ANALYSIS OF THE IMPACT OF CIRATA FLOATING SOLAR POWER PLANT INTEGRATION ON THE VOLTAGE STABILITY OF THE 500 kV JAVA-BALI SYSTEM

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ABSTRACT: This study analyzes the impact of integrating a solar photovoltaic power plant (PLTS) on the voltage stability of the 500 kV Java-Bali transmission system, with a case study on the Cirata Floating Solar Power Plant. With the increasing use of renewable energy, particularly solar PV, it is crucial to understand how the integration of this variable energy source affects the reliability and stability of the power system. The Cirata Floating Solar Power Plant, the largest of its kind in Asia, has a capacity of 145 MW AC or equivalent to 192 MWp. However, integrating the Cirata Floating Solar Plant into the transmission system may potentially affect voltage stability, necessitating an in-depth analysis to assess its impact. The methodology employed in this study includes static voltage analysis through PV curve evaluation and dynamic voltage analysis to assess the system's capability to maintain or restore voltage within permissible stability limits. The study utilizes DigSILENT PowerFactory software to simulate system conditions before and after the PLTS integration. The results indicate that the Cirata Floating Solar Plant's power injection of 192 MWp improves voltage quality and enhances system stability compared to the pre-integration conditions.

Keywords : Cirata Floating Solar Power Plant, DigSILENT PowerFactory, PV Curve Analysis, Static Stability Analysis, Voltage Stability.

1. Introduction

Electricity has become an essential need in daily life, yet challenges in providing equitable access to electricity persist in Indonesia. Although the national electrification ratio reached 99.87% in 2023, a small portion of the population remains unserved by the power system. Efforts are continuously being made to expand electricity coverage to remote and rural areas that still lack access. The government's target of achieving 100% electrification by 2024 demonstrates a strong commitment to addressing this disparity. This initiative is crucial not only to meet basic needs but also to support economic growth, social welfare, and technological advancement across the country. Through collaboration between the government, the private sector, and the community, it is expected that the electricity infrastructure can be developed in an equitable and affordable manner, ensuring that every individual in Indonesia benefits from adequate access to electricity[1].

The demand for clean, renewable, and sustainable energy has become increasingly urgent to address the negative impacts of climate change and the dependence on conventional energy sources, which are limited, less environmentally friendly, and pose long-term challenges. In Indonesia, an archipelagic country rich in renewable energy potential, floating solar power plants (PLTS) have emerged as a promising alternative to increase power generation capacity and reduce reliance on fossil fuels [2].

The Cirata Floating Solar Power Plant is the largest floating solar facility in Southeast Asia and the third largest in the world, located in Citaminang, Maniis District, Purwakarta Regency, West Java. The Cirata Floating Solar Plant has a capacity of 145 MW AC, equivalent to 192 MWp, covering a reservoir area of 200 hectares. The generated power is transmitted to the PLN substation at 500 kV and distributed across the Java, Madura, and Bali regions [3].

The Java-Bali power system serves as the backbone of Indonesia's economy, supporting various industrial sectors and residential areas. However, challenges related to system stability remain a critical issue. With the increasing penetration of renewable energy sources such as solar power plants (PLTS), changes in the power system dynamics are inevitable. Amid efforts to expand the utilization of renewable energy, a comprehensive understanding of the impact of PLTS integration on system stability is essential to ensure the sustainability of electricity supply in the Java-Bali region [4].

The increase in load demand affects voltage levels, thereby heightening the risk to voltage stability within the system. The established stability standard, set at ±5% of the nominal value, serves as a critical parameter in determining the balance and operational performance of the power network[5].

This study aims to analyze the impact of the Cirata Floating Solar Power Plant integration on the Java-Bali transmission system stability using PowerFactory DigSILENT software. The simulations are focused on evaluating voltage stability in the Java-Bali Power System due to the integration of the Cirata Floating Solar Plant, particularly under disturbance conditions and load increments[6].

2. Literature Review

An electric power system is a network consisting of conductors and equipment required to transmit electrical energy from generation sources to consumers. Stability is crucial to ensure the safe operation of the power system, especially in interconnected networks affected by variations in connected loads.

2.1 Voltage Stability Analysis

Voltage stability is a critical aspect of power system operation, ensuring a continuous power supply with good quality while minimizing the risk of blackouts. System stability refers to the ability of the power system to maintain normal operating conditions or recover from disturbances without causing outages or the disconnection of components within the affected area. To maintain this stability, the integrity of the system must be preserved to prevent disconnections on both the generation and load sides [7].

