Assessing Voltage and Frequency Instability in Renah Kemumu's Micro Hydro Power Plant

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ABSTRACT — The increasing demand for energy and the need for environmental sustainability have led to the adoption of renewable energy sources, such as micro-hydropower plants (PLTMH), in isolated communities in Indonesia. However, voltage and frequency instability issues are commonly encountered in PLTMH systems, which undermine their performance. In 2009, a micro-hydropower plant with a capacity of 30 KW was built in Renah Kemumu village. Ranah Kemumu village is located in Jangkat sub-district, Merangin district, Jambi province. In this study, the voltage and frequency instability of PLTMH in Renah Kemumu Village were investigated. The methodology employed in this study was observational. The voltage and frequency data were measured and recorded during peak load hours from 18.00 to 21.00 over one month. The percentage increase relative to the standard voltage and frequency was calculated. Boxplots were generated to visualize the distributions. The voltage measurements showed maximum and minimum values of 270 V and 264 V, representing increases of 22.72 % and 20.45% from the 220 V (standard set by the power utility (PLN)). The frequency ranged from 66.32 Hz to 57.46 Hz, corresponding to 30.92% and 14.92% deviations from the 50 Hz (standard set by the power utility (PLN)). These values exceeded the tolerance limits of the State Electricity Company of Indonesia. The analysis indicates that the voltage and frequency levels at the PLTMH in Renah Kemumu Village are unstable during peak loads, with fluctuations stemming from changing water flows, load currents, and weather conditions.

KEYWORDS — PLTMH, Voltage Instability, Frequency Instability, Peak Load, Water Flow Regulation, Load-Current Fluctuations

I. INTRODUCTION

The escalating demand for energy and the imperative for environmental sustainability are driving the exploration of alternative energy sources such as micro-hydropower plants (PLTMH). PLTMHs, known for their lower production capacity compared to larger generators, have emerged as a novel solution for isolated communities, such as Renah Kemumu Village, which have not yet been integrated into the national power grid. The adoption of these micro hydro plants in such locales not only bolsters the movement towards clean energy [1] but also plays a significant role in enhancing the well-being of the community by ensuring a consistent and dependable source of electricity,[2], [3].

However, the deployment of these systems often encounters technical hurdles, particularly in maintaining consistent voltage and frequency levels [4], [5], [6]. This aspect is crucial, as it has a direct impact on supply reliability and efficiency. Fluctuations in the voltage and frequency can lead to disruptions in electronic devices and diminish the infrastructure lifespan [7], [8]. In Renah Kemumu Vilage, addressing these issues is a priority, given the unique aspects of the PLTMH system and the specific geographical factors that influence plant performance.

Thus, an in-depth analysis of the instabilities in the voltage and frequency within PLTMH systems is critical. This study is dedicated to pinpointing the root causes of these instabilities [9], [10] and devising effective strategies to enhance the functionality of PLTMHs in Renah Kemumu Village. The insights gained from this study are expected to guide the development of PLTMH systems in other regions in similar contexts, aiding the broader mission of fortifying the dependability of renewable energy sources in Indonesia.

II. THEORY

A. PREVIOUS STUDIES

The research presented in this paper includes the development and testing of innovative control techniques aimed at enhancing the performance of power generation systems, with a particular focus on micro-hydropower plants (PLTMH). Zulfatman and his team investigated Flow Valve Control (FVC) and Electronic Load Control (ELC) strategies to expedite response times and minimize Total Harmonic Distortion (THD) in PLTMH outputs [11]. The simulation outcomes indicated notable improvements in the response times and reductions in THD with the implementation of these control techniques. Ari Rahyuningtyas and colleagues [12] delved into load regulation systems within PLTMH, striving to uphold electrical voltage and frequency stability. This system proactively adjusts to load variations, ensuring consistent loading of the turbines and generators to maintain the system equilibrium.

