

# Optimization Of Frequency Stability for a 10 MW On-Grid Solar System in the Electricity System Of Nusantara Capital City

Didik Darmawan<sup>1</sup>, Poetro Lebdo Sambegoro<sup>2</sup>, Agustriadi<sup>3</sup>

<sup>1</sup>PT PLN UP3 Samarinda UID Kalimantan Timur

<sup>2</sup>Faculty of Mechanical Engineering and Aerospace, Institut Teknologi Bandung

<sup>3</sup>PT PLN (Persero) UIP3B Kalimantan

**Abstract.** The Increasing demand for electrical energy and global warming are driving the use of renewable energy. Environmental issues regarding increased air pollution emissions due to various human activities that cause climate change are in the global spotlight. Solar energy as a form of renewable energy is abundant, clean and free. However, the addition of solar PV into the electricity system does not always have a positive impact due to its intermittent nature and dependence on unruly primary energy. In the electricity system of Nusantara Capital City a 10 MW photovoltaic PV is connected On Grid and synchronized with the Balikpapan System via 20 KV. The performance of PV is highly dependent on solar radiation and weather. This causes the PV output power to always fluctuate. PV fluctuations will be dampened by the battery so as not to unduly affect the performance of other plants. This simulation will use DigSILENT 15.1 software. In this simulation, several case studies are carried out, namely the effect of PV integration on system frequency, PV penetration on system stability the effect of loading on free governor and hybrid simulation with batteries for system stability. So that this simulation is able to determine the limit of system stability when this PV has operated up to 50 MW with this optimal capacity certainly does not interfere with the stability of the system frequency.

**Keywords:** *Renewable energy, Solar PV, Frequency System*

## Nomenclature

|       |   |                                       |
|-------|---|---------------------------------------|
| AM    | = | Air mass coefficient                  |
| BESS  | = | Battery Energy Storage System         |
| Bn    | = | Direct Normal Irradiance              |
| Dh    | = | Diffuse Horizontal Irradiance         |
| FF    | = | Wind Speed                            |
| GW    | = | Giga Watt                             |
| Hz    | = | Hertz                                 |
| IRENA | = | International Renewable Energy Agency |
| kV    | = | Kilo Volt                             |

|     |   |                          |
|-----|---|--------------------------|
| MW  | = | Mega Watt                |
| NRE | = | New and Renewable Energy |
| PV  | = | Photovoltaic             |
| SLD | = | Single Line Diagram      |
| Ta  | = | Temperature Ambient      |
| Td  | = | Dew Point Temperature    |

## 1 Introduction

Renewable energy continues to grow rapidly, with power generation capacity increasing by 171 GW and an annual growth rate of approximately 7.9%, according to data from the International Renewable Energy Agency (IRENA). This growth is driven by decreasing costs, advancements in technology, and improved performance. Among renewable energy sources, PV systems are the fastest-growing technology, with a capacity increase of 94 GW [1].

Presidential Regulation No. 5/2006 on National Energy Policy outlines Indonesia's strategy for the energy sector. The policy prioritizes energy diversification, environmental sustainability and optimizing the use of renewable resources. Limited fossil energy reserves led the government to create the policy by including a target to achieve 23% of the total energy mix from new and renewable energy (NRE) by 2025. Currently, renewable energy development in Indonesia focuses on geothermal, hydro, and biomass resources, while solar PV is usually used for on grid systems [2].

Solar PV systems offer several advantages compared to other renewable energy sources, including the absence of moving mechanical parts, noiseless operation, compact size, and minimal maintenance requirements. As renewable energy grows and becomes more integrated into conventional power generation and grids to meet rising energy demands, there is an urgent need to analyze its impact on existing power networks. Additionally, developing effective control systems is crucial to support and enhance the overall stability of energy systems [3].

The utilization of renewable energy as an energy source for electricity generation raises issues due to its intermittency nature which can cause a decrease in power quality and disruption of stability in the power system [4]. With the rapid growth of photovoltaic (PV) power generation, concerns have been raised that its intermittency causes power system instability and uncertainty. The high penetration of PV brings great challenges to thermal power plants, especially when thermal units cannot meet the increased load demand caused by PV reduction due to their ramp rate limitations[5].

