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Analysis of North Jakarta 500 kV Extra High Voltage Transmission Line using Shunt Reactor

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Abstrak. Untuk memenuhi kebutuhan energi listrik di Indonesia, khususnya di DKI Jakarta, PT PLN (Persero) membangun Pembangkit Listrik Tenaga Gas dan Uap (PLTGU) Muara Karang, yang dilengkapi fasilitas start-stop harian dengan kapasitas 500 MW dan saluran udara tegangan ekstra tinggi (SUTET) 500 kV sepanjang 30 km antara Muara Karang – Duri Kosambi. Pada saluran transmisi tegangan tinggi dan tegangan ekstra tinggi, muncul fenomena pengisian saluran di mana tegangan sisi penerima lebih besar atau lebih kecil daripada tegangan sisi pengirim. Penelitian ini bertujuan untuk merancang reaktor shunt sebagai kompensasi daya reaktif yang dapat mengatasi masalah perbedaan tegangan tersebut. Pemodelan dilakukan menggunakan perangkat lunak ETAP 20.0. Nilai reaktor shunt yang dibutuhkan adalah 164,8 MVAR. Terdapat penurunan daya reaktif yang dihasilkan pada pembangkit PLTGU Muara Karang sebesar 157,878 MVAR akibat pemasangan reaktor shunt. Dengan demikian, hal ini dapat meningkatkan penurunan tegangan pada bus beban dari Gardu Induk Tegangan Ekstra Tinggi (GITET) Duri Kosambi, dengan masing-masing memiliki nilai pu tegangan pada bus GI Cengkareng sebesar 92,52%, bus GI VVIP Duri Kosambi sebesar 93,91%, bus GI Grogol Baru sebesar 93,7%, dan GIS Cengkareng sebesar 94,25%. Hal ini dapat menjaga keandalan pada saluran transmisi GITET 500 kV Muara Karang.

Kata Kunci: Saluran transmisi, reaktor shunt, tegangan ekstra tinggi, faktor daya, analisis aliran daya

Abstract. To meet the need for electrical energy in Indonesia, especially in DKI Jakarta, PT PLN (Persero) built the Muara Karang Combined-Cycle Power Plant (CCPP), which has daily start-stop facilities with a capacity of 500 MW and 500 kV extra high voltage overhead lines between Muara Karang – Duri Kosambi is 30 km long. In high voltage and extra high voltage transmission lines, channel filling appears where the receiving side voltage is greater or smaller than the sending side voltage. This research aims to design a shunt reactor for reactive power compensation that can overcome the problem of voltage differences. The modeling uses ETAP 20.0 software. The required shunt reactor value is 164.8 MVAR. There was a decrease in the reactive power produced at the Muara Karang CCPP plant by 157,878 MVAR due to installing a shunt reactor. So that it can improve the voltage drop on the load buses from Extra High Voltage Substation (EHVS) Duri Kosambi, with each having a voltage pu value on the Cengkareng GI bus of 92.52%, Duri Kosambi VVIP GI bus of 93.91%, Grogol Baru GI bus of 93.7%, and GIS Cengkareng at 94.25%. This can maintain reliability on the 500 kV Extra High Voltage Substation Muara Karang transmission line.

Keywords: transmission line, shunt reactor, extra high voltage, power factor, load flow analysis.

INTRODUCTION

To meet consumer load needs, the Muara Karang Combined-Cycle Power Plant (CCPP) was built. It has daily start-stop facilities and a capacity of 500 MW [1]. This effort will use environmentally friendly energy resources to help reduce CO^2 emissions [2]. PT PLN (Persero) will build a new generator and develop 500 kV 'Extra High Voltage Overhead Lines for 30 km between Muara Karang and Duri Kosambi.

In transmission networks with high or very high voltage, Muara Karang - Duri Koambi experiences an effect known as "line charging", where the voltage on the receiving side can be different, either higher or lower, from the voltage on the sending side. This scenario can also arise when the electrical load is minimal [3]. The impact of line charging can vary depending on several factors, including voltage, frequency, line capacitance, and overall power system characteristics.

This research aims to overcome line charging in the Muara Karang - Duri Kosambi area in the city of North Jakarta. The method used is to install a shunt reactor. A shunt reactor is needed to absorb reactive power and balance the effects of line charging [4], [5]. We approach this by simulating ETAP software to analyse and maintain voltage stability, avoiding excessive voltage spikes or drops on the receiving side to maintain the safety of equipment on the receiving side [6].

This research contributes to power and voltage improvements. With a better power factor, the capacity of the power line will increase, and ultimately, the number of customers that can be served will be higher.

METHOD

Voltage instability in medium and long-distance transmission lines is the inability of the system to provide reactive power. Installing a shunt reactor is the right choice to compensate for reactive power and improve voltage stability. Shunt reactors are used in transmission lines to increase the reliability of the transmission network and reduce voltage variations that occur on the receiving side due to stray capacitance, which has the potential to create line-charging situations [5], [7], [8].

A shunt reactor is an inductive component that can balance reactive power to keep the voltage in the transmission network within a safe range. Its function is to prevent potential damage to electronic equipment in voltage instability situations [6], [9]. Using a shunt reactor on the South Bandung – Ungaran channel to compensate for MVAR [10]. Using a shunt reactor is because line charging occurs in the channel, which results in the current and reactive power becoming greater. Reactive power generation by 500 KV extra high voltage overhead lines is around 1 MVAR per kilometer. With the distance between Ungaran and South Bandung being around 342,847 kilometers, the total reactive power produced is estimated to be around 343 MVAR. The impact is that the voltage on the receiving side will exceed the voltage on the sending side, exceeding the tolerance limit permitted by PT PLN (Persero), exceeding 5% of the nominal voltage of 500 KV. To overcome the voltage, increase on the receiving side, which is higher than the sending side (especially on long lines), the solution is to install a compensation device in the form of a shunt reactor at both ends, both on the receiving side and the sending side.

