



Study of ACSR Conductor Characteristics on Power Losses and Voltage Drop in 500 kV Transmission Lines: A Case Study at Krian-Ungaran

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Abstrak

Sistem transmisi merupakan tahap penyaluran listrik dari pembangkit menuju gardu induk hingga ke sistem distribusi. Selama proses penyaluran daya listrik, terjadi regulasi tegangan yang harus diperhatikan apakah masih berada dalam batas aman atau tidak, karena jika melebihi batas aman dapat menyebabkan kerusakan pada peralatan listrik. Kehilangan daya dapat terjadi karena beberapa faktor, yaitu kebocoran pada isolator, jarak, dan faktor lainnya. Salah satu permasalahan yang diidentifikasi adalah penggunaan konduktor ACSR (Aluminum Conductor Steel Reinforced), yang meskipun umum digunakan karena kekuatan mekanisnya dan biaya yang relatif rendah, juga menyebabkan kehilangan daya yang signifikan akibat resistansi dan kerentanannya terhadap pengaruh lingkungan seperti kenaikan suhu. Jaringan transmisi dalam penelitian ini menggunakan kawat konduktor tipe ACSR jenis Dove dengan luas penampang 327,77 mm² sepanjang 251 km, dengan nilai resistansi sebesar 0,1024 Ω/km. Metode perhitungan manual digunakan dengan mencatat nilai arus dan tegangan yang berubah setiap hari selama satu bulan. Kesimpulan yang diperoleh dari perhitungan manual terhadap kehilangan daya dan regulasi tegangan adalah bahwa persentase regulasi tegangan pada saluran transmisi selama satu bulan tetap berada dalam batas aman, di mana batas maksimum yang diperbolehkan adalah 10%. Namun, meskipun tegangan masih dalam batas regulasi, tercatat kehilangan daya yang cukup signifikan, dengan kehilangan tertinggi sebesar 16,79 MW dan terendah sebesar 6,01 MW. Total kehilangan daya pada jaringan transmisi selama satu bulan mencapai 272,92 MW, dengan rata-rata sebesar 9,09 MW per hari. Temuan ini menyoroti kelemahan penggunaan konduktor ACSR pada saluran transmisi jarak jauh, sehingga perlu dipertimbangkan penggunaan jenis konduktor alternatif atau strategi pengurangan rugi-rugi daya untuk meningkatkan efisiensi transmisi.

Abstract

The transmission system is the stage of electricity distribution from the generator to the substation to the distribution system. During the process of distributing electric power, there is a voltage regulation that occurs whether it is still within safe limits or not because if it exceeds safe limits it can cause damage to

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electrical equipment. Power losses can occur due to several factors, namely insulator leaks, distance, and others. One of the issues identified is the use of ACSR (Aluminum Conductor Steel Reinforced) conductors, which, although commonly used due to their mechanical strength and relatively low cost, also contribute to significant power losses due to their resistance and susceptibility to environmental effects such as temperature rise. The transmission network in this study uses ACSR type conductor wire with a Dove type and a cross-sectional area of 327,77 mm² over a distance of 251 km, with a resistance value of 0.1024 Ω/km. The manual calculation method was employed by recording current and voltage values that change every day for one month. The conclusion obtained from manual calculations of power losses and voltage regulation is that the percentage of voltage regulation on transmission lines for one month remains within the safe limit, where the maximum allowed is 10%. However, despite the voltage being regulated within limits, significant power losses were recorded, with the highest loss being 16,79 MW and the lowest 6,01 MW. The total power losses on the transmission network for one month reached 272,92 MW, with an average of 9,09 MW per day. These findings highlight the drawback of using ACSR conductors in long-distance transmission lines, emphasizing the need for consideration of alternative conductor types or loss-reduction strategies to improve overall transmission efficiency.

Introduction

Electrical energy has become an essential necessity for modern society, where almost every human activity depends directly or indirectly on its availability. From residential lighting and communication to industrial production and transportation, electrical energy supports critical functions that drive economic growth and improve quality of life (Widagdo *et al.*, 2025). With the rapid advancement of technology and the ongoing development of Industry 4.0, the demand for reliable and efficient electrical energy supply continues to rise significantly, both for industrial applications and everyday consumer needs. This growing demand presents challenges in ensuring the sustainability and efficiency of power systems, particularly in the transmission stage where electrical energy is conveyed from generation centers to distribution networks and ultimately to end users (Widagdo *et al.*, 2024).

