Small signal stability analysis due to the development of renewable energy generators in Sulawesi electricity

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Abstract. The problem of small signal stability is one of the main problems in the current power system because the purpose of operating the system is close to the limit. Small signal stability is important because small disturbances in the form of non-dampened electromechanical oscillations have limited the power flow limit in a steady state, so the oscillation will affect the operating system in a security and quality review. The entry of renewable energy in the Sulawesi interconnection system certainly has an impact on system stability and the emergence of electromechanical oscillations. An estimated 75 MW of power will come from the PLTB that will be built in Sidrap and 62.5 MW in Jeneponto. This study aims to analyze small signal stability due to the development of EBT generators on the Sulawesi interconnection system through eigenvalue characteristics and participation factors. The PLTB that will be integrated in the Sulawesi system certainly affects power flow which has an impact on small signal stability.

1. Introduction
The problem of small signal stability is one of the main problems in the current power system because the purpose of operating the system is close to the limit. Power oscillations are produced in a system, following a small load change or a disturbance, when there is an insufficient damping [1]. In these large interconnected system low frequency electromechanical oscillations exist due to weak tie lines or high power transfer to long distances [2]. These oscillations may be classified in two major modes as control modes concern with the control system like exciter, governor etc. and the electromechanical oscillation modes with frequency 0.1-2.0 Hz. These rotor angle modes, which are further classified as local mode (0.8-2.0Hz) and inter area mode (0.1-0.8Hz), should be damped for secure and reliable operation of the power system [3].

The small signal stability depends on the load conditions and the power system topology. Small signal stability can be interpreted as the stability of the system for small disturbances in the form of electromechanical oscillations that are not dampened because this oscillation has limited the power flow limit in a steady state, then the oscillation will affect the operating system both in economic and security reviews. The stability of the power system itself is the ability of a system to maintain a balanced operation and the ability of the system to return to normal operating conditions when there are 2 disturbances. The instability is basically related to rotor angle oscillation.

The integration of the generation of renewable energy sources is also a popular trend in current power systems, which gives advantages in reducing new feeder installations, saves generation costs and
increases supply reliability. The inclusion of PLTB in the Sulawesi interconnection system certainly has an impact on system stability and the emergence of electromechanical oscillations. An estimated 75 MW of power will come from the PLTB that will be built in Sidrap and 62.5 MW in Jeneponto. The PLTB that will be integrated in the Sulawesi system certainly affects system configuration and affects power flow which has an impact on small signal stability. From the above explanation, it is considered necessary to conduct research on the analysis of the stability of small signals before and after the integrated power plant in the Sulawesi electricity system.

2. Background

2.1. Power system stability
Power system stability is defined as the ability to remain in equilibrium during normal operating conditions and to regain an acceptable equilibrium after being subjected to a physical disturbance with most system variables bounded [4]. Broadly speaking the stability of a power system is classified as follows:

2.1.1. Voltage stability. The capability of a power system to remain the voltages of all the buses in steady state under normal operating conditions and after a disturbance.

2.1.2. Frequency stability. The capability of a power system to restore the balance between the system generation and the load with minimum loss of the load.

2.1.3. Rotor angle stability. The ability of each generating machine in an interconnected power system to maintain or regain the equilibrium between mechanical torque and the electromagnetic torque.

In general, disturbance is divided into 2 categories, namely:

- Small disturbance, that is, one of the dynamic system elements that can analyzed using linear equations (small signal analysis). Small disturbances that occur in the form of changes in load on the side of the load or generator randomly, slowly, and falling in tiers. The trip experienced by the electric power network is considered a small disturbance if the effect on power flow before disturbance with the network is not significant.
- Large disturbance. This disturbance is sudden, which is a disturbance that produces a sudden voltage shock on the bus voltage. This big disturbance must be immediately removed, if not removed immediately, large disturbance greatly affects the stability of the system. Not just a nuisance, time of disturbance also affects the stability of the system.

2.2. Small signal stability
Generally, power systems are always liable to small disturbances resulting from minor load changes to changes in mechanical inputs of system generators. Under these small disturbances the power system state variables follow transient oscillations with frequencies known as Eigen Frequencies or Modes of Oscillation. These modes of oscillation generally result from electromechanical interactions in generators and exciter-field voltage-current responses. The study of such transient effects is called as Small Signal Analysis.