Meanwhile, in other research, the required capacity of the shunt reactor installed in the system is to obtain a maintained voltage level and the system voltage conditions when experiencing voltage changes and after the shunt reactor is installed [9]. Installing a shunt reactor is used to improve the voltage on the 150 kV Barikin - Tanjung transmission line using the Power World version 7 software simulation. In the simulation, to improve the voltage on the 150 kV Barikin - Tanjung transmission line, a reactor capacity of 60 MVAR is required; by using a shunt reactor, the transmission voltage can be maintained constantly from 165.7 kV to 150 kV.

Along with the addition of generators, changes occur in the transmission network, and load requirements also increase. To overcome this, installing a shunt reactor in the JAMALI electrical system was used to improve the voltage value in the system. In the JAMALI electrical system, an over-voltage condition was detected on Bus 17 (Tanjung Jati) with a voltage of 1.08 pu. After a shunt reactor with a capacity of 279.8 MVAR was installed, the voltage on Bus 17 decreased to 1.016 pu. Thus, the shunt reactor plays a role in maintaining the voltage level in the system to remain within safe limits [11].

To maintain the stability of the generator which will be transmitted to consumers, a 66 kV substation was simulated using the ETAP program with Load Flow Analysis and also to correct the voltage drop problem based on actual data from the 66 kV substation. The results are that the ETAP program can detect voltage drop problems by installing a capacitor bank of 5.5 MVAR on capacitor 1 and 8 MVAR on capacitor 2, installed on the 66 kV substation bus. There was an increase in voltage due to the capacitor bank installation by 5.1% from the original total of 92.7% [12], [13].

The effect of installing a shunt reactor on the electrical energy system, be it generation, transmission or distribution. The shunt reactor installation is carried out in the receiving section of the transmission line. This includes installation of the capacitor bank, installation of the shunt reactor, and installation of both. Installation of a shunt reactor on the receiving side affects the stability of system parameters on both sides, both receiving and sending. This aims to maintain system voltage parameters within a tolerance limit of ±5% of the nominal voltage, ensure the system frequency is within a tolerance range of ±1% of the nominal frequency, and maintain a power factor above 0.85 in the lagging state and 0.9 in the leading state [3], [6], [14].

Transmission Line

Transmission lines are the means used to send electrical energy from power generation stations and transmission systems to central consumption (load) points. Electrical energy is transmitted through conductor materials called electrical transmission lines [12]. When electricity is supplied, there is quite a distance between the generator and the load. This condition decreases voltage quality and power losses resulting from energy loss in the network. Therefore, devices are needed to reduce the effects of voltage drops. The amount of power loss can be calculated based on the conductor properties and path length. Figure 1 illustrates how electric power flows from producers to consumers through a distribution system [15].

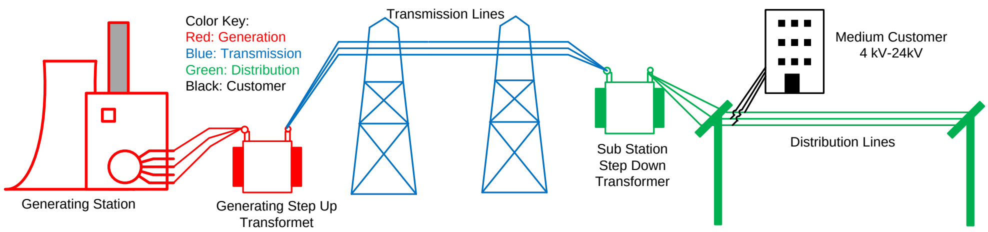

FIGURE 1. Distribution of electric power systems [15]

The power factor is very important to calculate in this system. Equation 1 is used to find the network's apparent power value [8].

$$S = \sqrt{P^2 + Q^2} \tag{1}$$

Where:

P = Active Power
Q = Reactive Power
S = Real Power.

Meanwhile, to find the network's power factor value (cos φ), you can use Equation 2 [9].

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$$Cos\varphi = \frac{P}{S} \tag{2}$$

To obtain the R_{total} value of the transmission cable, use Equation 3, multiplying the cable's R value by the transmission distance [8].

$$R_{Total} = R \times l_{line} \tag{3}$$

Where:

R : cable resistance value
l : transmission length.

Next, using Equation 4, the value of the channel impedance can be obtained by entering the value of R_{total} and the value of the cable reactance obtained previously.

$$Z = R + jX \tag{4}$$

where:

Z : Impedance
X : Reactance.

Equation 5 can be used to find the voltage on the transmission line. Meanwhile, Equation 6 can be used to find the source voltage or reference voltage.

$$V_R = \frac{V_R + I_R \times Z}{\sqrt{3}} \tag{5}$$

$$V_S = V_R + I_R + Z \tag{6}$$

where:

V_R : Network Voltage
V_S : Source Voltage.

Voltage Drop

The voltage lost in the transmission line is the difference between the voltage at the sending end and the voltage at the receiving end of the electricity flow. In lines that carry alternating current, the magnitude of this difference depends on the impedance and admittance of the line, the connected load, and the power factor. The relative difference in voltage experienced is referred to as voltage regulation and is expressed in the form of Equation 7 [12]:

$$\Delta V = \frac{V_S}{V_r} \times 100\% \tag{7}$$

where:

V_S : voltage at the delivery base (kV)
V_r : voltage at the receiving end (kV)
ΔV : percentage voltage drop.

At short distances, the impact of voltage regulation is usually insignificant (only around a few per cent), but for medium and long distances, the impact can reach the range of 5-15% [12], [13]. If the load on the extra-high-voltage transmission line is not too large, the power system is run with constant regulation to avoid the impact of high-loading currents. To minimize these regulations, transmission lines are operated by maintaining a constant voltage at the receiving and sending ends without considering the load. If the voltage at the receiving end drops due to an increase in load, an on-load voltage regulator keeps the output voltage constant, even though the input voltage changes [12].

GMD (Geometric Mean Distance) and GMR (Geometric Mean Radius)

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The concepts of GMD and GMR are used for calculations to reduce the used conductor to the equivalent of a single conductor and to obtain an equivalent separation of return conductors. GMR is the average geometric radius of the conductor itself, while *GMD* is the average geometric distance between conductors and each other. The values of *GMR* and *GMD* can be determined based on Equation (8) and Equation (9) [16].

$$GMR = \sqrt[N]{N \times r \times A^{N-1}}\,(m) \tag{8}$$

where m (meter) is the unit of *GMR*, while for *GMD* [15]:

$$GMD = [D_{12} \times D_{23} \times D_{31}]^{1/3} \tag{9}$$

The following equation (10) can be used to find the value of *A* to get the GMR value.

$$A = \frac{S}{2 \times \sin \frac{\pi}{N}} \tag{10}$$

where:

- *D* : distance between conductors (meters)
- *A* : Cross-sectional area
- *N* : Number of conducting reactors
- *r* : Radius of the conducting wire.