Many studies have been conducted on solar PV systems, focusing on the steady-state and frequency stability of grid-connected systems. Some papers highlight both the positive and negative impacts of high levels of PV system penetration into the grid [6]. Other research discusses various inverter technologies with different capabilities and how they affect grid stability. Additionally, some studies explore the effects of grid disturbances on the operational performance of PV systems [7].

Each PV location has different solar radiation variations at each time, causing fluctuations in the output power of the PV. The 10 MW solar power plant planned for up to 50 MW for Nusantara Capital City must be integrated stably into the electricity system. Frequency stability, which refers to the ability of the system to maintain a stable operating condition after a disturbance, is a critical aspect in this regard [8]. Given the intermittent nature of solar energy, variations in electrical output can affect the quality and reliability of electricity supply. The fluctuations affect the output power that must be generated by other plants. When the solar farm produces a small output power then the other plants have to work harder to produce a large output power in order to keep meeting the load demand. When the solar power plant produces a large output power, the output power of other plants can be adjusted [9].

The main contributions of this paper are as follows, a formula model to solve the frequency stability problem is used with DigSILENT 15.1 software simulation with Newton Raphson as the background. In this simulation, several case studies are carried out, namely the effect of PV integration on system frequency, PV penetration on system stability, the effect of loading on free governor, and hybrid simulation with batteries for system stability. This simulation is able to determine the limit of system stability when this PV has operated up to 50 MW with this optimal capacity certainly does not disturb the stability of the system frequency [10].

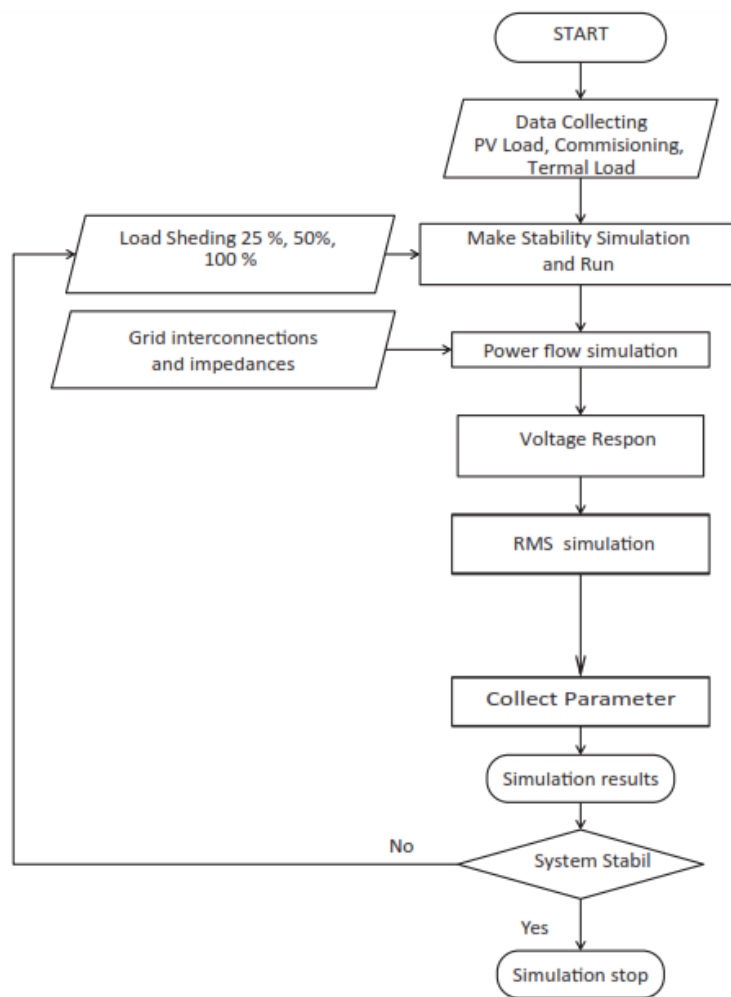
The rest of the paper is organized as follows. Section 2 introduces the overview of the parameters and system of the PV and the method chosen to solve the frequency stability problem. Section 3 presents the simulation results and evaluation of several scenarios of frequency stability of PV under load, free governor and battery energy storage system. Finally, Section 4 draws conclusions from this research and recommendations on the simulations.

