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Voltage Regulation and Power Loss Analysis on 500 kV EHV Transmission Line Krian-Grati

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Abstract— The transmission system distributes electricity from power plants to substations before reaching consumers. During this process, obstacles such as power loss and voltage regulation occur, which must meet specific standards to prevent equipment damage. Power loss can result from factors like corona effects and insulator leakage. This study aims to analyze power loss and voltage regulation based on daily peak load data at 14:00 over 15 days, recording current and voltage values on the extra-high voltage Krian-Grati transmission network. This system uses ACSR Gannet conductors with a cross-sectional area of 392.84 mm² and a length of 79.41 km, having a resistance of 0.00086 Ω/km. Manual calculations for short transmission lines show a voltage difference between sending and receiving ends, with the sending voltage being slightly higher due to reactance, preventing a drastic voltage drop. Over 15 days in December 2024, voltage regulation did not exceed the standard maximum of <10%, with the highest recorded value at 4.7%. The highest power loss occurred on day 7 at 0.089 MW, while the lowest was on day 9 at 0.023 MW. The total power loss over 15 days reached 1.024 MW, with a daily average of 0.068 MW.

Keywords: Extra High Voltage Main Substation, Power Loss, Transmission Lines, Voltage Regulation

INTRODUCTION

The Krian-Grati transmission network faces various challenges related to efficiency and power losses. One of the main issues is overloading and network congestion, which result in increased current in the conductors and amplifies resistive power losses [1]. When the network is overloaded, more energy is lost in the form of heat, leading to a decrease in system efficiency. Additionally, power congestion may require power to be rerouted through longer or suboptimal paths, further increasing transmission losses [2]-[3]. The relatively long transmission distance in the Krian-Grati network also affects efficiency. The longer the transmission line, the higher the network impedance, leading to greater power losses. In transmission systems, power losses can reach 2-10% of the total transmitted power, depending on network conditions and load [4]-[6]. Beyond distance, load fluctuations and

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voltage disturbances can also reduce efficiency. Unstable loads can affect the system voltage, increasing reactive current and amplifying losses. Frequent voltage disturbances can cause equipment to operate outside optimal conditions, ultimately increasing reactive power consumption [7].

In the calculation of power losses in the transmission network, factors such as the length of the line, wire type, and the spacing between wires on the spacer play a significant role. The resistance of the wire for the transmission line is also influenced by the length of the transmission line, leading to increased power losses as the line length increases. Furthermore, the spacing between wires on the spacer determines the line impedance, which affects the distribution of current and voltage along the transmission line [8]. The greater the spacing between wires, the higher the capacity of the line to transmit power, but excessive spacing can increase reactive power losses. Therefore, selecting the appropriate wire type and designing efficient spacers is crucial in minimizing power losses. Transmission lines that use wires with low resistance, such as copper or better copper alloys, will reduce power losses. On the other hand, optimal wire spacing on the spacer can help reduce excessive current distribution, thereby alleviating the load on conductors and improving transmission efficiency [9].

A number of previous researchers have conducted studies related to voltage regulation and power loss analysis which are closely related to this research topic. The research carried out by Anggoro [10] and his team aims to determine power losses and voltage drops on short transmission lines with a length of 21.55 km. The method used is manual calculation and simulation using ETAP software. The research results show a comparison between manual calculations and the ETAP 12.6.0 simulation, with a difference in power loss calculations of 2.5% and a difference in manual working voltage loss calculations of 1.96% compared to ETAP results of 1.42%. Power losses in the Pati to Jekulo main substation transmission network increased to 6.8%, exceeding the service percentage limit according to PLN Standard (SPLN) No. 72 of 1987 with a maximum limit of +5% and a minimum of -10%. Devyanti [11] carried out an analysis of power losses on the short transmission line between the Waru and Sidoarjo main substations with a distance of 19,913 km. The method used is manual calculation and simulation using ETAP software. The research results show a comparison between simulation results and manual calculations with a difference of 6.04%. In Siregar's research [12], researchers used the Newton-Raphson method to calculate power losses. The calculation results using this method are compared with the reference standards used by PT. PLN (Persero), shows power loss values of 2.664% and 3.570% which are still within safe limits according to PLN Standard (SPLN) No. 1 of 1995, with a standard limit of 10% to avoid excessive voltage.