Transmission Line Capacitance

Capacitance in a transmission line arises due to the potential difference between the conductors. This causes the conductor to become charged, similar to what happens to the plates of a capacitor when there is a potential difference between them. The capacitance between parallel conductors is a fixed value that depends on the dimensions and distance between the conductors. Suppose alternating voltage is applied to a transmission line. In that case, charge will flow in the conductors at each point, increasing or decreasing in line with the instantaneous voltage change between the conductors. The current produced by the charge flow is called the channel charging current. This charging current flows in the transmission line even when the line is open.

This phenomenon impacts the reduction of voltage along the line, the quality of the efficiency and power factor of the line, and the overall stability of the system in which the line is an essential component. If we express the capacitance of the transmission line as *C*, we can describe it using the capacitive reactance in a three-phase single-circuit circuit, then use Equation 11. The unit of Cn is Farad per meter (F/m).

$$C_n = \frac{2\pi k}{\ln(\frac{GMD}{GMR})} \tag{11}$$

where:

- *k* : Permittivity of vacuum (8.85×10^{-12})
- *GMD* : Geometric Mean Distance
- *GMR* : Geometric Mean Radius.

The capacitive reactance per phase can be formulated in Equation 12 and Equation (13) as follows.

$$XC_n = \frac{1}{2\pi f \times C_n} \tag{12}$$

$$XCn = \frac{\ln(\frac{GMD}{GMR})}{2\pi^2 f \times k} \tag{13}$$

where:

- XC_n : Capacitive reactance per phase

f : frequency.

Shunt Reactor

A shunt reactor is a device that reduces the effects of line charging caused by long-distance transmission [5]. When a disturbance occurs on the transmission line, the auto recloser will operate to cut off the fault current. Reactors are often placed on buses with high or low voltage levels on transmission lines. This aims to increase system reliability, especially when the load is minimal [2]. Based on their function and location, they can be divided into [2]:

a. Series Reactor. The series reactor functions as a short-circuit current barrier to limit the magnitude of the fault current
b. Reactor Grounding. The grounding reactor is used to compensate for capacitive current disturbances and minimize the effects of current disturbances that occur due to line capacitance
c. Shunt Reactor. The shunt reactor acts as a source of inductive reactive power to compensate for capacitive reactive power that may arise due to the length of the transmission network. Figure 2 is a replacement circuit for installing a shunt reactor.

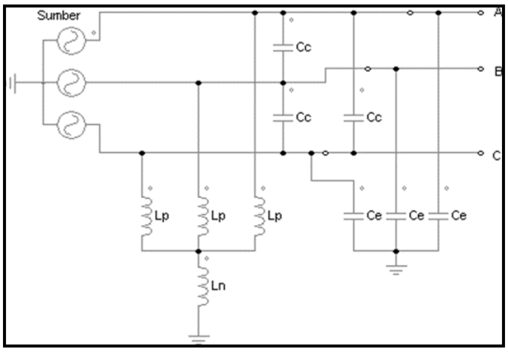

FIGURE 2. Replacement circuit for shunt reactor installation [2]

From Figure 2, the size of L_p (shunt reactor) is formulated in Equations 14, 15 and 16 [5]:

$$L_p = \frac{1}{\varpi^2 \times k \times (C_E + 3C_C)} \quad (14)$$

$$X_L = \frac{V^2}{Q} \quad (15)$$

$$X_L = 2\pi f L \quad (16)$$

where:

ω : Angular frequency
L_P : Shunt Reaktor
k : Constant (0.6)
C_C : Capacitance between phase wires
C_E : Capacitance of phase cable to ground.

It can be formulated using equation 17 [2] to find the equivalent capacitance between phases. Figure 3 is a shadow charge method for determining H12, H23, H31.

$$C_E = \frac{2\pi\varepsilon_0}{\ln(\frac{GMD}{GMR}) - \ln(\frac{\sqrt[3]{H_{12} \times H_{23} \times H_{31}}}{\sqrt[3]{H_1 \times H_2 \times H_3}})} \quad (17)$$

where:

C_E : Equivalent capacitance between phases
ε_0 : 8.654×10^{-12}

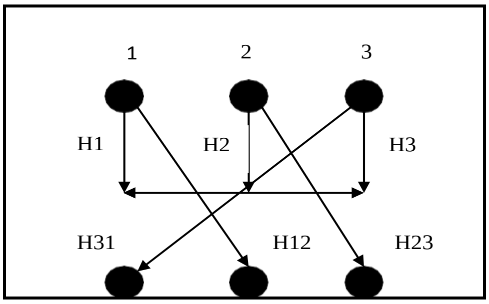

FIGURE 3. Shadow charge method [2]

Table 1 shows the Existing Muara Karang -Duri Kosambi Network System Generator data used in the Muara Karang CCPP system. It provides an overview of the types and rating values of generators that provide electrical energy to the Muara Karang CCPP. CCPP GT uses gas power, while CCPP ST uses steam power to drive a turbine.

TABLE 1. Muara Karang CCPP **Generator** Data

Generator	Rating Limit	Voltage (kV)	Active Power (MW)	Reactive Power (MVAR)
CCPP GT 1.2	90 MW	11.5	85	4.526
CCPP GT 1.3	90 MW	11.5	85	59.254
CCPP ST 1.0	124 MW	11.5	94.84	102.822

The system used is radial in the 500 kV Muara Karang – Duri Kosambi network system. In this system, the power flow starts from generation. It is continued through several transformers (transformers) to increase the voltage to reach customers or loads far from the generator. At CCPP Muara Karang, a step-up transformer increases the voltage from the generation before being distributed to the transmission network.

Furthermore, in the distribution network that will go to customers, a step-down transformer reduces the voltage to a level that suits the load requirements. Tables 2 and 3 are data on generating transformers and transformers that connect to various loads (distribution).