## **2 Methodology**

This section describes the design of the current research used to attain the proposed goals and objectives. This research explores various strategies and techniques to ensure that solar integration does not destabilize the grid, especially

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in the face of inherent output fluctuations in solar energy sources. The methodology is used to facilitate simulation and analyze the data that has been obtained, as well as to make it easier to understand this research. Simulation steps and analysis can be seen in fig 1.



**Figure 1** Modelling Simulation Flow Chart

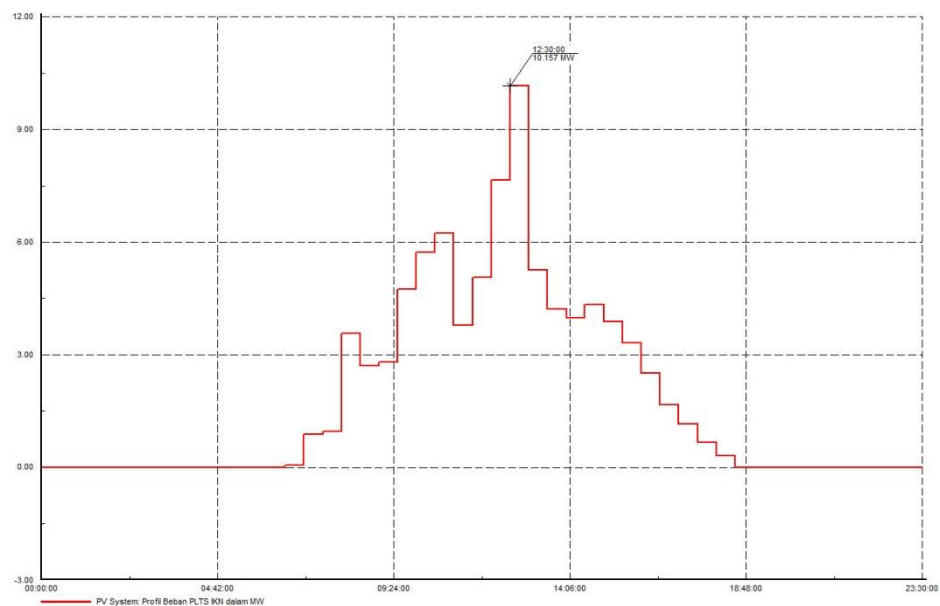
Nusantara Capital City PV system is a 20 kV electricity system that has 2 reinforcements, namely Gersik 1 and Gersik 2. Primary energy sources in Nusantara Capital City that can be utilized for electricity generation in potential energy sources are steam energy and solar energy both centrally and hybrid PV. For PV, Nusantara Capital City still distributes through a 20 kV network. Currently, the system needs at Nusantara Capital City have a peak load of 9.5 MW which is supplied from PV and Steam Power Plant operating on a 20 kV medium voltage network. The single line diagram (SLD) of the 20 kV PV system can be seen in Figure 2.

## 2.2 Load Profile PV

A load profile describes how the electrical power consumption of a solar power plant varies over time, typically over a 24-hour day. This profile is very important for the operation and analysis of solar systems, especially in on-grid and hybrid systems.

