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Steady-State Security and Frequency Stability Assessment of the Ambon Power System Expansion Plan

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RADITYA JAYESWARA, CANDRA FEBRI NUGRAHA, MUHAMMAD ZAKI MUHARRAM, DAVID DANINDRA ADI RAJASA

Departemen Teknik Elektro dan Informatika, Sekolah Vokasi,
Universitas Gadjah Mada, Indonesia
Email: candra.febri.nugraha@ugm.ac.id

ABSTRAK

Penelitian ini mengevaluasi keamanan kondisi tunak serta stabilitas frekuensi rencana pengembangan sistem tenaga listrik Ambon berdasarkan RUPTL 2025–2034. Evaluasi dilakukan dengan mempertimbangkan penambahan pembangkit dan pengembangan transmisi 150 kV. Simulasi dilakukan menggunakan DIgSILENT PowerFactory melalui analisis aliran daya, kontingensi N-1, hubung singkat tiga fasa, dan stabilitas frekuensi. Hasil menunjukkan seluruh tegangan bus berada dalam batas, dengan nilai terendah 0,992 p.u. Pembebanan saluran maksimum mencapai 25,86% pada kondisi normal dan 43,75% saat kontingensi N-1. Arus hubung singkat maksimum sebesar 8,7 kA, sedangkan nadir frekuensi terendah 49,725 Hz. Hasil ini menunjukkan bahwa rencana pengembangan sistem Ambon berdasarkan RUPTL memenuhi kriteria keamanan teknis.

***Keywords**: Analisis aliran daya, analisis hubung singkat, analisis kontingensi, RUPTL, sistem tenaga listrik Ambon, stabilitas frekuensi.*

ABSTRACT

This study evaluates the steady-state security and frequency stability of the Ambon power system expansion plan based on the 2025–2034 RUPTL. The evaluation considers generation additions and the development of the 150 kV transmission network. Simulations were performed using DIgSILENT PowerFactory through power flow, N-1 contingency, three-phase short-circuit, and frequency stability analyses. The results show that all bus voltages remain within the allowable limits, with the lowest value of 0.992 p.u. The maximum line loading reaches 25.86% under normal conditions and 43.75% during the N-1 contingency. The maximum short-circuit current is 8.7 kA, while the lowest frequency nadir is 49.725 Hz. These results indicate that the Ambon power system expansion plan based on the RUPTL satisfies the technical security criteria.

***Keywords**: Ambon power system, contingency analysis, frequency stability, power flow analysis, RUPTL, short-circuit analysis.*

1. INTRODUCTION

Ambon is an island in Maluku Province located in eastern Indonesia. Due to its geographic characteristics, the Ambon power system is not interconnected with a large power grid. Similar conditions exist in many power systems across eastern Indonesia. Increasing electricity demand requires comprehensive power system planning to determine generation and network infrastructure investments. **(Plaga et al., 2024)**. Such planning should support regional development objectives while ensuring affordability, reliability, and environmental sustainability **(Tumiran, et al., 2022)**.

Utilities and policymakers undertake generation expansion planning (GEP) and transmission expansion planning (TEP) to identify the optimal generation capacity additions over a planning horizon and the corresponding transmission infrastructure required to ensure secure system operation **(Saidi, 2022)**. In recent years, the global power sector has shifted toward more sustainable and resilient energy systems, making renewable energy utilization essential for meeting growing electricity demand while reducing greenhouse gas emissions. **(Shakerighadi et al., 2020)**.

Remote power systems such as Ambon rely heavily on costly fossil-fuel generation that must be transported over long distances, making the integration of local renewable energy sources (RESs) a priority **(Parera et al., 2026)**. Ambon has significant geothermal, biomass, solar, and wind potential. However, the intermittency of RESs, particularly solar and wind, poses challenges to system reliability and security **(Islam et al., 2024)**. The generation and transmission expansion plans for the Ambon power system have been outlined in the Electricity Supply Business Plan (RUPTL) **(PT PLN (Persero), 2025)**. However, comprehensive assessments of static operating conditions and dynamic stability are still needed to ensure the secure operation of the power system. These assessments are essential to ensure that the system can operate reliably under normal operating conditions and remain stable during disturbances or contingencies **(Emmanuel et al., 2020)**.

Several studies have incorporated power system analysis into transmission planning frameworks. Transmission expansion planning (TEP) models commonly employ AC load flow analysis to ensure that transmission lines operate within their thermal limits under both normal and contingency conditions **(Farrag et al., 2019)**. Load flow analysis has also been used in transmission expansion planning studies to verify whether a planned system satisfies technical requirements under both normal and single-contingency operating conditions **(Dhamala & Ghassemi, 2023)**. Moreover, with the increasing penetration of renewable energy sources, power flow and contingency analyses are widely used to assess system performance under large-scale wind power integration scenarios **(Sajadi et al., 2020)**.