TABLE 2. Muara Karang CCPP transformer data

Transformer	Type	Active Power (kW)	Reactive Power (kVAR)	Current (Amp)
T1	Transf. 2W	142570	6788.3	7166
T2	Transf. 2W	142570	6788.3	7166

In our research, peak load sampling at 18.00 was carried out from several substations we will use as samples. Details of the loading on each substation can be seen in Table 4.

TABLE 3. Distribution trafo

Transformer	Type	Active Power (MW)	Reactive Power (MVAR)	Current (Amp)
T3	Transf. 2W	83809.7	55705.2	118.2
T4	Transf. 2W	83809.7	55705.2	118.2
T5	Transf. 2W	56396.7	32080.4	76.24
T6	Transf. 2W	56396.7	32080.4	76.24
T7	Transf. 2W	40696	19286.4	180
T8	Transf. 2W	40696	19286.4	180
T9	Transf. 2W	55480.4	28208.3	254.6
T10	Transf. 2W	55480.4	28208.3	254.6
T11	Transf. 2W	84172.5	55414.7	394.5

TABLE 4. *Load* data

Load	Voltage (kV)	Active Power (MW)	Reactive Power (MVAR)	Current (Amp)
Load1	20	22,967	9,185	812,2
Load2	20	29,282	11,711	1025
Load3	20	43,922	17,566	1538
Load4	20	38,651	15,458	1367
Load5	20	38,651	15,458	1367
Load6	20	21,849	8,738	767
Lump3	20	59,5	36,875	2282

Initial simulation of the existing network

The initial simulation is carried out by entering the generator, transformer and load parameter values. The results of the voltage on each bus can be seen in Table 5. Table 5 shows that there has been a decrease in voltage on each bus. The yellow sign indicates that the bus has a voltage drop below the standard set by PLN (SPLN 95), which refers to the IEC 60038 standard [7].

TABLE 5. Results of load flow simulation on the bus before installing the shunt reactor

Bus ID	Voltage (kV)	PF (%)	Power	
			Active (MW)	Reaktive (MVAR)
GI CENGKARENG	17.584	92.9	100.27	40.101
GI DURI KOSAMBI	136.424	89.3	102.028	51.54
GI DURI KOSAMBI VVIP	17.713	87.2	81.349	45.613
GI GROGOL BARU	17.759	92.9	73.204	29.276
GIS CENGKARENG	134.346	89.1	100,514	51,105
GIS DURI KOSAMBI	139.999	86.8	156.382	89.555
GIS GROGOL BARU	137.078	90.4	73.326	34.75
EHVS DURI KOSAMBI	467.641	84.4	258.936	164.797
EHVS MUARA KARANG	477.428	88.4	264.238	139.414

For the initial parameters in calculating the voltage drop, we refer to Table 5. Equation 1 is used to find the network's apparent power value [8]. With P and Q, respectively, the active and reactive power of Extra High Voltage Substation Muara Karang is 264.238 MW and 139.414 MVAR. So, the apparent power (S) in the network is 298.937 MVA; meanwhile, to find the power factor value (cos φ) of the network, you can use Equation 2 [9]. From the calculation results for the power factor (cos φ), the power factor value is 0.884. With a value (cos φ) of 0.884, the current value using current data (I_{line}) obtained previously is 180.6 A. The R-value of the cable is 0.70504 Ω/km, while the reactance value of the cable is 16.353 Ω. To obtain the R_total value of the transmission cable using Equation 3, the transmission distance between Muara Karang – Duri Kosambi is 30 km. So, the value of R_{total} is 21.15 Ω. Because the Muara Karang – Duri Kosambi 500 kV transmission line is a short circuit, the value of capacitive reactance can be ignored [8].

Equation 4 is used to find the Z value. The channel impedance value is 26.734 Ω. Based on Table 5, the V_{RLine} value is 467.641 V, then use Equation 5 [8] and 6 [2]. The calculations using Equations 5 and 6 show that the values of V_R and V_S are 269992 V and 274820 V, respectively. So, by using Equation 7, the voltage drop value (ΔV) is obtained [6]. Thus, the value of the voltage drop (ΔV) obtained is 1.788% of the nominal value, namely 500 kV or 8940 V. This drop value results in voltage instability in the network, which becomes a load on the transmission line. This voltage instability can be seen in Table 5.

Shunt Reactor Design

The shunt reactor that will be designed in this research will be designed using calculations consisting of calculating the values of GMD, GMR, Phase Cable Capacitance, and Equivalent Capacitance between Phases [2]. If the voltage variation in the initial simulation exceeds the standard limits set previously [7], then one way to correct it is to install a shunt reactor on the receiving side (Duri Kosambi) [2].

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Because the ideal wire distance between phases for extra high voltage overhead lines is 13.2 m to avoid swing effects, which can cause flashover between phases [2], the wire distance between phases for 500 kV lines is 13.2 m. So D_{ab} = 13.2 m, D_{bc} = 13.2 m, D_{ac} = 26.4 m, while the height of the phase wire (H_1) used is 50 m, (H_2) is 50 m, and (H_3) of 50 m. The distance between the conductors is illustrated in Figure 4.

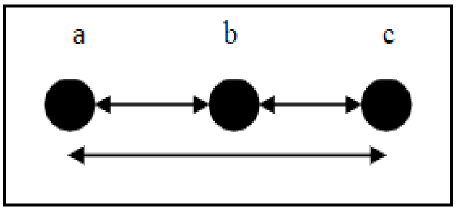

FIGURE 4. Distance between conductors a, b, and c [2]

By using Equation 8 and Equation 9, the GMD [10] value is 16.63 m. Meanwhile, for the GMR value, considering the number of conducting reactors N = 1 [2], the respective values of GMR and A are 0.668 m and 4.1 m.

Calculation of Phase Cable Capacitance and Equivalent Capacitance between Phases

After getting the value of GMD and GMR, you can get the value of the phase cable capacitance using Equation 11 [11], where for the value k =8.85×10^{-12} [11], then the value of C_n is 0.006 μF/m, (reactive) because the phase cable capacitance value obtained is too small, this value can be ignored [2]. Meanwhile, for the equivalent capacitance between phases, the values of H1, H12, H23, and H31 are needed first using the shadow charge method [2]. So the respective values of H1, H12, H23, and H31 are 99.124 m, 99.124 m, and 99.869 m. So, to obtain the equivalent capacitance between phases obtained using Equation 15 [2], the C_E value obtained is 4.51×10^{-12} F.