Electric power systems are generally divided into three primary stages: generation, transmission, and distribution. The transmission stage plays a crucial role in transporting large volumes of electric power over long distances, often spanning hundreds or even thousands of kilometers. This distance separation between power plants and load centers introduces technical challenges such as voltage regulation and energy losses that can compromise the reliability and quality of supply. Power loss in transmission lines is a significant issue, arising

due to inherent electrical resistance in conductors and environmental factors including temperature fluctuations, insulator degradation, corona discharge, and mechanical wear (Widagdo *et al.*, 2023). These losses not only reduce the efficiency of power delivery but also lead to increased operational costs and potential damage to electrical equipment if voltage levels fall outside permissible limits (Dirgantara, 2018).

Several previous studies have investigated the magnitude and causes of power losses and voltage drops in transmission lines. For example, Ismawan & Santoso (2021) conducted an analysis on short-distance transmission lines of approximately 3 km and found that conductor resistance is the primary contributor to power loss, with voltage drops exacerbating the problem. Similar issues have been identified in distribution substations, where power loss affects the final delivery of electricity to consumers. At the 150 kV transmission line connected to the KIM Main Substation, companies have focused on minimizing these losses by analyzing operational data and implementing engineering solutions based on both internal studies and external references (Dani, 2021). These efforts have yielded encouraging results, with power losses maintained within safe and acceptable limits, and voltage drops kept under regulatory thresholds. Extending the scope to larger transmission networks, Cahyadi *et al.* (2022) reported that energy losses vary according to load levels and time of day in a 150 kV transmission system. The highest losses, reaching 1,148 MW, occurred during afternoon and evening peak hours between the Langsa Main Substation and the Pangkalan Brandan Main Substation. Conversely, the lowest recorded losses were 0,635 MW during off-peak periods. These fluctuations underline the importance of continuous monitoring and adaptive management strategies to optimize transmission efficiency.

To regulate and limit power losses, SPLN Standard No. 72 of 1987 mandates that losses in transmission systems must not exceed 5% of the transmitted power (Dalila *et al.*, 2022). Compliance with this standard is crucial for maintaining system stability and ensuring that consumers receive electricity within prescribed voltage limits, thereby preventing equipment damage and service interruptions. Consequently, routine power loss analysis is indispensable for the timely identification of inefficiencies and the implementation of corrective actions. Among the technical factors affecting power loss, the choice of conductor material plays a significant role. Aluminum Conductor Steel Reinforced (ACSR) conductors are widely used due to their favorable mechanical strength and cost efficiency. Nevertheless, ACSR conductors exhibit increased electrical resistance at elevated temperatures, which results in higher energy

dissipation during daytime operation under thermal stress (Rifal *et al.*, 2020). Recent efforts to improve transmission efficiency have focused on reconductoring, specifically the replacement of ACSR conductors with Aluminum Conductor Composite Core (ACCC) conductors. A case study on the Singkawang–Parit Baru Substation transmission line demonstrated that this reconductoring reduced active power losses from 11,102 MW to 10,025 MW, amounting to a 3,153% reduction. This improvement corresponds to daily cost savings of approximately IDR 42,507,552.96. Moreover, the bus voltage along the transmission line remained within the permissible range of +5% to -10%. These results underscore both the technical efficacy and economic advantages of conductor upgrades in transmission systems (Pratama *et al.*, 2022).

Despite progress made, there remains a research gap concerning the combined effects of conductor type, transmission distance, and environmental factors such as ambient temperature and solar radiation. Most studies have either focused on short-distance lines or neglected the temperature-dependent increase in conductor resistance, particularly in tropical climates where high daytime temperatures are common. This study aims to address this gap by examining the performance of ACSR conductors on long-distance transmission lines, with a focus on how daytime temperature rises impact electrical resistance, power losses, and voltage regulation. By integrating environmental variables into the analysis, the research seeks to provide a more comprehensive and realistic assessment of transmission efficiency, thereby informing strategies for conductor selection and network optimization in tropical regions.

Method

This study commenced with the systematic collection of relevant data concerning ACSR conductors, including both physical and electrical properties necessary for precise transmission line modeling. Subsequently, the inductive (L) and capacitive (C) parameters of the transmission line were determined by applying geometric modeling techniques, specifically through the calculation of the Geometric Mean Distance (GMD) and Geometric Mean Radius (GMR). These parameters served as critical inputs for computing the transmission line's impedance, which provided the foundation for further analysis. Following the development of the transmission line model, a comprehensive analysis was performed to assess the influence of ACSR conductors on power losses and voltage regulation, with particular focus on long-distance transmission lines. Data collection was deliberately conducted during daytime conditions to capture the effects of elevated ambient temperatures that result in increased

conductor temperatures. This approach enabled the evaluation of conductor performance under thermal stress, yielding valuable insights into the maximum transmission capacity and efficiency of ACSR conductors under realistic conditions. In this context, long-distance transmission lines are defined as those exceeding 250 km in length. It is noted that as the length of the transmission line increases, the magnitudes of parallel capacitive reactance and conductance decrease, resulting in increased leakage current. Therefore, for long transmission lines, accurate calculation of resistance (R), inductance (L), and capacitance (C) parameters is mandatory to ensure precise modeling and analysis.