Voltage stability is determined by system characteristics, with acceptable voltage limits ranging from -5% to +10% of the nominal value [8]. When voltage levels exceed these limits, the condition is referred to as a voltage collapse, which can trigger voltage instability. Voltage instability occurs when the system fails to maintain voltage within stable limits, typically between 0.95 pu and 1.05 pu, across some or all buses under normal conditions or after disturbances. This instability may result from rare single contingencies or a combination of factors leading to a gradual and uncontrolled voltage decline[9].

Voltage stability analysis is categorized into two types: static voltage stability analysis and dynamic voltage stability analysis. Static voltage stability analysis is essential for real-time operations due to its relatively fast calculation process[10]. In contrast, dynamic analysis provides a higher level of accuracy compared to static analysis. Both methods are valuable for addressing voltage instability by analyzing its causes and mechanisms. These analyses also facilitate the identification of network areas vulnerable to voltage weaknesses and the determination of the most effective mitigation measures. Furthermore, voltage stability can be significantly improved through system development and expansion[11].

2.2 Static Voltage Stability Analysis

Common methods used in static voltage stability analysis include the active power-voltage (P-V) curve and the reactive power-voltage (Q-V) curve[12]. These methods aim to identify the critical point at which the voltage experiences a significant drop under the maximum load that the system can accommodate. Voltage collapse typically occurs when the system encounters disturbances or a deficiency in reactive power supply[13].

2.2.1 P–V Curve Analysis (Active Power vs. Voltage)

The P-V curve analysis method (Active Power versus Voltage) is the most commonly used approach in static stability analysis and serves to determine the voltage security level. This method is frequently employed to evaluate voltage stability by determining the available active power margin before the system reaches its critical point [14].

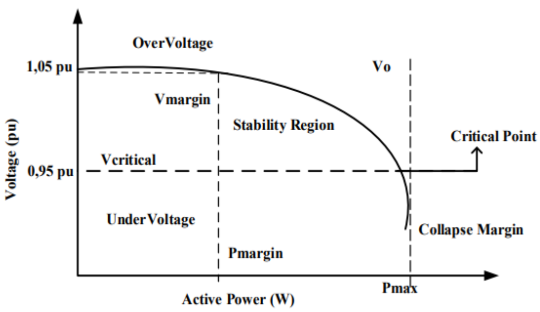


Figure 1 P–V Curve Graph (Active Power vs. Voltage)

Figure 1 illustrates the P-V curve (Active Power versus Voltage), depicting a gradual voltage decline as power demand increases. The voltage continues to decrease until it reaches the peak of the curve, known as the nose point. At this point, further increases in active power no longer yield adequate voltage levels, leading to a condition referred to as voltage collapse. The distance between the operating point and the nose point is termed the active power margin, while the distance between the operating point and the critical point is known as the voltage margin. [15].

2.2.2 Q–V Curve Analysis (Reactive Power vs. Voltage)

Voltage stability analysis using the Q-V curve aims to determine the total load condition (in MVar) at which the system voltage collapses. This indicates that the system's ability to supply reactive power has exceeded its capacity. The V-Q curve is shown in Figure 2[16].

The dashed line in Figure 2 represents the critical point limit. This point indicates the load capacity boundary under steady-state conditions for network voltage stability. The region above the critical point represents a stable operating condition, while the area below the critical point indicates an unstable operating condition [17].

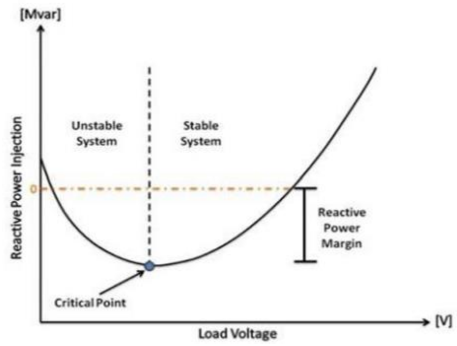


Figure 2 Q–V Curve (Reactive Power vs. Voltage)

2.3 Dynamic Voltage Stability Analysis

Dynamic voltage stability analysis plays a crucial role in power network planning during system operation. This approach is based on differential equations to observe how busbar voltage changes due to variations in system operating parameters[18]. Various parameters of the floating solar power plant (PLTS), such as solar irradiance (solar radiation and temperature), along with dynamic modeling (power electronic converters and reactive power compensators), are vital in analyzing dynamic voltage stability in grid-connected systems[19].

