitian ini bertujuan untuk menganalisa pengaruh integrasi PLTS Cirata terhadap stabilitas dinamis dan small signal pada sistem Jawa Bali 500kV. Sistem damping dan pergerakan eigenvalue kritis yang berhubungan dengan local dan interarea modes dari generator sinkron akan dianalisa. Dari hasil simulasi dan analisa eigenvalue menunjukkan peningkatan injeksi daya PLTS Cirata berpengaruh pada pergerakan nilai eigenvalue yang bergeser ke kiri menjauhi sumbu imajiner, dari σ = -1.253 menjadi σ = -1.255. Dan diikuti dengan peningkatan rasio redaman/damping sistem dari 10,85% menjadi 10,88%. Hasil ini menunjukkan bahwa integrasi PLTS Cirata memberikan kontribusi positif untuk meredam osilasi dan meningkatkan kestabilan sistem ketika dihadapkan pada gangguan kecil yang berpotensi menyebabkan ketidakstabilan.

Kata kunci: *small signal stability, local dan interarea modes, damping ratio, osilasi, PLTS*

ABSTRACT

Renewable energy resources (RES) integration significantly affects power system stability, corresponding with the system to maintain stable conditions when the system is subjected with small disturbance. In this research, the effects of Cirata integration on the Jawa Bali 500kV power system network's dynamic and small signal stability are analyzed. The critical eigenvalue trajectories showed that increasing power injection from PLTS improved the stability, it is indicated by the movement of critical eigenvalues to the left away from the imaginary axis, from *σ = -1.253 to σ = -1.255*. And is followed by an increase in the system damping ratio from 10,85% to *10,88%*. These results indicate that the integration provides a positive contribution to damping oscillations and increasing system stability when faced with small disturbances.

Keywords: *small signal stability, local dan interarea modes, damping ratio, osilasi, PLTS*

1. INTRODUCTION

In Recent years, the development of Renewable Energy Resources (RES) has been increasing significantly. Some factor encouraged the development of RES based power plants are the decline of fossil fuel reverse which affect the sustainability of energy supply, the rapid development of RES technology conversion devices, the increase of green house effect and the environmental concern. In Indonesia, RES based power generation has also been developed inline with the government vision of green and clean energy. Based on data from the Ministry of Energy and Mineral Resources of the Republic of Indonesia (ESDM), the installed capacity of Solar Power Plants (PV) experienced a significant increase, reaching approximately 473 MW by 2023. This development aligns with the government's commitment to accelerating the energy transition toward solar energy in order to reduce dependence on fossil fuels and support the achievement of Net Zero Emissions. In the publication of the 2021–2030 Electricity Supply Business Plan (RUPTL), the government set a target of achieving 4.6 GW within ten years **(Hermawan et al., 2023)**. Targeting, the installed capacity of RES based power generation, power system network in Indonesia gradually introduces and integrate the RES based power plant. Cirata Solar Power Plant (PLTS Cirata), one of the largest floating solar power plants in Southeast Asia with a capacity of 145 MW, is expected to make a substantial contribution to clean energy supply within the Jawa-Bali system **(Iskandar et al., 2023)**.

Introducing RES based power plant has some advantages in terms of the abundant availability of energy resources and environmentally friendly energy generation. On the other hand, the weather dependant of RES is the most concern should be carefully handled. The uncertainty and intermittency of RES have become main challenges in integrating of such RES power plant. The fluctuating conditions of RES may affect the stability of power system involving frequency and voltage stability. Sudden change of RES potentially results in large deviation of system frequency and voltage, affecting the system stability. It also may contribute to the oscillatory stability concern in power system corresponding to the small signal stability. The integration of PLTS, specifically PLTS Cirata into the 500-kV Jawa-Bali system requires careful and comprehensive assessment given the intermittent nature of solar power. Its electrical output fluctuates depending on weather conditions, which may induce oscillations in system frequency and bus voltage **(Rahman et al., 2022)**. The increasing penetration of large-scale solar power into the grid can also lead to a reduction in system inertia, as PLTS units do not possess rotating elements like synchronous generators. This reduction in inertia may decrease the damping ratio, a parameter that indicates the system's ability to attenuate oscillations following a disturbance **(Mishan et al., 2025) (Zhang et al., 2025)**.

