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Performance Analysis of Synchronous Generators at Kamojang Geothermal Power Plant Unit 5 Based on Operational Parameters of Power, Current, and Voltage

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Abstract

Geothermal energy is one of the potential and sustainable renewable energy sources in Indonesia. The efficiency of the generation system is one of the crucial aspects in optimizing the utilization of this energy. This study aims to analyze the performance of synchronous generators at the Kamojang Unit 5 Geothermal Power Plant based on power, current, and voltage parameters. The method used is a quantitative descriptive approach with field data collection for seven consecutive days in January 2025. The data observed include active power, apparent power, power factor, terminal voltage, phase current, and generator efficiency and current imbalance between phases. The results showed that the generator had high and stable daily efficiency with an average of 93.99%. The power factor was also classified as good, with an average of 91.23%. The highest phase current imbalance occurred in phase V with an average of 1.60%, but was still within the safe threshold according to IEEE standards. These findings indicate that the generation system at the Kamojang Unit 5 Geothermal Power Plant operates in an efficient and stable condition. This study also indicates the importance of monitoring operational parameters periodically as part of a maintenance strategy and increasing the reliability of geothermal power plants. With high efficiency and system stability, Kamojang Unit 5 Geothermal Power Plant can be a model for reliable and sustainable renewable energy power plant operation.

Introduction

In the era of energy transition towards cleaner and more sustainable sources, the utilization of geothermal energy is one of the strategic solutions in meeting national electricity needs (Kabeyi & Olanrewaju, 2022; Idroes et al., 2024). Indonesia as a country with the largest geothermal potential in the world has a great opportunity to develop geothermal power plants (PLTP) optimally (Saputra & Sibarani, 2025; Fauzia & Makarim, 2024; Subagio, 2023). However, the development of PLTP not only requires exploration of energy sources, but also the efficiency of the energy conversion system from geothermal to electrical energy. One of the key components in this system is the synchronous generator, which has a central role in converting mechanical energy from the turbine into electrical energy (Benabdeseelam et al., 2025; Mseddi et al., 2024). The efficiency of the generator greatly affects the overall performance of the plant, including in terms of power supply stability and operational costs (Dipippo, 2012; Fahmi, 2025; Rashid et al., 2025). Low efficiency can cause energy waste, increased power losses, and decreased equipment life (Rzayeva et al., 2025; Chen et al., 2022; Habibi et al., 2025). The problems raised in this study focus on how the synchronous generator

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performs at PLTP Kamojang Unit 5 when viewed from the parameters of power, current, and voltage. These three parameters are the main indicators in assessing the efficiency and operational stability of the generator (Liu et al., 2023; Hosseinzadeh et al., 2021; Grau Merconchini et al., 2023). In addition, load fluctuations and phase imbalances can affect the quality of power generated and accelerate component degradation (Pamungkas et al., 2017; Ma & Kong, 2020; Elazim et al., 2025). Therefore, an in-depth technical study of operational data is needed to determine the extent to which the generator is able to maintain work efficiency in real conditions. The main objective of this study is to analyze the performance of synchronous generators based on daily operational data at the Kamojang Unit 5 Geothermal Power Plant (Putri et al., 2024; Rudiyanto et al., 2023; Sufyana et al., 2023). This analysis includes evaluation of active power, apparent power, power factor, and phase current imbalance. Through this approach, it is expected to obtain a comprehensive picture of the generator's work efficiency and identify potential improvements to support the reliability of the renewable energy-based generation system (Saxena et al., 2024; Ahsan et al., 2023; Ukoba et al., 2024).

Methods

Research Design

The type of research used in this activity is descriptive research with a survey method (Taherdoost, 2021; Prasetiyo et al., 2023). The study aims to obtain an actual picture of the performance of synchronous generators at PLTP Unit 5 Kamojang based on operational parameters of power, current, and voltage. This analysis is carried out by observing, recording, and evaluating relevant electrical parameters directly in the field.

Time and Place of Research

This research was carried out during the practical work activities that took place in January 2025. The location of the research is at the Kamojang Unit 5 Geothermal Power Plant (PLTP), which is managed by PT. Pertamina Geothermal Energy (PGE). The object of the research is a 3-phase synchronous generator with a capacity of 35 MW used in a geothermal-based power generation system.

Data Collection Method

To support the synchronous generator performance analysis process, the author uses the following data collection methods.