Based on previous research, the author plans to develop research regarding voltage regulation and analysis of power losses in transmission lines. Energy losses must be analyzed so that they do not exceed the limits set by PLN Standards (SPLN). A shortage of electricity supply in the area could lead to low voltage and, in the worst-case scenario, a power outage. In this research, the object that will be researched is to analyze a 79.41 km long underground transmission line to regulate strain and power losses using manual calculation methods. This research is expected to provide a significant contribution to the development of a more efficient and reliable electricity transmission system.

METHOD

This research was conducted at PT. PLN (Persero) UPG ULTG Krian, 500 kV Malang Extra High Voltage Main Substation, especially on the 500 kV Extra High Voltage Grati-Krian transmission line. The initial approach involves a literature study regarding power losses and voltage drops between the substation and the load. The main objective of this research is to calculate the increase in power losses that occur due to voltage drops in 500 kV transmission lines. The method used involves collecting daily data for 15 days during peak hours at 2:00 PM. The data was collected at this specific time, coinciding with the peak load period in the industrial area, to evaluate the impact of rising ambient temperatures on power losses in the Krian-Grati transmission network. This time was specifically selected to observe how temperature variations influence power loss under peak demand conditions, providing valuable insights into the network's performance in such scenarios. Data collection was carried out at the 500 kV Extra High Voltage Main Substation Krian using a control panel equipped with devices to facilitate reading of current, voltage and electrical power without the need to carry out manual measurements. This control panel has an important role in recording the data. The object of this research is the Bay Line Grati 500 kV Transmission Line, with a length of 79.41 km. This channel uses GANNET ACSR (Aluminum Conductor Steel Reinforce) cable with a cross-section of 392.84 mm², diameter of 25.76 mm, weight of 1.365 kg/km, and a resistance value of 0.008 Ω/km [13].

A. Short Distance Transmission Lines

Short transmission lines are less than 80 km long. In this type of line, the leakage current to ground is very small compared to the load current, so the capacitance effect can be ignored. Short transmission lines are often used to connect power plants to regional distribution networks or to connect adjacent substations. Because the distance is relatively short, power losses and voltage drops are generally minimal, so voltage regulation is not too complicated. However, managing short transmission lines still requires special attention to ensure operational efficiency and overall system reliability.

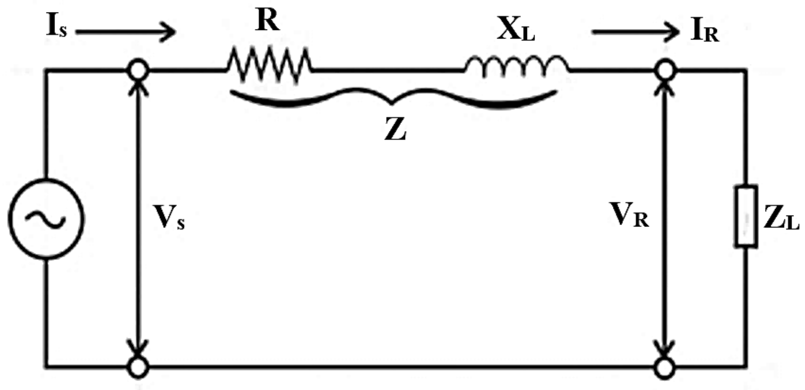

Figure 1. Equivalent Circuit for Short Transmission Lines [14]

B. Calculation of Line Impedance Values

To calculate the impedance value of a conductor, the first step that needs to be taken is to find the resistance value of the conductor. This is a crucial step as resistance plays a significant role in determining the overall impedance. By understanding the resistance, we can move forward with the impedance calculation with greater accuracy and confidence. The formula used to calculate resistance is as follows [15]:

$$R_{total}(ACSR) = R \times l \quad (1)$$

Where,

$R_{total}(ACSR)$ = Total Resistance (ohm)

R = Individual Resistance (ohm/km)

l = Transmission length (km)

The GMD (Geometric Mean Distance) value is the average distance between the geometric radius or curved radius. These two values can be calculated using the following formula [16]:

$$GMD = \sqrt[12]{d_{12}d_{13}d_{15}d_{16}d_{23}d_{26}d_{34}d_{35}d_{45}d_{45}d_{46}d_{56}} \tag{2}$$