Beyond load flow analysis, power system stability analysis is also a critical aspect of transmission planning. Power systems with high RES penetration are more susceptible to stability issues due to increased variability and reduced synchronous inertia **(Saha et al., 2023)**. A stability prediction approach based on simple stability-index criteria has been proposed to assess rotor angle stability in power systems with significant wind generation **(Chen et al., 2020)**. In addition, time-domain simulations have been applied to evaluate frequency stability in long-term planning, ensuring that the frequency nadir remains above the specified threshold under credible disturbance scenarios **(Tumiran et al., 2022)**.

Although previous studies have addressed generation expansion planning in isolated Indonesian power systems, limited attention has been given to the combined steady-state security and frequency stability assessment of Ambon power system expansion plan. In particular, the technical adequacy of the planned 150 kV transmission backbone and system frequency response under the loss of the largest generator has not been comprehensively evaluated. Therefore, this study contributes a simulation-based assessment framework that integrates power flow, N-1 contingency, short-circuit, and frequency stability analyses to verify the operational security of the planned Ambon system expansion. The objective of this research is to assess the technical feasibility and operational security of the proposed expansion plan, ensuring its capability to accommodate future load growth while maintaining system security and stability.

2. METHOD

2.1 Research Workflow

Power system expansion planning comprises generation expansion planning and transmission expansion planning **(Ahmadi et al., 2017)**. This research is conducted after the planning results have been established, as it focuses on evaluating the power system performance of the predetermined expansion plan. As a result, the load forecasting, GEP, and TEP are referring to the RUPTL document, with the planning horizon of 2025 to 2034. The overall workflow and assessment framework of this study are illustrated in Figure 1.

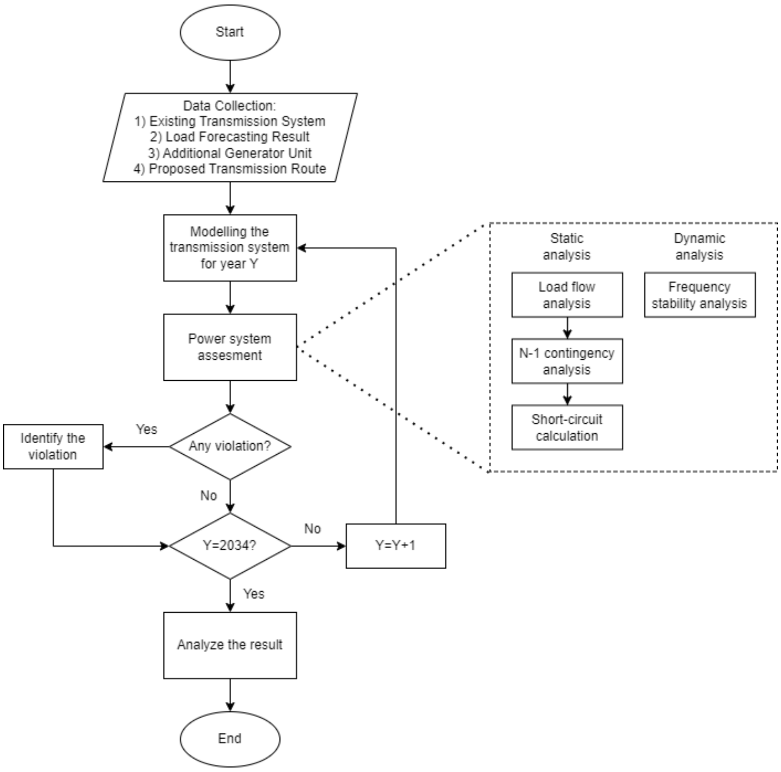

Figure 1. Research workflow for power system expansion planning assessment

Power flow analysis is employed to evaluate voltage profiles and component loading under normal operating conditions. Subsequently, N-1 contingency analysis is performed to assess the system's resilience to single-element outages, such as transmission lines or generators. Short-circuit analysis is conducted to determine fault current levels, which serve as the basis for selecting appropriate circuit breaker ratings. In addition, dynamic stability analysis focusing on frequency response is carried out to ensure system stability under severe disturbances. All analyses are performed for the planning scenarios of 2025, 2030, and 2034.

2.2 Ambon Power System Expansion Plan

Load growth forecasting is a critical component of electrical power system planning. The projected annual peak load of the Ambon power system is presented in Figure 2, indicating an average peak load growth rate of 3.61% over the 2025–2034 forecast period. This projection serves as the primary basis for determining generation capacity expansion. Ambon Island has diverse potential for new power plant development, and the planning of additional generation capacity refers to the RUPTL 2025-2034 document. Table 1 summarizes generation capacity, technology type, and commercial operation date (COD). The results indicate that gas-based generation provides the largest contribution to installed capacity, complemented by increasing penetration of renewable energy sources, particularly from solar photovoltaic (PV) and wind power plants.