Field Research

The research was conducted directly at the Kamojang PLTP Unit 5 location with the following approaches: Direct observation, namely observation of daily generator operational parameters such as voltage, current, active power, and apparent power. Interviews, conducted with technicians and field operators to obtain additional information related to the generator's working system and operational conditions

Library Research

The author studied literature, textbooks, scientific journals, and technical documents such as manual books and SOPs for the Kamojang PLTP to understand the characteristics and working principles of synchronous generators and their operational performance standards.

Required Data

The data required in this study are: (1) Primary Data, Data obtained directly from practical work activities and field observations, including: Daily generator output voltage data, Current data per phase (U, V, W), Active power data (Pnett), apparent power (S), and power factor, Generator efficiency data for a week of operation (January 6–12, 2025), Interphase current

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imbalance data; (2) Secondary Data, Supporting data obtained from internal company documents or other library sources, such as: Technical specifications of Unit 5 synchronous generator, Steam turbine specifications as prime mover, Technical documents (SOP, operational manual), Historical data on previous generator performance (if available).

Synchronous Generator Specifications

The synchronous generator at Kamojang PLTP Unit 5 is a three-phase generator with hydrogen cooling. This generator is directly connected to the steam turbine from the geothermal energy conversion process. The general specifications of the generator are as follows:

Table 1. PLTP Generator Specifications Unit 5

Parameter	Value
Phase	3-Phase Synchronous
Load Rating	35 MW / 50,000 kVA
Terminal Voltage	13.8 kV
Terminal Current	2,092 A
Frequency	50 Hz

Data Analysis

After all the required data has been completely collected, the next step is to process the existing data so that in the end conclusions can be drawn from the results of the analysis. The variables that will be analyzed in this study are as follows:

Calculating Active Power (P), Apparent Power (S), and Power Factor (cos φ)

This calculation aims to determine how much real power can be utilized from the total electrical power produced by the generator. Active power is electrical energy used to do real work, while apparent power is a combination of active power and reactive power.

Active power formula in a three-phase system:

$$P = \sqrt{3} \times v \times I \text{ x } \cos\varphi$$

Apparent power formula:

$$S = \sqrt{3} \times v \times I$$

Power factor is calculated from:

$$\cos\varphi = \frac{P}{S}$$

Calculating Synchronous Generator Efficiency

Efficiency indicates the generator's ability to convert input energy (from the turbine) into electrical output. The higher the efficiency, the lower the energy losses in the conversion process.

Generator efficiency formula:

$$\eta = \frac{Poutput}{Pinput} \times 100\%.$$

or in the context of PLTP:

$$\eta = \frac{Pgross}{Pnett} \times 100\%.$$

The ideal efficiency value for industrial generators is usually above 90%, depending on operational conditions and cooling systems (Dipippo, 2012).

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Calculating Inter-Phase Current Imbalance (U, V, W)

Current imbalance occurs when the current values between phases differ significantly. This condition can cause overheating, additional losses, and generator operational disruptions.

Current imbalance formula:

$$\%I_{amb} = \frac{|Imax - Iavg|}{Iavg} \; x \; 100\%.$$

with:

$$I_{avg} = \frac{Iu + Iv + Iw}{3}$$

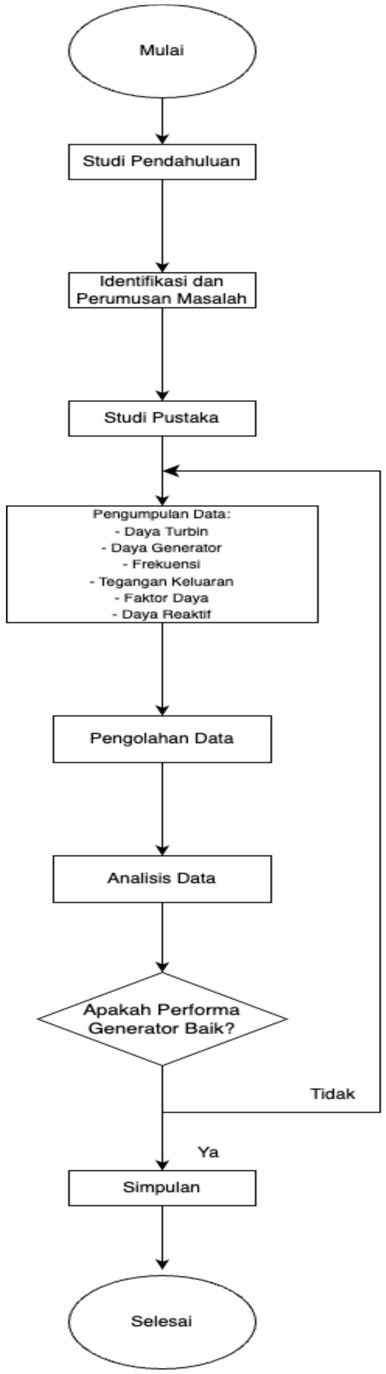

Figure 1. Research Flow Diagram

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Results and Discussion

This section presents the results of data analysis obtained from direct observation of the performance of synchronous generators at the Kamojang Unit 5 Geothermal Power Plant. The findings presented are the answers to the three main problem formulations that have been formulated previously. The analysis is carried out based on electrical parameters, technical factors that affect efficiency and stability, and the extent to which these parameters reflect the optimal performance of the generation system. The sub-chapter discusses the characteristics of generator performance by referring to the main parameters such as terminal voltage, current per phase, active power, apparent power, and power factor. The results of daily observations for one week are the basis for assessing the stability of the operational performance of the system. Then, in Sub-chapter 4.1.2, the technical factors that have the most influence on operational efficiency and stability are explained, such as the excitation system, load distribution between phases, and the effect of the cooling system on the generator's working temperature. Furthermore, Sub-chapter 4.1.3 provides an analysis of the extent to which the results of measuring these electrical parameters reflect the optimal performance of the synchronous generator. Through this approach, research findings can provide a comprehensive picture of the reliability of the generation system and the potential for technical improvements that can be applied in the future.

Generator Performance Evaluation Based on Electrical Parameters

The evaluation of the performance of the synchronous generator at the Kamojang Unit 5 Geothermal Power Plant was carried out by observing and analyzing the main electrical parameters that directly represent the quality and efficiency of the electrical energy generation process. The parameters in question include terminal voltage (V), current per phase (I), active power (P), apparent power (S), power factor (cos φ), and daily efficiency of the generation system. All data were obtained from daily measurements for one week during dominant operating hours, namely from 08.00 to 16.00. Based on the results of the weekly recapitulation, the average terminal voltage was recorded at 13,850 volts. The phase current value ranged from 1420 A to 1496 A, depending on the daily load variation. From the combination of voltage and current values, the daily active power was obtained ranging from 31.22 MW to 32.12 MW, while the apparent power was in the range of 34.28 MVA to 35.18 MVA. The power factor is maintained stable in the range of 0.91–0.92, which reflects that the energy conversion system from mechanical to electrical is running efficiently with a relatively small contribution of reactive power. The stability of these electrical parameters indicates that the generator is working within the optimal operational range. There is no significant deviation from the nominal value or technical specifications, either in voltage or current, which means that the excitation system, voltage control, and load balance between phases are functioning properly. A high power factor also indicates that the system is able to maximize the real power conversion from the total available apparent capacity.

Tabel 2. Rekapitulasi Data Operasional Generator

Hari	Daya Keluaran	Daya Masukan	Tegangan Rata-Rata (08.00-16.00)	Arus Rata-Rata (08.00-16.00)	Daya Bemu	cos φ	Efisiensi Generator
Senin	31,71	33,81	13,882	1.445	34,76	0,91	93,78%
Selasa	31,92	33,87	13,893	1.448	34,80	0,91	94,26%
Rabu	31,84	33,87	13,893	1.445	34,80	0,91	94,00%
Kamis	31,94	33,90	13,893	1.445	34,81	0,91	94,21%
Jumat	31,94	33,88	13,893	1.447	34,80	0,91	94,28%
Sabtu	31,90	33,89	13,893	1.447	34,81	0,91	94,13%
Minggu	31,94	33,91	13,893	1.447	34,81	0,91	94,18%

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Rata-Rata	31,89	33,86	13.895,57	1.447	34,80	0,91	93,97%