Table 1. Load Data of PV Nusantara Capital City

| Hours    | Trafo 1 | Trafo 2 | Load (kW) | Hours    | Trafo 1 | Trafo 2 | Load (kW) |
|----------|---------|---------|-----------|----------|---------|---------|-----------|
| 06:00:00 | -       | -       | -         | 12:30:00 | 5.108   | 5.049   | 10.157    |
| 06:30:00 | 30      | 29      | 59        | 13:00:00 | 2.628   | 2.612   | 5.240     |
| 07:00:00 | 430     | 434     | 863       | 13:30:00 | 2.104   | 2.102   | 4.207     |
| 07:30:00 | 478     | 474     | 952       | 14:00:00 | 1.985   | 1.981   | 3.966     |
| 08:00:00 | 1.772   | 1.799   | 3.571     | 14:30:00 | 2.165   | 2.169   | 4.334     |
| 08:30:00 | 1.366   | 1.327   | 2.693     | 15:00:00 | 1.941   | 1.933   | 3.874     |
| 09:00:00 | 1.395   | 1.405   | 2.801     | 15:30:00 | 1.664   | 1.652   | 3.315     |
| 09:30:00 | 2.370   | 2.367   | 4.737     | 16:00:00 | 1.252   | 1.254   | 2.506     |
| 10:00:00 | 2.864   | 2.867   | 5.731     | 16:30:00 | 826     | 824     | 1.650     |
| 10:30:00 | 3.135   | 3.097   | 6.232     | 17:00:00 | 573     | 573     | 1.145     |
| 11:00:00 | 1.924   | 1.868   | 3.792     | 17:30:00 | 331     | 332     | 662       |
| 11:30:00 | 2.560   | 2.503   | 5.063     | 18:00:00 | 150     | 151     | 302       |
| 12:00:00 | 3.843   | 3.802   | 7.645     | 18:30:00 | -       | -       | -         |



**Figure 3** Load Profile PV Nusantara Capital City

Figure 3 show load profile of the photovoltaic (PV) at Nusantara Capital City displayed on the graph shows a typical daily energy consumption pattern for a solar power generation system. In the morning, the load starts to rise gradually from 06:00 to 10:30, reflecting the increase in power production as the intensity of solar radiation increases. The load peaks at 12:30 with a maximum power of 10.157 MW, which coincides with the sun's position at zenith where the solar panels produce optimal power. Technically, this reflects the peak efficiency of the photovoltaic (PV) modules that take advantage of the best solar irradiation conditions and minimal losses due to the angle of incidence of sunlight. After passing the peak, the load starts to decrease gradually from 12:30 to 18:00 due to the reduced solar intensity and decreased PV panel output, which is characteristic of direct radiation-based solar systems.

At night, the load profile shows zero power production (0 MW), which illustrates the reliance on auxiliary energy sources, such as batteries or the PLN grid, to meet load requirements in the absence of solar radiation. From an engineering aspect, this load profile data is very important in designing the capacity of solar panels, inverters, and energy storage systems. Energy storage, such as batteries, needs to be designed to hold enough energy from the day to be used at night, taking into account the storage efficiency and life cycle of the batteries as well as determining the ratio of inverter power to load capacity so that the system remains stable when facing fluctuations in power production during the day reliably and efficiently.

### 2.3 Solar Irradiation

Solar irradiation data sourced from Meeonorm uses satellite data measurements with modeling to obtain estimates of ground radiation based on cloud parameters and atmospheric conditions. Based on the Meeonorm data, the daily average solar irradiation in the Nusantara Capital City area is 5.04 kWh/m<sup>2</sup>/day. The daily average irradiation can be seen in table 2. The table contains data on Global Horizontal Irradiance (Gh), Diffuse Horizontal Irradiance (Dh), Direct Normal Irradiance (Bn), Air Temperature (Ta), Dew Point Temperature (Td) and Wind Speed (FF)