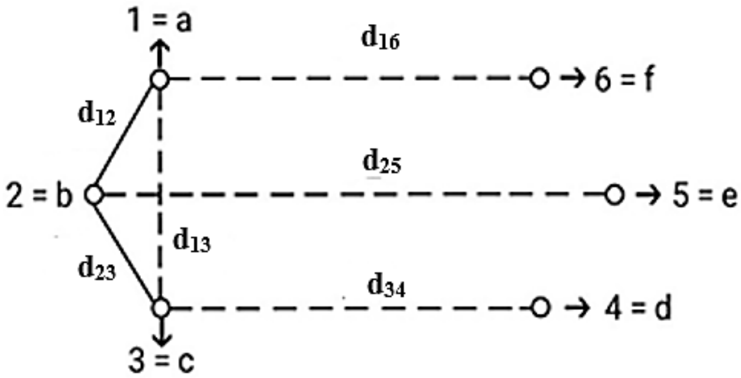

Figure 2. Double circuit lattice tower specifications

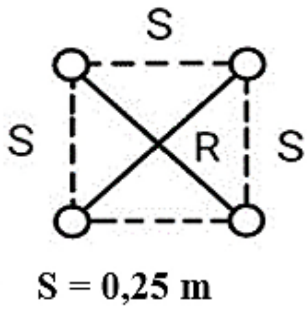

Figure 3. Spacer on 500 kV conductor

Then, calculate the r_1' value (geometric average radius) by calculating the distance data on the 500 kV conductor according to the following equation [16]:

$$R = \frac{S}{\sqrt{2}} \tag{3}$$

Where,

R = Spacer radius (m)

S = Distance between conductors (m)

After knowing the R value on the conductor spacer, then calculate the r_1' value using the following equation [16]:

$$r_1' = R.e^{\frac{1}{4}} \tag{4}$$

Once the r_1' value is known, then calculate the GMR value using the following equation [16]:

$$GMR = \sqrt[6]{(r_1')^3 \ x \ d_{14} d_{25} d_{36}} \tag{5}$$

After knowing the GMD (Geometric Mean Distance) and GMR (Geometric Mean Radius) values, the next step before calculating the line's impedance value is to determine the ACSR (Aluminum Conductor Steel Reinforced) Gannet inductive reactance value. The inductive reactance value can be calculated using the following formula [16]:

$$X_L = 0.14467 \ log \ \frac{GMD}{GMR} \tag{6}$$

After determining the X_L (inductive reactance) value then the impedance value can be calculated using the following formula [16]:

$$Z = \sqrt{R^2 + (X_L)^2} \tag{7}$$

C. Voltage Regulation Calculations

Data from impedance calculations is used to calculate various electrical parameters such as the voltage at the reception point, voltage drop, power losses, and received power. These parameters are critical for understanding the efficiency and performance of electrical systems. By accurately calculating impedance, engineers can predict and optimize the behavior of electrical circuits. The formula used for these calculations is as follows:

Voltage Receive (V_R)

Calculate the received voltage using the following formula:

$$V_R = \frac{V_{R\,(line)}}{\sqrt{3}} \tag{8}$$

Where,

V_R = Voltage received (Volt)

$V_{R\,(line)}$ = Voltage received phase-phase (Volt)

After knowing the receiving voltage value, a calculation is carried out to determine the sending voltage value on the extra high voltage main substation Krian-Grati transmission line according to the following equation [17]:

$$V_S = V_R + IZ \tag{9}$$

Where,

V_S = Voltage sent (Volt)

V_R = Voltage received (Volt)

I = Lines Current (Ampere)

Z = Lines Impedance (Ohm)

To calculate the rate of drop voltage that occurs on the extra high voltage main substation Krian-Grati transmission line, careful and accurate calculations are required. The voltage drop is the difference between the initial voltage at the source and the voltage received at the end of the line. Understanding these voltage drops is critical to ensuring the efficiency and reliability of electrical transmission systems. The voltage drop can be calculated using the following equation [17]:

$$\Delta V = \left|\frac{Vs - Vr}{Vs}\right| x100\% \quad (10)$$

Where,

ΔV = Voltage Regulation

V_S = Voltage sent (Volt)

V_R = Voltage received (Volt)

D. Power Loss on Transmission Lines

Power losses are the difference between the power sent and the power received, namely the power lost due to resistance in the transmission line. Power losses occur in each phase (R, S, T) of the channel, and the magnitude of the power loss value in each phase can vary. To calculate the power losses that occur in a transmission line, the first step is to find the line resistance value. Calculation of power losses on transmission lines can be expressed with the following equation [18]:

$$P_{Losses} = I^2 . R_{total} \quad (11)$$

Where,

P_{Losses} = Power losses (Watt)

I = Current lines (Ampere)

R = Total Impedance (Ω)

