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Operation Feasibility Study of the Prafi Substation and 150 kV Manokwari-Prafi Transmission Line Project

Kelayakan Operasi Proyek Gardu Induk Prafi dan Transmisi 150 kV Manokwari-Prafi

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Abstract

The rising demand for electricity in Manokwari, the capital of West Papua Province, Indonesia, necessitates urgent improvements to the existing 20 kV distribution system, which struggles to maintain voltage compliance with grid code standards and meet projected future loads. This study examines two operational alternatives: (1) the construction of a 150 kV transmission line from the Gas Engine Power Plant (PLTMG) substation to the Prafi Substation, and (2) the development of an express feeder from the same source. Using DigSILENT PowerFactory software, operational feasibility is assessed through voltage regulation, transformer and line loading analysis, and N-1 contingency compliance. The investigation includes power flow simulations, short-circuit fault analysis, and system stability evaluations, focusing on rotor angle, voltage, and frequency stability. Findings provide technical recommendations to enhance the reliability, resilience, and sustainability of Manokwari's power infrastructure, supporting strategic planning and operational optimization.

Keywords: demand, grid code, system stability.

***SDGs*:**

Abstrak

Meningkatnya kebutuhan listrik di Manokwari, ibu kota Provinsi Papua Barat, membutuhkan perbaikan sistem distribusi 20 kV yang kesulitan mempertahankan tegangan sesuai standar grid code dan memenuhi proyeksi beban masa depan. Studi ini mengevaluasi dua alternatif solusi: (1) pembangunan saluran transmisi 150 kV dari Gardu Induk PLTMG ke Gardu Induk Prafi, dan (2) pengembangan saluran ekspres dari sumber yang sama. Kelayakan operasional dianalisis menggunakan DigSILENT PowerFactory, dengan fokus pada regulasi tegangan, pembebanan, dan kriteria kontingensi N-1. Kajian meliputi simulasi aliran daya, gangguan hubung singkat, dan evaluasi stabilitas sistem, termasuk kestabilan sudut rotor, tegangan, dan frekuensi. Hasil penelitian memberikan rekomendasi untuk meningkatkan keandalan, ketahanan, dan keberlanjutan sistem kelistrikan Manokwari, serta mendukung perencanaan infrastruktur dan optimalisasi operasional.

Kata Kunci: permintaan, kode jaringan, stabilitas sistem.

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1. INTRODUCTION

The increasing demand for electricity in developing regions must be matched with strategic infrastructure planning to ensure reliable and sustainable power delivery (Ehtiwesh *et al.*, 2023). In Indonesia's West Papua Province, the Manokwari electrical system—one of six major systems with capacities exceeding 2 MW—plays a critical role in meeting regional energy needs. As of December 2023, the system's peak load reached 35.74 MW, supplied by a combination of PLN-owned and leased power plants with a total installed capacity of 45.29 MW (PLN, 2021).

Currently, the Manokwari system operates on a 20 kV distribution network. However, this configuration faces significant limitations in maintaining voltage stability, ensuring compliance with grid code parameters, and supporting the anticipated increase in load demand. To address these challenges, a system upgrade is planned through the construction of a 150 kV transmission line and a new 150 kV substation in Prafi. This interconnection will facilitate more efficient power evacuation from the PLTMG (Gas Engine Power Plant) Manokwari and improve supply reliability, especially for the Prafi region.

Despite these planned developments, the operational feasibility of the 150 kV transmission and substation infrastructure under real-world load conditions remains unverified. Past studies have predominantly focused on generation expansion and load forecasting (Hatziargyriou *et al.*, 2011), but there is a lack of system-level operational analysis tailored to Manokwari's unique network topology and growth dynamics. This constitutes a critical research gap in supporting data-driven decision-making for infrastructure investment.