Shunt Reactor Calculations

After getting the equivalent capacitance value between phases, the Q value of the shunt reactor can be obtained by getting the value of L_p with Equation 14, then converting the L_p value using Equations 12 and 13 [2], where the value of L_p = 1404 H. After that, after converting it with Equation 15, where L = 1404/3 = 468 H, the value X_L = 146,952 Ω is obtained. Furthermore, the Q value of the shunt reactor using equation 14 (value of V = 500 kV) is 164.8 MVAR.

By previous calculations, the designed shunt reactor value is 164.8 MVAR. After obtaining the required shunt reactor value, the reactor will be installed on the receiving side of the Muara Karang CCPP, namely on the Extra High Voltage Substation Duri Kosambi 500 kV bus side. Figure 5 shows the results of running load flow from adding a shunt reactor with a value of 164.8 MVAR.

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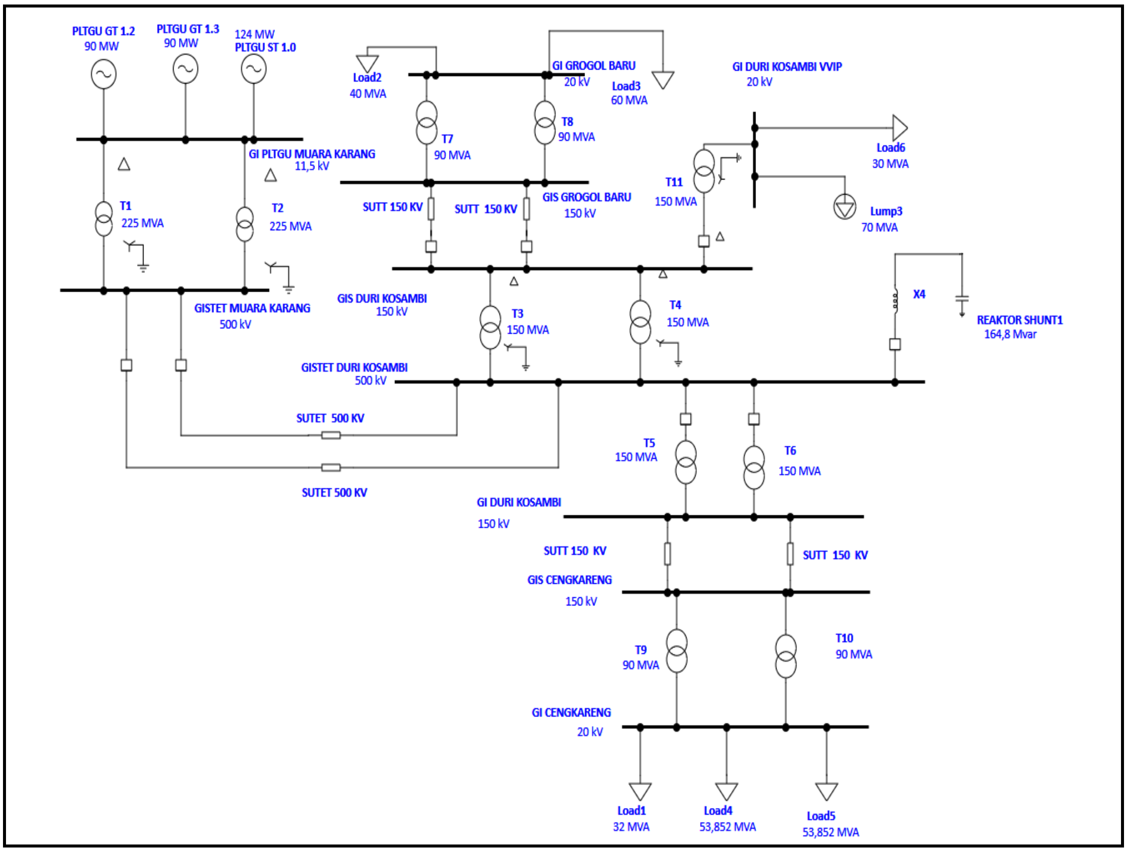

FIGURE 5. Transmission design by adding a shunt reactor.

RESULTS AND DISCUSSION

The results are given in figure 6, and the results for voltage and power can be seen in table 6. We compare the important parameters of the design results with those before the shunt reactor. We highlight yellow for significant results that are problematic in this research.