Then, to understand the three-phase power losses, you can use the equation [19]:

$$P_{Losses}RST = P_{Losses}R + P_{Losses}S + P_{Losses}T \quad (12)$$

So that the sending power on the transmission network [20]:

$$P_S = P_R + P_{Losses} \quad (13)$$

Where,

P_S = Sending power (Watt)

P_R = Received power (Watt)

P_{Losses} = Losses power (Watt)

RESULT AND DISCUSSION

The Krian–Grati transmission line is a short distance transmission line, namely less than 80 km. The observation data is used to calculate the amount of power loss in the conductor wire, delivery power and voltage regulation. Transmission lines consist of a set of conductors that carry electrical energy and transmit it from the generating center to the substation. The conductors of the transmission line are hung on insulators that are attached to the tower arms.

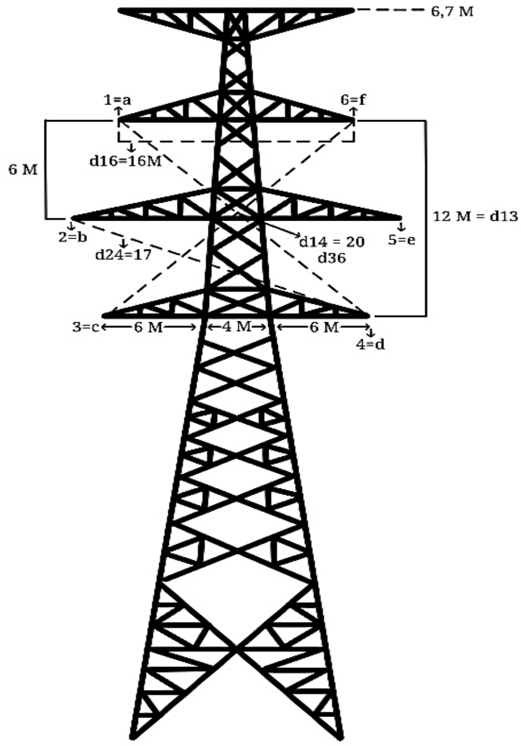

Figure 4. Double circuit transmission tower on the 500 kV Krian-Grati lines

Table 1. Conductor Parameters in Krian-Grati Transmission

Parameter	**Value**
R (Resistance)	0.00086 ohm/km
l (Transmission Length)	79.41 km
Frequency	50 Hz
Conductor Diameter	25.76 mm^2

Table 2. Double Circuit Geometry on Transmission Towers

Parameter	**Length (m)**
$d_{12}, d_{23}, d_{45}, d_{56}$	8
d_{13}, d_{46}	12
d_{14}, d_{36}	20
$d_{15}, d_{24}, d_{26}, d_{35}$	17
d_{25}	16
d_{16}, d_{34}	16

A. Determining Inductive Reactance

To calculate the power loss that occurs in a conductor, the resistance value must first be found. By using equation (1), the total resistance can be calculated on the Krian-Grati transmission line as follows:

$$R_{total}(ACSR) = R \times l$$

$$R_{total}(ACSR) = 0.00086\ \Omega/\text{km}\ \times 79.41\ \text{km}$$

$$R_{total}(ACSR) = 0.068\ \Omega$$

After determining the total resistance of the channel, then calculate the GMD (Geometric Mean Distance) value. GMD (Geometric Mean Distance) is an important parameter in calculating inductance and capacitance in electrical transmission systems. The GMD value is used to determine the inductive effect of a conductor that has several conductors. To determine the GMD value, the steps to determine the GMD are as follows:

$$\mathrm{GMD} = \sqrt[12]{d_{12}d_{13}d_{15}d_{16}d_{23}d_{26}d_{34}d_{35}d_{45}d_{45}d_{46}d_{56}}$$

$$GMD = \sqrt[12]{8 \times 12 \times 17 \times 16 \times 8 \times 17 \times 17 \times 16 \times 17 \times 8 \times 12 \times 8}$$

GMD = 12.35 m

Before calculating the GMR, the first thing to look for is r_1' by finding the 500 kV conductor spacer distance using equation (3). By looking at Figure 3, the r_1' value is obtained as follows.