Therefore, this study aims to assess the operational feasibility of the 150 kV transmission project through comprehensive power system analysis using DigSILENT software (Kim and Kim, 2023). The research focuses on validating key technical parameters—voltage compliance, transformer and transmission line loading, and N-1 contingency fulfillment—under various operating scenarios (Gazafroudi, Neumann and Brown, 2022). In addition, the study investigates system stability by analyzing rotor angle, voltage, and frequency behaviors (Chivunga *et al.*, 2024).

The results are expected to provide actionable insights for optimizing infrastructure development, reducing dependence on diesel-based generation, and ensuring long-term reliability in the Manokwari electrical system (see Figure 1).

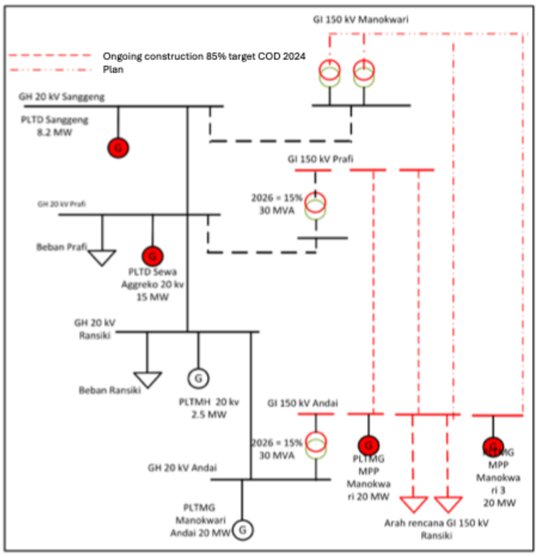

Figure 1. Manokwari electricity system and development plan (PLN, 2021).

2. METHODOLOGY

2.1. Background and Theoretical Framework

The growth in electricity demand within a region is generally driven by demographic expansion and economic development. As posited by Hatziargyriou et al. (Hatziargyriou *et al.*, 2011), factors such as industrialization, urbanization, and the integration of energy-intensive technologies lead to increased electricity consumption (Jin and Huang, 2023). In developing regions like Manokwari, effective long-term planning is essential to avoid power shortages and instability due to underdeveloped infrastructure (Narayan and Smyth, 2008).

The 2021-2030 RUPTL (PLN, 2021), forecasts a 5.81% annual increase in electricity demand in Manokwari, reflecting trends seen in similar growth regions. To ensure reliable supply, system planners must assess infrastructure capacity and resilience (Kuusaana, Smith and Monstadt, 2025).

Simulation tools such as DIgSILENT PowerFactory are crucial for evaluating power system performance. They enable detailed analysis of load flows, voltage stability, and system contingencies. According to Wood & Wollenberg, such tools support planners in meeting grid code standards and maintaining operational safety under various load and fault conditions (Wood, Wollenberg and Sheblé, 2013). For example, the Indonesian Grid Code requires voltage to remain within +5% to -10% of nominal values at the 150 kV level (Tasrif, 2020).

Power systems must also meet the N-1 contingency criterion, which ensures continued operation even after the failure of one major component (Grigsby, 2012; Aeggegn, Salau and Gebru, 2020). This is especially critical in Manokwari, where multiple small generators supply a geographically dispersed load.

2.2. Research Gap, Objective, and Hypothesis

The Prafi region encounters voltage quality challenges; however, there has been limited technical evaluation of potential infrastructure solutions via simulation.

The aim of this study is to assess the practical effectiveness of two technical solutions designed to enhance voltage stability and supply reliability in Manokwari: The findings indicate the need for a 150 kV transmission line and substation to be established in Prafi. The study further aims to implement a 20 kV express feeder from PLTMG Manokwari to Prafi.

The hypothesis suggests that establishing a new 150 kV transmission line and substation will offer a more effective solution to voltage and reliability challenges compared to the 20 kV express feeder, especially in N-1 contingency scenarios.

