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Analysis of Voltage Regulation and Power Losses on 500 kV Transmission Line Extra High Voltage Main Substation Krian-Grati

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***Abstract*— The transmission system distributes electricity from the generator to the substation and finally to the consumer. During distribution, obstacles such as power losses and voltage regulation occur, which must meet specified standards to prevent equipment damage. Power loss can result from factors like corona effects and insulator leaks. This analysis aims to determine power loss and voltage regulation by examining daily peak load data at 14:00 over 15 days, recording current and voltage values on the extra high voltage main substation Krian-Grati transmission lines. This network uses ACSR conductors, type Gannet, with dimensions of 392.84 mm 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 send and receive voltages, with the send voltage being slightly higher due to the reactor, preventing drastic voltage drops. Over 15 days in March 2024, the voltage regulation did not exceed the standard maximum of <10%, with the highest being 4.7%. The highest power loss occurred on day 7 at 0.089 MW, and the lowest on day 9 at 0.023 MW. The total power loss over 15 days was 1.024 MW, averaging 0.068 MW per day.**

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

I. Introduction

THE electric power system is an inseparable unit from generation, energy distribution to the use of electrical energy by consumers [1]-[3]. Electricity is the most practical form of secondary energy used by humans, where electricity is produced from the conversion process of primary source energy such as coal, oil, gas, geothermal, water potential and wind energy. The need for electricity in society is increasing along with the increasing use of electric power in household equipment, offices and so on, so that the electricity supply must be increased, namely by building new power plants [4].

Apart from the availability of sufficient generation, another thing that must also be determined is whether a transient condition if a disturbance occurs will disrupt the normal operation of the system or not. This will be related to the quality of electricity that reaches consumers, namely frequency and voltage stability [5]. A good electric power system is a power system that can serve loads continuously at constant voltage and frequency. Voltage and frequency fluctuations that occur must be within the permitted tolerance limits so that consumer electrical equipment can work properly and safely. Truly stable system conditions never actually exist. Load changes always occur in the system. Adjustments by the generator will be carried out through the governor of the prime mover and generator excitation [6]-[8].

Changes in the voltage conditions on the receiving side usually occur due to short circuit disturbances in the electric power system, and sudden removal or addition of the load. As a result of changes in the working conditions of this system, the state of the system will change from the old state to the new state. Voltage drops on the receiving side of medium distance transmission lines can also occur due to voltage drops in the line due to the series impedance of the line resulting from line resistance parameters and line inductive reactance, as well as ground admittance, namely the influence of the electric field produced by the air conductor on the ground [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 Bayu Andik 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 Nico Yupiter 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.

II. Methods

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 14.00 WIB. 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 ohm/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.

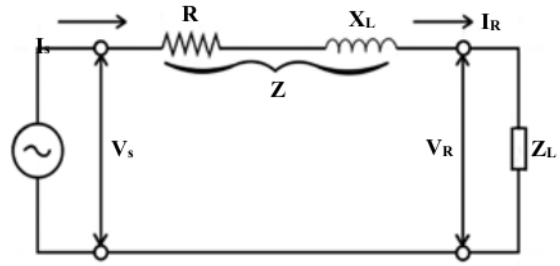


Fig. 1. Equivalent Circuit for Short Transmission Lines [14]

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]:

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

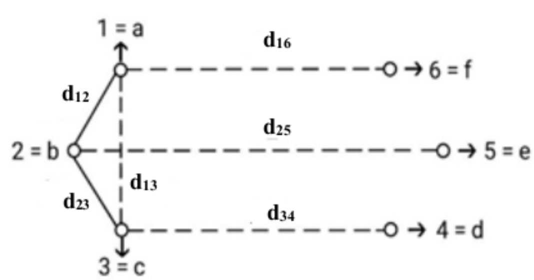
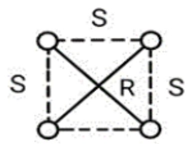


Fig. 2. Double circuit lattice tower specifications



S = 0,25 m

Fig. 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:

a. 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]:

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

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]:

$$P_{Losses} = I^2.R_{total} \tag{11}$$

Where,

P_{Losses} = Power losses (Watt)

I = Current lines (Ampere)

R = Total Impedance (Ohm)

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)

III. Result and Analysis

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.

