

Analysis of Compensator Requirements in the Grid System with Variation Load

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ABSTRACT: Reactive power management and voltage control are critical challenges in modern power systems, particularly in extra high voltage (EHV) networks operating under low loading conditions. This study analyzes the requirement and placement of reactive power compensators in the 275 kV Sulbagsel transmission system based on the RUPTL 2025–2034 planning scenario using DlgSILENT PowerFactory.

The system exhibits low transmission line loading, resulting in dominant capacitive effects due to line charging, which leads to overvoltage conditions. Power flow simulations under various load scenarios from 2023 to 2030 indicate that line loading remains below 10%, causing excessive reactive power in the system.

To maintain voltage within the permissible grid code limits, additional reactive power compensation is required. The results show that a total of 200 MVar shunt reactor is needed, optimally installed at Bungku and Kendari substations, each with a capacity of 100 MVar.

This study contributes to long-term reactive power planning in lightly loaded EHV systems and provides practical insights for transmission system development under high uncertainty of industrial load growth.

KEYWORDS: Reactive power, EHV system, compensator, voltage stability, power flow.

I. INTRODUCTION

The demand for electrical energy continues to increase annually, driven by population growth and industrial development. This trend is particularly evident on Sulawesi Island, where electricity demand is expanding to support economic activities and community needs. As load demand grows with uneven geographical distribution, proper power system planning becomes essential, including both generation expansion and transmission development, to ensure a balance between energy supply and demand.

Based on projected load growth and primary energy potential, long-term system planning indicates that a 500 kV transmission network would be required to meet all technical criteria. However, due to the slower load growth following the pandemic, the RUPTL 2025–2034 plan specifies that the Sulawesi system will continue to operate with 275 kV as the highest voltage level [1].

Operating at the 275 kV level, categorized as an extra high voltage (EHV) system, introduces technical challenges, particularly in maintaining voltage stability. Voltage stability is strongly influenced by the availability and proper management of reactive power within the system.

Reactive power plays a crucial role in AC power systems, as it directly affects voltage regulation and

system stability. Inadequate reactive power support may result in overvoltage or undervoltage conditions, reduced transmission capability, and, in severe cases, system instability [2]. Therefore, proper planning of reactive power resources is necessary to maintain reliable system operation.

Voltage control in power systems is achieved through coordinated regulation of several components, including generator excitation, transformer tap settings, and reactive power compensators such as shunt reactors and capacitors. In PLN systems, reactors are typically used to absorb excess reactive power and mitigate overvoltage due to their inductive characteristics, while capacitors are used to supply reactive power to address undervoltage conditions. However, the impact of these compensators is generally localized, making their placement a critical aspect of system planning.

Effective reactive power management plays a key role in ensuring voltage stability and secure system operation. Optimization of reactive power distribution involves controlling generator voltages, transformer taps, and the strategic placement of compensators. The location of these devices significantly affects voltage profiles and overall system performance [3], [4].

In transmission systems, reactive power is primarily supplied by synchronous generators, shunt capacitors, and reactors. During disturbances, the

active power flow tends to remain relatively stable, while reactive power flow can change significantly due to voltage variations. A reduction in voltage, for example, can increase reactive power losses and reduce the system's ability to maintain stability. Therefore, sufficient reactive power reserve must be available to respond to system disturbances. This reserve represents the capability of generators or compensators to support voltage under varying operating conditions [5].

Recent studies have explored the application of reactive power compensators for various purposes, including load balancing, industrial applications such as electric arc furnaces, and voltage stability enhancement [6]–[9]. However, limited attention has been given to compensator planning in lightly loaded EHV systems, where capacitive effects dominate due to line charging.

II. METHODS

A. SITE LOCATION

The main objective of this study is to determine the optimal location and sizing of reactive power compensators in the South Sulawesi power system (Sulbagsel). This study evaluates the technical feasibility of compensator implementation through comprehensive simulations, including power flow analysis under normal operating conditions, short-circuit analysis, and transient stability assessment. The system modeling, load projections, and generation assumptions are developed based on the RUPTL 2025–2034 planning data.