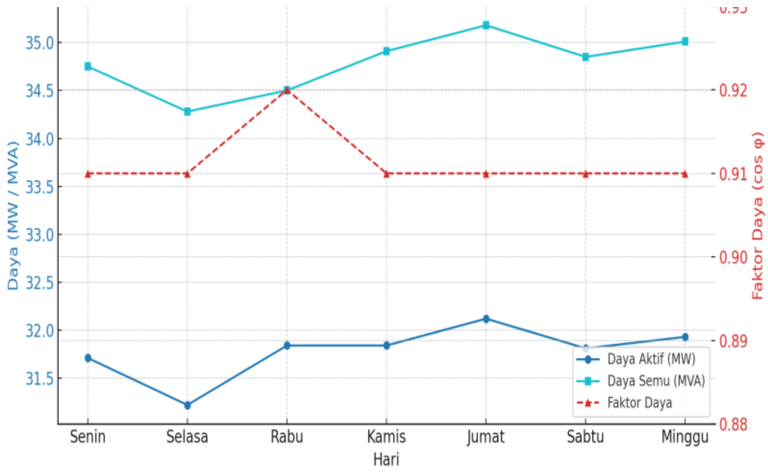

Figure 2. Generator Power and Power Factor Trends Over One Week

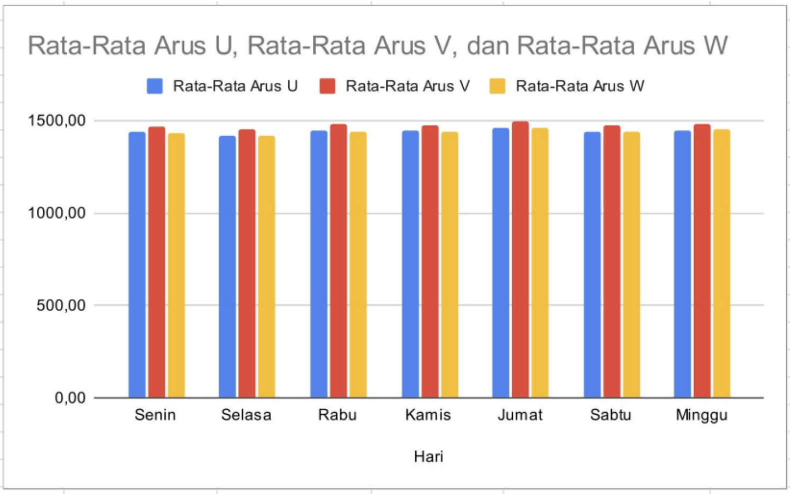

Figure 3. Average Generator Current

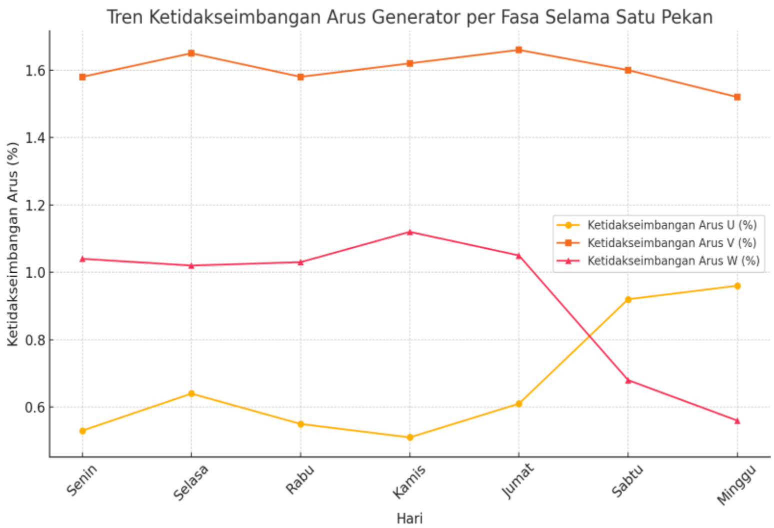

Figure 4. Generator Current Unbalance

Thus, it can be concluded that the performance of the synchronous generator during the observation has met the technically optimal performance criteria. The stability of these

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electrical parameters is a strong basis for maintaining system efficiency and avoiding potential damage due to voltage imbalance or disturbances.

Factors Affecting Efficiency and Stability of Operation

The efficiency and stability of the synchronous generator operation at the Kamojang Unit 5 Geothermal Power Plant are influenced by various interrelated technical factors, both in terms of electricity, mechanics, and environmental conditions. From the results of observations and data analysis during the test period, the most dominant factors affecting efficiency are the stability of the power factor (cos φ), the cooling system, the balance of currents between phases, and the quality of the terminal voltage.