Dynamic voltage stability analysis is used to evaluate voltage behavior during disturbances and load increases in the transmission system. This is achieved by studying time-domain analysis while considering disturbances at specific locations and times. Methods used for dynamic voltage analysis include small-signal stability analysis, time-domain simulation, and bifurcation method analysis.

The dynamic voltage stability analysis in this study will be conducted by applying a short-circuit disturbance at the load busbar with a fault duration setting of 0.5 seconds and by increasing the load by 20% using DigSILENT PowerFactory. [20].

2.4 Cirata Floating Solar Power Plant (PV)

The Cirata Floating Solar Power Plant (PLTS) is an on-grid power generation model directly connected to the Java-Bali transmission network. Located in Citaminang, Maniis District, Purwakarta Regency, West Java, the Cirata Floating Solar Power Plant has a capacity of 145 MW AC, equivalent to 192 MWp, occupying a 200-hectare reservoir area[21].

The impact of voltage stability on a system integrated with a PLTS requires a comprehensive analysis of both static and dynamic voltage stability. Adding active power from the PLTS to the bus as a power source can alter the permissible voltage stability limits[22].

Figure 3 Cirata Floating Solar Power Plant (PV)

Figure 3 shows the location of the Cirata Floating Solar Power Plant.

2.5 Single Line Diagram of the Java-Bali Transmission System

This study focuses on investigating the voltage stability of the Java-Bali 500 kV transmission system due to the integration of the Cirata Floating Solar Power Plant (PLTS) into the network using static and dynamic voltage stability analyses.

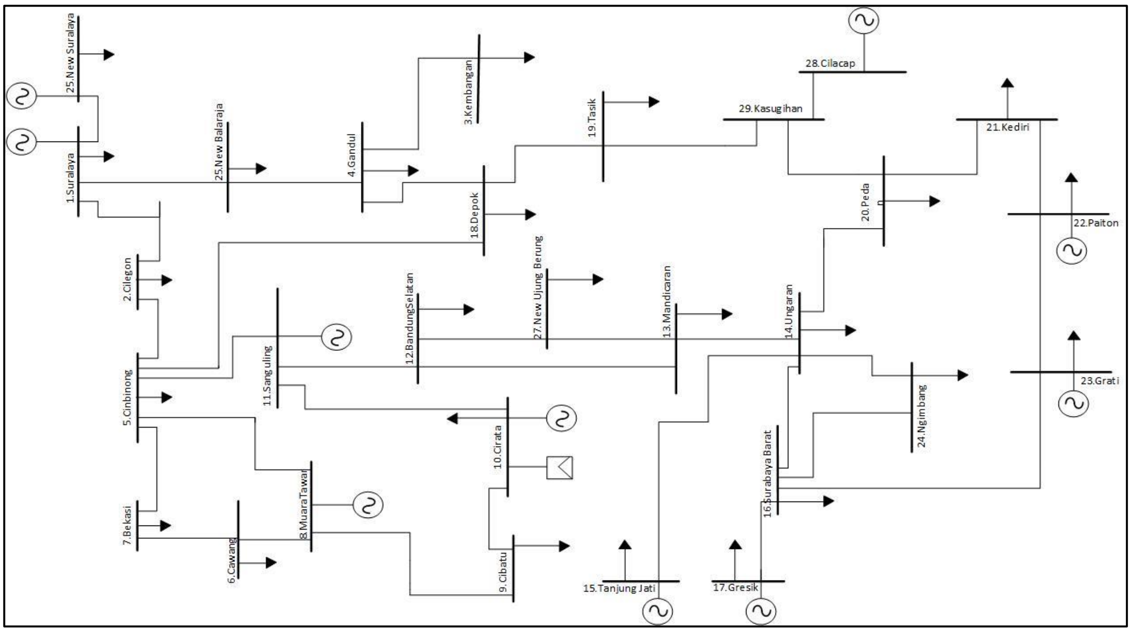


Figure 4 Single Line Diagram of the Java-Bali 500 kV Transmission System

Figure 4 presents the data used in this research, which includes a Single Line Diagram. The Java-Bali 500 kV system data comprises 29 buses, 35 transmission lines, 1 slack bus, 9 generator buses, and 24 load buses.

3. Results and Discussion

This chapter discusses the simulation results and analysis of static and dynamic voltage stability using DIgSILENT PowerFactory software.