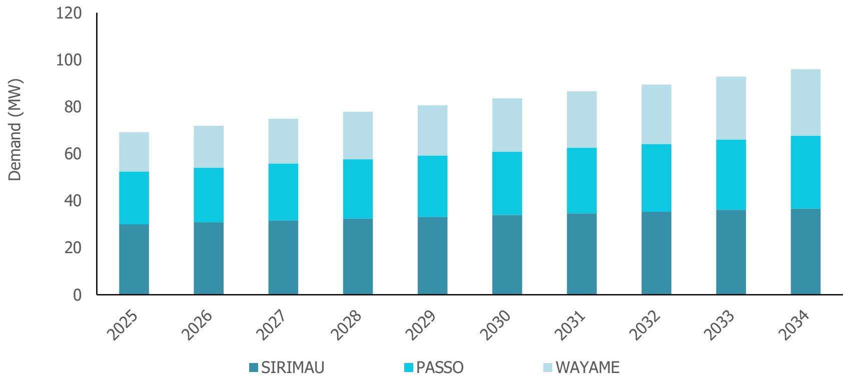

Figure 2. Forecasted peak load from 2025 to 2034

Table 1. Generator expansion plan for the 2025-2034 period (PT PLN (Persero), 2025)

Type	Site Name	Capacity (MW)	COD (year)
Gas Engine power plant	Ambon 2	2x25	2025
Gas Engine power plant	MPP Sambelia	30	2026
Solar PV power plant	Ambon (distributed quota)	30	2027
Solar PV Power Plant	Ambon (distributed quota)	10	2029
Geothermal power plant	Tulehu (FTP2)	2x10	2031
Wind power plant	Ambon (distributed quota)	30	2031
Solar PV power plant	Ambon (distributed quota)	10	2033

The transmission system development plan for Ambon Island is centered on a 150 kV high-voltage network serving as the system backbone. The transmission expansion plan refers to the RUPTL 2025–2034 document, with candidate transmission projects summarized in Table 2. Based on this plan, a total of approximately 30 km of new transmission circuits will be installed. The proposed transmission expansion is primarily intended to support the interconnection of new power plants and ensure adequate transmission capacity for future system operation.

Table 2. Transmission expansion planning for the 2025-2034 period (PT PLN (Persero), 2025)

From Bus	To bus	Voltage (kV)	Length (km)	COD (year)	Type
30 MW Solar PV Power Plant	Existing / Planned Ambon System Substation	150	10	2027	New, 2 cct, ACSR 1xHawk
Geothermal Power Plant (FTP Tulehu 2)	Incomer 1 Phi (Passo-Ambon)	150	10	2031	New, 2 cct, ACSR 1xHawk
Wind Power Plant	Existing / Planned Ambon System Substation	150	10	2031	New, 2 cct, ACSR 1xHawk

2.3 Power System Modelling

The Ambon power system is modeled using DIgSILENT PowerFactory, a power system simulation software based on the network and expansion planning data outlined in the RUPTL 2025–2034 document. The system single line diagram is presented in Figure 3. Figure 3(a) shows the 2025 system configuration, representing the initial network condition after the addition of the Ambon 2 gas-engine power plant. Figure 3(b) illustrates the 2030 configuration, which includes intermediate-stage generation additions and network expansion. Figure 3(c) shows the 2034 configuration, representing the final planning condition with the integration of geothermal, solar PV, and wind generation as well as the associated 150 kV transmission expansion. This model serves as the foundation for conducting power flow, short-circuit, contingency, and frequency stability analysis.

2.4 Assessment Method and Criteria

Power Flow Analysis

Load flow analysis is used to evaluate steady-state operating conditions, including bus voltage profiles, component loadings, and power factors. In practice, outages of generators or transmission lines can significantly alter power flows, leading to voltage deviations and overloads that may exceed permissible limits and degrade power supply quality. To assess system security under such disturbances, N-1 contingency analysis is performed by simulating the outage of a single system component. This analysis aims to identify potential overloads and voltage violations following contingencies. The allowable limits for voltage profiles and component loading under normal and N-1 conditions are summarized in

Table ***3***. The assessment criteria refer to the Indonesian Grid Code and adopt the voltage limits commonly used in power system planning studies **(Kementerian Energi dan Sumber Daya Mineral Republik Indonesia, 2020)**. In this study, the loading limits of transmission lines and transformers were defined as planning criteria based on utility operational and planning considerations for N-1 security assessment, with maximum allowable loading set at 50% under normal operating conditions and 100% under contingency conditions.