Electric power transmission involves transferring electricity from generation centers to load centers via high-voltage lines, typically operating at 150 kV for high voltage or 500 kV for extra-high voltage. Voltage is stepped down by transformers to sub-transmission levels (70 kV) and further reduced at substations to primary distribution voltages (20 kV). Distribution substations near load centers then lower voltage to consumer levels, such as 220/380 V, facilitated by conductor materials forming the transmission lines (Rudolf *et al.*, 2019). Figure 1 illustrates a basic block diagram of an electric power transmission and distribution system, comprising two generating stations (G1 and G2), multiple substations including interconnecting substations, and various commercial, residential, and industrial loads. The heavily shaded transmission segment primarily manages voltage regulation by adjusting voltage levels along the lines. International standards specify voltage ranges of 345 kV to 765 kV for extra-high voltage and 115 kV to 230 kV for high voltage lines.

In Indonesia, transmission voltages are standardized at 500 kV for extra-high voltage and 150 kV for high voltage. The overall effectiveness of the transmission system relies not only on adherence to these voltage standards but also on the selection of conductor types. Therefore, evaluating the performance of conductors such as ACSR under diverse operational conditions is essential to optimize both efficiency and reliability (Petrović *et al.*, 2018; Pavičić *et al.*, 2021). Given the considerable distances between generation and load centers, voltage quality deteriorates due to network losses, thereby necessitating the use of voltage stability equipment. Within the distribution network, substations reduce voltage from medium to low levels through step-down transformers equipped with automatic tap changers, enabling accurate regulation of low voltage. Typically, low voltage ranges from 120/240 V for single-phase lines to 600 V for three-phase lines, serving residential, commercial, institutional, and small industrial consumers (Wiguna *et al.*, 2020).