Muhammad Prambudi's team introduced the PID-GA and PID-PSO methods, aiming to enhance the frequency and voltage quality in power generation systems [13]. Testing of these methods demonstrated their effectiveness in sustaining the frequency and voltage stability of the PLTMH under fluctuating loads. Srikanta et al. explored the integration of fuzzy PID controllers combined with the L-CSA algorithm in power systems, successfully ensuring the frequency and power stability of connection lines, even under uncertain conditions. Syarifudin Nojeng [14] underscored the critical role of optimal load shutdown as an immediate strategy to boost transient stability in electrical power systems, particularly in stabilizing synchronous generators. These studies collectively underscore the advancement of novel control methodologies for maintaining frequency and voltage stability in power generation systems. This is particularly relevant in micro-hydropower contexts, as it ensures optimal performance with significant load variations. Ningsih et al. developed a micro-hydro-frequency and voltage stabilization control system [15]. This system utilizes a rotating generator to deliver voltage to the primary load. Voltage sensors relay information to a microcontroller via an Analog-to-Digital Converter (ADC), triggering a proportional-integral-derivative (PID) algorithm that feeds it into a Pulse-Width Modulation (PWM) unit. The PWM then directs the pulse signals to a dummy load-control circuit, acting as a switch. To maintain the generator voltage at 220 Vac, the system responds to the voltage fluctuations detected by the sensors, with the microcontroller interpreting this data and the PID algorithm minimizing errors before informing the PWM. PWM regulates dummy load. This dummy load balances the primary load, ensuring that the generator operates at 220 Vac. The ability of the system to maintain a generator voltage of 220 Vac and frequency of 50 Hz under varying dummy load conditions was confirmed by measurements. Furthermore, the adoption of an Induction Generator Controller (IGC) and a Dspic 30f4012 microcontroller enables automatic control of the generator. This study also highlighted that electronic load control can significantly reduce damage resulting from unstable frequency outputs in the distribution system [16].

B. VOLTAGE STABILITY

Voltage stability is defined as the ability of an electrical system to maintain a constant voltage at all busbars within the system under normal operating conditions and after disturbances. It must comply with established standards [17]. A system is considered to be voltage-unstable when faults occur, load demand increases, or system conditions change, leading to a gradual and uncontrolled decrease in voltage. The primary factor contributing to instability is the inability of the power system to satisfy the reactive power requirements. The core issue often lies in the voltage drop that occurs as active and reactive power flow through inductive resistors in the transmission network. Control of the voltage and system power will always be maintained if a stable voltage is maintained. The main factor that causes voltage instability is the limited capability of the transmission network to transmit power [18]. As some generators reach their reactive power limits, power transmission becomes increasingly restricted. Load is the primary cause of voltage instability. The distribution voltage regulators and additional load transformers are expected to mitigate these disturbances and restore the power consumed by the load. Load restoration increases the pressure on the high-voltage network, leading to greater voltage dissipation. This results in a voltage instability. Frequency stability refers to a system's ability to maintain the frequency within a predetermined range and to comply with standards [19]. Frequency stability can be influenced by the load shedding or disconnection of the generators in the system. Frequency instability can lead to load shedding and even cause generators to become unsynchronized in the system [20].

C. ANALYSIS OF VOLTAGE INSTABILITY AT PEAK LOAD

Voltage and frequency stability analysis involves periodic measurements and recording of voltage and frequency values according to a predefined schedule, typically hourly during peak-load conditions [21]. This process aims to capture changes in the voltage and frequency values, thereby facilitating the generation of graphical representations. The recorded values correspond to the voltage and frequency when the generator is under load, allowing the assessment of load-induced impacts on voltage and frequency variations. Notably, the standards set by the power utility (PLN) specify tolerances for voltage fluctuations, ranging from -10% to +5% of the nominal voltage of 220 V. These tolerances ensure that the voltage remains within an acceptable range of 198–231 V [22]. Voltage, also known as the potential difference (V), represents the effort required to move the charge from one component terminal to another. It can be conceptualized as the energy per unit charge released as a result of the actual work performed. Voltage stability issues, which lead to voltage collapse in the power system, can occur because of sudden load increases exceeding the capacity of the system or tripping of a generator unit. The voltage drops, known as voltage regulation, is determined by the difference between the sending and receiving end voltages, and is influenced by the impedance and admittance of the transmission line, load, and power factor. Effective voltage regulation is crucial in power systems, and involves adjustments at the substation, transmission lines, and generation levels to maintain voltage stability [23].