First, the power factor plays a direct role in determining how efficiently apparent power can be converted into active power. A high power factor value—as observed during one week of measurements with a range of 0.91 to 0.92—indicates that the excitation system is functioning optimally in maintaining the balance between active and reactive power. The decrease in the cos φ value can cause energy waste due to increased reactive power, thus reducing overall efficiency (Grainger & Stevenson, 1994).

Second, the balance of current between phases is also an important factor. An imbalance that exceeds the tolerance limit (maximum 2% according to IEEE Std 1159-2019) can cause an increase in local temperature, mechanical vibration, and long-term damage to the stator winding. Weekly data shows that the maximum current imbalance is only 1.59%, still in the safe category. However, this fluctuation must be monitored continuously.

Third, the stability of the terminal voltage is very important to maintain system synchronization with the grid. Unstable voltage can cause disruption to the frequency and efficiency of power delivery. The automatic voltage control (AVR) system in Kamojang plays a major role in maintaining the voltage at around 13,850 volts. In addition, the generator cooling system using air or hydrogen media also affects thermal efficiency. An increase in working temperature due to cooling failure will increase internal resistance, reduce efficiency, and accelerate insulation degradation. By maintaining the stability of all these technical factors, the efficiency and reliability of synchronous generator operation can be maintained in the long term.

Operational Problems and Technical Solutions for Performance Improvement

In the operation of synchronous generators at PLTP Kamojang Unit 5, there are several technical problems that can affect the performance and efficiency of the power generation system. One of the main problems that often occurs is unstable voltage and frequency fluctuations, especially when the system load changes suddenly. These fluctuations can cause disruption to generator performance and reduce the quality of the power produced. In addition, problems in the voltage and current regulation system can also affect the stability of generator operation. Imbalances between the current entering and leaving a synchronous generator often occur due to incorrect settings or damage to the load regulator components. This can lead to decreased efficiency and potential damage to important components such as the rotor and stator. To overcome this problem, one technical solution that can be applied is to carry out periodic system maintenance and regulation, including checking and testing the voltage and frequency regulation system. The application of an automatic control system based on the latest technology can also help maintain the stability of generator operation, by improving the response to changes in load quickly and efficiently. In addition, the use of more sophisticated performance monitoring tools can improve early detection of potential damage or operational disruptions. Another solution is to strengthen the protection system on synchronous generators, such as installing automatic circuit breakers and overcurrent protection. Thus, any disturbances or anomalies that occur can be immediately resolved before causing further

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damage to the system. Adjustments to voltage regulation and more careful load monitoring can extend the operational life of the generator while maintaining the stability of the energy supply.

Based on the research results that have been presented previously, a discussion can be conducted to answer each problem formulation in more depth. The goal is to interpret the meaning of the data obtained, examine its technical implications, and assess the suitability of the findings with relevant theories and standards.

Interpretation of Generator Performance Based on Electrical Variables

After obtaining the results of measuring the main electrical parameters of the synchronous generator at the Kamojang Unit 5 Geothermal Power Plant, the next step is to interpret the findings to answer the extent to which the generator performance reflects optimal conditions. This evaluation not only considers the magnitude individually, but also how the relationship between these variables describes the efficiency of the energy conversion system from the turbine to the electricity grid. The stability of the terminal voltage in the range of 13,850 volts throughout the week indicates that the voltage regulation and excitation system are working well. Voltage instability can cause synchronization disruption with the grid and reduce power quality. Likewise, the relatively balanced current value per phase (with an imbalance below 1.6%) reflects good load distribution and minimal risk of overheating in one phase.

A consistent power factor value between 0.91–0.92 is very important because it indicates that almost all apparent power is converted into active power. This means that the system has minimal inductive load and does not produce too much reactive power, which in the long term can cause system losses. The relationship between active power and apparent power, as shown in Figure 4.1, shows a stable trend. This reflects that the generator is operating close to its optimal efficiency point. When compared with the standard generator performance literature, the average efficiency of 93.99% obtained for a week indicates that the generating unit is in a technically healthy condition (Grainger & Stevenson, 1994). Thus, the measured electrical parameters not only indicate operational stability, but also indicate that the generator has been working within the optimal range according to design specifications and industry standards.