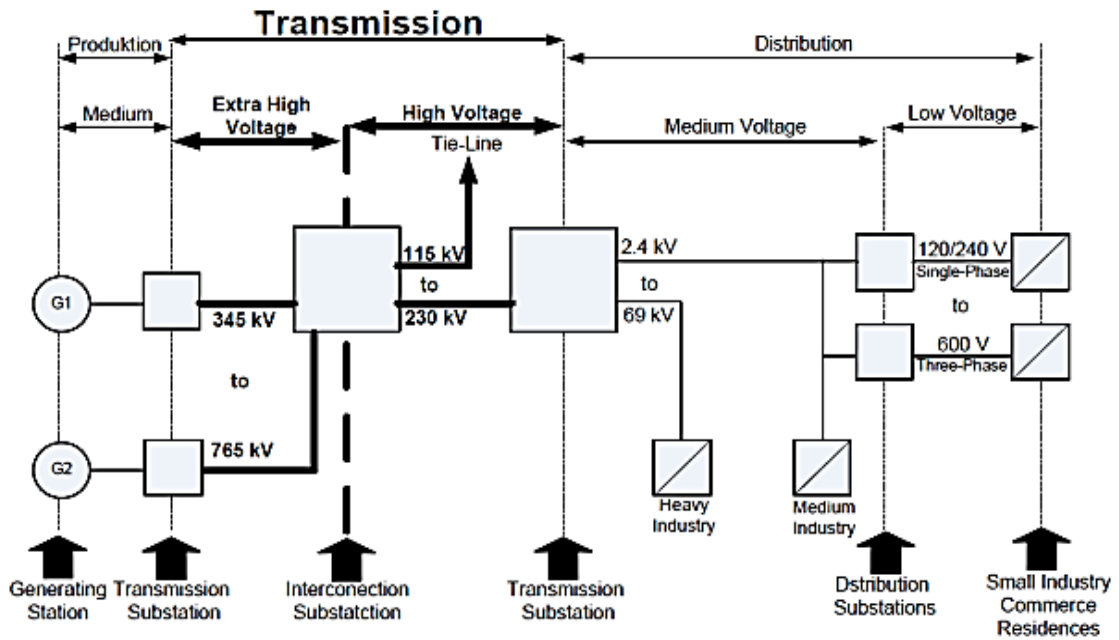


Figure 1. Block Diagram of an Electric Power System

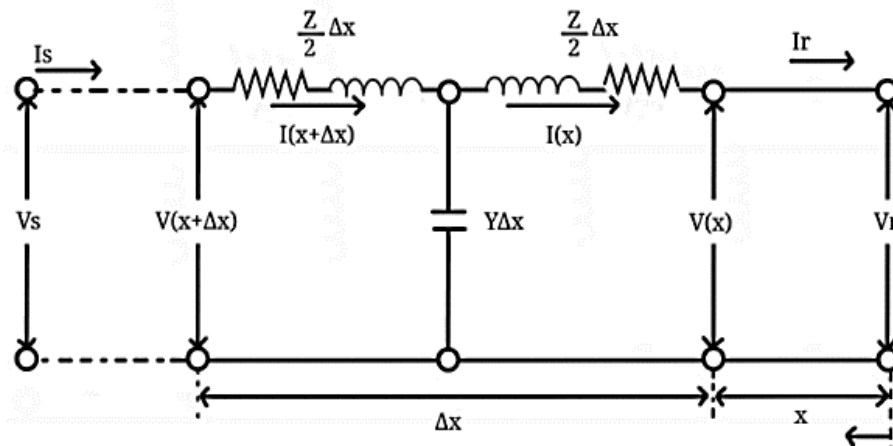


Figure 2. Equivalent Circuit of Long Line Transmission

Long Distance Transmission Line

Long-distance transmission lines are defined as those with lengths exceeding 250 km. As illustrated in Figure 2, a long transmission line can be modeled using nominal π (pi) and nominal T circuit configurations, similar to the modeling approach employed for medium-length transmission lines. An easier form of equation for calculating the current and voltage of a line is introduced using hyperbolic functions. So, calculations for current and voltage:

$$V_s = (\text{Cosh}\gamma L)V_R + (Z_c \text{sinh}\gamma L)I_R \quad (1)$$

$$I_s = \left[\frac{(\text{sinh}\gamma L)}{Z_c} \right] V_R + (\text{Cosh}\gamma L)I_R \quad (2)$$

So that,

$$A = D = \text{Cosh } \gamma \quad (3)$$

$$B = Z_C \text{ Sinh } \gamma L \text{ [ohm]} \quad (4)$$

$$C = \left[\frac{(Z_C \text{ Sinh } \gamma L)}{Z_C} \right] \text{ [mho]} \quad (5)$$

$$Z_C = \frac{Z}{Y} \quad (6)$$

$$\gamma = \sqrt{ZY} = \alpha + j\beta \quad (7)$$

$$\text{Cosh } \gamma L = \text{Cosh } \alpha L \text{ Cos } \beta + j \text{ Sinh } \alpha L \text{ Sin } \beta \quad (8)$$

$$\text{Sinh } \gamma L = \text{Sinh } \alpha L \text{ Cos } \beta + j \text{ Cosh } \alpha L \text{ Sin } \beta \quad (9)$$

Where,

Z_C : Characteristic Impedance

γ : Propagation Constant

α : Constant

β : Phase Constant

L : Line Length (Km)

Voltage Regulation

Voltage regulation on the line can be defined as the voltage increase when the full load is removed. Voltage regulation has an important role to ensure that the voltage supplied is still within safe limits and in accordance with applicable standards (Gbadamosi & Nwulu, 2021). Voltage regulation is used to prevent damage to electrical equipment, increase transmission efficiency, and maintain stable electrical power availability. To find the voltage regulation value on the transmission line, the following calculation is carried out (Shen *et al.*, 2018):

$$V_R = \frac{\frac{|V_S|}{|A|} - |V_{Re}|}{|V_{Re}|} \times 100\% \quad (10)$$

Where,

V_S : Voltage on the sending side (Volt)

V_{Re} : Voltage on the receiving side (Volt)

V_R : Voltage Regulation (%)

A : Constant

Power Losses in Transmission Lines

The use of ACSR conductors on long transmission lines, such as the 500 kV Krian–Ungaran line, significantly contributes to power losses due to their relatively high resistance.

As the line length increases, resistive losses also increase, making ACSR less efficient for long-distance transmission. While other losses like corona and insulator leakage exist, this study focuses on resistive losses, highlighting the impact of conductor resistance on total transmission losses (Aneke & Ngang, 2021).