D. FREQUENCY INSTABILITY ANALYSIS OF THE PEAK LOAD

Frequency is defined as the number of cycles per second, and in the context of electrical systems, it represents the quantity of electrical waves in seconds. The electrical frequency is a crucial parameter in electrical wave analysis and significantly influences the performance of an electrical system. Changes in frequency can have a substantial impact on certain devices, with one consequence being the instability of electric motor rotations, which is a critical driver in industrial production machinery. Frequency instability, particularly a drastic decrease, can lead to complete system blackout [24]. A strategy for anticipating a potentially drastic frequency drop involves shedding a portion of the load carried by the system. Releasing part of the load reduces the burden on the operating power generators, restoring the frequency to normal once a balance is achieved between generation and load. Load shedding must be promptly executed when the frequency of the system begins to decrease significantly. According to IEEE standards, the permissible frequency deviation is ±1% from the standard frequency, which is 50 Hz in Indonesia. The SPLN frequency standards in Indonesia aim not to fall below 49.5 Hz or exceed 50.5 Hz. In emergency situations and disturbance scenarios, the allowable frequency tolerance ranges from a decrease to 47.5 Hz and an increase to 52 Hz.

III. METHOD

The methodology employed in this study was observational and did not influence the variables under investigation. Rather, it serves the purpose of recording and observing the measured data. This research entails the collection of data concerning the rotational speed of the generator, voltage, frequency, and load on each phase, R, S, and T. The data utilized in this study are quantitative in nature, involving numerical figures, such as load measurements on each phase R, S, and T, and subsequent data processing. Upon data acquisition, a data processing procedure was initiated to derive conclusions from the results of the data analysis. The daily load of a micro-hydropower plant (PLTMH) or consumers encompasses the load of consumers within Renah Kemumu Village, Merangin Regency, Jambi Province. The village comprises 81 houses, one mosque, and one building used for weddings and customary events.

The analysis of the daily load was conducted during peak load hours, occurring between approximately 18:00 and 21:00. During this timeframe, residents heavily utilize electricity for cooking, washing, ironing, watching television, and other activities. Normal load conditions prevailed from 21:00 to 08:00 WIB. The PLTMH in Renah Kemumu Village operates solely from 21:00 to 8:00 WIB. Flow chart diagram for this study are figure 1

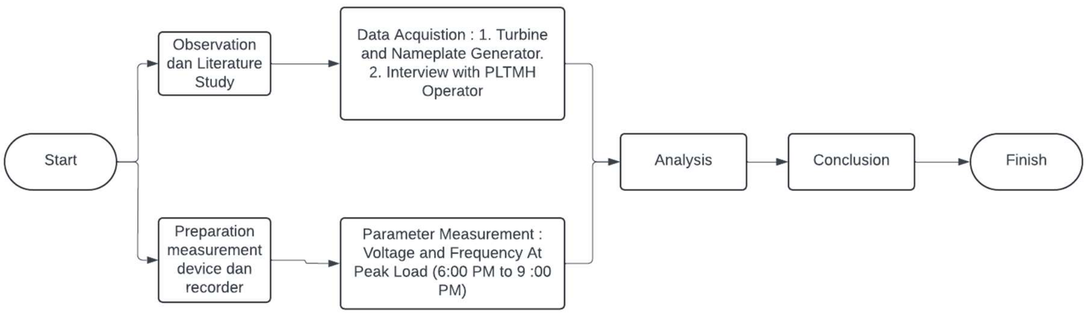

Figure 1. Flow Chart Diagram Methods of this study

IV. RESULT AND DISCUSSION

A. SPECIFICATION

The system employs two crossflow turbines capable of operating effectively within a head range of 5–200 m and processing flow rates ranging from 0.03 to 16 m3/s.

TABLE I
SPECIFICATION MICRO HYDRO

Parameter	Specification
Turbine Type	Crossflow
Number of Turbines	Two
Head Range	5-200 meters
Flow Rate	0.03-16 m^3/s
Capacity	10-7000 kW
Turbine Efficiency	84%
Generator Type	Synchronous Generator
Model	S274G100B3
Voltage	380 V
Phase	3 Phase
Field Voltage	37.8 V
Number of Poles	4 Poles
Rotational Speed	50Hz - 1500 rpm
Power Factor	0.8
Frequency	50 Hz
Excitation Current	9.5 A

With a capacity ranging from 10 kW to 7000 kW, the crossflow turbines exhibited an efficiency of 84%, illustrating their proficiency in converting water energy into electrical power. The synchronous generator, model S274G100B3, operates at 380 V in three phases, a field voltage of 37.8 V, and features four poles rotating at speeds ranging from 50 Hz to 1500 rpm. In addition, the generator maintained a power factor of 0.8, operated at a frequency of 50 Hz and required an excitation current of 9.5 A. This detailed analysis enhances the understanding of the operational and technical characteristics of crossflow hydroelectric power generation components, aiding the optimization of system performance for increased efficiency and productivity, as shown in Table 1.