$$R = \frac{S}{\sqrt{2}}$$

$$R = \frac{0.25}{\sqrt{2}} \times \frac{\sqrt{2}}{\sqrt{2}} = 0.175 \text{ m}$$

After the R value is calculated, then calculate the r_1' value using equation (4) as follows:

$$r_1' = R \cdot e^{\frac{1}{4}}$$

$$r_1' = 0.175 \cdot e^{\frac{1}{4}} = 0.136 \text{ m}$$

By using equation (5), it can be done to find the GMR value as follows:

$$GMR = \sqrt[6]{(r_1')^3 \times d_{14}d_{25}d_{36}}$$

$$GMR = \sqrt[6]{(0.136)^3 \times 20 \times 16 \times 20} = 1{,}59 \text{ m}$$

After knowing the GMD and GMR values, the inductive reactance value is then calculated. By using equation (6), calculations can then be carried out to find the channel inductance and inductive reactance values as follows.

$$\mathrm{X_L} = 0.14467 \log \frac{\mathrm{GMD}}{\mathrm{GMR}}$$

$$\mathrm{X_L} = 0.14467 \log \frac{12.35}{1.59} = 0.128\,\Omega$$

B. Analysis of Power Losses on the Transmission Lines

Once the total resistance value is known, the next step is to calculate the power losses for each R-S-T phase on the Krian-Grati extra high voltage transmission network. Mathematically using equation (11) – (12) as follows:

$$P_{Losses}\, R = (591)^2 A \times 0.068\,\Omega = 0.02 \text{ MW}$$

$$P_{Losses}\, S = (574)^2\, A \times 0.068\,\Omega = 0.02\, MW$$

$$P_{Losses}\, T = (584)^2\, A \times 0.068\,\Omega = 0.03\, MW$$

After calculating the power losses on each R, S and T phase for 15 days in December 2024 from data taken every 14:00 WIB and obtaining the results of the losses for each phase, a calculation was carried out to find the power losses for the three phases. By using formula (13), it is possible to calculate three-phase power losses for 15 days in December 2024 on the Bay Line Grati transmission line as follows:

$$P_{Losses}RST = 0.023\ MW + 0.022\ MW + 0.023\ MW$$

$$P_{Losses}RST = 0.069\ MW$$

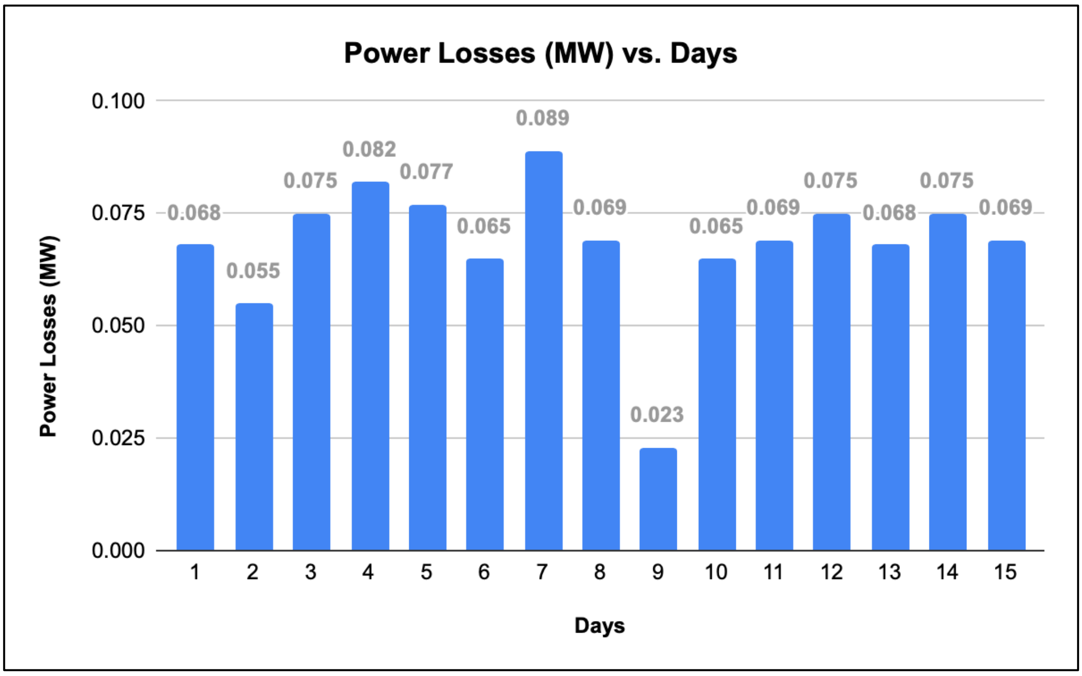

Figure 5. Power Losses on Krian-Grati Transmission

In Figure 5, there is data showing the number of losses that occurred on the Krian-Grati transmission line during a 15 days period in December 2024. Analysis of this graph illustrates significant fluctuations in the level of losses during this observation period. For example, on the 7th day, losses reached their peak with a value of 0.089 MW, while on the 9th day, the lowest losses were recorded with a value of 0.023 MW. These variations may be caused by various factors such as changing weather conditions, network load fluctuations, or other technical factors that affect transmission line operations. A deep understanding of patterns like this can provide valuable insight for system improvements and increased operational efficiency in managing losses on energy transmission lines in the future.