Resistance Loss

The resistance loss of a transmission line is expressed by the following equation:

$$P_L = 3 \times I^2 \times R \times l \quad (11)$$

Meanwhile, for long line where the load current is taken into account, it is stated as follows:

$$P_L = 3 \times R \times l \times (i^2 - i \cdot i_c^2) \quad (12)$$

Where,

P_L : Power Loss (Watt)

R : Resistance per phase (ohm)

l : Distance of line (km)

i : Load current (A)

i_c : Charge current at delivery point (A)

The percentage of power loss can be determined using the equation:

$$P_{\%} = \frac{\Delta P}{P_S} \times 100\% \quad (13)$$

Where,

$P_{\%}$: Power Loss Percentage (%)

ΔP : Resistance Power Loss (kW)

P_S : Power Delivered (kW)

The provided equations describe the calculation of power loss due to resistance in a three-phase transmission line. Additionally, the percentage of power loss relative to the power delivered is determined by comparing the resistance loss to the total power transmitted. These equations are essential for evaluating transmission efficiency and optimizing power system performance (Shevchenko *et al.*, 2023). Figure 3 shows a high-voltage transmission line connecting Krian Main Substation and Ungaran Main Substation, spanning 251 kilometers. Both substations include transformers for voltage step-up and step-down, and circuit breakers for protection and isolation. The line facilitates the transfer of electrical power over a long distance, requiring careful management of voltage regulation and system reliability.



Figure 3. Single Line Diagram of Krian-Ungaran Main Substation

Result and Analysis

This study systematically collected electrical data current, voltage, and power recorded daily over a one-month period on the Bay Line transmission corridor between Krian - Ungaran substations. Additional information such as conductor specifications, single-line substation diagrams, and conductor resistance values were also obtained. The transmission line employs Aluminum Conductor Steel Reinforced (ACSR) conductors, valued for their mechanical strength and cost efficiency. However, the performance of ACSR conductors regarding power losses and voltage regulation, especially on long-distance lines like Krian - Ungaran, requires thorough evaluation. The line's geometric configuration, including conductor spacing, arrangement, and height above ground, affects its inductance, capacitance, and impedance key factors influencing power losses and voltage stability. Therefore, an in-depth analysis of ACSR conductor use on this corridor is essential to identify inefficiencies and explore alternative conductor options for improved performance. The findings aim to support optimization of transmission line design and operation for similar high-voltage systems.

Table 1

Parameters of the 500 kV Krian-Ungaran Transmission Line

Parameter	Value
R (Resistance per phase)	0,1024 ohm/km
D (Distance Between Phases)	10 m
l (Transmission Length)	251 km
A (Wire Cross-sectional Area)	327,77 mm ²
Frequency	50 Hz
Conductor Diameter	23,55 mm

From several existing parameters, calculations are carried out to find the geometric mean distance (GMD). To calculate the geometric mean distance (GMD) you can find it using the following equation (Bulatov *et al.*, 2022).

$$GMD = \sqrt[3]{D_{ab} \cdot D_{bc} \cdot D_{ac}} \quad (14)$$

$$GMD = \sqrt[3]{10 \times 10 \times 20}$$

$$GMD = 12,59 \text{ m}$$

So from equation (14), the *GMD* value is 12,59 m. In the transmission line being analyzed, the conductor used is the DOVE type so it has a *D_s* value of 0,0314 feet, to convert it to meters it must be multiplied by 0,3048. Then, continue to find the *GMR* using the following equation:

$$GMR = 1,09 \sqrt[4]{D_s \times d^3} \quad (15)$$

$$GMR = 1,09 \sqrt[4]{0,0314 \times 0,3048 \times 0,6^3}$$

$$GMR = 0,2324 \text{ m}$$

From determining the *GMD* and *GMR* values, the inductance and capacitance values of the 500 kV Krian-Ungaran transmission line were obtained. The inductance and capacitance values represent the conditions of the equivalent circuit of a long distance 500 kV transmission line (Zeng & Dang, 2024). Determination of the inductance value and is obtained as follows.

$$L = 2 \times 10^{-7} \ln \frac{GMD}{GMR} \quad (16)$$

$$L = 2 \times 10^{-7} \ln \frac{12,59}{0,2324}$$

$$L = 7,984 \times 10^{-7} \text{ H}$$

Meanwhile for the capacitance value,

$$C = \frac{2\pi\epsilon_0}{\ln \frac{GMD}{GMR}} \quad (17)$$

$$C = \frac{2 \times 3,14 \times 8,854 \times 10^{-6}}{3,992}$$

$$C = 0,0000556 \text{ F}$$

So the total impedance value obtained is,

$$Z = \sqrt{R^2 + j(X_L - X_C)^2} \quad (18)$$

$$Z = 25,70 + (0,14 - 0,0000556)$$

$$Z = 25,70 + j0,14 \text{ Ohm}$$

Voltage Regulation

Voltage regulation on electricity transmission lines is very important to ensure that the voltage transmitted by transmission lines remains within specified limits. This is necessary so that the transmission system can operate efficiently and safely. The results of voltage regulation calculations on ACSR Dove conductors of 327,77 mm² with a resistance value of 0,1024 Ω at every distance of 1 km in August are presented in Table 2.