In this research, oscillatory stability problem of large-scale RES based power plant is analysed. It is important to carefully identify the risk of instability problem in power system due to small change and fluctuation of RES. Small Signal Stability in power systems is defined as the system's ability to remain stable following a small disturbance **(He et al., 2013)**. Small signal stability is typically caused by system dynamics. These disturbances cause the mechanical input power of generators to change slowly, while the electrical output power changes more rapidly, affecting rotor speed **(Sadid et al., 2023)**. The disturbance on rotor speed would influence the synchronized operation of the generators. The undamped low frequency oscillation in power system cause instability problem on critical modes corresponding to the local and inter-area electromechanical modes of the generators. Under undamped situation, the generators would swing and oscillate against each other, resulting unstable condition which eventually cause operation failure and tripping of the generators. Trajectories of the critical eigenvalues are important to analyse the risk of instability. Eigenvalue analysis is a proven method for accurately assessing small signal stability. By calculating eigenvalues, information regarding system stability such as oscillation frequency, damping factors, and other variables can be obtained **(Samanta et al., 2025)**.

Stability analysis can be conducted by examining the positions of the system’s eigenvalues on the complex plane. An eigenvalue is considered sTable when it has a negative real part, indicating that the system’s response to small disturbances is damped. Conversely, an eigenvalue with a positive or near-zero real part indicates poor damping and a potential risk of instability **(Kundur, 1998**). The increasing integration of solar PV power plants into the system alters the dynamic characteristics of the power grid, including reduced damping due to weakened coupling among generators, changes in the magnitude and distribution of effective system inertia, increased sensitivity to power variations, and modified response speeds to system disturbances **(Drishya & Jayaprakash, 2021)(Rezaei et al., 2022)**. Therefore, the movement of eigenvalues resulting from increased PV capacity becomes a key indicator in assessing how PV integration influences system dynamics and stability.

Given the growing penetration of PV power plants and their dependance on weather conditions, it is evident that system operating points will sight dynamically with changes in weather. These shifts in operating points affect the dynamic characteristics of the system, observable through changes in dominant eigenvalues and reductions in damping ratios of certain oscillation modes **(Drishya & Jayaprakash, 2021)**. Thus, eigenvalue analysis is essential not only to evaluate the system’s ability to maintain stability in the presence of small disturbances, but also to assess the sensitivity of power system stability to increasing levels of PV integration.

To analyze and evaluate system behavior under small disturbances, DigSILENT PowerFactory is used, as it is capable of modeling and assessing system stability based on the eigenvalues obtained. DigSILENT is considered reliable for this study due to its availability of realistic PV plant models and other components that accurately represent real field conditions **(Eidiani et al., 2023) (Irfanto & Sudiarto, 2023)**. Therefore, DigSILENT serves as an appropriate software tool for evaluating the impact of integrating the Cirata PV power plant on the small-signal dynamic stability of the 500-kV Jawa-Bali system.

2. METHODS

2.1 *Power System Stability*

Power system stability is defined as the ability of an electrical power system to maintain its equilibrium condition or return to its normal operating state after experiencing disturbances either small or large without losing synchronism **(Kundur, 1998) (Murty, 2017)**. The post-disturbance equilibrium condition refers to the system’s ability to return either to its pre-disturbance operating point or to a new equilibrium point.