The fluctuating power loss in the Krian-Grati transmission is primarily caused by the length of the transmission line and load fluctuations. The relatively long transmission network results in higher impedance, which directly increases power loss as the line distance increases. As the transmission line lengthens, the resistance encountered by the current increases, leading to higher power loss. Additionally, load fluctuations in the system play a significant role in causing variations in power loss. When the load on the network is unstable, the current flowing through the system changes suddenly, increasing resistive losses. These load fluctuations often lead to higher currents, which in turn increase power losses in the form of heat, further reducing transmission efficiency. Both factors, the length of the transmission line and load fluctuations, interact with each other, resulting in inconsistent power loss in the Krian-Grati transmission network.

C. Analysis of Voltage Regulation on the Transmission Lines

Voltage regulation on the line can be defined as the increase in voltage when the full load is removed. Essentially, it refers to the ability of a power system to maintain a constant voltage level despite changes in load conditions. This characteristic is crucial because it ensures that electrical equipment receives a stable and adequate voltage supply, which is essential for the proper functioning and longevity of the equipment. Voltage regulation plays an important role in ensuring that the voltage supplied to various electrical devices and systems remains within safe limits and adheres to the standards set by regulatory bodies. These standards are designed to protect both the equipment and the users from the potential hazards associated with voltage fluctuations. By maintaining the voltage within these prescribed limits, voltage regulation helps to minimize the risk of damage to electrical components, which can be caused by either overvoltage or undervoltage conditions. The initial step in determining voltage regulation is to calculate the total impedance value using equation (7).

$$Z = \sqrt{R^2 + (X_L)^2}$$
$$Z = \sqrt{(0.068)^2 + (0.128)^2} = 0.165\ \Omega$$
$$Z_{real} = \frac{0.145}{4} = 0.066\ \Omega$$

Once the impedance and receive voltage values are known, the next step is to find the send voltage value using equation (9) as follows:

$$V_s = V_R + IZ$$
$$V_s = 487 + (583 \times 0.036) = 698\ \text{kV}$$

To find out the percentage of voltage regulation that occurs on the Krian-Grati transmission line, the voltage regulation can be calculated using equation (10) as follows:

$$\Delta V = \left|\frac{Vs-Vr}{Vs}\right| x100\%$$
$$\Delta V = \left|\frac{508-487}{508}\right| x100\% = 4.1\%$$

Table 3. Voltage Regulation on Krian-Grati Transmission

Days	Sent Voltage (kV)	Received Voltage (kV)	Voltage Regulation ΔV (%)
1	508	487	4.1
2	503	485	3.6
3	508	486	4.3
4	506	483	4.3
5	507	485	4.3
6	509	488	4.1
7	511	487	4.7
8	511	490	4.1
9	498	486	2.4
10	502	481	4.2
11	506	485	4.1
12	505	483	4.3
13	508	487	4.1
14	510	488	4.3
15	505	484	4.1

After calculating the Sent Voltage and Received Voltage, the voltage regulation calculation is carried out. This involves determining the difference between the voltage levels at the sending and receiving ends of the transmission line and expressing it as a percentage of the sending end voltage. By performing these calculations, we can gain insights into the efficiency and stability of the power transmission system, identifying any significant deviations that might indicate potential issues. Next, a graph of the results of the voltage regulation data on the Krian-Grati transmission line for December 2024 is obtained as follows.

The graph visually represents the daily variations in voltage regulation over the course of the month, providing a clear picture of how the system performed during this period. By analyzing this graph, we can observe trends, identify peak values, and assess the overall stability of the transmission line. This graphical representation is crucial for making informed decisions about maintenance, improvements, and interventions needed to ensure optimal performance and reliability of the power transmission system.