The ability of the power system to maintain synchronism after subjected to small variations in load or generation is termed as Small Signal Stability. The nature of system response depends on a number of factors; however, the excitation controls are of primary concern. Generally, the instability may be caused due to lack of sufficient damping torque, thereby, resulting in rotor oscillations of increasing amplitude.

In practical power systems, the issue of small signal stability is associated with insufficient damping of oscillations. Generally, the following Modes of Oscillations are analyzed:
- Local Modes i.e. associated to the oscillations of Power Station with respect to the rest of the Power System [5].
- Inter Area Modes i.e. associated to the oscillations of Independent Groups of Power Units with respect to each other. The Groups of Power Units are located in different parts of the Power System and connected by weak ties [5].

2.3. Power system oscillation

Small signal stability is the ability of a power system to maintain synchronism when subjected to small disturbances, such as changes in power demand. The phenomenon is analysed using linear techniques based on valuable information about the natural dynamic characteristics of the system [2].

The most common approach for studying power system small signal stability is to use a linearized model of the power system.

\[
\begin{aligned}
\dot{x}(t) &= Ax(t) + Bu(t) \\
y(t) &= Cx(t) + Du(t)
\end{aligned}
\]  

Where \( x(t) \) is the vector of state variables, \( u(t) \) is the vector of control inputs, and \( A, B, C \text{ and } D \) are state, control, output and feed forward matrices, respectively.

Values of the scalar parameter \( \lambda \) that satisfy the following equations are known as eigenvalues of matrix \( A \). Only complex eigenvalues \( \lambda_i = \alpha_i \pm j\beta_i \) are considered.

The frequency of oscillation in Hz, representing the actual damped frequency, is given by:

\[
f_i = \frac{\beta_i}{2\pi}
\]

For a particular eigenvalue \( \lambda_i \), the damping ratio \( \zeta_i \) is defined as:

\[
\zeta_i = \frac{-\alpha_i}{\sqrt{\alpha_i^2 + \beta_i^2}}
\]

The damping ratio determines the rate of decay of the amplitude of the oscillation. The system is only stable if damping ratios of all oscillation modes are positive. The larger the damping ratio is, the quicker the oscillation is damped.

Dominant state variables in a particular mode can be identified with the help of participation factors. Participation factors are combination of left and right eigenvectors of matrix \( A \).

\[
P = [P_1, P_2, ..., P_n]
\]

\[
P_i = \begin{bmatrix}
P_{1i} \\
P_{2i} \\
\vdots \\
P_{ni}
\end{bmatrix} = \begin{bmatrix}
\phi_{1i} \psi_{1i} \\
\phi_{2i} \psi_{2i} \\
\vdots \\
\phi_{ni} \psi_{ni}
\end{bmatrix}
\]

In general, \( P_{ki} = \phi_{ki} \psi_{ik} \); \( \phi_{ki} \) is the \( k \)-th entry of the right eigenvector with \( i \)-th mode and \( \psi_{ik} \) is the \( k \)-th entry of left eigenvector associated with \( i \)-th mode. The participation factor is a measure of relative participation of the \( k \)-th state variable in the \( i \)-th mode.

Oscillation modes can be divided into electromechanical modes and control modes. One can determine that a mode is an electromechanical mode if the generator speed variables have the largest participation factor in this mode. Besides, participation factors also help to identify local modes (only one generator with significant participation factor) and inter-area modes (several inter-area generators with significant participation factors) [5].
3. Method

3.1. Research tool
A laptop with specifications that are capable of running the software used in research:

- Microsoft Office 2016
- Power Factory Digsilent

3.2. Materials
The material used for this study is the simulation of Sulawesi electricity using digsilent software.

3.3. Ways of research
The description of the research method to be carried out by the researcher is shown in the figure below:

![Figure 1. Research method.](image-url)

In this study a literature study was conducted to find out previous studies related to small signal stability in the electric power system. This is done in order to find out the reference used to be able to validate this research. Literature studies are also conducted to be able to find out the basic theory used to support this research. The main things sought on the basis of the theory are related to the analysis of small signal stability in the electric power system.

After conducting a literature study, data will be collected on the parameters that support the research, namely in the form of potential data on the development of power generation and transmission of the Sulawesi power system.

After collecting data, a model of the Sulawesi electrical system will be made in the Digsilent software.