Table 2
Voltage Regulation Calculation Results

Day	$V_{S(L-L)}$ (kV)	$V_{R(L-L)}$ (kV)	Power (MW)	Voltage Regulation ΔV (%)
1	488	501	174	2,78
2	488	501	186	2,78
3	490	503	305	2,76
4	486	499	187	2,80
5	486	499	173	2,80
6	488	501	160	2,78
7	488	501	163	2,78
8	488	501	161	2,78
9	488	501	160	2,78
10	486	499	168	2,80
11	488	501	161	2,78
12	488	501	160	2,78
13	488	501	155	2,78
14	486	499	246	2,81
15	486	499	257	2,81
16	481	497	297	3,39
17	487	502	370	3,33
18	484	500	261	3,35
19	486	502	256	3,32
20	486	502	251	3,32
21	486	502	270	3,32
22	490	506	301	3,27
23	486	502	253	3,32
24	488	504	274	3,30
25	486	502	186	3,32
26	486	502	172	3,32
27	488	504	161	3,29
28	495	510	213	3,20
29	486	502	146	3,32
30	486	502	146	3,32

Table 2 shows that voltage regulation (ΔV) on the Krian–Ungaran transmission line using ACSR conductors ranges from 2,76% to 3,39% over 30 days, staying well below the 10% limit. However, voltage regulation increases with higher transmitted power, rising from 2,78% at 186 MW to 3,39% at 290 MW. This trend highlights ACSR’s limitations in maintaining voltage stability under high loads on long-distance lines. The significant rise at peak loads suggests the conductor’s performance is nearing its limit, indicating the need to consider alternatives, such as reconductoring with more efficient conductors, to enhance system performance and reduce power losses.