B. VOLTAGE ANALYSIS AT PEAK LOAD

In Figure 2, there is a visual representation of three-phase voltage data measured over a one-month period at peak load, namely between 18.00 and 21.00. The three voltage channels, R, S, and T, exhibit significant voltage distribution characteristics. In the R channel, the median voltage recorded was 245 V, with the lower quartile (Q1) at 240 V and upper quartile (Q3) at 250 V. The interquartile ranges (IQR) reached 10. The S channel showed a median of 248 V, Q1 245 V, Q3 252 V, and IQR 7 V. Channel T has a median of 243 V, Q1 240 V, Q3 245 V, and IQR 5 V. The whiskers on each channel expanded until they reached the maximum and minimum values, with some outliers appearing as isolated points, indicating significant deviations from the main stress distribution. This analysis provides a deep understanding of stress variations and potential anomalies during peak load periods.

Examining the percentage of voltage increase during peak loads in the initial week, the highest and lowest increases were observed at 30.92% and 21.74%, respectively. In the second week, these percentages fluctuated between 30.92% and 14.92%, respectively. The third week witnessed a range of 32.64% to 21.74% in voltage increase, whereas the fourth week showed variations between 30.92% and 21.74%. According to (State Electricity Company of Indonesia) standards, the permissible deviation from the standard frequency of 50 Hz is ± 1 %. Consequently, frequencies should ideally not fall below 49.5 Hz or exceed 50.5 Hz.

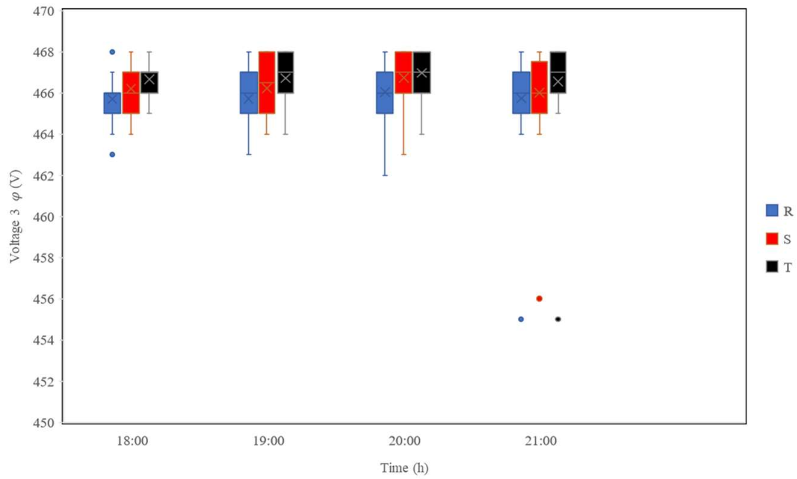

Figure 2. PLTMH voltage during peak load (18.00 to 21.00) in the span of 1 month

However, at the micro hydropower plant (PLTMH) in Renah Kemumu Village, the frequency variations during peak loads deviated significantly from the standard voltage allowed by the National Electricity Company (PLN). The highest and lowest frequency increases were 32.64% and 14.92%, respectively. These variations in the PLTMH of Renah Kemumu Village represent significant deviations from the SPLN standard, exceeding the allowed tolerance limits for frequency changes.