Static voltage stability is simulated through several modeling cases:

- Base case: System condition without PLTS injection.
- Case 1: The PLTS injects 25% of its capacity.
- Case 2: The PLTS injects 50% of its capacity.
- Case 3: The PLTS injects 75% of its capacity.
- Case 4: The PLTS injects 100% of its capacity.

Dynamic voltage stability analysis is conducted by applying a short-circuit disturbance and a load increase disturbance of 20%.

3.1 Voltage Profile

After successfully running the load flow analysis, the next step is to analyze the voltage profile to compare the system conditions between the base case and after the integration of the 192 MW PLTS into the system.

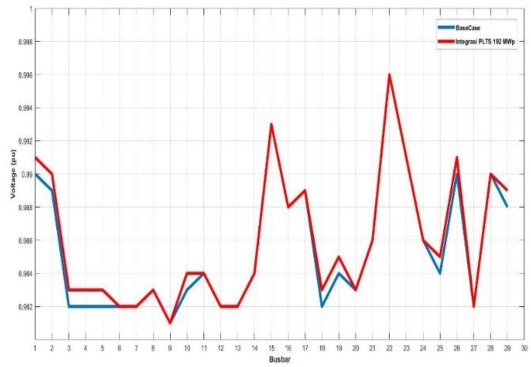
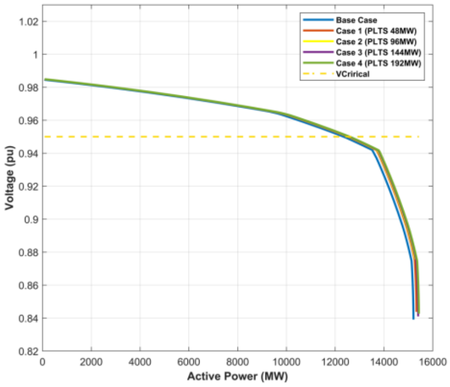


Figure 5 Load Flow Results on Voltage Profile

Based on the graph in Figure 6, the load flow analysis results show that the voltage profile at each bus varies due to differences in load demand at each busbar, both under the base case condition and after the integration of the 192 MW PLTS into the system. Additionally, the graph indicates changes at busbars 1, 2, 3, 4, 5, 10, 18, 19, 25, 26, and 29, where the voltage profile increased by 0.001 pu after the integration of the 192 MWp PLTS.

From these results, it can be concluded that the integration of the 192 MW PLTS into the transmission system improves the voltage profile, mitigating previously observed undervoltage conditions and enhancing overall voltage stability compared to the base case scenario.

3.2 P–V Curve Analysis (Active Power vs. Voltage)



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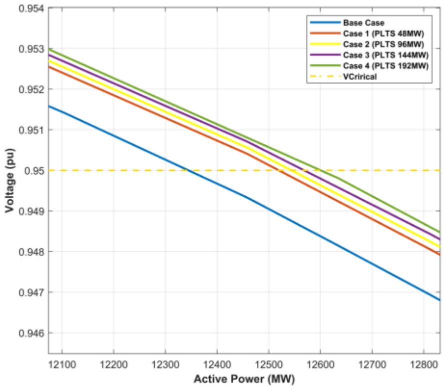

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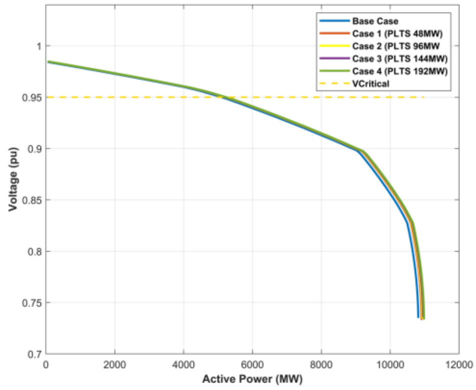
Figure 6 P–V Curve Results at Busbar 4 Gandul: (a) Nose Curve Condition Reached (b) Critical Voltage Condition

From Figure 6, the simulation graph at busbar 4 (Gandul) displays curves for the base case, case 1, case 2, case 3, and case 4. All five curves show a voltage decline until reaching the nose point of the curve. Under the base case condition, the nose point occurs at a load demand of 15,211.4 MW with a voltage of 0.8391 pu. In case 1, with a 25% PLTS injection into the system, the load demand reaches 15,335 MW at a voltage of 0.8437 pu. For case 2, with a 50% PLTS injection, the load demand is 15,361 MW at 0.8337 pu. In case 3, with a 75% PLTS injection, the load demand reaches 15,401 MW at 0.8411 pu. Lastly, in case 4, with a 100% PLTS injection, the load demand reaches 15,432 MW at a voltage of 0.8426 pu.