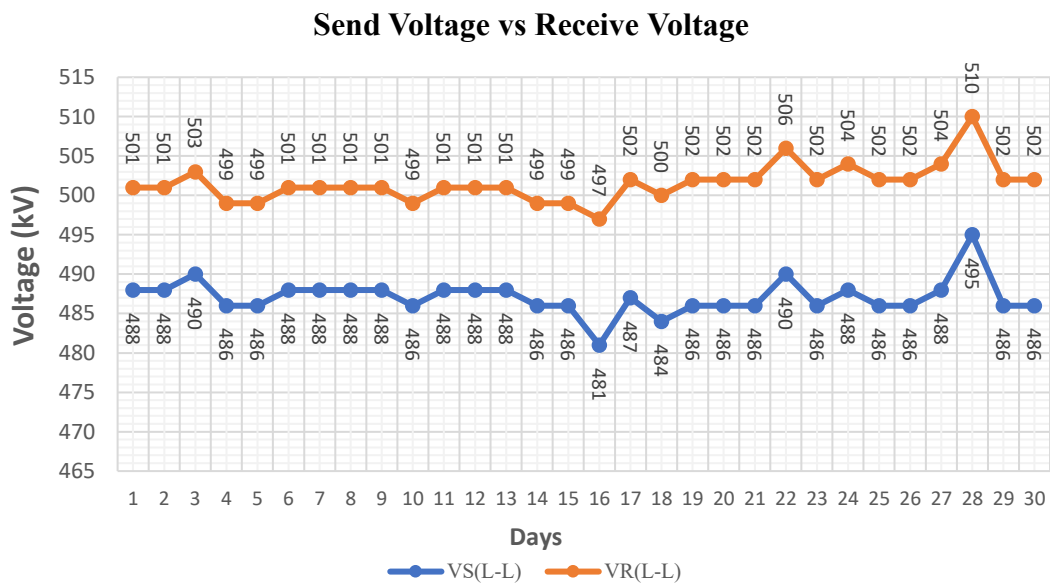


Figure 8. Sending Voltage and Receiving Voltage on Krian-Ungaran Main Substation

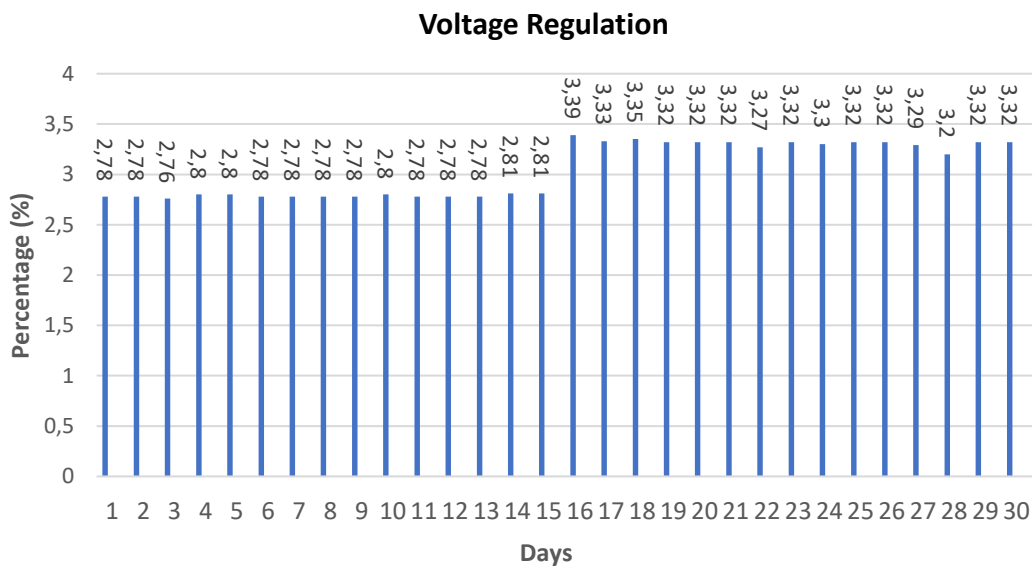


Figure 9. Percentage of Voltage Regulation on Krian-Ungaran Main Substation

Figure 8 illustrates the sending voltage on the Krian–Ungaran transmission line throughout August. The lowest sending voltage of 481 kV occurred on day 16, while the highest was 495 kV on day 28. Conversely, the received voltage ranged from a minimum of 497 kV on day 16 to a maximum of 510 kV on day 28. In long transmission lines, the receiving voltage tends to be higher than the sending voltage due to the line’s capacitance effect, which increases with line length. Figure 9 confirms that the voltage regulation percentage remains within acceptable limits, with a maximum allowed value of 10%.