2.3. Research Procedure

The research process is divided into the following structured steps:

1) Step 1: Data Collection
    - Historical load profiles and peak demand projections for 2026–2029
    - Existing transmission and distribution line configurations
    - Generator characteristics (PLTMG Manokwari and surrounding units)
    - Grid Code compliance requirements
2) Step 2: Scenario Development
    - Scenario 1: 150 kV substation in Prafi + transmission line from PLTMG
    - Scenario 2: 20 kV express feeder from PLTMG to Prafi
3) Step 3: Simulation Tools and Parameters
    - Software: DIgSILENT PowerFactory
    - Load flow analysis (P-Q performance)
    - Short circuit analysis
    - Transformer and line loading checks
    - Voltage profile analysis (±5% and -10% limits)
    - N-1 contingency analysis (single line/generator outage)
    - Rotor angle, voltage, and frequency stability
4) Step 4: Evaluation and Comparison
    - Technical feasibility and reliability of each scenario
    - Compliance with grid standards
    - Operational robustness under faults
5) Step 5: Decision Framework
    Recommendation based on performance metrics, including voltage stability, line loading, fault tolerance, and operational continuity.

3. RESULTS AND DISCUSSION

In this study, there are 2 scenarios solutions that will be studied: Scenario 1: Build substation 150 kV Prafi and Transmission Line from Substation PLTMG to substation Prafi - 40-kilometer circuit, Scenario 2: Building a 20 kV SUTM express feeder.

3.1. Scenario 1

Figure 2 and Figure 3 show the existing network configuration and the proposed condition after the implementation of the 150 kV transmission line from PLTMG Manokwari to the proposed Prafi Substation (40 km, 2x240 mm^2 ACSR Hawk).

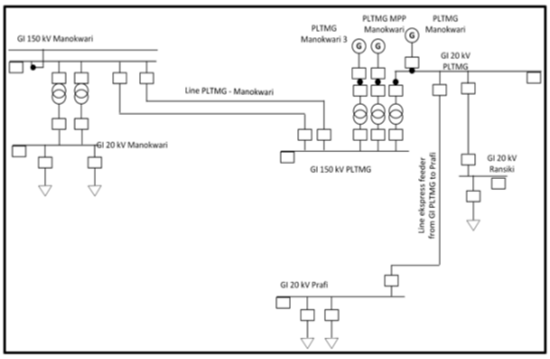

Figure 2. Existing single line diagram before construction of transmission and substation 150 kV PLTMG Manokwari – Prafi.

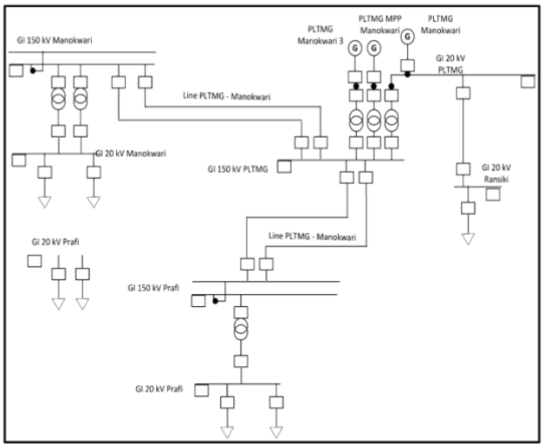

Figure 3. Single line diagram with transmission and substation 150 kV PLTMG Manokwari - Prafi built plan.

3.1.1. Power Flow Analysis Scenario 1

Based on the results of the load flow simulation using the DIgSILENT application with the assumption of peak load in 2026 according to the projected peak load of the Power Balance for the period 2024 - 2033, ACSR 2x Hawk 240 mm^2 transmission obtained transmission and transformer loading conditions, as well as voltage at several locations as follows in Table 1. Table 1 summarizes voltage levels in the 20 kV Prafi system before and after Scenario 1. The results indicate that:

- Before the substation was built, voltages in the Prafi 20 kv system were outside the standard service limits (below -10% of nominal voltage)
- After the 150 kV Prafi Substation was operational, voltage levels improved and complied with the Indonesian grid code (PLN, 2022) , which requires voltages within +5% to -10%.