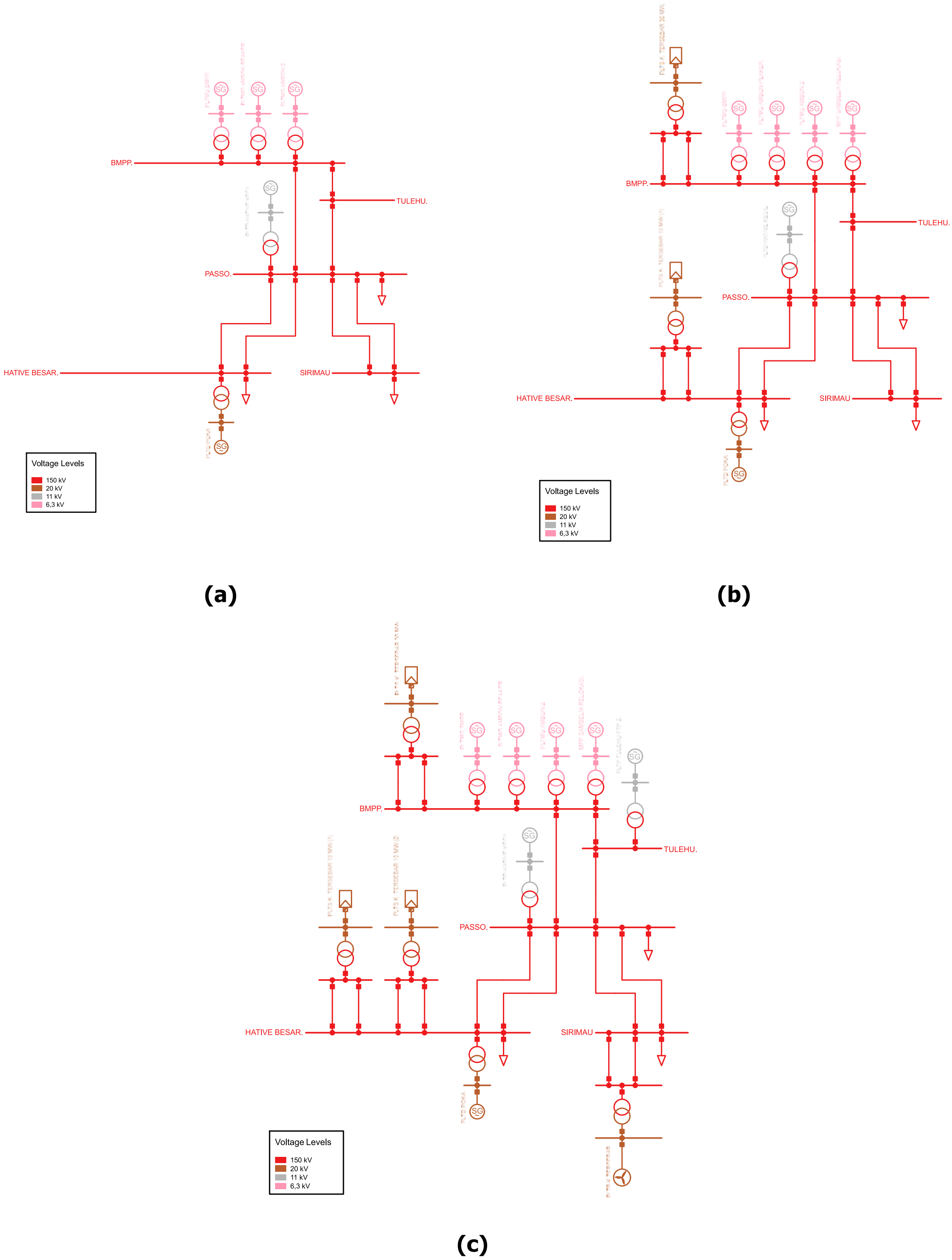

Figure 3. Single-line diagram of proposed expansion plan for (a) 2025, (b) 2030, and (c) 2034

Table 3. Allowable limits for voltage profile and thermal loading

Criteria	Allowable Value	
	Normal Condition	**Contingency N-1 Condition**
Voltage magnitude	≥0.9 p.u. and ≤1.05 p.u	≥0.9 p.u. and ≤1.05 p.u
Loading of the transformer and transmission line	≤50%	≤100%

Short Circuit Analysis

Power systems must be designed to operate safely under both normal and abnormal conditions, such as short-circuit events. Short-circuit analysis is therefore essential to determine fault current levels, ensure adequate protection coordination, verify system short-circuit strength, and select appropriate equipment ratings. Accordingly, this study applies three-phase short-circuit analysis to determine the maximum breaking current levels. The allowable short-circuit current limits for 70 kV and 150 kV voltage levels are summarized in Table 4.