Rotor angle stability, meanwhile, refers to the capability of the power system to maintain synchronism among interconnected generators following a disturbance, ensuring that generators remain synchronized despite changes in mechanical or electrical torque. This type of stability is classified into small-signal stability and transient stability. Small-signal stability is defined as the ability of the system to remain synchronized under small, everyday fluctuations such as minor load variations or small disturbances **(Kundur, 1998) (Murty, 2017) (Andic et al., 2022)**.

2.2 Small Signal Stability

Small-signal stability refers to the ability of a power system to maintain synchronism when subjected to small disturbances **(Baillieul & Samad, 2021)**. Because the disturbances are minor, the nonlinear differential–algebraic Equations that describe the system can be linearized around a stable operating point. Instability in this context may manifest as a steady increase in rotor angle due to insufficient synchronizing torque, or as oscillations with increasing amplitude caused by inadequate damping torque **(Gibbard et al., 2016)**. An advantage of using small-signal stability analysis is that eigenvalues provide a comprehensive representation of the system's small-disturbance stability under the current operating condition. In comparison, transient stability analysis captures only a single event at a specific moment through time-domain simulation **(Virulkar & Gotmare, 2016)**.

2.3 Eigenvalue

Eigenvalues are characteristic values that describe the dynamic behavior of a power system when subjected to small disturbances. In small-signal stability analysis, the eigenvalue (λ) is calculated from the system's state matrix, which has been linearized around its operating point, and is represented in the form of complex numbers **(Rouco, 1998)**.

$$\lambda = \sigma \pm j\omega \tag{1}$$

Equation (1) shows the real part (σ) determines the damping characteristics of the system, while the imaginary part (ω) represents the oscillation frequency. A negative σ indicates a sTable system in which oscillations decay exponentially, whereas a positive σ signifies instability, where oscillations grow continuously. Referring to Equation (2), the oscillation frequency (*f*) in Hertz can be calculated from the ω component using the formula:

$$f = \frac{\omega}{2\pi} \tag{2}$$

The frequency value is used to classify oscillation modes into inter-area modes, local modes, or control modes.

2.4 Modal Analysis

Modal analysis is a method used to understand the dynamic behavior of a power system by examining the oscillation modes that arise due to small disturbances around the operating point **(Rogers, 2000)**. Each mode represents a specific oscillatory pattern determined by its eigenvalue (frequency and damping) and mode shape (the direction of movement of the state variables). Through modal analysis, it is possible to identify which modes have the greatest influence on system stability (dominant modes), as well as which variables or generators contribute most significantly to these modes through the participation factor. The participation factor is a measure of how strongly a state variable (such as a generator's rotor angle) is involved in an oscillatory mode, and it is used to determine optimal control locations in power system stability analysis. With reference to Equation (3), the linearization of the system in modal analysis can be represented by the following Equation:

$$\Delta x = A\Delta\dot{x} + B\delta u \tag{3}$$

Where
Δ = The symbol denoting deviation from the operating point (example: $\Delta x = x - x^0$)
A = Matriks Jacobian $\delta f/\delta x[nxn]$
B = Matriks Jacobian $\partial f/\partial u[nxm]$

Equation (3) when represented in the Jacobian matrix form, becomes the following:

$$A = \partial f/\partial x|_{x^0,u^0} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \cdots & \frac{\partial f_2}{\partial x_n} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{\partial f_n}{\partial x_1} & \frac{\partial f_n}{\partial x_2} & \cdots & \frac{\partial f_n}{\partial x_n} \end{bmatrix}$$

$$B = \partial f/\partial u|_{x^0,u^0} = \begin{bmatrix} \frac{\partial f_1}{\partial u_1} & \frac{\partial f_1}{\partial u_2} & \cdots & \frac{\partial f_1}{\partial u_m} \\ \frac{\partial f_2}{\partial u_1} & \frac{\partial f_2}{\partial u_2} & \cdots & \frac{\partial f_2}{\partial u_m} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{\partial f_n}{\partial u_1} & \frac{\partial f_n}{\partial u_2} & \cdots & \frac{\partial f_n}{\partial u_m} \end{bmatrix}$$

2.5 DigSILENT PowerFactory

DigSILENT PowerFactory is used to analyze the impact of integrating the Cirata PV power plant into the system because this software includes small-signal disturbance analysis features capable of providing quantitative evaluations of the system's dynamic characteristics through the calculation of eigenvalues, oscillation modes, and damping ratios from a system model linearized around its operating point **(Gonzalez-Longatt & Rueda-Torres, 2014)**.