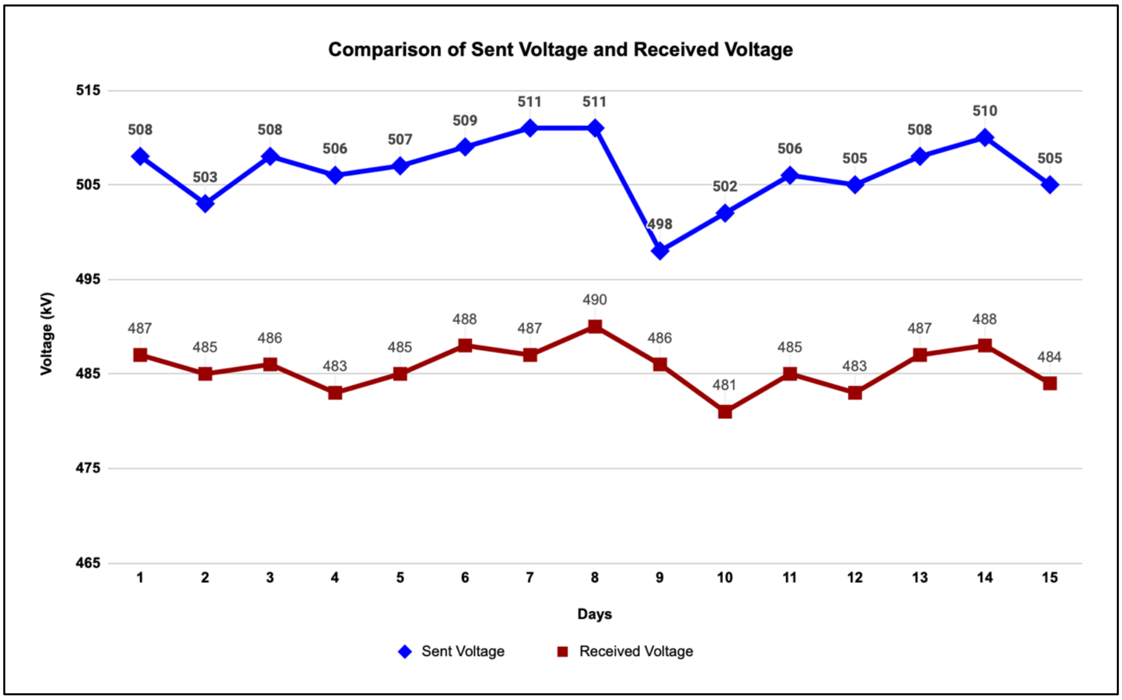

Figure 6. Comparison of the Values of Sent and Received Voltage

Figure 6 shows the sending voltage on the Krian-Grati transmission line for 15 days in December 2024. The figure shows that the lowest sending voltage occurred on the 9th day with a value of 498 kV, while the highest sending voltage occurred on the 7th day and the 8th day with a value of 511 kV. Likewise, the receiving voltage is the same as the sending voltage, where the lowest receiving voltage occurs on the 10th day with a value of 481 kV.

The difference between the sending-end and receiving-end voltage in the Krian-Grati transmission line can be analyzed by considering several interacting technical factors. One of the primary causes is the impedance of the transmission line, which leads to a voltage drop along the line. As the length of the transmission line increases, the resistance and reactance that the current must pass through also increase, resulting in a more significant voltage drop at the receiving end. Additionally, power loss due to the resistance of the line contributes to this phenomenon, as energy lost in the form of heat reduces the amount of energy reaching the receiving end, causing a lower receiving voltage compared to the sending voltage. Furthermore, load variations on the receiving side play a crucial role in the extent of the voltage drop, where higher loads lead to a more pronounced reduction in voltage.