Table 4. Allowable short-circuit current for each voltage level (Wijoyo et al., 2018)

Voltage Level (kV)	Short-Circuit Current (kA)
70	≤20
150	≤40

Frequency Stability Analysis

Frequency stability is analyzed to assess the system’s ability to maintain frequency within acceptable limits after disturbances. The primary parameter evaluated is the frequency nadir, defined as the minimum system frequency reached after a disturbance. The frequency nadir is an essential indicator of the system's frequency stability **(Nugraha et al., 2024).** In the Indonesian power system, the nominal frequency is 50 Hz; a frequency decline below 49.5 Hz requires manual load shedding, while a further drop below 49 Hz triggers automatic underfrequency load shedding relays. Figure 4 illustrates the system frequency response following a disturbance, including the frequency nadir and the corresponding load-shedding thresholds. Accordingly, this study examines whether the frequency nadir remains above the load shedding thresholds under a simulated generator outage scenario.

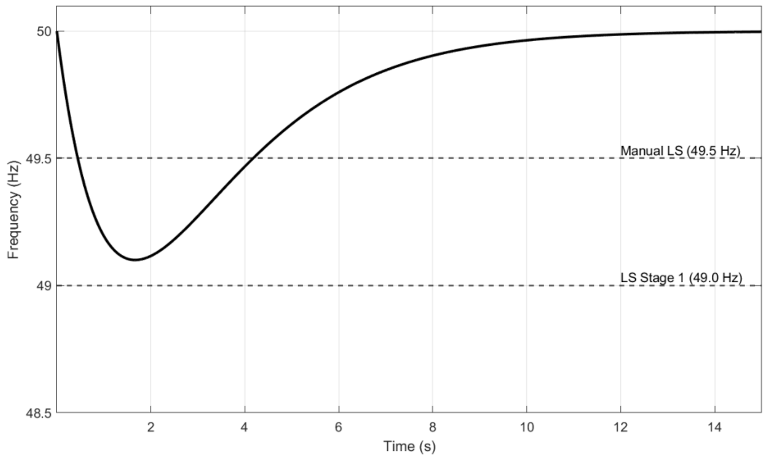

Figure 4. Frequency response and load-shedding thresholds following a generation outage

To ensure an accurate representation of frequency response, the frequency stability analysis employs a detailed system model based on the single-line diagram (SLD) of the studied power system. In this model, each generator is represented by a dynamic control model consisting of a governor and an automatic voltage regulator (AVR). Different governor and AVR models are implemented for each generation type to reflect variations in response speed, and inertia contribution. This modeling approach enables a more realistic simulation-based analysis of frequency nadir following disturbances. The governor and AVR models applied to each power plant type are summarized in Table 5.

Table 5. Governor and AVR models used for frequency stability analysis

Generator Type	Governor Model	AVR Model
Diesel engine	DEGOV	IEEET1
Gas engine	GAST	IEEET1
Steam turbine	IEEEG1	IEEET1

3. RESULT AND DISCUSSION

This section presents a detailed discussion of the simulation results, which includes power flow analysis, contingency (N-1) analysis, short-circuit analysis, and frequency stability analysis. Each analysis is described and interpreted in the following subsections.

3.1 Power Flow Analysis

Figure 5 illustrates the voltage profiles of the substations in the Ambon power system for the planning years 2025, 2030, and 2034. The simulation results indicate that, for all scenarios, substation voltages remain within the acceptable operational limits of 0.9–1.05 p.u. The voltage magnitudes across the substations exhibit minimal variation, with an average value of approximately 0.996 p.u. By the end of the planning horizon, the lowest voltage is observed at GI Sirimau 70 kV, reaching 0.992 p.u., primarily due to increased local load demand. Conversely, the highest voltage level is predicted at GI BMPP, with a magnitude of 0.9988 p.u.

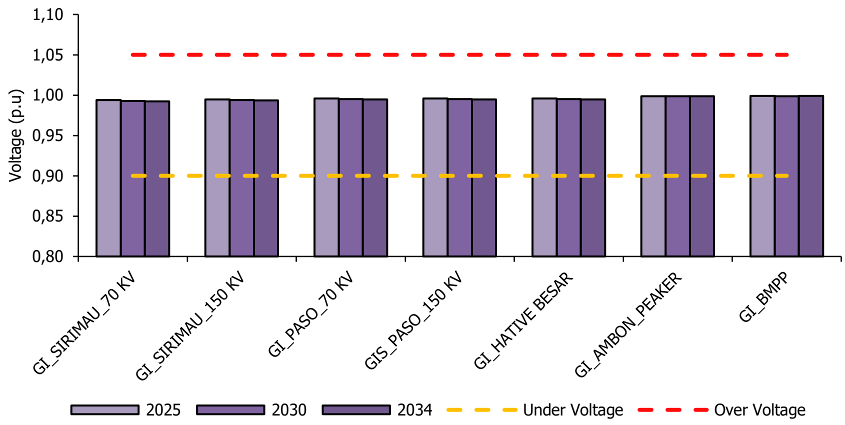

Figure 5. Voltage profile on each substation under normal operation

Figure 6 presents the transmission line loading levels throughout the planning period. The simulation results indicate that, under normal operating conditions, all transmission lines operate well within the safe loading threshold, remaining below 50% of their rated capacities for all simulated years. By 2034, the highest line loading is observed on the Ambon Peaker–Passo 2B line, reaching 25.86%. This relatively higher loading is attributed to the role of the Ambon Peaker–Passo 2B line, together with the Ambon Peaker–Passo 1 line, as the primary power transfer corridors for generation from the Ambon Peaker and BMPP busbars. In 2034, these sources collectively supply 79.4 MW, accounting for approximately 82.79% of the total system demand.