When the voltage reaches the permissible limit of 0.95 pu, the graph indicates that the critical load demand under the base case is 12,104 MW. For case 1, it remains at 12,104 MW, while case 2 reaches 12,458 MW, case 3 reaches 12,811 MW, and case 4 achieves a critical load demand of 12,634 MW.

These results demonstrate that the integration of the 192 MWp PLTS into the system improves voltage stability compared to the base case condition.



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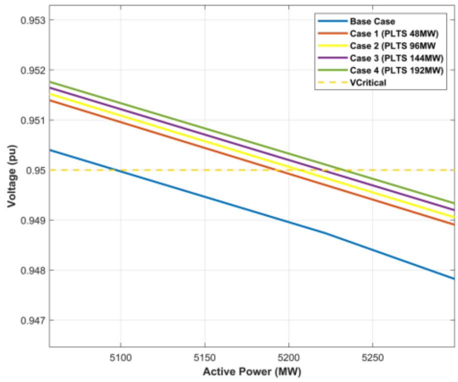

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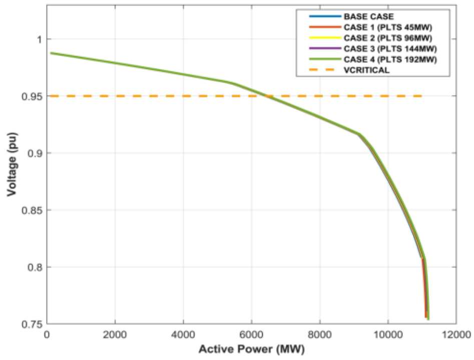
Figure 7 P–V Curve Results at Busbar 12 Bandung Selatan: (a) Nose Curve Condition Reached (b) Critical Voltage Condition

In Figure 7, the simulation graph at busbar 12 (South Bandung) presents a comparison between the base case, case 1, case 2, case 3, and case 4. All five curves show a voltage decline until reaching the nose point of the curve. Under the base case condition, the nose point occurs at a load demand of 10,814 MW with a voltage of 0.7349 pu. In case 1, with a 25% PLTS injection into the system, the load demand reaches 10,912 MW at a voltage of 0.733 pu. For case 2, with a 50% PLTS injection, the load demand is 10,938 MW at 0.7342 pu. In case 3, with a 75% PLTS injection, the load demand reaches 10,958 MW at 0.7357 pu. Lastly, in case 4, with a 100% PLTS injection, the load demand reaches 10,981 MW at a voltage of 0.7334 pu.

When the voltage reaches the permissible limit of 0.95 pu, the graph indicates that the critical load demand under the base case is 5,014 MW. For case 1, it reaches 5,428 MW, case 2 reaches 5,635 MW, case 3 reaches 5,842 MW, and case 4 achieves a critical load demand of 6,255 MW.

These results demonstrate that the integration of the 192 MWp PLTS into the system improves voltage stability compared to the base case condition.



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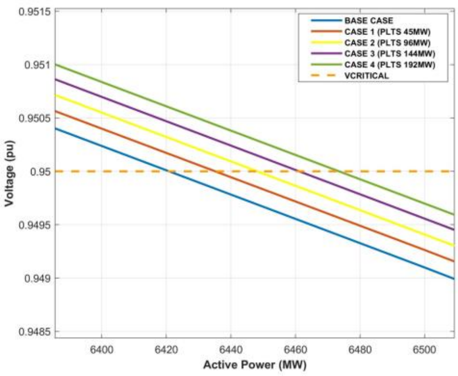

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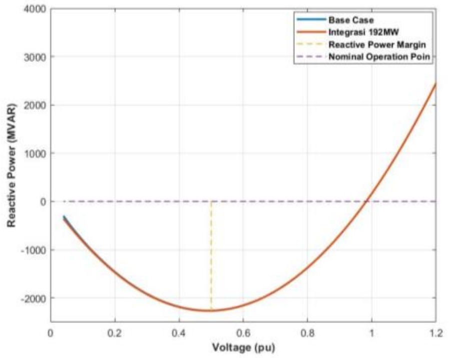
Figure 8 P–V Curve Results at Busbar 9 Cibatu: (a) Nose Curve Condition Reached (b) Critical Voltage Condition