Table 2. Nusantara Capital City Irradiation Data

| Month     | Gh<br>kWh/m <sup>2</sup> | Dh<br>kWh/m <sup>2</sup> | Bn<br>kWh/m <sup>2</sup> | Ta<br>°C | Td<br>°C | FF<br>m/s |
|-----------|--------------------------|--------------------------|--------------------------|----------|----------|-----------|
| January   | 164                      | 84                       | 119                      | 27,1     | 24,1     | 1,6       |
| February  | 148                      | 74                       | 105                      | 27,3     | 24,1     | 1,8       |
| March     | 161                      | 78                       | 115                      | 27,3     | 24,3     | 1,6       |
| April     | 150                      | 78                       | 103                      | 27,5     | 24,6     | 1,3       |
| May       | 148                      | 73                       | 112                      | 27,9     | 24,9     | 1,4       |
| June      | 143                      | 70                       | 109                      | 27,5     | 24,6     | 1,6       |
| July      | 158                      | 66                       | 140                      | 27,3     | 24,3     | 2         |
| August    | 163                      | 78                       | 120                      | 27,5     | 24,1     | 2,4       |
| September | 158                      | 76                       | 115                      | 27,8     | 24,3     | 2,2       |
| October   | 147                      | 82                       | 91                       | 28       | 24,5     | 1,7       |
| November  | 150                      | 77                       | 109                      | 27,6     | 24,5     | 1,3       |
| December  | 149                      | 69                       | 119                      | 27,4     | 24,3     | 1,4       |

The operating system of PV Nusantara Capital City which supplies the capital's electricity with operations from 06.00 am to 19.00 pm, the capacity of PV Nusantara Capital City for now has a capable power of 10 MW supplied by 2 transformers, each transformer has 25 with 450 string inverters. The following output load is supplied by PV with the highest load of around 9,922 kW at 12.00 noon as shown in table 2.

## 2.4 The Newton Raphson Method

The Newton-Raphson method offers advantages in mathematical calculations compared to other methods. It is particularly well-suited for large power systems due to its efficiency and practicality. This method is used to solve power flow equations involving one or multiple variables by applying Taylor Series calculations. By doing so, it converts non-linear equations into linear ones. The Taylor Series equation is as follows:

$$f(x) = f(x^{(0)}) + \left(\frac{df}{dx}\right)(0)\Delta x^{(0)} + \frac{1}{2!} \left(\frac{d^2f}{dx^2}\right)(0) (\Delta x^{(0)})^2 + \dots = c \quad (1)$$

$$\begin{aligned} \text{if } V_i &= |V_i| < = |V_i|e^{jq_i} \\ q_k &= q_i - q_k \\ Y_{ik} &= G_{jk} - jB_{ik} \end{aligned}$$

Then the above equation can be expressed in the form of an equation



$$Q_i = |V_i| \sum_j |V_j| \{ G_{ij} \sin(\theta_i - \theta_j) + B_{ij} \cos(\theta_i - \theta_j) \} \quad n_j=1 \quad (3)$$

| No. | Case Number | Case Name                                                                                                                                         |
|-----|-------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
| 1.  | Case 1      | Loss Of Power Supply From The Existing PV Nusantara Capital City (10 MW) By 100% Without Free Governor Kit Response                               |
| 2.  | Case 2      | Loss Of Power Supply From PV Nusantara Capital City With An Output Condition Of 10 MW By 100% With A Free Governor Kit.                           |
| 3.  | Case 3      | Loss Of Power Supply From PV Nusantara Capital City With 50 MW Output Condition By 100% Without Response Of Free Governor Kit And Battery (BESS). |
| 4.  | Case 4      | Loss Of Power Supply From PV Nusantara Capital City With 50 MW Output Condition Of 100% With Battery (BESS) Response Without Free Kit.            |
| 5.  | Case 5      | Loss of power supply from PV Nusantara Capital City with 50 MW output condition of 100% with battery and free kit governor response.              |