After making the electrical system model in Sulawesi, a small signal stability simulation was carried out with Digsilent software. This was done to determine the effect of developing renewable energy plants in the Sulawesi electricity system.
Based on the results of the simulation and analysis conclusions will be drawn that refer to the formulation of the problem and the purpose of the study. Suggestions for developing further research and addressing the problems carried out by researchers in this study.

4. Results and discussion

4.1. Small signal stability analysis

4.1.1. 275 kV scenario. A small signal stability analysis will be carried out to determine the system's ability to maintain synchronization when experiencing minor disturbances. Analysis will be carried out in 2026.

a) Small signal stability analysis in 2026

Based on the RUPTL, in 2026, the Sulbagut and Sulbagsel systems have been interconnected at a voltage level of 275 kV. In the interconnection of these two systems, it is necessary to analyze the small signal stability to determine the ability of the system against small disturbances. The analysis carried out was modal analysis, observability, and participation factor.

1) Small signal stability analysis in 2026 with modal analysis

Modal Analysis (eigenvalue) can provide information about the stability of the system through eigenvalue values that are owned by the system.

![Figure 2. Eigenvalue in the modal analysis simulation during normal conditions in 2026.](image)

From figure 2, the eigenvalue value of the system is 442. From the resulting values, it can be concluded that the system is stable because all the real parts of the eigenvalue value are negative and are to the left of the imaginary axis.

![Figure 3. Eigenvalue in the capital analysis simulation during the contingency conditions of the Sidrap PLTB in 2026](image)
Whereas in figure 3, it is the eigenvalue value in the event of a contingency at the 75 MW Sidrap PLTB plant. From the picture, it can be concluded that the system is still stable when there is contingency. This is indicated by the system eigenvalue values which are all to the left of the imaginary axis.

![Figure 3](image)

**Figure 4.** Eigenvalue in the capital analysis simulation when the contingency conditions of Sidrap PLTB and Punagaya PLTB in 2026.

Whereas in figure 4, it is the eigenvalue value in the event of a contingency at the 75 MW Sidrap PLTB and 60 MW Punagaya PLTB. From the picture, it can be concluded that the system is still stable when there is contingency. This is indicated by the system eigenvalue values which are all to the left of the imaginary axis.

2) Small signal stability analysis in 2026 with mode shape

Of the 442 eigenvalues the damping ratio value is taken with a limit value below 10%. The following figure results in a mode with a damping ratio below 10%.

![Table](image)

**Figure 5.** Mode value results with a damping value ratio <10% in the 2026 capital analysis simulation.

From several modes when normal conditions, observability will be examined. The mode to be examined is the mode with the smallest damping ratio value and the largest time constant. This means that in that mode, when a disturbance occurs, the system will return to the steady state condition for a longer time and the oscillation will be longer than other modes. This mode is 00163 modes, so this mode will be plotted in the form of a phasor to see the generator that caused the value and type of oscillation.
Figure 6. Observability results in mode 00163 in 2026.

From figure 6 above, there are two images of direction, right and left, namely cluster 1 which is dominated by Sulbagut area generator and cluster 2 which is dominated by Sulbagsel area generator, with oscillation frequency value is 0.628 Hz, so the oscillation mode is inter-area oscillation mode. To see the generator that has the most influence on the oscillation, then it will then analysis of participation factor was carried out.

| Name   | Normal Real part 1/s | Normal Imaginary part rad/s | Normal Damping Ratio | Kontingensi PLTB Sidrap 75 MW Real part 1/s | Kontingensi PLTB Sidrap 75 MW Imaginary part rad/s | Kontingensi PLTB Sidrap 75 MW Damping Ratio |
|--------|----------------------|-----------------------------|----------------------|---------------------------------------------|-----------------------------------------------|---------------------------------------------|
| Mode 00163 | -0.16431           | 4.25938                     | 0.03854             | Mode 00159                                  | -0.13605                                      | 0.03292                                      |
| Mode 00164 | -0.16341           | -4.25938                    | 0.03854             | Mode 00160                                  | -0.13605                                      | -4.13022                                    | 0.03292                                      |
| Mode 00153 | 0.52731            | 7.37283                     | 0.07133             | Mode 00089                                  | -0.37554                                      | 1.38797                                    | 0.2704                                      |
| Mode 00154 | 0.52731            | -7.37283                    | 0.07133             | Mode 00090                                  | -0.37554                                      | -1.38797                                    | 0.2704                                      |

Figure 7. Comparison of shape modes during normal conditions and at the contingency of Sidrap PLTB in 2026.