The Sulbagsel system is an interconnected network consisting of South Sulawesi (Sulsel), West Sulawesi (Sulbar), Central Sulawesi, and Southeast Sulawesi (Sultra). This interconnected system was established in 2019 following the integration of the 150 kV Sulsel–Sultra transmission network, including the 275/150 kV Wotu inter-bus transformer (IBT).

Future development plans include the construction of a transmission backbone in southern Sulawesi operating at 275 kV (Bakaru II – Palopo – Sidrap – Daya Baru – Punagaya). In addition, a 500 kV transmission system is planned for the southeastern region; however, it will initially operate at 275 kV (Wotu – Bungku – Andowia – Kendari) to reduce investment costs and accommodate gradual load growth.

In the Southeast and Central Sulawesi regions, electricity demand is significantly influenced by the rapid development of nickel processing industries (smelters), which require large and concentrated power consumption. This condition introduces additional challenges in system planning, particularly in

maintaining voltage stability and managing reactive power.

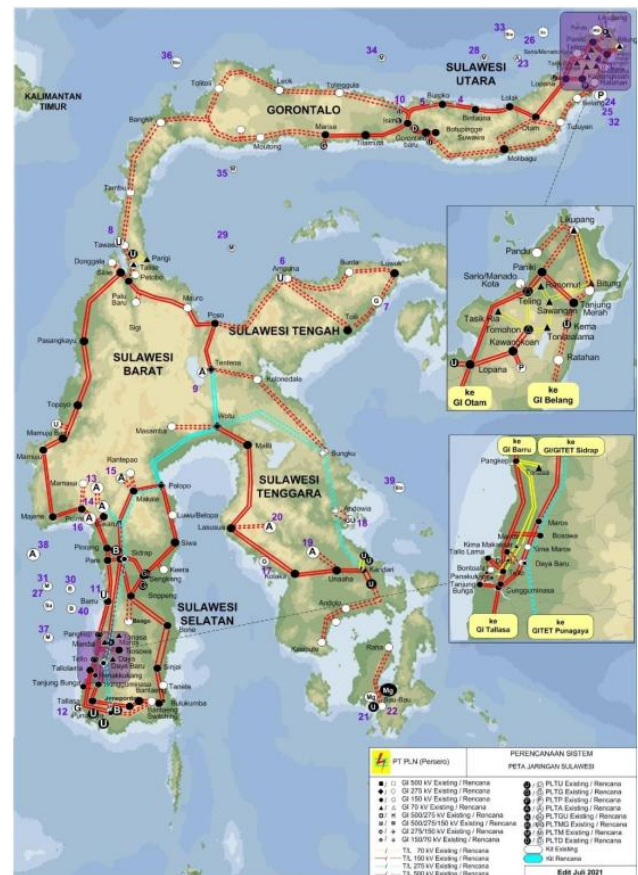


Fig 1. Sulbagsel Electrical Route

B. STUDY SCENARIO

In this study, power flow analysis is conducted under normal operating conditions for the period 2023–2030. The Sulbagsel system is assumed to operate at a transmission voltage level of 275 kV, consistent with the RUPTL 2025–2034 planning scenario. The system is subject to significant load uncertainty, particularly due to the integration and distribution of large-scale smelter loads.

According to the RUPTL 2025–2034, electricity demand projections in the Sulbagsel system have incorporated the anticipated contribution of smelter industries [1]. Based on these projections, power flow simulations are performed to evaluate system operating conditions, including bus voltage profiles and reactive power requirements at each substation.

The system model is developed based on existing conditions, including generation, transmission, and load configurations, and is further expanded according to the planned developments outlined in the RUPTL. All simulations are carried out using DIGSILENT PowerFactory, as illustrated in Fig. 2. This approach ensures a systematic evaluation of reactive power imbalance and voltage deviation under varying load conditions.