In addition, from the DIgsilent simulation, the loading on transmission lines and transformers is also obtained as in Table 2. The table shows that loading levels for both the transformers and transmission lines remaian below 100%, satisfying the N-1 Contingency criterion, a key reliability standard in transmission planning.

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The next simulation carried out is to conduct an N-1 analysis with a disturbance on the substation PLTMG transmission line towards Prafi. Figure 4 shows the simulation of disturbance applied to the transmission line.

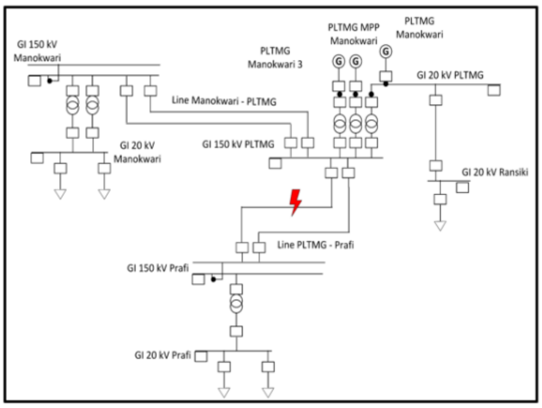

Figure 4. Simulation of N-1 disturbance on transmission.

Table 1. Voltage before and after scenario 1.

No	Location	Voltage (kV)	Before		After	
			Voltage (kV)	Voltage (PU)	Voltage (kV)	Voltage (PU)
1	150 kV Substation Manokwari	150	149.50	0.99	149.60	0.99
2	150 kV Substation Prafi	150	-	-	148.30	0.98
3	150 kV PLTMG Manokwari	150	150.10	1.00	150.20	1.00
4	20 kV Substation Manokwari	20	19.90	0.99	19.90	1.00
5	20 kV Substation Prafi	20	17.30	0.87	19.70	0.99
6	20 kV Ransiki	20	18.70	0.93	18.70	0.93
7	20 kV PLTMG	20	20.00	1.00	20.00	1.00

Table 2. Transformer and transmission loadings before and after scenario 1.

No	Location	Voltage (kV)	Before		After	
			Voltage (kV)	Voltage (PU)	Voltage (kV)	Voltage (PU)
1	150 kV Substation Manokwari	150	149.50	0.99	149.60	0.99
2	150 kV Substation Prafi	150	-	-	148.30	0.98
3	150 kV PLTMG Manokwari	150	150.10	1.00	150.20	1.00
4	20 kV Substation Manokwari	20	19.90	0.99	19.90	1.00
5	20 kV Substation Prafi	20	17.30	0.87	19.70	0.99
6	20 kV Ransiki	20	18.70	0.93	18.70	0.93
7	20 kV PLTMG	20	20.00	1.00	20.00	1.00

Table 3. Transformer and transmission line loadings after the occurrence of PLTMG-Prafi transmission disturbances.

No	Location	Loading (%)	Loading (MW)
1	Transmission PLTMG-Prafi #1	-	-
2	Transmission PLTMG-Prafi #2	5.8	15.1
3	Trafo #1 Prafi	50.5	14.8
4	Transmission PLTMG-Substation Manokwari #1	5.5	14.3
5	Transmission PLTMG-Substation Manokwari #2	5.5	14.3
6	Trafo #1 Prafi-Manokwari	47.4	14.2
7	Trafo #2 Manokwari	47.4	14.2

Table 4. Voltage in simulation of the occurrence of disturbances on the PLTMG – Prafi#1 transmission line.

No	Location	Nominal Voltage (kV)	Voltage (kV)	Voltage (PU)
1	Substation 150 kV Manokwari	150	150	1.00
2	Substation 150 kV Prafi	150	146.7	0.98
3	150 kV PLTMG Manokwari	150	150.6	1.00
4	20 kV GI Manokwari	20	20	1.00
5	20 kV Substation Prafi	20	19.5	0.98
6	20 kV Ransiki	20	18.7	0.93
7	Trafo #2 Manokwari	150	150.6	1.00

Table 5. Short circuit current simulation results.