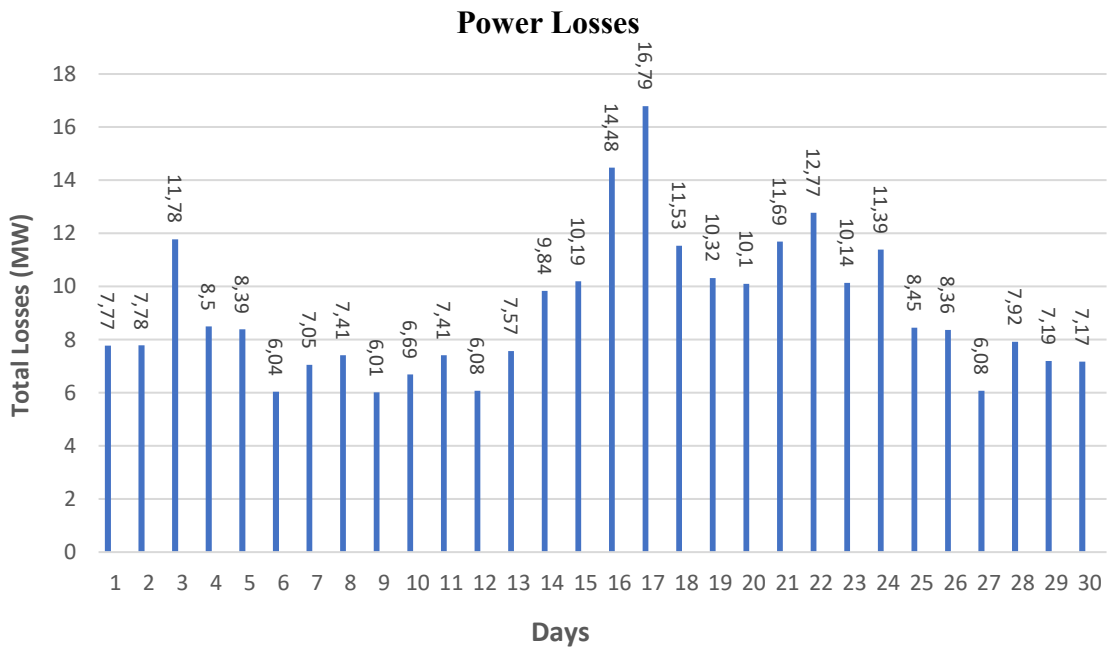


Figure 10. Total Power Loss on Krian-Ungaran Main Substation

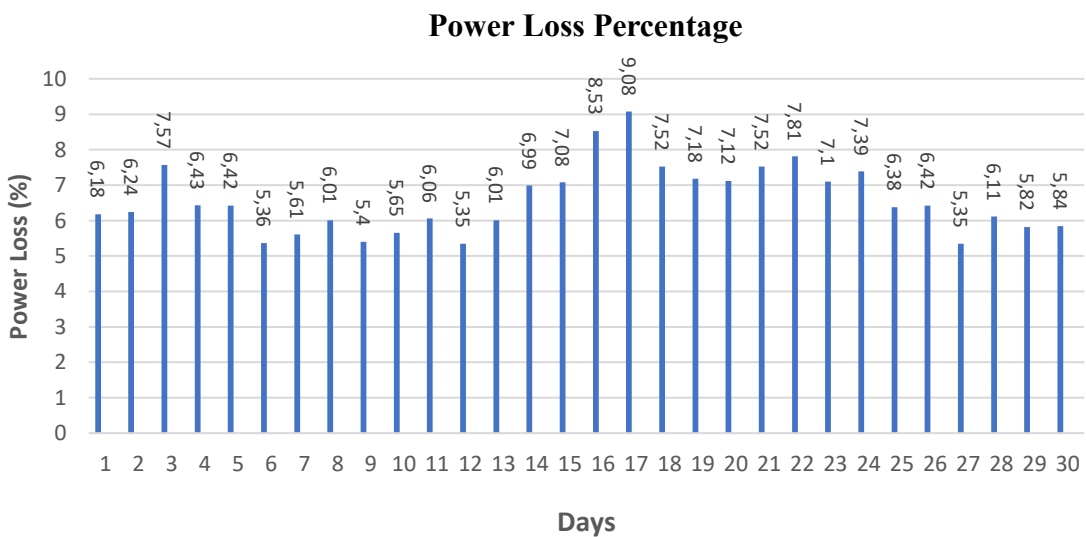


Figure 11. Percentage of Power Loss in a One Month Period

Figure 10 shows the power losses on the Krian–Ungaran transmission line during August 2023, with the highest loss of 16,79 MW occurring on day 17 and the lowest loss of 6,01 MW on day 9. Figure 11 presents the percentage of power losses over the month, ranging from 5,35% to 9,08%. Power losses in the 500 kV transmission network are influenced by the distance to the load center. At the Krian–Ungaran substation, the voltage is stepped down from 500 kV to 150 kV near the load center, reducing additional losses in the lower voltage lines. Placing the generation source closer to the load center reduces losses by minimizing current flow in the 150 kV network. In contrast, operating the 500 kV line from a more remote location increases losses, as longer 150 kV lines must carry higher currents (Mohanty *et al.*, 2024).

Transmission lines inherently experience power losses due to conductor resistance. Using conductors with better conductivity, such as ACCC instead of ACSR, can effectively reduce these losses (Song *et al.*, 2022). The study of ACSR conductors on the Krian–Ungaran line highlights both benefits and limitations. Sending voltages ranged from 481 to 495 kV, while receiving voltages were higher (497 to 510 kV) due to capacitive charging typical of long lines. Despite these variations, voltage regulation remained within the 10% standard, demonstrating adequate voltage stability. However, power losses between 6,01 MW and 16,79 MW (5,35% to 9,08%) indicate ACSR's inefficiency over long distances. Although ACSR conductors offer mechanical strength and cost advantages, their higher resistance compared to ACCC results in greater losses and limited thermal capacity (Qin *et al.*, 2024). For high-capacity, long-distance transmission, replacing ACSR with conductors of superior electrical and thermal properties is recommended to enhance efficiency and performance.

Conclusion

On long distance transmission lines, there is a voltage difference between the send voltage and the receive voltage, where the value of the receive voltage will increase compared to the send voltage. This is caused by the capacitance effect where the longer the transmission line, the greater the capacitance value. The results of calculating the percentage of voltage regulation on the Krian–Ungaran Main Substation 500 kV transmission line over a one-month period show that the percentage of voltage regulation does not exceed the standard limit of 10%, indicating that voltage conditions remain stable and within safe operating parameters. From manual calculations, the highest power loss was recorded on day 17 at 16,79 MW, while the lowest occurred on day 9 at 6,01 MW. The total power losses throughout the transmission



line for one month reached 272,92 MW, with the percentage of power losses ranging from a minimum of 5,35% to a maximum of 9,08%.

These findings highlight that although ACSR conductors can maintain voltage regulation within acceptable standards, they exhibit relatively high energy losses over long distances. ACSR is favored for its mechanical strength and cost efficiency, but its electrical resistance and limited thermal performance present significant drawbacks in high-voltage, long-distance applications such as the Krian–Ungaran line. Therefore, it is important to consider more advanced conductor types like ACCC, which offer lower resistance and higher current-carrying capacity. Implementing such alternatives could improve transmission efficiency, reduce power losses, and enhance the overall reliability of the power system.

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