### 3.1 Test system and consider

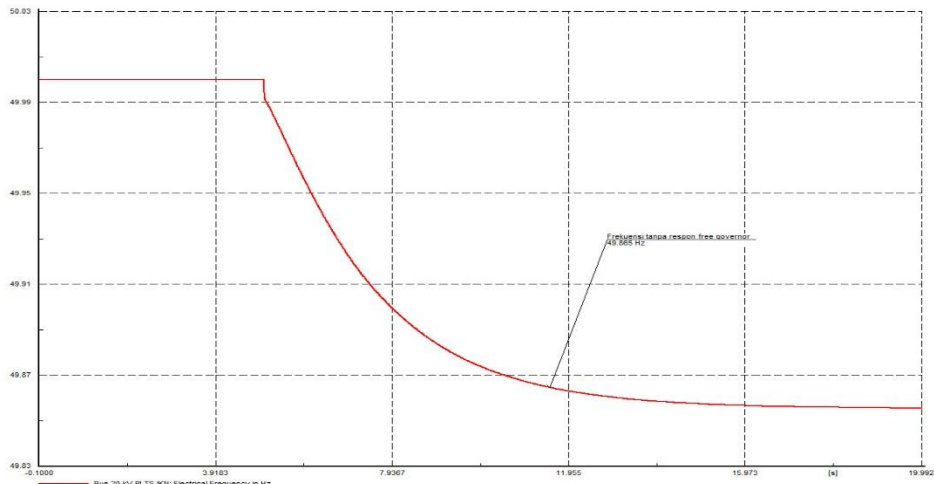
Time domain simulation (by time with 5th second lost). In this time domain simulation, a photovoltaic in the capital city of the archipelago is tested under dynamic conditions. At the 5th second of operation, a load loss of 10 MW occurs, simulating a sudden disturbance to the system. The test aimed to analyze the frequency response of the system, including voltage, frequency, and overall stability. Key considerations include ensuring initial system stability with nominal load and PV output, monitoring dynamic effects such as frequency overshoot and recovery time, and evaluating PV control mechanisms, such as inverters. Mitigation strategies, such as activating backup power or auxiliary controls, will also be assessed to maintain reliable operation during disturbances.

### 3.2 Simulation Frequency Stability

Frequency stability is carried out to analyze the impact of intermittency of PV

#### 3.2.1 Loss of power supply from the existing PV Nusantara Capital City (10 MW) by 100% without free governor kit response

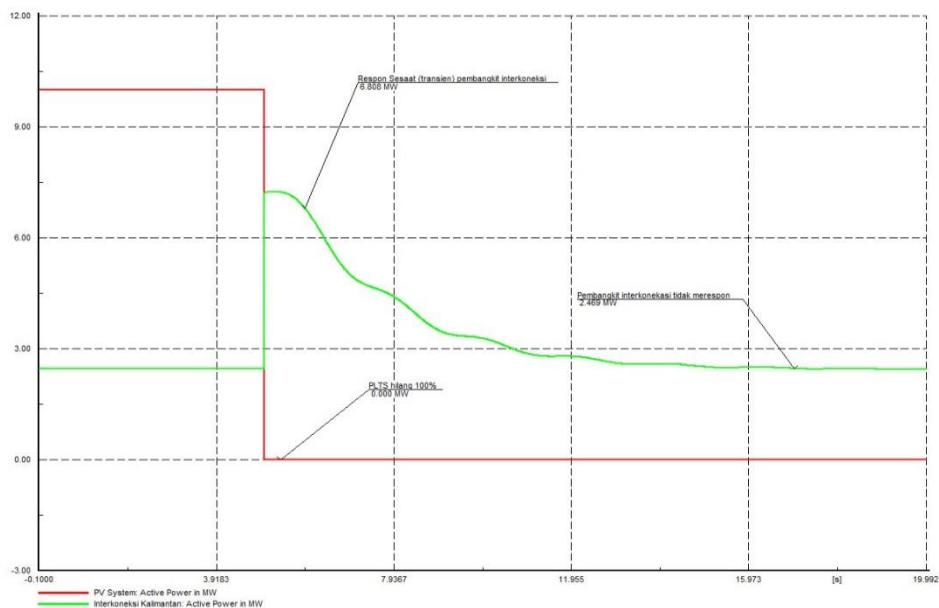
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**Figure 5** Loss of power supply from the existing PV Nusantara Capital City (10 MW) by 100% without free governor kit response