No	Location	Before		After	
		kA 3Ph	kA 1Ph	kA 3Ph	kA 1Ph
1	20 kV Manokwari	7	7.656	7	7.67
2	20 kV Prafi	2.55	2.42	2.32	3.47
3	20 kV Ransiki	0.98	0.86	0.98	0.86
4	20 kV PLTMG	8.18	9.7	8.18	9.72
5	Substation Manokwari150 kV	1.05	1.16	1.05	1.41
6	Substation PLTMG 150 kV	1.17	1.408	1.17	1.16
7	Substation Prafi 150 kV	-	-	0.74	0.67

In this simulation, the loading on transmission lines and transformers will be observed to see if the loading exceeds 100% when an n-1 fault occurs on substation of the PLTMG transmission line to Prafi. From the simulation, it was found that the loading value on each transformer and transmission line did not exceed 100%. For details, it can be seen in Table 3. In addition, this simulation is also carried out to see the voltage on each busbar and it is found that the voltage value on each busbar still meets the service standard/grid code standard which is +5% or -10% of the nominal voltage. Details can be seen in Table 4.

3.1.2. Short Circuit Analysis Scenario 1

Short circuit currents before and after the substation installation, 2024 condition, are presented in Table 5. The analysis reveals that:

- All short circuit currents remain within safe operational margins (Youssef and Abouelenin, 2016), below the breaking capacity thresholds for 150 kV equipments (40 kA).
- These results ensure that protection devices and switchgear can operate reliably.

3.1.3. System Stability Analysis Scenario 1

Stability analysis is needed to determine the ability of the power system to achieve a stable operating state after experiencing a disturbance (Banejad, Kazeminejad and Hosseinzadeh, 2022). The stability analysis that will be simulated consists of rotor angle stability, frequency stability and voltage stability (Mora *et al.*, 2002).

Rotor angle stability is focused on the ability of the interconnection of synchronous machines of the power system to remain synchronous within the operating limits when a disturbance occurs (see Figure 5). This depends on the ability to maintain or restore the stability point between the electromagnetic and mechanical forces of each synchronous machine in the system (Amin *et al.*, 2025). After a fault on one of the 150 kV circuits, all generator units remained synchronized, demonstrating angular stability.

Voltage stability focuses on the ability of the power system to keep its voltage stable at all buses when a disturbance occurs (Boričić and Popov, 2025). Voltage is closely related to reactive power so if the system experiences a lack of reactive power, a voltage drop occurs. The bus voltages oscillate briefly but stabilize, as shown in Figure 6 the voltage response graphs.

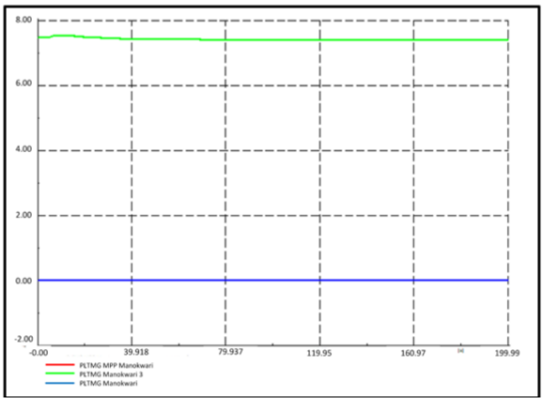

Figure 5. Rotor angle stability after Prafi transmission line fault #1.

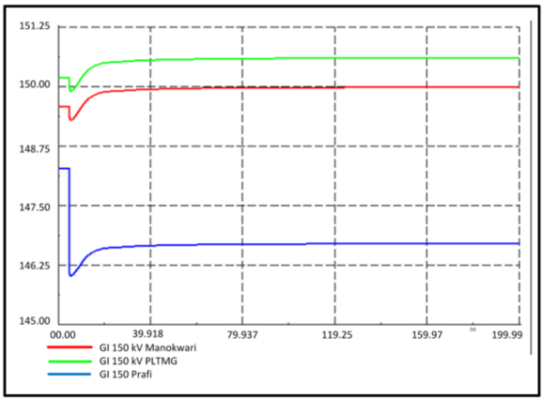

Figure 6. Voltage stability after Prafi transmission line fault #1.