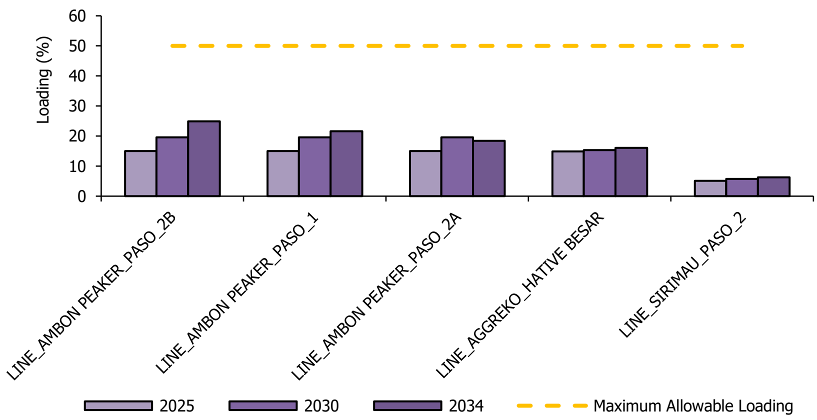

Figure 6. Loading profile of transmission lines under normal operation

3.2 Contingency (N-1) Analysis

Based on the power flow simulation results, the Ambon Peaker–Passo 2A transmission line exhibits the highest loading for all simulated years (2025, 2030, and 2034). To evaluate system performance under contingency conditions, an outage of this transmission line was simulated. The resulting bus voltage profiles under contingency conditions are illustrated in Figure 7. Compared to normal operating conditions, a slight reduction in voltage levels is observed across most buses. This voltage decrease is attributed to the disconnection of one of the main transmission corridors, which increases the loading on the remaining parallel lines, leading to higher power losses and larger voltage drops. Nevertheless, all bus voltages remain within the permissible operating limits.

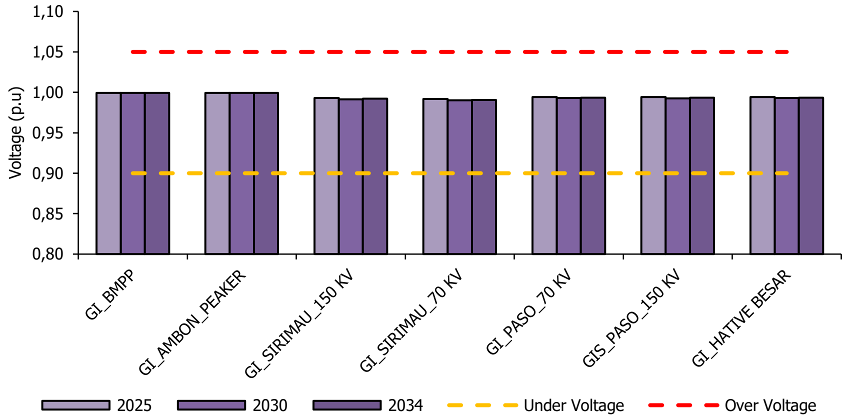

Figure 7. Voltage profile during the line outage

The outage of the Ambon Peaker–Passo 2A transmission line causes a significant redistribution of power flow across the remaining transmission network. The resulting loading profile of each transmission line under this contingency scenario is presented in Figure 8. The most pronounced impact is observed on the Ambon Peaker–Passo 1 line, where the loading increases to approximately 43.75% in 2034, nearly doubling compared to normal operating conditions. This substantial increase occurs because the Passo 1 line operates in parallel with the Passo 2A line. When the Passo 2A line is disconnected, the power flow previously shared between the two parallel circuits is fully transferred to the Passo 1 line, resulting in a marked increase in its loading level.