In Figure 8, the simulation graph at busbar 9 (Cibatu) shows a comparison between the base case, case 1, case 2, case 3, and case 4. All five curves display a voltage drop until reaching the nose point of the curve. Under the base case condition, the nose point occurs at a load demand of 10,977 MW with a voltage of 0.8083 pu. In case 1, with a 25% PLTS injection into the system, the load demand reaches 11,023 MW at a voltage of 0.802 pu. In case 2, with a 50% PLTS injection, the load demand reaches 11,030 MW at 0.8071 pu. In case 3, with a 75% PLTS injection, the load demand reaches 11,508 MW at 0.7609 pu, and in case 4, with a 100% PLTS injection, the load demand reaches 11,175 MW at a voltage of 0.7532 pu.

When the voltage reaches the permissible limit of 0.95 pu, the graph shows that the critical load demand under the base case is 6,073 MW. For case 1, it reaches 6,499 MW; case 2 reaches 6,606 MW; case 3 reaches 7,032 MW; and case 4 achieves a critical load demand of 7,885 MW.

These results indicate that the integration of the 192 MW PLTS into the system improves voltage stability compared to the base case or the condition before the PLTS was integrated into the system.

3.3 Q–V Curve Analysis (Reactive Power vs. Voltage)



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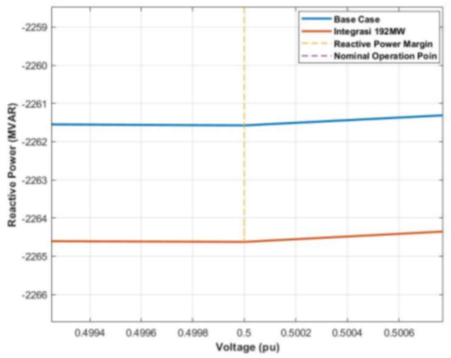

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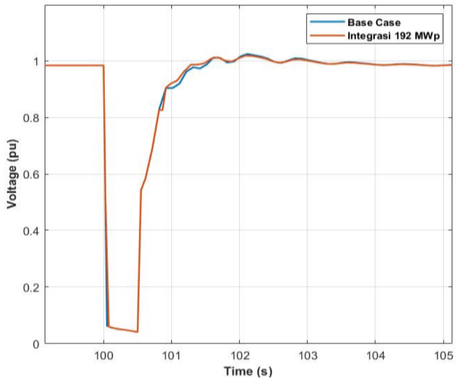
Figure 9 Q–V Curve Results at Busbar 10 Cirata:(a) Full Curve Condition (b) Reactive Power Margin

Based on Figure 9, the base case represents the normal condition before the integration of the PLTS. Under the base case condition, the system can sustain a reactive power (Q) load of -2261.5 Mvar. After integrating the 192 MW PLTS into the system, it can sustain a reactive power (Q) load of -2264.5 Mvar.

From the analysis of the reactive power versus voltage curve, it can be observed that the lower (minimum) the reactive power margin value, the better the system's capability to handle reactive power (Q) loading. In other words, the lower this value, the greater the bus's ability to maintain the voltage profile even under higher reactive power (Q) loading conditions.

3.4 Dynamic Stability Analysis under Short Circuit Disturbances



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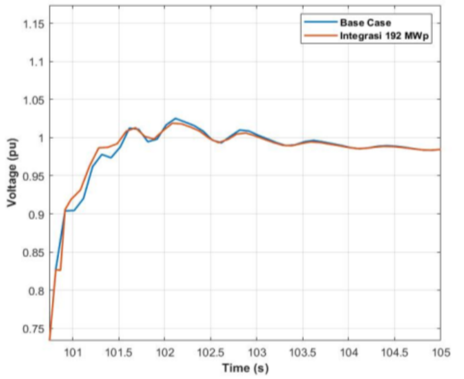

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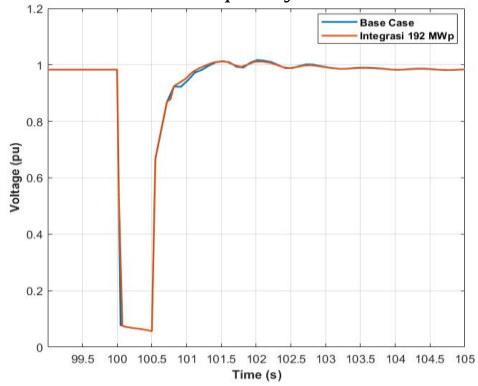
Figure 10 Dynamic Voltage Response Graph at Bus 25: (a) Full Graph Condition (b) Overshoot

In Figure 10, the dynamic voltage stability analysis results show the voltage response after a disturbance occurs at load bus 4. In the base case condition, a 0.5-second short-circuit event at 100 seconds causes a voltage drop reaching 0.062 pu. During the PLTS integration, the same 0.5-second short-circuit event at 100 seconds results in a voltage drop of 0.059 pu.