Frequency stability focuses on the ability of the power system to keep the system frequency stable under load and generator instability (power deficiency) (Dieng *et al.*, 2025). Frequency is closely related to active power so if there is a power deficiency between the generator and the load, the system frequency will drop below its nominal value. A decrease in frequency value is dangerous for the system because it can break synchronization and eventually blackout the system. Frequency dips temporarily but returns to nominal levels, indicating the system can recover from power imbalances without blackout risk. These results confirm that Scenario 1 provides a technically robust solution, ensuring reliable operation of the Manokwari system under both normal and contingency conditions (see Figure 7).

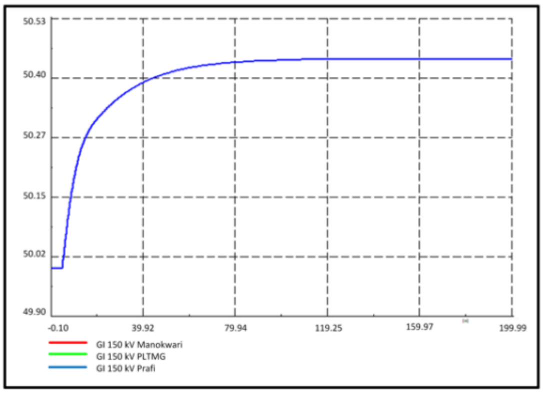

Figure 7. Frequency stability after Prafi transmission line fault #1.

Figure 7 shows the frequency response of electricity at 150 kV Substation Manokwari, Substation Prafi and Substation PLTMG when a fault occurs on the 150 kV transmission line from PLTMG Manokwari to Substation Prafi.

3.2. Scenario 2

3.2.1. Power Flow Analysis Scenario 2

The scenario is to build a 20 kV express feeder from the Manokawari PLTMG as shown in Figure 8, as a comparison can be seen in the existing conditions in Figure 2.

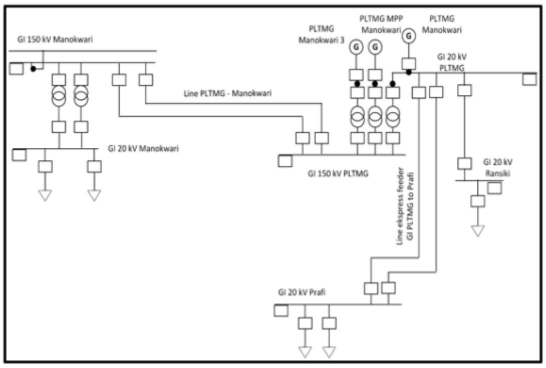

Figure 8. Single line diagram with express feeder plan 20 kV PLTMG Manokwari - Prafi.

Based on the results of load flow simulations using the DIgSILENT application with the assumption of peak load in 2026 according to the projected peak load of the Power Balance for the period 2024 - 2033, through the existing 20 kV SUTM, transmission and transformer loading conditions are obtained, as well as voltages at several locations as shown in Table 6 and Table 7.

From the simulation conducted on DIgSILENT, it is found that there is an improvement in voltage after the addition of express feeders in the 20 kV SUTM network. The voltage that was originally outside the service voltage limit has improved by increasing the voltage to the service voltage limit (according to the grid code) -10% or +5%.

The next analysis is condition N-1. In this simulation, the loading on the transmission line and transformer will be observed to see if the loading exceeds 100% when an n-1 fault occurs on the SUTM towards Prafi. From the simulation, it was found that the loading value on each transformer and transmission line and express feeder did not exceed 100%. For details, it can be seen in Table 8. In addition, this simulation was also carried out to see the voltage on each busbar and it was found that the voltage value on the 20 kV Prafi busbar experienced a voltage drop to below the service standard (grid code standard). This resulted in the construction of the express feeder being not feasible. For details can be seen in Table 9.