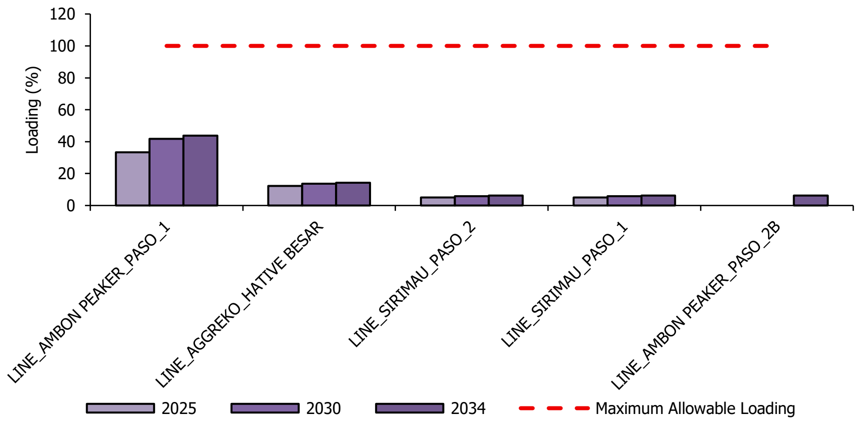

Figure 8. Highest-loaded transmission lines under the line outage

In addition, the Ambon Peaker–Passo 2B transmission line exhibits a relatively higher loading in 2034, primarily due to the active power injection from the Tulehu FTP2 geothermal power plant, which is transmitted through this corridor. Despite this increase, the transmission line loadings under the contingency scenario involving the outage of the most heavily loaded line remain within acceptable operational limits throughout the planning horizon. All line loadings stay below the recommended maximum of 100%, in accordance with the thermal ratings specified for contingency conditions.

3.3 Short Circuit Analysis

The symmetrical short-circuit currents at all substations in the Ambon system were simulated, as shown in Figure 9. The results indicate that all fault current magnitudes remain well below the allowable limits of 20 kA for 70 kV systems and 40 kA for 150 kV systems. GI Sirimau 70 kV and GI Passo 70 kV exhibit slightly higher currents, approximately 2 kA above other substations. GI Passo 70 kV records the highest short-circuit current in all evaluated years, increasing from 7.11 kA in 2025 to 8.7 kA in 2034, while GI Sirimau 150 kV shows the lowest values. Overall, all substations operate safely within the circuit breaker short-circuit withstand limits.

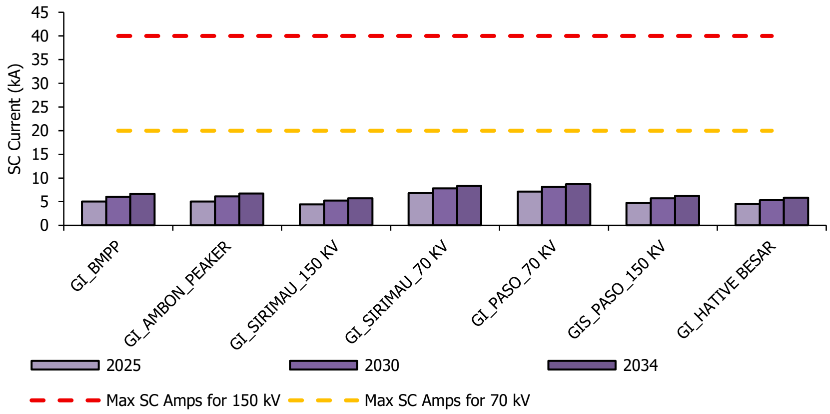

Figure 9. Symmetrical short-circuit currents at each substation

3.4 Frequency Stability Analysis

Frequency stability simulations were performed by tripping the generator with the largest power contribution to the system, namely the Ambon 2 power plant. The resulting frequency nadir following this disturbance is shown in Figure 10. Throughout the planning horizon, the minimum system frequency remains above the manual load shedding threshold of 49.5 Hz, indicating adequate frequency stability under severe contingency conditions. Consequently, the system is capable of maintaining frequency without requiring load shedding following a major generator outage. For example, the tripping of the Ambon 2 power plant in 2034 results in a frequency nadir of 49.725 Hz, as illustrated in Figure 11.