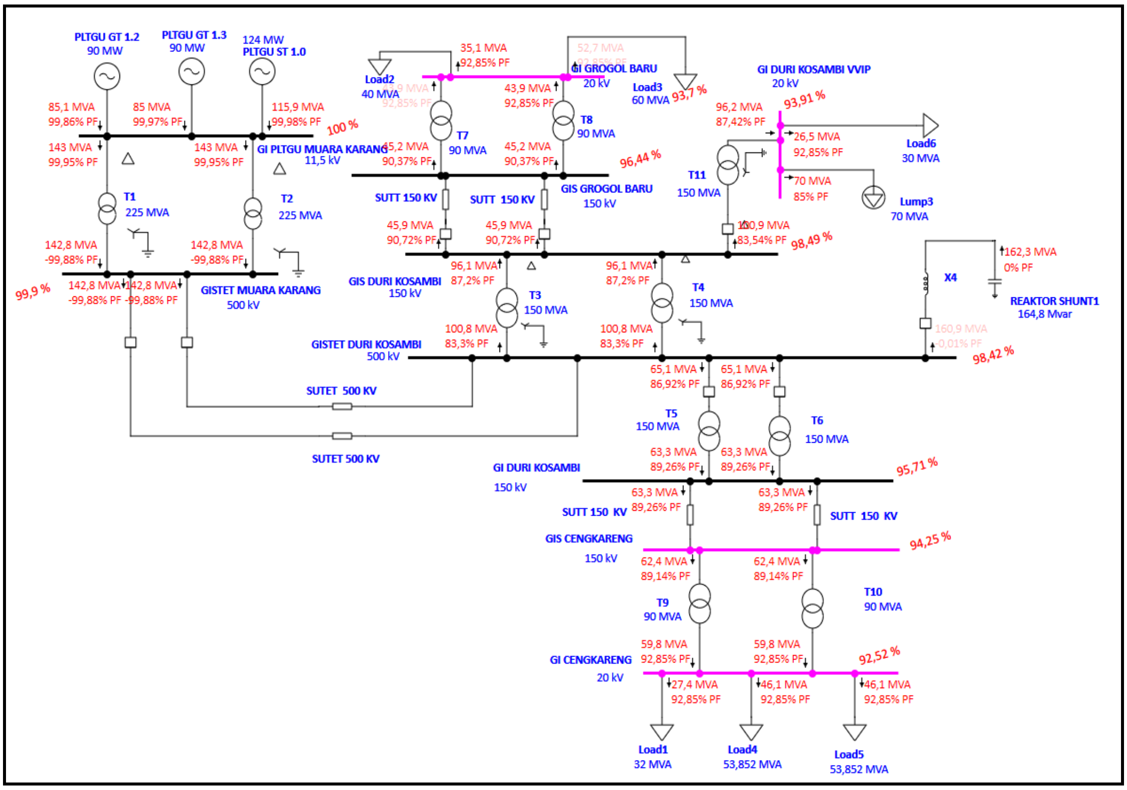

FIGURE 6. Load flow analysis of shunt reactor design results.

TABLE 6. Voltage and power values after installation of reactor shunt.

Bus ID	Voltage (kV)	Load	
		Active (MW)	Reactive (MVAR)
GI CENGKARENG	18.504	111	44.404
GI DURI KOSAMBI	143.558	112.977	57.071
GI DURI KOSAMBI VVIP	18.781	84.06	46.698
GI GROGOL BARU	18.74	81.519	32.602
GIS CENGKARENG	141.371	111.3	56.6
GIS DURI KOSAMBI	147.736	167.584	94.1
GIS GROGOL BARU	144.653	81.654	38.7
EHVS DURI KOSAMBI	492.094	281.129	175.9
EHVS MUARA KARANG	499.484	285.344	14

Voltage Analysis on Transmission Lines

After obtaining the simulation results, a stress analysis was carried out on the shunt reactor. In Figure 6, it can be seen that the decrease in voltage, which previously affected voltage stability, has now reached a level of stability. This is marked in pink on buses that were previously red. This means that the voltage on the bus is still within the tolerance limits set by PLN [7]. The voltage drop calculation results are given in table 7.

TABLE 7. Voltage drop calculation value.

Parameter	Value
Power on	285.687 MVA
Power Factor Cosφ	0.998
R_{Total}	21.15 Ω
Impedance (Z)	24.516 Ω
V_{Rline}	492094 V
V_R	284110 V
V_S	284506 V
ΔV	0.139%

A voltage drop of 0.139% after installing the shunt reactor indicates that the impact of installing the shunt reactor can increase the voltage. In contrast, the condition before the shunt reactor was installed experienced a voltage drop of 1.788% with a difference in voltage drop of 1.649%, so the voltage on the line decreased to 0.139%. %. Table 8 shows the results of network voltage measurements.

TABLE 8. Comparison of voltage before and after installing the reactor

Bus ID	Voltage (kV)		
	Before	After	IEC 60038 standard
GI CENGKARENG	17.584	18.504	18 - 22
GI DURI KOSAMBI	136.424	143.558	135 - 165
GI DURI KOSAMBI VVIP	17.713	18.781	18 - 22
GI GROGOL BARU	17.759	18.74	18 - 22
GIS CENGKARENG	134.346	141.371	135 - 165
GIS DURI KOSAMBI	139.999	147.736	135 - 165
GIS GROGOL BARU	137,078	144.653	135 - 165
EHVS DURI KOSAMBI	467.641	492.094	450-550
EHVS MUARA KARANG	477.428	499.484	450-550

Analysis of Transmission Line Conditions Before Reactor Installation

Figure 7 shows an analysis of the Power Flow to the Generator after simulation by adding a shunt reactor. A disturbance occurred on the CCPP GT 1.3 generator side, resulting in a decrease in the power factor value to 82.03%.

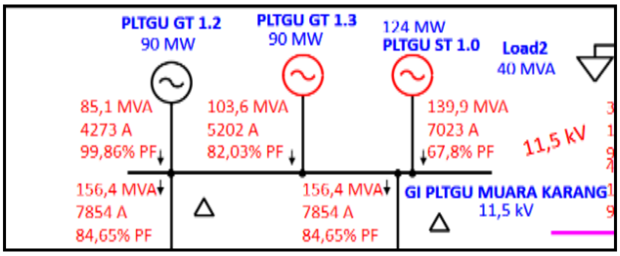

FIGURE 7. Generator at Muara Karang CCPP before reactor installation.

Regarding load substation buses, the same thing happened at several substations, in Figure 8 there is a substation with problems. One of the substation buses having problems is the GIS Cengkareng bus.

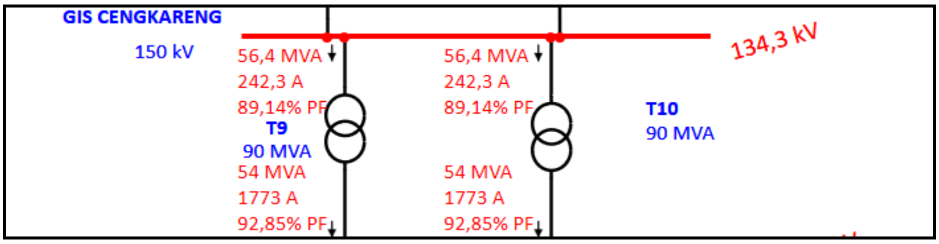

FIGURE 8. Cengkareng 150 kV GIS bus before shunt reactor installation

In Figure 8, the nominal voltage that should be distributed to the GIS Cengkareng load substation bus of 150 kV has experienced a voltage drop, with a *pu* value (per unit) of 89.56%.

Analysis of Transmission Line Conditions After Shunt Reactor Installation

For the generator after installing a shunt reactor on the receiving side, we carried out load flow analysis again, and the results showed the influence of installing a shunt reactor as seen in Figure 9.