3.2.2. Short Circuit Analysis Scenario 2

The results of the 2026 short circuit study before and after the inclusion of the express feeder on the 20 kV SUTM from the Substation PLTMG to the Prafi Substation are shown in Table 10. From the Table 10, the short circuit current that occurs is still below the breaking capacity value for 20 kV voltage which is 25 kA and 150 kV which is 40 kA, so the electric power equipment contained in the system is in a safe condition to operate.

3.2.3. System Stability Analysis Scenario 2

In this simulation, the express feeder 1 in the direction of Prafi will experience a disturbance at the 5th second and will produce a stability graph as shown in Figure 9. Based on simulations conducted on DIgSilent, it is found that the rotor angle of all plants can stabilize again after the disturbance occurs on the first express feeder. Two plants experienced small oscillations before returning to stability until the end of the simulation (200 s).

For Voltage Stability Based on the simulation conducted on DIgSILENT, it is found that when a disturbance occurs on express feeder #1, the voltage will oscillate before stabilizing until the

Table 6. Transmission, express feeder, and transformer loadings - scenario 2.

No	Location	Before		After	
		Load (%)	Load (MV)	Load (%)	Load (MV)
1	Feeder existing PLTMG-Prafi	50.4	17.4	23.1	8
2	Express feeder PLTMG-Prafi #1	-	-	23.1	8
3	Express feeder PLTMG-Prafi #2	-	-	-	-
4	Transmission PLTMG- Substation Manokwari #1	5.5	14.2	5.5	14.2
5	Transmission PLTMG- Substation Manokwari #2	5.5	14.2	5.5	14.2
6	Trafo #1 Manokwari	47.3	14.1	47.3	14.1
7	Trafo #2 Manokwari	47.3	14.1	47.3	14.1

Table 7. Voltage values before and after simulation express feeder development towards Prafi.

No	Location	Voltage (kV)	Before		After	
			Voltage (kV)	Voltage (PU)	Voltage (kV)	Voltage (PU)
1	Substation 150 kV Manokwari	150	149.50	0.99	149.70	0.99
2	Substation 150 kV Prafi	150	-	-	-	-
3	150 kV PLTMG Manokwari	150	150.10	1.00	150.30	1.00
4	20 kV Substation Manokwari	20	19.90	0.99	20.00	0.99
5	Substation 20 kV Prafi	20	17.30	0.87	18.80	0.94
6	Substation 20 kV Ransiki	20	18.70	0.93	18.70	0.94
7	20 kV PLTMG	20	20.00	2.00	20.10	1.00

Table 8. Transformer and transmission line loading during a fault on express feeder #1 towards Prafi.

No	Location	Load (%)	Load (MW)
1	Feeder existing PLTMG-Prafi	18.5	6.4
2	Express feeder PLTMG-Prafi #1	-	-
3	Express feeder PLTMG-Prafi #2	4.4	15.4
4	Transmission PLTMG- Substation Manokwari #1	5.5	14.5
5	Transmission PLTMG- Substation Manokwari #2	5.5	14.5
6	Trafo #1 Manokwari	47.8	14.5
7	Trafo #2 Manokwari	47.8	14.5

Table 9. Voltage when a fault occurs on express feeder #1 in the direction of Prafi.

No	Location	Loading (%)	Loading (MW)
1	Substation 150 kV Manokwari	151.3	1.01
2	Substation 150 kV Prafi	-	-
3	Substation 150 kV PLTMG Manokwari	151.9	1.01
4	20 kV Substation Manokwari	20.2	1.01
5	20 kV Substation Prafi	17.9	0.89
6	20 kV Substation Ransiki	18.9	0.93
7	20 kV PLTMG Andai	20.3	1.01

Table 10. Short circuit current simulation results - scenario 2.