According to the **(Technical Documentation, 2021)**, the small-signal stability analysis module in PowerFactory provides eigenvalue analysis suitable for representing both balanced and unbalanced networks. The calculations can be configured to account for all oscillation modes in the system, or to perform analyses that consider not only conventional generation but also non-conventional sources such as wind turbines, PV systems, and HVDC systems. The results can be visualized in eigenvalue plots, which also include information on oscillation frequencies, damping, and damping ratios **(Gonzalez-Longatt & Rueda-Torres, 2014)**.

2.6 Flowchart

Figure 1 presents the flowchart used in this study. The process begins with constructing the Single Line Diagram of the Jawa-Bali system and entering all required data, including generator data, load data, transmission line parameters, PV plant capacity, and other relevant information. A load-flow simulation is then performed for the base-case condition to obtain the initial system state as a reference. Modal analysis is subsequently carried out to determine the eigenvalues and damping ratios under the base-case condition. Referring to IEEE standards, the damping ratio threshold is set at 5%. The next stage involves the gradual integration of the PV power plant through four increment scenarios: the addition of 50 MW, 100 MW, 150 MW, and 192 MW of PV capacity. For each increment of PV integration into the system, modal analysis is performed to identify changes in the damping ratio under each condition.

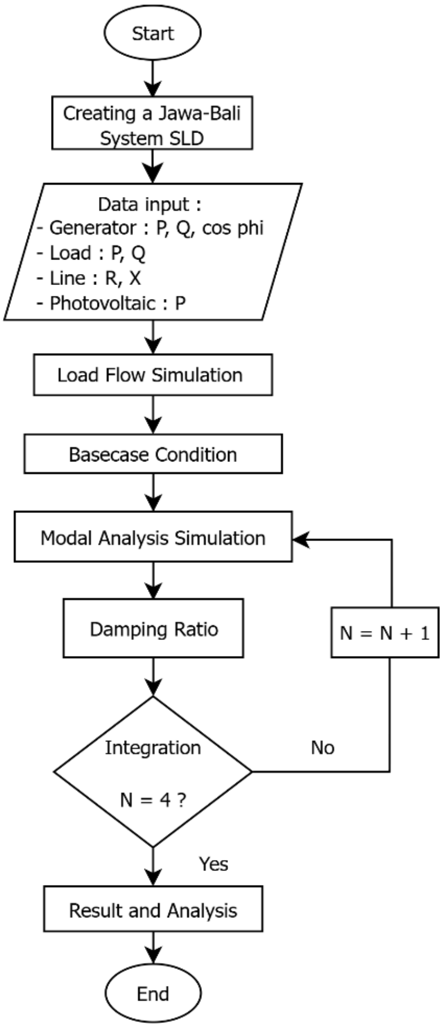

Figure 1. Flowchart

3. RESULTS AND DISCUSSION

The Single Line Diagram of the 500-kV Jawa-Bali system is shown in Figure 2. The system consists of 10 generating units and 29 buses interconnected through 500-kV transmission lines. The initial analysis is carried out using DigSILENT PowerFactory to obtain the base operating condition, which serves as a reference for subsequent simulations and analyses.

The next step is to perform modal analysis simulation under the system's initial or base-case condition. This simulation yields the system's eigenvalues for two oscillation modes: the local mode and the inter-area mode. The results of the base-case modal analysis for the local mode and inter-area mode are presented in Tables 1 and 2, respectively.