Figure 8. Comparison of shape modes during normal conditions and at the contingency of Sidrap PLTB and Punagaya PLTB in 2026.

While in figure 7, it shows a comparison of several eigenvalue values with the smallest damping ratio value during normal conditions and during contingency. The value of the real part of the eigenvalue at the time of contingency has a more positive value than during normal conditions. This shows that the stability of the system when contingency is worse than during normal conditions due to the release of channels and power plants in the system.
3) Small signal stability analysis with participation factor

The participation factor simulation is carried out on two state variables, namely phi (rotor angle) and speed (speed). From each of these states, which generators will contribute the most to instability.

![Figure 9. Participation Factor (phi) Simulation of Normal Conditions in 2026.](image)

![Figure 10. Participation factor simulation (speed) normal condition in 2026.](image)

| Mode Index | Object            | State Variable | Participation (phi) | Participation (speed) |
|------------|-------------------|----------------|---------------------|-----------------------|
| 103        | PLTG KENDARI 50 MW| phi            | 0.19426             | 0.18502               |
| 103        | PLTG KENDARI 100 MW| phi            | 0.17886             | 0.17886               |
| 103        | PLTU ISMU 50 MW   | phi            | 0.20485             | 1.57156               |
| 103        | PLTU KAWANGOANOAN 25 MW| phi | 0.26515             | 1.32995               |
| 103        | PLTU KAWANGOANOAN 100 MW| phi | 0.37778             | 1.78109               |
| 103        | PLTU KAWANGOANOAN 150 MW| phi | 0.39007             | 1.55108               |
| 103        | PLTU KAWANGOANOAN 200 MW| phi | 1.0                  | 0.0                   |

![Figure 11. Results of participation factor (phi) normal conditions in 2026.](image)

| Mode Index | Object            | State Variable | Participation (phi) | Participation (speed) |
|------------|-------------------|----------------|---------------------|-----------------------|
| 159        | PLTU ISMU 50 MW   | speed          | 0.14538             | -177.6                |
| 159        | PLTU KENDARI 50 MW| speed          | 0.17075             | -176.1                |
| 159        | PLTU KENDARI 100 MW| speed         | 0.20475             | -177.1                |
| 159        | PLTU KENDARI 150 MW| speed         | 0.28217             | -176.1                |
| 159        | PLTU KENDARI 200 MW| speed         | 0.29110             | -175.7                |
| 159        | PLTU KAWANGOANOAN 100 MW| speed | 0.39210             | -174.3                |

![Figure 12. Results of participation factor (speed) normal conditions in 2026.](image)

From the simulation of the participation factor in the figure and table above, it can be seen that in the Sulbagut system, the most influential power plant with instability is the 100 MW Kawangkoan PLTG and 150 MW Kawangkoan PLTG when viewed from the participation rotor angle factor (phi) and speed, if viewed from the participation factor, it is necessary to give special treatment to AVR and the governor at the related plant so that it will be better in anticipating interference.
Figure 13. Participation factor (phi) simulation of the contingency conditions of Sidrap power plant in 2026.

Figure 14. Participation factor simulation (speed) contingency conditions of Sidrap power plant in 2026.

Figure 15. Results of participation factor (phi) contingency conditions Sidrap PLTB 2026.

Figure 16. Results of participation factor (speed) contingency conditions Sidrap PLTB 2026.
Figure 17. Participation factor (phi) simulation of contingency conditions for Sidrap PLTB and Punagaya PLTB in 2026.

Figure 18. Participation factor simulation (speed) contingency conditions of Sidrap PLTB and Punagaya PLTB in 2026.

Figure 19. Results of participation factor (phi) contingency conditions for Sidrap PLTB and Punagaya PLTB 2026.

Figure 20. Results of participation factor (speed) contingency conditions of PLTB Sidrap and PLTB Punagaya 2026.

5. Conclusion

- The system before and after the entry of the PLTB remains stable marked by an eigenvalue which is to the left of the imaginary axis
- With added AVR and PSS can increase system stability
- With the introduction of PLTB it will increase the stability of the small signal

References

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