Illustrates figure 5 the simulation of the solar power plant when the load is lost by 100%, the frequency response of the 20 kV bus in the solar power plant system (PV) after a load loss of 10 MW. Initially, the system operates at a stable frequency around the nominal 50 Hz. In about 3.91 seconds, PV was load rejected. This decrease in frequency reached the lowest point of about 49.87 Hz. This simulation took more than 11 seconds because no generator accepted the load so that the frequency fell to 49.87 Hz. This frequency drop is equivalent to 85/Hz. This simulation makes the need for more sophisticated control strategies, such as virtual governor or bess, to improve system frequency stability and resilience to load drop

### 3.2.2 PV off-load 100% output with no synchronous plant response

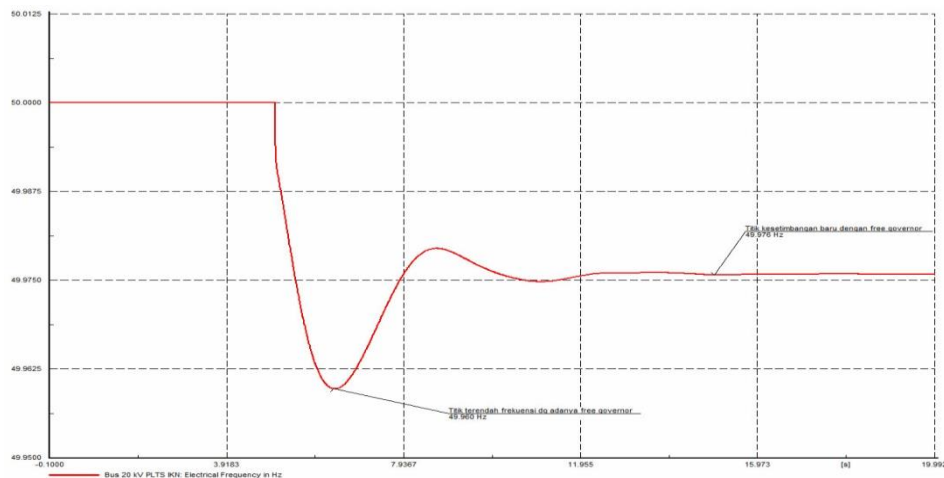


**Figure 6 . PV off-load 100% output with no synchronous plant response**

Figure 5 shows the active power response of the PV system and the Kalimantan interconnection plant when there is a total (100%) PV load shedding. At the 3rd second, the PV loses its output power completely, which is shown by the red line (PV power) dropping to 0 MW. This triggers the interconnection plant to provide a momentary response frequency, which can be seen from the increase in the active power of the interconnection plant to around 6.806 MW. However, after this transient phase, the active power of the interconnected plant slowly decreases until it stabilizes at around 2,469 MW. The graph also notes that the interconnection plant does not fully respond to the loss of power from the solar farm optimally, causing the system to only be able to maintain a portion of the lost power. This unresponsiveness may indicate limitations in the control system or delays in the frequency response mechanism of the interconnection plant, which should be designed to maintain grid stability more efficiently.

This analysis highlights the importance of coordination settings between solar PV and interconnected generation, as well as the need for power stability on the grid.

### 3.2.3 Loss of power supply from PV Nusantara Capital City with 50 MW output condition of 100% with free kit governor response