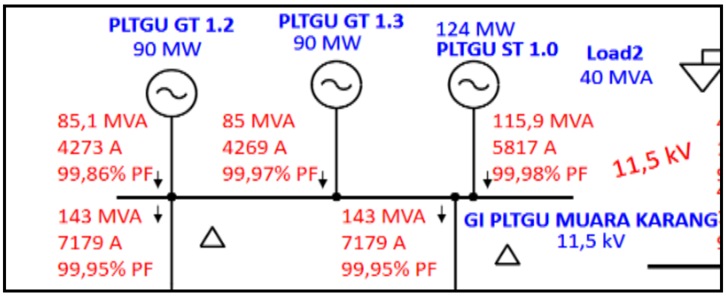

FIGURE 9. Muara Karang CCPP generator after shunt reactor installation.

In Figure 9, it can be seen that there has been an increase in performance on the CCPP GT 1.3 generator, which previously experienced a decrease in the power factor (pf) value. After installing the shunt reactor, the generator experienced an increase in power factor and reached a value of 99.7%.

Like the generator, the substation bus, which initially experienced a decrease in voltage, is now experiencing an increase in voltage. This change is the result of a shunt reactor intervention that aims to increase voltage stability in the system and ensure that the voltage received by the load substation remains within the limits set by PLN standards. Figure 10 is a substation bus experiencing an increase in voltage.

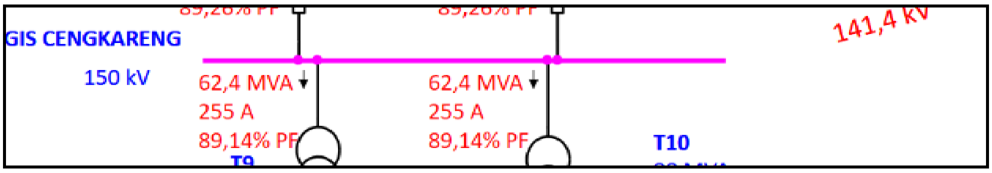

FIGURE 10. Cengkareng GIS substation bus after installation of shunt reactor.

Comparison of Conditions Before and After Shunt Reactor Installation

This comparison focuses on the effect on generators, load substation buses which initially experience a voltage drop, and loads. However, for short circuit conditions, there is no need to make a comparison because the maximum current conditions on the load substation bus remain the same before and after the installation of the shunt reactor. Table 9 is the simulation result on the CCPP Muara Karang generator.

TABLE 9. Comparison of Muara Karang CCPP generators

CCPP	Rating (MW)	Rating (kV)	MW		MVAR		Amp		% PF		Generation (%)	
			B	A	B	A	B	A	B	A	B	A
GT 1.2	90	11.5	85	85	4.526	4.526	4273	4273	99.86	99.86	94.4	94.4
GT 1.3	90	11.5	85	85	59.25	2.099	5202	4269	82.03	99.97	94.4	94.4
ST 1.0	124	11.5	94.84	115.84	102.82	2.099	7023	5817	67.8	99.98	76.5	93.4

In table 9, there was a decrease in the reactive power produced before installing the shunt reactor at Extra High Voltage Substation 500 kV Duri Kosambi with a value for absorbing reactive power of 164.8 MVAR. The reactive power produced by the Muara Karang CCPP generator was 166.02 MVAR and was then compensated by the shunt reactor to 157.878 MVAR after the shunt reactor was installed.

Apart from that, there was an increase in the pf (power factor) value of the generator, which resulted in the optimization of generation because the reactive power, which was previously large and became a load on the generator, can now be compensated for. Thus, the generator's performance can function according to its generating capacity. This can be seen from the performance of the CCPP S.T 1.0 generator, whose generation increased from around 76.5% to 93.4%. A comparison graph of the reactive power of the Muara Karang CCPP generator under conditions before and after the installation of the shunt reactor can be seen in figure 11.

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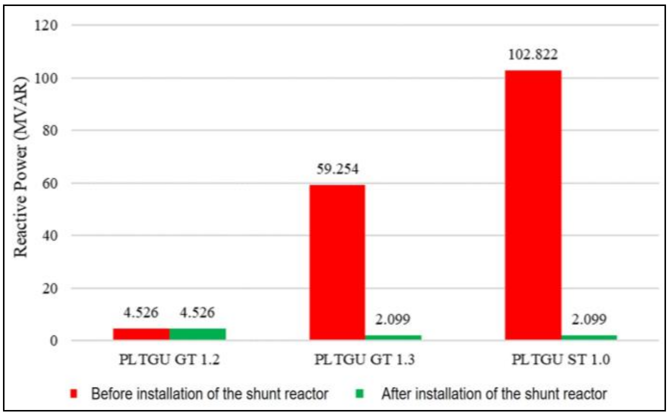

FIGURE 11. Comparison graph of reactive power on the CCPP Muara Karang generator

Meanwhile, figure 12 is a comparison graph of the power factor (pf) % of the CCPP Muara Karang generator under conditions before and after the installation of the shunt reactor.

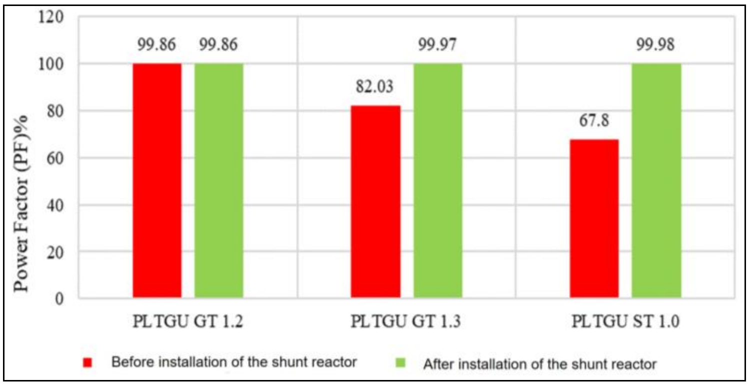

FIGURE 12. Power factor comparison graph for the CCPP Muara Karang Generator

In figure 12 it can be seen that there was an increase in the power factor on the CCPP GT 1.3 and CCPP ST 1.0 sides after the installation of a shunt reactor at EHVS Duri Kosambi 500 kV. As a result, generator performance is optimized according to capacity. The simulation results of loading on the substation of the Muara Karang – Duri Kosambi 500 kV network are presented in Table 10.