The dynamic voltage response at bus 25, both before and after PLTS integration, indicates that integrating the PLTS into the system can improve the dynamic voltage stability response. This improvement is evidenced by the reduced overshoot during the 192 MW power injection from the PLTS. Furthermore, with the PLTS integration, the oscillation damping time when the system attempts to maintain voltage stability is shortened by 0.03 seconds. This demonstrates that the system can sustain voltage levels and reach a stable condition more quickly.



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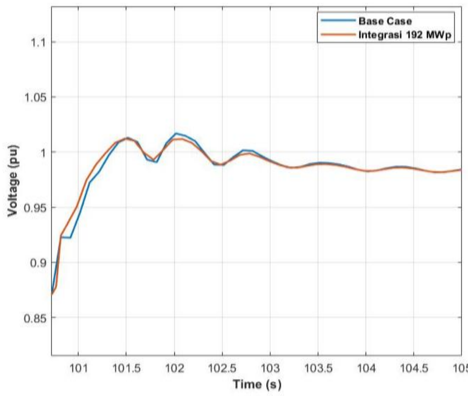

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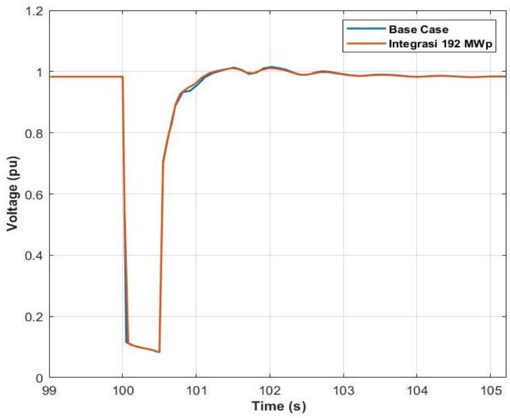
Figure11 Dynamic Voltage Response Graph at Bus 8: (a) Full Graph Condition (b) Overshoot

In Figure 11, the dynamic voltage stability analysis results show the voltage response after a disturbance occurs at load bus 9. Under the base case condition, a 0.5-second short-circuit event at 100 seconds causes a voltage drop reaching 0.099 pu. During the PLTS integration, the same 0.5-second short-circuit event at 100 seconds also results in a voltage drop of 0.099 pu.

The dynamic voltage response at bus 8, both before and after PLTS integration, indicates that the integration of the PLTS into the system can improve the dynamic voltage stability response. This improvement is evident from the reduced overshoot when the 192 MW power injection from the PLTS is considered. Additionally, with the PLTS integration, the oscillation damping time as the system attempts to maintain voltage stability is reduced by 0.03 seconds. This demonstrates that the system can sustain voltage levels and reach a stable condition more quickly.



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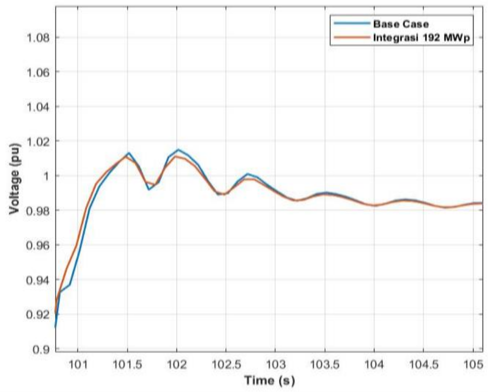

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Figure 12 Dynamic Voltage Response Graph at Bus 11: (a) Full Graph Condition (b) Overshoot

In Figure 12, the dynamic voltage stability analysis results show the voltage response after a disturbance occurs at load bus 12. Under the base case condition, a 0.5-second short-circuit event at 100 seconds causes a voltage drop reaching 0.072 pu. During the PLTS integration, the same 0.5-second short-circuit event at 100 seconds results in a voltage drop of 0.075 pu.