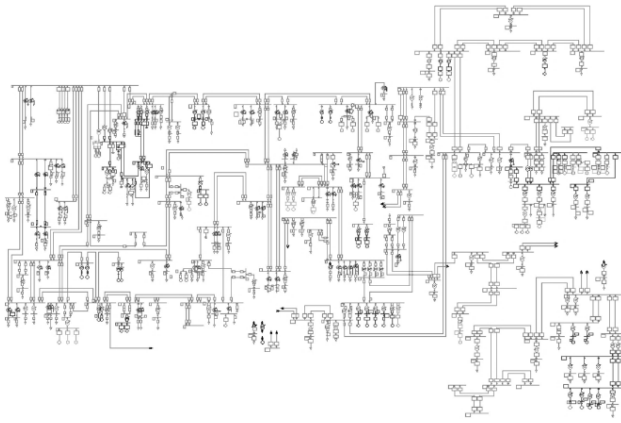


Fig 2. Sulbagsel Electricity System Model

C. SIMULATION METHOD

The output of active and reactive power plants in synchronous generators can be represented as: [10]

$$P_g = \frac{E_g V_g}{x_d} \sin \delta + V_g^2 \left(\frac{1}{x_d} + \frac{1}{x_q} \right) \sin 2\delta \quad (1)$$

$$Q_g = \frac{E_g V_g}{x_d} \cos \delta - V_g^2 \left(\frac{\sin^2 \delta}{x_d} + \frac{\cos^2 \delta}{x_q} \right) \quad (2)$$

Where is the generator terminal voltage based on the system per unit and , where is the field current. $V_g E_q = i_{gfd} i_{gfd}$ From the two equations above, the maximum corrective power with the field current limit is:

$$Q_{g \max} = -\frac{V_g^2}{x_d} + \sqrt{\frac{V_g^2 I_{gfd \max}^2}{x_d^2} - P_g^2} \quad (3)$$

Thus, the maximum reactive power of the generator is determined by the maximum field current. This relationship also shows that maximum reactive generation is a function of the terminal voltage. The maximum reactive power output must also meet the field current constraints as follows:[10]

$$Q_{g \max} = \sqrt{V_g^2 I_{gfd \max}^2 - P_g^2} \quad (4)$$

$$Q_{g \max \text{ res}} = Q_{g \max} - Q_g \quad (5)$$

where is the smaller of the two values obtained from (3) and (4), and is the output of reactive power under normal operating conditions. If it is lower than $Q_{g \max} Q_g Q_g Q_{g \max}$, then the reactive reserve of the generator is calculated by (5). However, if it reaches its limit, the reactive reserve is set to zero and varies as a function of the terminal voltage [10].

D. POWER FLOW METHOD

Power flow analysis is performed to analyze the power flow in the network, voltage in the busbar, loading of lines and transformers, system losses, etc.

This power flow simulation is a simulation that becomes the basis for further analysis such as short circuit analysis, transient stability analysis, and frequency stability analysis.

For simulation of this power flow using the Newton-Rapshon method. To apply the Newton-Rapshon method to the solution of the power flow equation, the bus voltage and line admittances are made in polar form, and the equation is obtained [11]:

$$P_i = |V_i|^2 (i_{ii} + \sum_{n \neq i}^N |V_n Y_{in}| \cos(\theta_{in} + \delta_n - \delta_i) \quad (6)$$

$$Q_i = |V_i|^2 B_{ii} - \sum_{n \neq i}^N |V_n Y_{in}| \sin(\theta_{in} + \delta_n - \delta_i) \quad (7)$$

Analysis of this power flow is performed on two conditions, namely scenarios *peak load* and scenarios *off-peak load*. All power flow simulation conditions must meet the criteria set out in *grid code/ Power System Network Rules*. In this case, the system voltage must be maintained within the limits according to the Sulawesi Electric Power System Network Rules contained in the Decree of the Minister of Energy and Mineral Resources of the Republic of Indonesia Number 20 of 2020 concerning Electric Power System Network Rules (*Grid Code*). In the Network Rules, it is stated that the system voltage must be maintained within the following limits:

Tbl 1. Normal Voltage Limitation [12]

Nominal Voltage	Normal Conditions
500 kV	+5%, -5%
275 kV	+5%, -5%
150 kV	+5%, -10%
66 kV*	+5%, -10%

From this power flow simulation, the state of a system in normal operating conditions will be obtained When the 275 kV system is operated, the analysis will focus on the EHV substation. As written in the 2025-2034 RUPTL, the projection electricity demand in the Sulbagsel System has taken into account the load of the smelter that will enter.