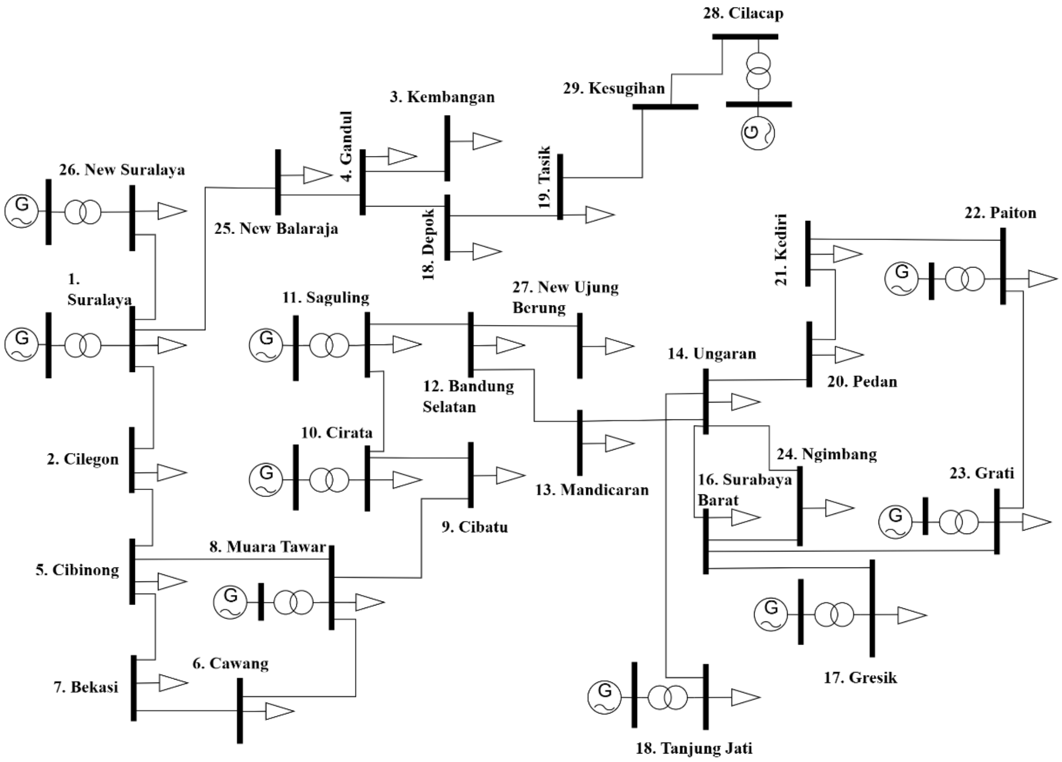

Figure 2. Single Line Jawa Bali 500 Kv

Table 1 presents the base-case simulation results, showing four pairs of eigenvalues categorized as local modes. State variables involved in the local modes are rotor angle (δ) and angular speed (ω) of the generators. Among these four pairs, the lowest damping ratio (ζ) occurs in the mode pair -1.052 ± 10.416, with a damping ratio of 10,05%. The variables involved include δ Tanjung Jati, δ Paiton dan ω Tanjung Jati.

Table 1. Base-Case Simulation Results for the Local Mode

Modes	State Variables	ζ (%)
-1.413 ± 11.862	δ Gresik δ Grati ω Gresik ω Grati	11.83
-1.67 ± 11.390	δ Gresik δ Paiton ω Gresik	11.06
-1.200 ± 11.178	δ Cilacap ω Cilacap	10.67
-1.052 ± 10.416	δ Tanjung Jati δ Paiton ω Tanjung Jati	10.05

Meanwhile. Table 2 shows two pairs of eigenvalues classified as inter-area modes. Among these two eigenvalue pairs, the lowest damping ratio occurs in the mode pair -0.707 ± 9.017, with a damping ratio (ζ) of 7.82%. The variables involved include δ Paiton, δ Suralaya, ω Gresik, ω Tanjung Jati, and ω Grati.