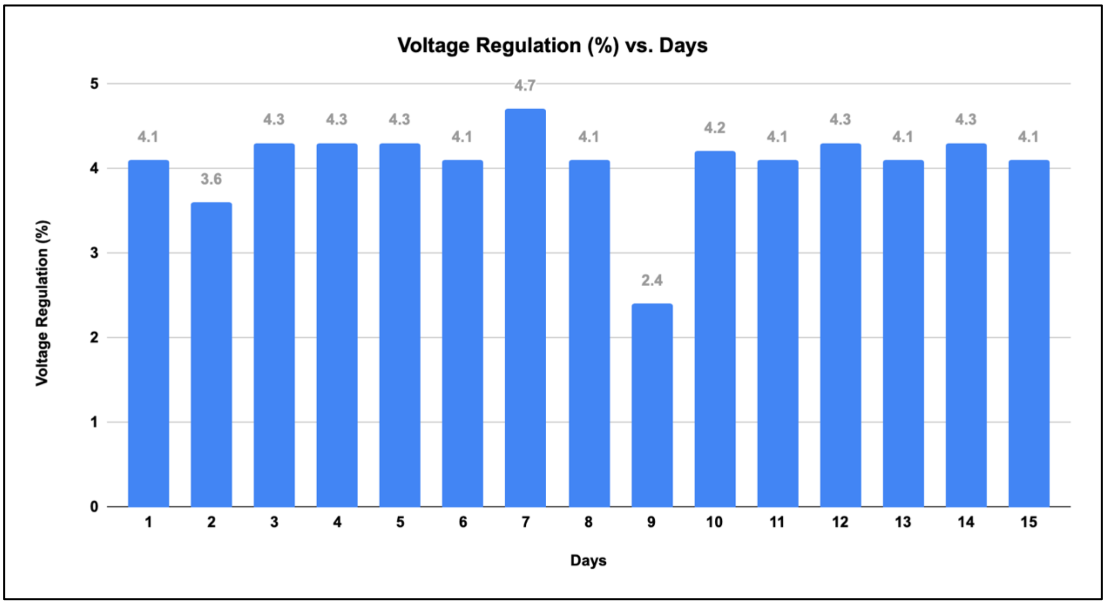

Figure 7. Voltage regulation on the Krian-Grati Transmission

Figure 7 shows that the percentage of voltage regulation on the Krian-Grati transmission line during December 2024 is 15 days. This indicates that for half of the month, the voltage regulation experienced variations that deviated from the norm. These results show that the percentage of voltage regulation can still be tolerated, as the maximum safe limit for voltage regulation is 10%. Although the observed percentage is within an acceptable range, it is important to monitor and manage voltage regulation closely to ensure it remains within the safe limit to prevent potential issues.

To minimize power losses in the Krian-Grati transmission network, several practical measures can be implemented. One of the most effective approaches is improving the quality of transmission lines by utilizing high-conductivity materials such as high-grade aluminum or copper, which can significantly reduce resistance and associated losses. Additionally, operating the transmission system at higher voltages helps decrease power loss, as higher voltage levels reduce the current required for the same power transfer, thereby minimizing resistive losses. The installation of transformers and proper voltage regulation at both ends of the transmission line can also enhance efficiency by ensuring stable voltage levels and mitigating unnecessary fluctuations.

Furthermore, managing load distribution effectively by preventing overloading and implementing automatic load-shedding systems can help optimize power flow and reduce transmission losses. Regular maintenance and inspections are crucial in identifying and addressing issues such as loose connections, corrosion, or damaged conductors, which may increase resistance and contribute to additional power losses. Shortening transmission distances where possible or adopting more efficient transmission line configurations can also help reduce energy dissipation along the network. Moreover, the strategic installation of capacitors to compensate for inductive reactance plays a vital role in voltage stabilization and loss reduction. By implementing these strategies, power losses in the transmission system can be minimized, leading to improved operational efficiency, enhanced system reliability, and reduced energy costs. In terms of voltage regulation, this study found that the sending voltage is higher than the receiving voltage. However, the voltage remains within safe limits due to the presence of a reactor that helps maintain voltage stability. This finding aligns with the study conducted by Anggoro [10], which also observed that although a voltage drop occurs, its value does not exceed the threshold that could cause disruptions to substation equipment.

Furthermore, the study confirms that voltage regulation on the Krian-Grati line remains within the 10% limit set by SPLN No. 1 of 1995.

CONCLUSION

Based on the result, several conclusions can be drawn. On short transmission lines, the send voltage is greater than the receive voltage, but neither experiences a drastic voltage drop. This is caused by the presence of a reactor which ensures that the received voltage does not exceed the specified voltage requirement. If the received voltage exceeds the specified limit, it can cause equipment damage at the substation. The results of calculating the voltage regulation percentage on the Krian-Grati transmission line for 15 days in December 2024 show that the voltage regulation percentage does not exceed the safe limit, namely a maximum of 10%. Based on manual calculation results, the highest losses on the Krian-Grati transmission line occurred on the 7th day at 0.089 MW. On the other hand, the lowest losses on this transmission line occurred on day 9, amounting to 0.023 MW. This data shows daily variations in power losses that occur on the transmission line. This calculation is important to understand the efficiency of the transmission system and identify days with significant losses for further analysis and possible improvements. Total power losses on the transmission network for 15 days were 1.024 MW with average losses per day of 0.068 MW.

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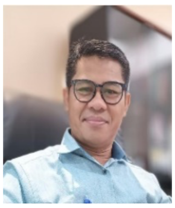

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