The dynamic voltage response at bus 11, both before and after PLTS integration, indicates that the integration of the PLTS into the system can improve the dynamic voltage stability response. This improvement is evident from the reduced overshoot when the 192 MW power injection from the PLTS is considered. Additionally, with the PLTS integration, the oscillation damping time as the system attempts to maintain voltage stability is reduced by 0.03 seconds. This demonstrates that the system can sustain voltage levels and reach a stable condition more quickly.

3.5 Dynamic Stability Analysis under 20% Load Increase Disturbance

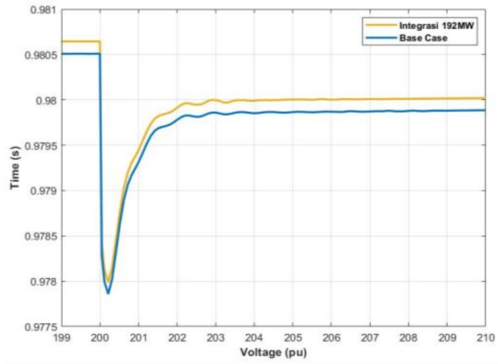

Figure 13 Dynamic Voltage Response Graph at Bus 9 during Load Increase

In Figure 13, the dynamic voltage stability analysis results under a disturbance caused by a 20% load increase at 200 seconds are presented. Under the base case condition, the voltage reaches 0.978 pu, while during the PLTS integration condition, the voltage reaches 0.979 pu.

The dynamic voltage response at bus 9, both before and after the PLTS integration, demonstrates that the PLTS integration improves the dynamic voltage response. This improvement is evident from the enhanced voltage profile following the load increase when the 192 MW power injection from the PLTS is considered.

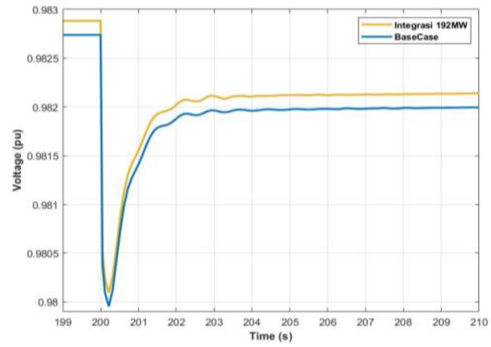

Figure 14 Dynamic Voltage Response Graph at Bus 12 during Load Increase

In Figure 14, the dynamic voltage stability analysis results under a disturbance caused by a 20% load increase at 200 seconds are presented. Under the base case condition, the voltage reaches 0.981 pu, while during the PLTS integration condition, the voltage reaches 0.982 pu.

The dynamic voltage response at bus 10, both before and after the PLTS integration, demonstrates that the PLTS integration improves the dynamic voltage response. This improvement is evident from the enhanced voltage profile following the load increase when the 192 MW power injection from the PLTS is considered.

4. Conclusions

Based on the results and analysis of the impact of the Cirata Floating PV integration into the 500 kV Java-Bali transmission system, the following conclusions can be drawn:

The load flow analysis indicates that the voltage profile at each bus varies depending on the load differences. The integration of the 192 MWp PV plant at bus 10 (Cirata) results in a voltage increase of 0.001 pu at several buses, specifically at buses 1, 2, 3, 4, 5, 10, 18, 19, 25, 26, and 29. This demonstrates that the additional power from the PV plant contributes to voltage enhancement within the system.

The P–V curve analysis shows that load increments lead to increased power demand. The integration of the 192 MWp PV plant into the Java-Bali transmission system helps maintain voltage levels, with an average improvement of 0.01 pu compared to the base case under increased loading conditions. This indicates that the PV plant positively contributes to maintaining the system's voltage stability.

The Q–V curve analysis reveals that a lower reactive power margin correlates with improved system capability to withstand reactive power loading. The integration of the PV plant results in a reactive power margin reduction of -3 Mvar, enhancing the bus's ability to sustain the voltage profile despite increased reactive power demand.

The dynamic stability analysis under 0.5-second short circuit disturbances at buses 25, 8, and 11 shows that integrating the 192 MW Cirata Floating PV improves the system's dynamic response, with an average voltage increase of 0.002 pu at 100 seconds. This is characterized by a reduction in overshoot magnitude and a shorter oscillation period during fault conditions, thereby enhancing overall system stability.

The dynamic voltage stability analysis shows improved voltage response at buses 9 and 10 under a 20% load increase disturbance. Following the integration of the 192 MW PV plant, there is a voltage rise of 0.0002 pu, indicating the PV plant's positive contribution to maintaining system voltage stability.

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