TABLE 10. Load on the substation before and after reactor installation

Bus ID	Load Before		Load After	
	MW	MVAR	MW	MVAR
GI CENGKARENG	100.27	40.101	111	44.404
GI DURI KOSAMBI	102.028	51.54	112.977	57.071
GI DURI KOSAMBI VVIP	81.349	45.613	84.06	46.698
GI GROGOL BARU	73.204	29.276	81.519	32.602
GIS CENGKARENG	100.514	51.105	111.3	56.6
GIS DURI KOSAMBI	156.382	89.555	167.584	94.1
GIS GROGOL BARU	73.326	34.75	81.654	38.7
EHVS DURI KOSAMBI	258.936	164.797	281.129	175.9
EHVVS MUARA KARANG	264.238	139.414	285.344	14

In table 11, an increase in load on each substation bus is observed due to installing a shunt reactor. Apart from that, the reactive power on each substation bus has also increased. The comparison graph of loads on this transmission line can be illustrated in Figure 13.

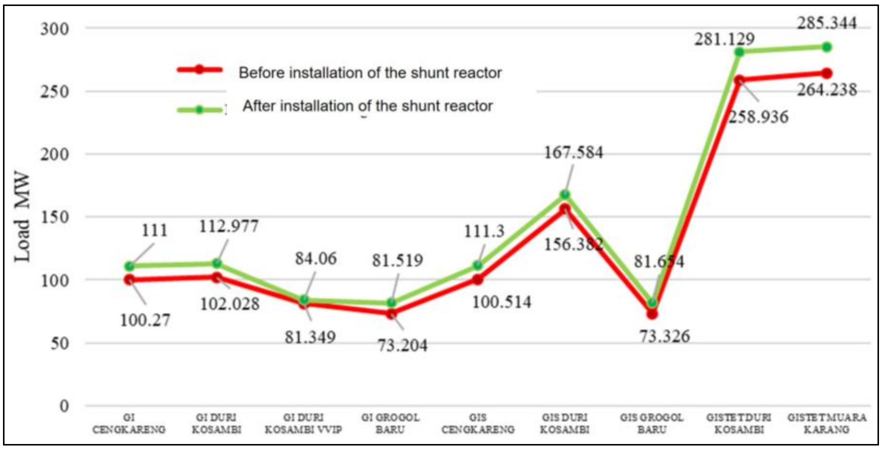

FIGURE 13. Load comparison graph at the substation

The graph in figure 13 illustrates the increase in load on each bus due to the reduction in reactive power on the generator side after the shunt reactor was installed. Meanwhile, a comparison of voltage before and after installation of the shunt reactor can be seen in Figure 14.

FIGURE 14. Voltage comparison graph (pu)

The graph in figure 14 shows that before the installation of the shunt reactor, there was a voltage drop below the tolerance limit of 0.9 (<90%) on the buses of GI Cengkareng, GI Duri Kosambi VVIP, GI Grogol Baru, and GIS Cengkareng. This condition exceeds the limits permitted by PLN standards [24]. However, after the shunt reactor was installed at EHVS Duri Kosambi, there was an increase in voltage on the buses of GI Cengkareng, GI Duri Kosambi VVIP, GI Grogol Baru, and GIS Cengkareng. This shows that installing a shunt reactor on the power receiving side, namely EHVS Duri Kosambi can significantly increase voltage stability on buses that previously experienced voltage problems.

CONCLUSIONS AND RECOMMENDATIONS

The value of the shunt reactor to compensate for the reactive power produced at CCPP Muara Karang is 164.8 MVAR, and the reactive power that can be compensated is 157.878 MVAR. Before installing the shunt reactor, a voltage drop on the 500 kV Muara Karang – Duri Kosambi transmission line was 1.788%. After installing the shunt reactor the voltage drop became 0.139%. There was an improvement in voltage of 1.649%. The short circuit current disturbance at GI Grogol Baru produces a short circuit current value of 16.2375 kA ∠-80.95° for the three-phase short circuit current value. In contrast, the single-phase short circuit current value to the ground is 20.462 kA ∠-82.02081 ° when the load on the Grogol Baru GI is 100 MVA (full load). Before installing the voltage shunt reactor on buses, GI Cengkareng had a pu value of 87.92%, GI Duri Kosambi VVIP had a pu value of 88.57%, GI Grogol Baru had a pu value of 88.79%, and GIS Cengkareng had a pu value of 88.79%. 89.56%. Then after installing the shunt reactor, the voltage value on the bus increased. Cengkareng GI has a pu value of 92.52%, Duri Kosambi VVIP GI has a pu value of 93.91%, Grogol Baru GI has a pu value of 93.7%, and Cengkareng GIS has a pu value of 94.25%.

The power factor of the GT 1.3 Generator and ST 1.0 Generator has a power factor value of 82.03% for the GT 1.3 Generator and 67.8% for the ST 1.0 Generator, respectively. After installing the shunt reactor, the generator experienced an increase in the power factor value with values of 99.7% for the GT 1.3 Generator and 99.8% for the ST 1.0 Generator, respectively. So that the voltage produced by the generator to the network becomes more stable. There is voltage stability on the 500 kV transmission line between Muara Karang - Duri Kosambi due to the use of shunt reactors on EHVS Duri Kosambi because there is no voltage drop on the Muara Karang - Duri Kosambi network that exceeds the predetermined standard limit (SPLN 95). This can maintain the reliability of the Extra High Voltage Substation Muara Karang 500 kV transmission line.

This research suggests that only a certain number of substations are used as samples. However, for further research, it is recommended that all substations connected to CCPP Muara Karang be used. The aim is to identify the reliability and stability of the 500 kV transmission line after the construction between Muara Karang and Duri Kosambi is completed. The installation of a shunt reactor needs to be adjusted to reduce or increase the load that will occur in the future. Thus, future research will provide a more comprehensive picture of the impact of using a shunt reactor on the system as a whole.

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