Table 2. Base-Case Simulation Results for the Inter-Area Mode

Modes	State Variable	ζ (%)
-1.253 ± 11.475	δ Cirata δ Gresik, δ Saguling δ New Suralaya δ Muara Tawar δ Suralaya ω Cirata ω Saguling ω Paiton ω Muara Tawar	10,85
-0.707 ± 9.017	δ Paiton δ Suralaya ω Gresik ω Tanjung Jati ω Grati ω Paiton	7,82

The simulation is then continued by gradually adding PV capacity to the system. Four sequential scenarios are used, consisting of PV additions of 50 MW, 100 MW, 150 MW, and 192 MW. This approach is intended to analyze the system's response to increasing levels of PV integration. The simulation results obtained from each addition are compared with the base-case values, which serve as the reference.

Table 3. Eigenvalue Values Resulting from PV Integration - Local Mode

Eigenvalue Local Modes With PLTS			
50 MW	100MW	150 MW	192 MW
-1.413 ± 11.861	-1.413 ± 11.861	-1.413 ± 11.861	-1.413 ± 11.861
-1.267 ± 11.389	-1.267 ± 11.389	-1.267 ± 11.388	-1.267 ± 11.388
-1.201 ± 11.176	-1.201 ± 11.176	-1.201 ± 11.175	-1.201 ± 11.174
-1.052 ± 10.416	-1.052 ± 10.416	-1.052 ± 10.416	-1.052 ± 10.416

The eigenvalues obtained from the simulation results for the local mode under PV integration are presented in Table 3. It can be observed that with a PV power injection from 50 MW until 192 MW, the eigenvalues remain located in the left half of the complex plane. The slight shift of the eigenvalues can be observed, particularly in the third mode where the imaginary part decreases from ±11.176 to ±11.174. This indicates an improvement in system stability as a result of the additional PV power injection. The enhancement of the system's small-signal stability due to the contribution of PV power increases system damping under disturbances, enabling the system to maintain its stability

Table 4. Damping Resulting from PV Integration-Local Mode

Basecase	Damping Ratio Of Local Mode (%)			
	50 MW	100 MW	150 MW	192 MW
11.83	11.83	11.83	11.83	11.83
11.06	11.06	11.06	11.06	11.06
10.67	10.68	10.68	10.68	10.68
10.05	10.05	10.05	10.05	10.05

The damping values under PV integration for the local mode can be seen in Table 4. An increase in the damping ratio of 0.01% occurs when 50 MW of PV capacity is integrated. The damping ratios for the other modes remain unchanged under successive PV integration levels. This indicates that the system can still maintain adequate damping even with the integration of large PV capacities. Furthermore, the increase in damping ratio signifies an improvement in system stability when subjected to disturbances, enabling the system to better withstand such events..

Table 5. Eigenvalue Values Resulting from PV Integration - Inter-Area Mode

Inter Area Modes With PLTS			
50 MW	100MW	150 MW	192 MW
-1.255 ± 11.464	-1.255 ± 11.464	-1.255 ± 11.463	-1.255 ± 11.461
-0.708 ± 9.017	-0.708 ± 9.019	-0.708 ± 9.019	-0.707 ± 9.019

The critical mode that most strongly influences system stability is the inter-area mode. This mode represents oscillations occurring between generators located in different regions. The movement and dynamics of the inter-area mode must be carefully observed, as it has the potential to trigger system instability. The trajectories or movements of the inter-area mode resulting from PV power injection are shown in Table 5. The first mode can be observed that the imaginary part decrease from ±11.464 to ±11.461. In the second mode, the imaginary part increase from ±9.017 to ±9.019 and the real part shift to the right from -0.708 to -0.707. Although the eigenvalue of the second mode slight shifts to the right in the complex plane, it still consistently remain in the left half of the complex plane. This indicates that the system is within sTable limits.