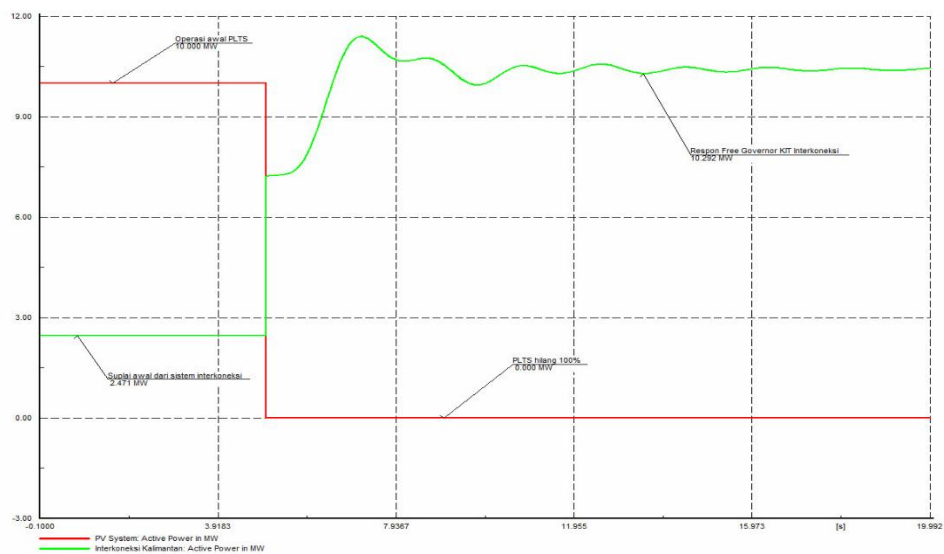


**Figure 7 . Loss of Power Supply from PV Nusantara Capital City with 10 MW output condition of 100% with kit free governor**

This graph 6. shows the frequency response at the 20 kV bus of the PV in Nusantara Capital City during a 100% load loss, with the influence of the free governor mechanism from the interconnected generator. Initially, the system frequency was stable at 50 Hz. When the PV load was fully disconnected (100%) at around 3.91 seconds, the frequency immediately dropped due to the loss of power contribution from the PV. The frequency reached its lowest point at 49.960 Hz (around 7.93 seconds), reflecting the impact of the sudden power imbalance. Afterward, the system began to recover gradually, thanks to the free governor response from the interconnected generator, which adjusted the power supply to compensate for the lost load. As a result, the system reached a new equilibrium at 49.976 Hz (after 15.97 seconds), still below the nominal 50 Hz due to the system's response limitations.

This response demonstrates that the free governor mechanism of the interconnected generator can help mitigate the impact of significant load losses on the system, although it does not fully restore the frequency to its nominal value. This highlights the importance of having a free governor mechanism to maintain frequency stability in the power grid during major disturbances, especially in systems relying PV without internal frequency control mechanisms.

### 3.2.4 Loss of Power Supply from PV with 10 MW output condition of 100% with synchronous plant response in MW



**Figure 8 . Loss of Power Supply from PV Nusantara Capital City with 10 MW output condition of 100% with kit free governor**

This graph 7. illustrates the response of the power system when the PV loses load completely (100%) under initial operating conditions with an output power of 10 MW. Before the load shedding, the solar PV contributes 10 MW of power, while the Kalimantan interconnection system supplies 2.471 MW of initial power to maintain load balance. When the PV lost load completely at around the 3,918th second, the active power from the PV immediately dropped to 0 MW. This causes a power imbalance in the system, which triggers a free governor response from the Kalimantan interconnection plant. In this condition, the Kalimantan interconnection plant responds by significantly increasing its output power until it reaches its peak, which is 10.292 MW. This response aims to stabilize the system and maintain power supply to existing loads.

After the peak response is reached, the output power of the interconnection plant slowly decreases towards a stable value in order to dynamically adjust the system needs. This shows that the free governor mechanism works well in compensating for sudden changes in the system due to the loss of power contribution from the solar PV. However, this response does not fully restore the system to its initial state as it depends on the interconnected generation capacity and system characteristics. Therefore, the free governor mechanism of the interconnected plant is the main solution in dealing with this condition

#### **4 Conclusion**

The power system study related to the planned entry of PV Nusantara Capital City into the Kalseltengtimra Interconnection System at this feasibility study stage has been completed. The conclusions of the study are as follows:

1. The free governor mechanism in the interconnected generator plays a crucial role in mitigating the effects of the disturbance. It responds promptly by increasing power output to compensate for the loss of PLTS generation, stabilizing the system and preventing further frequency decline.
2. New Equilibrium Frequency: While the free governor helps the system recover, it does not restore the frequency to its nominal value of 50 Hz. Instead, the system settles at a slightly lower equilibrium frequency, indicating a residual imbalance due to system limitations.

Overall, the interconnected system effectively maintains frequency stability despite the severe disturbance, but improvements in grid frequency control and PV capabilities could further enhance stability and resilience.

#### **5 Acknowledgement**

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