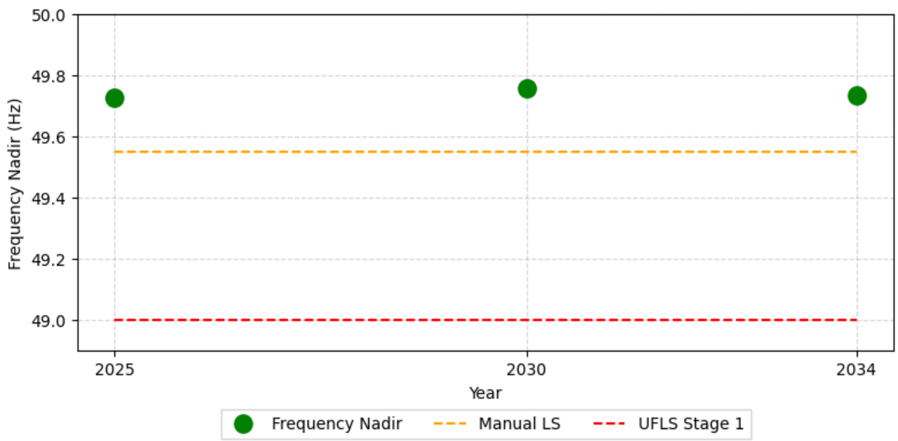

Figure 10. Frequency nadir in each simulation year due to generator outages

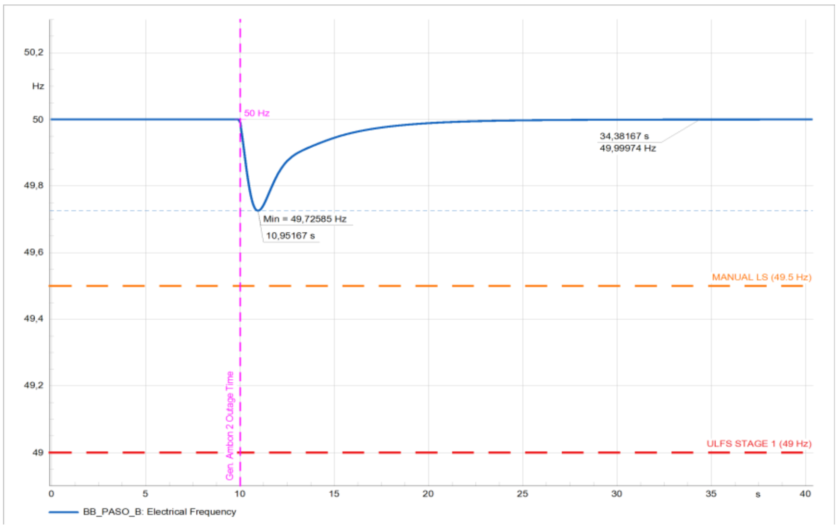

Figure 11. Frequency response due to the Ambon 2 power plant outage in 2034

3.5 Static Security and Dynamic Stability Assessment Summary

The power system assessment results over the planning horizon are summarized in Table 6. In this study, static security assessment consists of power flow, N-1 contingency, and short-circuit analyses, while the dynamic stability assessment focuses on frequency response following the outage of the largest generator.

Power flow analyses under both normal and contingency (N-1) conditions indicate that the system maintains acceptable voltage profiles and component loadings, confirming that the selected transmission conductors are adequate to transfer power without overloading. In addition, the simulated short-circuit currents remain below the allowable limits of 40 kA for 150 kV systems and 20 kA for 70 kV systems, demonstrating the adequacy of the protection system and supporting appropriate circuit breaker selection.

Dynamic analysis focuses on frequency stability by simulating the outage of the largest contributing generator. In all scenarios, the frequency nadir remains above 49.5 Hz, indicating that the remaining generation is sufficient to maintain system stability. Overall, both static and dynamic simulation results confirm that all evaluated parameters remain within standards, demonstrating that the power system expansion plan stated in the RUPTL 2025-2034 document is technically viable and secure.

Table 6. Summary of the power system security evaluation results

Assessment	Analysis	Parameter	Planning Period		
			2025	2030	2034
Static Security	Load flow under normal conditions	Voltage magnitude Loading of the transmission line	Meets the limit of 0.9-1.05 p.u Less than 50%		
	Load flow under N-1 line contingency	Voltage magnitude Loading of the transmission line	Meets the limit of 0.9-1.05 p.u Less than 100%		
	Short circuit	Symmetrical short-circuit current	Less than 40 kA (150 kV system) and 20 kA (70 kV system)		
Dynamic Stability	Frequency stability	Frequency nadir	Above 49.5 Hz (Manual LS threshold)		

4. CONCLUSION

This study assessed the steady-state security and frequency stability of the isolated Ambon power system expansion plan for the 2025–2034 period based on the RUPTL document. The results show that the planned system can maintain secure operation under peak-load conditions in 2025, 2030, and 2034. Under normal operation, all bus voltages remain within the allowable range of 0.9–1.05 p.u., with the lowest voltage of 0.992 p.u. observed at GI Sirimau 70 kV in 2034. The maximum transmission line loading under normal operation is 25.86%, indicating that the proposed transmission capacity is adequate. Under the N-1 outage of the Ambon Peaker–Passo 2A line, the highest line loading increases to 43.75%, but remains below the 100% contingency loading limit. The maximum three-phase short-circuit current is 8.7 kA at GI Passo 70 kV, which is significantly lower than the 20 kA limit for the 70 kV system and the 40 kA limit for the 150 kV system. The frequency stability simulation shows that the system reached a frequency nadir of 49.725 Hz following the outage of the Ambon 2 power plant, remaining above the 49.5 Hz manual load-shedding threshold. These findings indicate that Ambon power system expansion plan stated in the RUPTL is technically secure, supports the integration of planned renewable generation, and is capable of accommodating projected demand growth through 2034

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