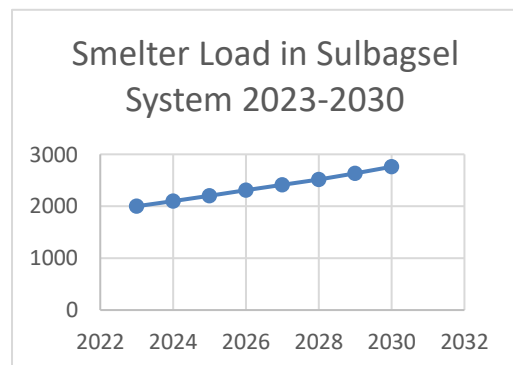


Fig 3. Smelter load projection

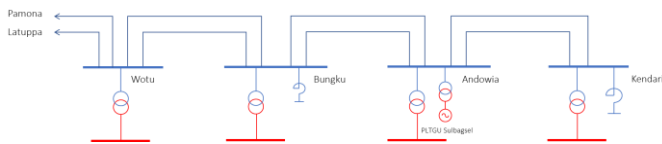


Fig 4. SLD of Wotuhungku – Bungku – Andowia – Kendari EHV

III. RESULT AND DISCUSSION

A. POWER FLOW ANALYSIS

The results of this study primarily focus on the loading of the 275 kV transmission lines along the Wotuhungku–Bungku–Andowia–Kendari substations. The analysis indicates that bus voltages at all substations remain within the permissible operating limits specified by the Sulawesi Grid Code. This condition confirms that the system operates within acceptable voltage constraints despite varying load scenarios.

Tbl 2. Power Flow Result

Tahun	Wotuhungku-Bungku		Bungku-Andowia		Andowia-Kendari	
	Transfer (MW)	Loading (%)	Transfer (MW)	Loading (%)	Transfer (MW)	Loading (%)
2023	58.01	2.56	52.41	2.61	-	-
2024	128.14	4.41	145.19	5.03	100.91	3.49
2025	128.23	4.32	140.78	4.97	101.63	3.48
2026	128.68	4.61	145.51	5.11	92.28	4.66
2027	138.77	5.42	153.85	5.75	86.87	4.45
2028	142.95	5.58	154.06	5.74	85.42	4.39
2029	150.14	5.73	152.44	5.88	88.48	4.41
2030	164.339	6.45	164.67	6.27	87.45	4.13

The simulation results indicate that all bus voltages remain within the permissible limits specified by the Sulawesi Grid Code. Despite this, the loading of the 275 kV transmission corridor along Wotuhungku–Bungku–Andowia–Kendari remains relatively low, with a maximum loading of approximately 11%. This condition suggests that the system operates under lightly loaded conditions, which may lead to dominant capacitive effects due to line charging.

In 2023, the transmission segments Wotuhungku–Bungku and Bungku–Andowia are in operation, while the Andowia–Kendari segment is not yet commissioned and is scheduled for commercial operation in 2024. Under this condition, power flow is primarily directed from GITET Wotuhungku toward GITET Andowia, with a transfer of approximately 60 MW. Although a relocated combined-cycle power plant (PLTGU) is available at Andowia, it is not dispatched in the simulation due to its relatively higher generation cost compared to other available units.

In 2024, the commissioning of the Andowia–Kendari transmission segment completes the 275 kV transmission corridor. This development enables increased power transfer toward GITET Kendari, reflecting improved system connectivity and load supply capability.

For the period 2025–2030, not all generation units are operated simultaneously due to the presence of a reserve margin, which ensures system reliability during contingencies or maintenance conditions. In this study,

the Subagsel PLTGU is not dispatched due to its higher operating cost. As a result, power transfer from GITET Wotuhungku toward GITET Kendari increases progressively over time, driven by continuous load growth in the system.

B. TRANSIENT ANALYSIS

Transient stability analysis is performed to evaluate the angular stability of generators under short-circuit disturbances. In this study, a fault is applied at the midpoint of the transmission line and cleared after 100 ms, in accordance with the Sulawesi Grid Code, without automatic reclosing. System instability is identified when one or more generators lose synchronism with the rest of the system.