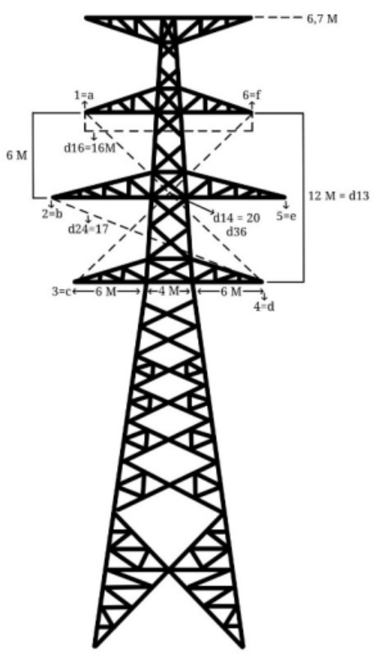


Fig. 4. Double circuit transmission tower on the 500 kV Krian-Grati lines

TABLE I
Conductor Parameters in Krian-Grati Transmission

Parameter	Nilai
R (Resistance)	0,00086 [ohm/km]
l (Transmission Length)	79,41 [km]
Frequency	50 [Hz]
Conductor Diameter	25,76 [mm^2]

TABLE II
Double Circuit Geometry on transmission towers

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

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:

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

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

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.

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

$$R = \frac{0{,}25}{\sqrt{2}} \times \frac{\sqrt{2}}{\sqrt{2}} = 0{,}175\ [m]$$

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

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

$$r_1' = 0{,}175.e^{\frac{1}{4}} = 0{,}136\ [m]$$

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

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

$$GMR = \sqrt[6]{(0{,}136)^3 \times 20 \times 16 \times 20} = 1{,}59\ [m]$$

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.

$$X_L = 0{,}14467\ \log \frac{GMD}{GMR}$$

$$X_L = 0{,}14467\ \log \frac{12{,}35}{1{,}59} = 0{,}128\ [\Omega]$$

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:

$$P_{Losses}\ R = 591^2 [A] \times 0{,}068\ [\Omega] = 0{,}02\ [MW]$$

$$P_{Losses}\ S = 574^2\ [A] \times 0{,}068\ [\Omega] = 0{,}02\ [MW]$$

$$P_{Losses}\ T = 584^2\ [A] \times 0{,}068\ [\Omega] = 0{,}03\ [MW]$$

After calculating the power losses on each R, S and T phase for 15 days in March 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 March 2024 on the Bay Line Grati transmission line as follows:

$$P_{Losses}RST = 0{,}023\ [MW] + 0{,}022\ [MW] + 0{,}023\ [MW]$$

$$P_{Losses}RST = 0{,}069\ [MW]$$

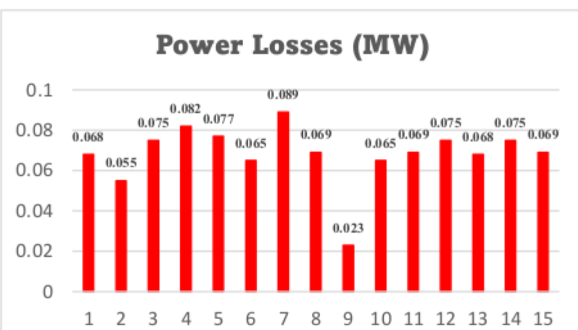


Fig. 5. Power losses on Krian-Grati transmission

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 March 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.

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:

$$V_s = V_R + IZ$$

$$V_s = 487 + (583 \times 0{,}036) = 698\ [kV]$$

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 III
VOLTAGE REGULATION ON KRIAN-GRATI TRANSMISSION

Day	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 Send Power and Receive Power, 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 March 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.

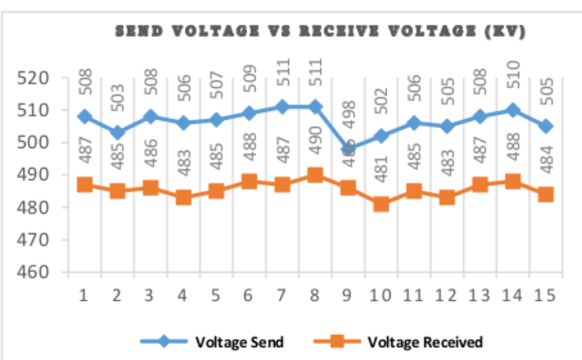


Fig. 6. Comparison of the values of sent and received voltage

Figure 6 shows the sending voltage on the Krian-Grati transmission line for 15 days in March 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.

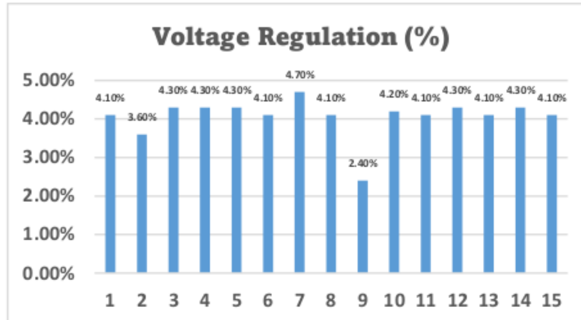


Fig. 7. Voltage regulation on the Krian-Grati Transmission

Figure 7 shows that the percentage of voltage regulation on the Krian-Grati transmission line during March 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.

IV. CONCLUSION

Based on the results of the analysis during the research, 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 March 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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