No	Location	Before		After	
		kA 3Ph	kA 1Ph	kA 3Ph	kA 1Ph
1	20 kV Manokwari	7.01	1.16	7.01	7.66
2	20 kV Prafi	2.55	2.42	4.02	4.13
3	20 kV Ransiki	0.98	0.98	0.98	0
4	20 kV PLTMG	8.18	8.18	8.18	0.85
5	Manokwari Substation150 kV	1.05	1.16	1.05	1.16
6	PLTMG 150 kV Substation	1.17	-	8.18	1.41
7	Prafi 150 kV Substation	-	-	-	-

end of the simulation (200 s) as shown in Figure 10.

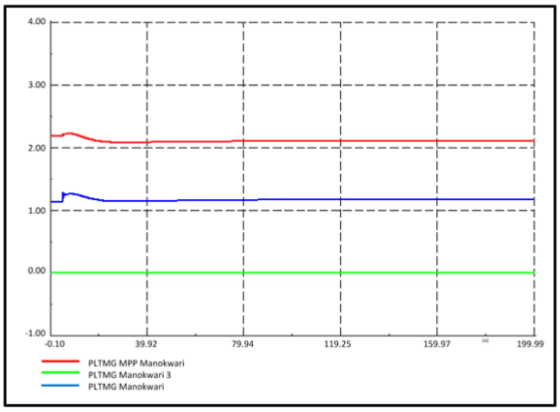

Figure 9. Rotor Angle Stability during a disturbance on express feeder #1.

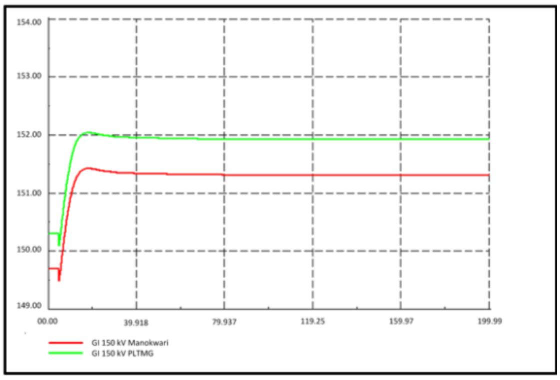

Figure 10. Voltage stability during a fault on express feeder #1.

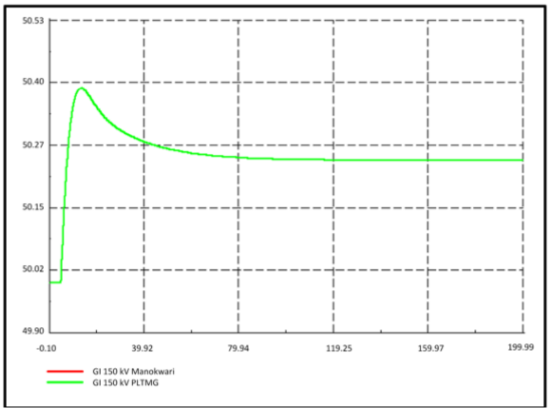

Figure 11. Frequency stability during faults on express feeder #1.

Frequency Stability Based on the simulation conducted on DIgSILENT, it is found that when a disturbance occurs on express feeder #1, the frequency will experience oscillations before stabilizing until the end of the simulation (200 s) as shown in Figure 11.

4. CONCLUSION

This study evaluated two technical scenarios to improve power evacuation in the Manokwari electrical system: the construction of a 150 kV transmission line and substation, and the development of a 20 kV express feeder. Through simulation-based analysis using DigSILENT, the 150 kV solution was found to be the most effective in ensuring voltage compliance, reducing transmission and transformer loading, and maintaining system stability under N-1 contingency conditions.

The findings contribute to power system engineering by demonstrating a structured, simulation-driven approach to sub-transmission planning in underdeveloped regions. This approach supports evidence-based decision-making and infrastructure investment, aligning with national grid code standards and long-term energy planning policies.

However, the study is limited to technical simulations and does not address the economic, regulatory, or environmental dimensions of the proposed solutions. Future research is recommended to include financial feasibility studies, field validation of simulation results, and exploration of renewable energy integration to enhance system sustainability.

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