The primary parameter evaluated is the first swing of the generator rotor angle, as it represents the critical period for transient stability assessment. In addition, bus voltage responses are also analyzed to observe system recovery following disturbance clearance.

The simulations are conducted for the period 2023–2030 under two types of fault conditions: single-phase-to-ground faults and three-phase faults. Each fault is evaluated under two contingency scenarios:

- N-1: fault in one transmission circuit
- N-2: simultaneous fault in both transmission circuits

To represent the most critical operating condition, the analysis focuses on the scenario with the highest

power transfer. Based on the power flow results, the maximum loading occurs in 2028 on the Wotu–Bungku transmission segment. Therefore, this condition is selected as the worst-case scenario for transient stability evaluation.

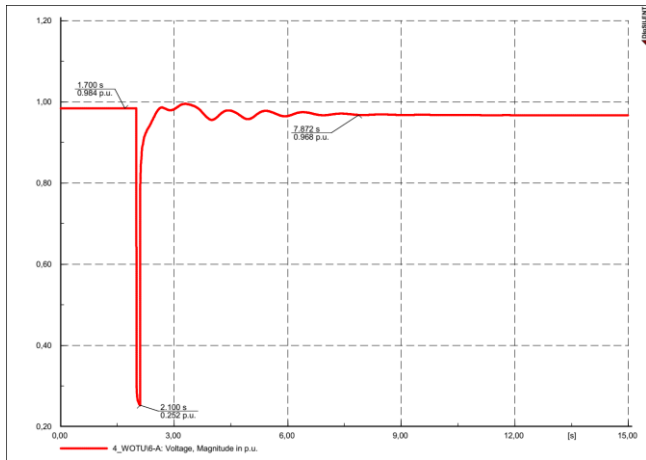


Fig 5. Voltage (pu) – N-1 Short Circuit event in Wotu – Bungku 275 kV

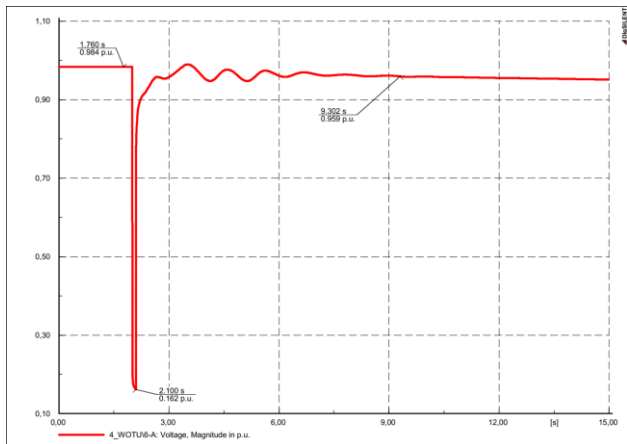


Fig 6. Voltage (pu) – N-2 Short Circuit event in Wotu – Bungku 275 kV

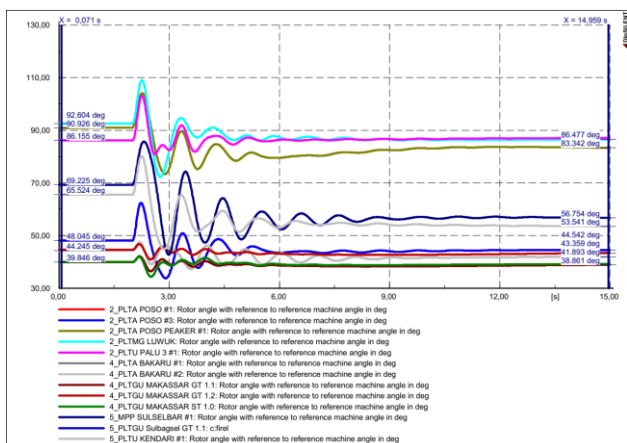


Fig 7. Rotor angle (deg) – N-1 Short Circuit event in Wotu – Bungku 275 kV

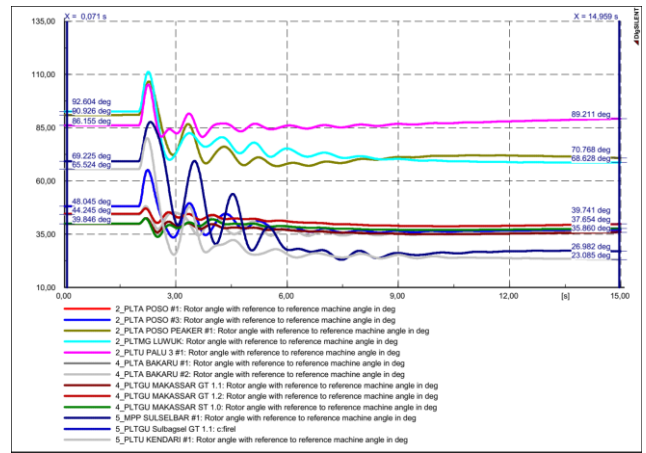


Fig 8. Rotor angle (deg) – N-2 Short Circuit event in Wotu – Bungku 275 kV

The figure illustrates the voltage at Wotu and the generator rotor angle during a single-phase-to-ground fault on the Wotu–Bungku transmission segment. This type of disturbance is selected because it is the most common fault in transmission systems, particularly in extra-high voltage networks.

The simulation results reveal a clear difference between disturbances occurring in a single transmission circuit (N-1) and those occurring simultaneously in both circuits (N-2). The N-2 contingency produces a more severe impact on system stability, as indicated by deeper voltage drops and larger rotor angle deviations.

At Wotu substation, the voltage decreases to approximately 0.25 p.u. under an N-1 condition. In contrast, during an N-2 condition, the voltage drops further to about 0.162 p.u., indicating a more critical disturbance scenario.