C. FREQUENCY ANALYSIS AT PEAK LOAD

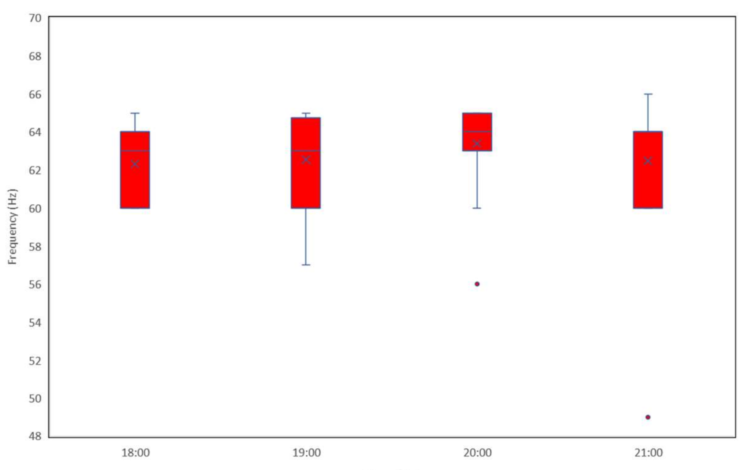

Figure 3. PLTMH frequency during peak load (18.00 to 21.00) within 1 month

Figure 3 shows a box plot representing the frequency data over time during peak load hours from 18:00 to 21:00, collected over a month. The horizontal axis is labeled "Times (h)" and marks the time slots at 18:00, 19:00, 20:00, and 21:00. The vertical axis is labeled "Frequency (Hz)" and shows a range from approximately 48 Hz to 70 Hz.

Each box plot represents data for one of the hours mentioned, with the central box depicting the interquartile range (IQR), which contains the middle 50% of the data. The line inside the box indicates the median frequency, and the 'X' within the box denotes the mean frequency. The whiskers extend from the top and bottom of the box to the highest and lowest values within 1.5 times the IQR from the upper and lower quartiles, respectively. Points outside this range are considered outliers, and are represented by dots.

Comparing the observed frequencies with the standard frequency range permitted by the Indonesian electricity company PLN (49.5 Hz to 50.5 Hz), it is clear that the values are significantly higher than the standard range. This could indicate an over-frequency condition, which may suggest that the power system is experiencing a lower load than anticipated, or that there is an excess of generation relative to demand. It is important to maintain the frequency within prescribed standards to ensure the stability and reliability of the power grid. Deviations from this range can lead to equipment damage and operational inefficiency.

D. ANALYSIS

This research identified several factors contributing to voltage and frequency instability in the micro hydropower plant (PLTMH) of Renah Kemumu Village. The primary cause of this instability is the fluctuating water flow controlled by the operator, which affects the turbine rotation, leading to high generator speeds, and consequently, high voltage and frequency outputs. Additional factors include the constantly changing load currents and rainy weather conditions. These variable load currents result in inconsistent generator rotations, which destabilize the generated voltage and frequency.

Specifically, voltage instability during the peak load periods was noted, with the highest and lowest voltages recorded at 270 V and 264 V, respectively, and the highest and lowest percentage increases from the standard voltage of 22.72% and 20.45%, respectively. The highest and lowest observed frequencies were 66.32 Hz and 57.46 Hz. with the percentage increasing from the standard frequency to 30.92% and 14.92%, respectively. These measurements and data analyses indicate that the voltage and frequency levels at PLTMH in Renah Kemumu Village during peak loads are not in accordance with the standards and exceed the tolerance limits allowed by (State Electricity Company of Indonesia)

V. CONCLUSION

This research identified several factors contributing to voltage and frequency instability in the micro hydropower plant (PLTMH) of Renah Kemumu Village. The primary cause of this instability is the fluctuating water flow controlled by the operator, which affects the turbine rotation, leading to high generator speeds, and consequently, high voltage and frequency outputs. Additional factors include the constantly changing load currents and rainy weather conditions. These variable load currents result in inconsistent generator rotations, which destabilize the generated voltage and frequency. Specifically, voltage instability during the peak load periods was noted, with the highest and lowest voltages recorded at 270 V and 264 V, respectively, and the highest and lowest percentage increases from the standard voltage of 22.72% and 20.45%, respectively. The highest and lowest observed frequencies were 66.32 Hz and 57.46 Hz. with the percentage increasing from the standard frequency to 30.92% and 14.92%, respectively. These measurements and data analyses indicate that the voltage and frequency levels at PLTMH in Renah Kemumu Village during peak loads are not in accordance with the standards and exceed the tolerance limits allowed by the State Electricity Company of Indonesia.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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