Table 6. Damping Resulting from PV Integration - Inter Area Mode

Basecase	**Damping With PLTS On Interarea Mode (%)**			
	50 MW	100 MW	150 MW	192 MW
10.85	10.88	10.88	10.88	10.88
7,82	7.82	7.82	7.82	7.82

The damping conditions associated with the inter-area mode are presented in Table 6. The Table shows that the inter-area mode damping increases by 0.03% when 50 MW of PV capacity is integrated into the system. This indicates that PV power injection has a positive effect on improving system damping and maintaining system stability under disturbance conditions.

Time-domain analysis is required to observe the system's dynamic response during disturbances, particularly those related to local and inter-area modes that may lead to instability. The system's dynamic response is monitored by applying a three-phase-to-ground fault in the 500-kV Jawa-Bali system, specifically at the Bandung Selatan bus. The dynamic response of generator rotor angles before PV integration and after the full PV capacity has been integrated is shown in Figure 3.

Before PV integration, rotor angle deviations exhibit a relatively large overshoot, around -16.5, indicating the system's effort to regain stability after being subjected to a disturbance. With the integration of 50 MW of PV power, the dynamic rotor angle response shows slight improvement. This is evidenced by the smaller overshoot, decreasing from -16.5 to -16.4. Although the change is small, the reduced overshoot indicates better damping and an improved ability of the systems to maintain stability.

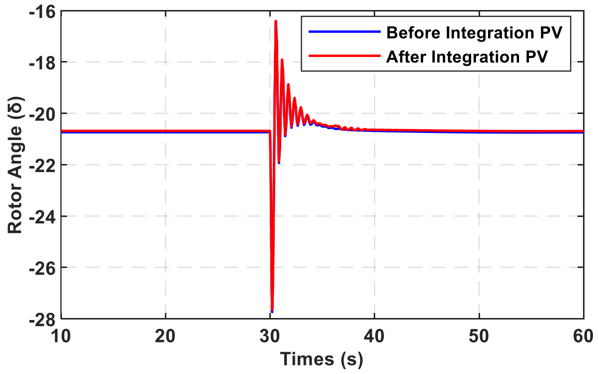

Figure 3. Rotor Angle Before and After Integration

Figure 4 illustrates the rotor speed response of the generator to a short-circuit disturbance in the 500-kV Jawa–Bali system, specifically at the Bandung Selatan bus. Under the condition prior to the integration of the PV power plant, the rotor speed response exhibits oscillations of approximately 0.0025pu with an amplitude of 0.0108pu and low damping. Following the integration of the Cirata PV plant injecting 50 MW, the dynamic rotor speed response during the disturbance event (around the 30-second mark) showed an amplitude of 0.0110pu with oscillations of approximately 0.0023pu and high damping. This reduction in oscillations indicates that the integration of the PV plant enhances the overall stability of the system.