During the fault, the generator rotor angle accelerates due to the sudden imbalance between mechanical input power and electrical output power. This behavior is reflected in the first swing of the rotor angle, which increases significantly relative to the reference angle. After the first swing, the rotor angle continues to oscillate with decreasing amplitude and eventually settles into a new steady-state condition, indicating that the system remains transiently stable.

C. REQUIREMENT OF COMPENSATOR ANALYSIS

In this study, Wotu, Bungku, Andowia, and Kendari Substations will be connected through an extra high voltage transmission circuit. The extra high voltage studied is fixed operation in 275 kV. The tower construction will not significantly affect the capacitance and impedance of the transmission line so that it does not have a direct impact on the difference in reactor requirements. In the RUPTL load, the line

loading is very low so that the transmission line is capacitive.

Tbl 3. Reactor Requirements

Substation	Voltage	Status	2023	2024	2025	2026	2027	2028	2029	2030
GI Mamuju	150 kV	Existing	50	50	50	50	50	50	50	50
GI PLTMG Luwuk	150 kV	New	50	50	50	75	75	75	75	75
GITET Bungku	275 kV	New	100	100	100	100	100	100	100	100
GITET Kendari	275 kV	New	-	-	-	100	100	100	100	100
Total (MVar)			150	200	200	325	325	325	325	325

In addition to the need for reactive power compensators needed to compensate for line charging / capacitive current generated from Wotu - Bungku - Andowia - Kendari, of course, the need for capacitors / reactors to maintain voltage within the range regulated in the Sulawesi grid code will also be reviewed, especially due to additional smelter loads.

In addition to operating the reactor at GI Mamuju, an additional reactor is needed at PLTMG Luwuk of 50 MVar starting in 2023 and becoming 75 MVar

starting in 2026. In addition to the two reactors at the 150 kV level, reactors are needed at GITET 275 kV, namely at GITET Bungku 275 kV with a capacity of 100 MVar starting in 2023 and at GITET Kendari 275 kV sebesar 100 MVar mulai tahun 2026.

For the RUPTL load, only a capacitor at 70 kV GI Power is needed to solve the substation undervoltage problem, as shown in Table Below.