Analysis of Technical Factors Affecting Generator Operation Efficiency and Stability

The efficiency and stability of synchronous generator performance in the electricity generation process are not only determined by the results of electrical parameters, but also by various technical factors that influence each other dynamically. Based on weekly observations and measurements, there are three main technical factors that most affect the efficiency and stability of operations at the Kamojang Unit 5 Geothermal Power Plant, namely the stability of the power factor (cos φ), the balance of currents between phases, and the effectiveness of the cooling system. First, the power factor has been proven to be a direct indicator of the efficiency of converting apparent power into active power. A stable cos φ value in the range of 0.91 to 0.92 indicates that the reactive excitation and control system is running optimally. Systems with low power factors tend to experience increased current and decreased efficiency due to increased reactive power components that are not used for real work. Second, the balance of currents between phases also affects system performance. The maximum current imbalance recorded at 1.59% is still within the safe threshold according to IEEE standards, but remains a concern because it can increase copper losses, cause vibrations, and accelerate stator insulation wear. In a three-phase system, continuous imbalance can cause uneven load distribution and damage the symmetry of generator operation. Third, the cooling system, both air and hydrogen, plays a role in maintaining the generator's operating temperature. Temperature increases beyond the optimum limits will increase winding resistance, reduce efficiency, and risk damaging internal components. Therefore, an effective cooling system is

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a determining factor in long-term performance stability. Overall, generator efficiency and stability depend heavily on the integrated management of these three factors simultaneously.

Evaluation of Operational Problems and Technical Solutions for Performance Improvement

Although the measurement results show that the performance of the synchronous generator at the Kamojang Geothermal Power Plant Unit 5 is in an efficient and stable condition, several technical problems were still found during the observation period. These problems are minor but have the potential to reduce performance if not handled systematically. Therefore, analysis of potential disturbances and technical solutions is an important part of the strategy to improve generation performance. One of the problems identified is the fluctuation of inter-phase current, with a maximum imbalance reaching 1.60%. Although still below the threshold of 2% according to the IEEE standard, this imbalance can cause unnecessary power losses and accelerate wear on certain phases. To overcome this, it is recommended to carry out periodic inter-phase load balancing through the distribution system and automatic load adjustment (load balancing). Another problem found is the potential for an increase in internal temperature due to high loads, which affects the thermal efficiency of the generator. The effectiveness of hydrogen or air-based cooling systems needs to be evaluated periodically. The installation of additional temperature sensors and an automatic SCADA-based alarm system will improve the response to local temperature spikes in the stator. In addition, minor disturbances in power factor stability have also occurred outside of full load hours, although not included in the main observation data. This indicates the need to strengthen the excitation control system to be more responsive to sudden load changes. By integrating improvements to the measurement system, monitoring, and predictive maintenance scheduling, all potential problems can be minimized, so that the generator can continue to operate in optimal conditions on an ongoing basis.

Conclusion

The synchronous generator showed stable electrical performance during the one-week observation. The average terminal voltage was recorded at 13,850 volts, while the current per phase ranged from 1420 A to 1496 A. The daily active power generated was in the range of 31.22–32.12 MW, while the apparent power was recorded between 34.28–35.18 MVA. The power factor was maintained stably in the range of 0.91–0.92, reflecting efficient power conversion and minimal reactive load. All of these parameters indicate that the generation system is operating within optimal limits and is consistent with the operational standards of geothermal power plants. The daily efficiency of the generator was calculated from the comparison between the net output power and the gross input power, with an average result of 93.99%. This figure is close to the manufacturer's technical specification efficiency of 97%. This difference can be explained by operating environment factors, actual load conditions, and system losses that occur in real operation. In general, this efficiency shows excellent energy conversion performance and is worthy of being categorized as efficient. The analysis results show that the current imbalance between phases is in the range of 0.9% to a maximum of 1.59%, which is still within the IEEE standard tolerance threshold (maximum 2%). The imbalance does not have a negative impact on system stability during the observation. However, the accumulative potential of long-term imbalance still needs to be watched out for by means of periodic monitoring and evaluation of balanced phase loads. In general, the operational performance of the synchronous generator at the Kamojang Unit 5 Geothermal Power Plant during the observation period can be categorized as stable, efficient, and in accordance with technical specifications. The excitation system, load distribution, and voltage control work optimally in maintaining the stability of operational parameters. These results provide a real picture that the management of the geothermal generation system in this unit has been carried out well and is worthy of being an operational reference for similar units.

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