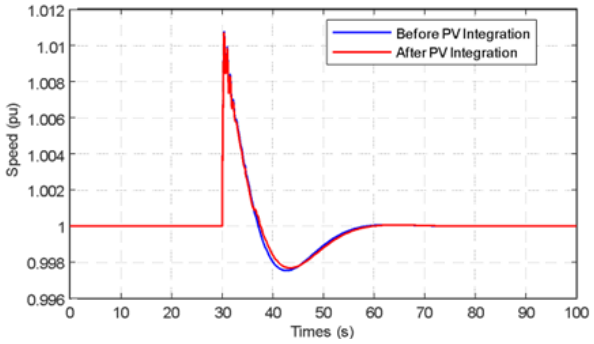

Figure 4. Generator Speed Response

Figure 5 illustrates the system voltage response during a three-phase-to-ground fault on the 500 kV Jawa–Bali network. Prior to PLTS integration, the voltage drop occurred rapidly, from the nominal value of approximately 1.0pu to about 0.05-0.10pu, indicating a severe transient disturbance. The voltage rapidly recovers and reaches approximately 0.95pu within about 1-2 seconds. Following the addition of the Cirata PV plant, the voltage dip becomes smaller due to the additional active power contribution from the PV system. The post fault voltage recovery becomes slightly faster. the voltage rises above 0.95pu in less than approximately 1 second and stabilizes near 1.0pu around 33-34 s. Nevertheless, both conditions demonstrate good voltage recovery capability, with the voltage returning relatively quickly to approximately 1 pu. This indicates that the system remains within an accepTable voltage stability margin.

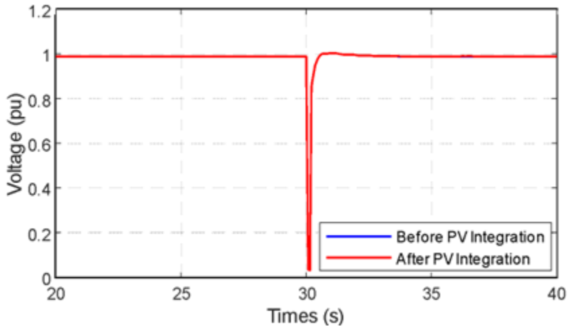

Figure 5. System Voltage Response During Disturbance

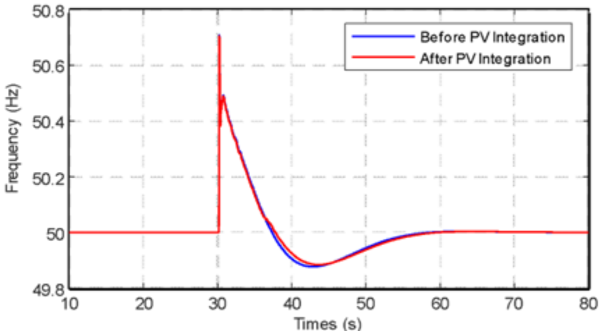

Figure 6. Frequecny Response During Disturbance

Figure 6 illustrates the system frequency response during a three-phase short-circuit fault on the 500 kV Jawa–Bali system. Prior to the integration of the PV plant, the system frequency overshoot to approximately 50.7 Hz and reach the frequency nadir of around 49.87 Hz, followed by small-amplitude oscillations before eventually stabilizing near 50 Hz. After the integration of the PV plant, the frequency response exhibits a noticeably different behavior. When the fault occurs, the system frequency initially rises approximately 50.7 Hz, then drops with an undershoot, reaching frequency nadir of approximately 49.88 Hz, lower than pre-integration condition.

4. CONCLUSION

Based on the simulation results, this study demonstrates that the gradual increas in the penetraiton of the Cirata PV power plant into the 500 kV Jawa-Bali system leads to an improvement in system damping. As the PV power injection increases, the eigenvalues shift further to the left, away from the imaginary axis, and the damping ratio increases. Overall, the findings indicate that the integration of the 192 MW Cirata PV plant can be implemented in the Jawa–Bali system without compromising small-signal stability, and that the system retains an adequate stability margin to withstand minor disturbances. Further short-circuit disturbance simulations show that the system maintains sTable transient behavior after PV integration. The rotor speed deviation remains limited to approximately ±0.011pu, and the oscillations were successfully damped. In terms of voltage stability, the system experienced a temporary voltage drop of approximately 0.05-0,10pu during the disturbance, but the voltage quickly recovered to above 0.95pu within about 1-2 seconds after the disturbance was resolved and stabilized near 1.0pu. the frequency response show a transient overshoot reaching approximately 50.7-50.8 Hz, followed by a through of approximately 49.8-49.9 Hz, before stabilizing at the nominal value of 50hz within approximately 55-60 seconds. These results indicate that, although higher PV penetration reduces the system's mechanical inertia, the overall damping characteristics and dynamic stability of the system are preserved.

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