Tbl 4. Additional Capacitor Requirements

Substation	Voltage	Status	2023	2024	2025	2026	2027	2028	2029	2030
GI Force	70 kV	Existing	20	20	20	20	20	20	20	20

IV. CONCLUSION

Maintaining voltage stability in a power system requires coordinated control of several components, including transformer tap settings, generator excitation, and reactive power compensators such as shunt reactors and capacitors. In PLN systems, these compensators play a key role in voltage regulation. Shunt reactors are used to absorb excess reactive power and mitigate overvoltage due to their inductive characteristics, while capacitors are utilized to supply reactive power and correct undervoltage conditions.

In the Sulbagsel system, the Wotu, Bungku, Andowia, and Kendari substations are interconnected through a 275 kV extra high voltage (EHV) transmission network. Under this operating condition, the system experiences low loading levels, leading to dominant capacitive effects from transmission line charging.

To maintain system voltage within the permissible limits defined by the grid code, additional reactive power compensation is required, particularly due to the influence of smelter loads and EHV transmission operation. The analysis indicates that a total of 200 MVar shunt reactor is needed, optimally installed at Bungku and Kendari substations, each with a capacity of 100 MVar. This configuration effectively compensates for the reactive power generated by the Wotu–Bungku–Andowia–Kendari transmission line.

This study provides practical insights for reactive power planning in lightly loaded EHV transmission systems under high uncertainty of industrial load growth.

REFERENCES

- [1] PLN, “Electricity Supply Business Plan (RUPTL),” 2025
- [2] M. N. I. Sarkar, L. G. Meegahapola, and M. Datta, “Reactive power management in renewable rich power grids: A review of grid-codes, renewable generators, support devices, control strategies and optimization Algorithms,” *IEEE Access*, vol. 6, pp. 41458–41489, May 2018, doi: 10.1109/ACCESS.2018.2838563.
- [3] M. N. I. Sarkar, L. G. Meegahapola, and M. Datta, “Reactive power management in renewable rich power grids: A review of grid-codes, renewable generators, support devices, control strategies and optimization Algorithms,” *IEEE Access*, vol. 6, pp. 41458–41489, May 2018, doi: 10.1109/ACCESS.2018.2838563.
- [4] H. Jiang, M. He, L. Liu, H. Ji, and D. Shan, “Reactive power compensation devices optimization based on improved ant colony algorithm,” in *Proceedings - International Conference on Electrical and Control Engineering, ICECE 2010*, 2010, pp. 1523–1526. doi: 10.1109/iCECE.2010.376.



- [5] F. Dong, B. H. Chowdhury, M. L. Crow, and L. Acar, "Improving voltage stability by reactive power reserve management," *IEEE Transactions on Power Systems*, vol. 20, no. 1, pp. 338–345, Feb. 2005, doi: 10.1109/TPWRS.2004.841241.
- [6] A. Alsulani, M. Bongiorno, and K. Srivastava, "Balancing Asymmetrical Load Using a Static Var Compensator," *5th IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, 2014.
- [7] A. A. Nikolaev, G. P. Kornilov, T. R. Khramshin, I. Akcay, and Y. Gok, "Application of static Var compensator of ultra-high power electric arc furnace for voltage drops compensation in factory power supply system of metallurgical enterprise," in *Proceedings - 2014 Electrical Power and Energy Conference, EPEC 2014*, Institute of Electrical and Electronics Engineers Inc., Feb. 2014, pp. 235–241. doi: 10.1109/EPEC.2014.18.
- [8] Z. Xu, Y. Chen, B. Zhai, G. Chen, Q. Yang, and J. Chen, "A Comparative Study of the Virtual Synchronous Compensator on the Voltage Stability Enhancement," in *2022 International Conference on Renewable Energies and Smart Technologies, REST 2022*, Institute of Electrical and Electronics Engineers Inc., 2022. doi: 10.1109/REST54S687.2022.10023396.
- [9] G. Reed, M. Kempeker, and D. Sullivan, "Technical requirements and design of the Indianapolis power & light 138 kV southwest static var compensator," 2016.
- [10] C. W. Taylor, *Power System Voltage Stability*. 1994.
- [11] J. J. Grainger and W. D. Stevenson JR, "POWER SYSTEM ANALYSIS," 1994.
- [12] "Permen ESDM RI No 20 Tahun 2020," 2020

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