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Impact of Distributed Generation on Power Losses and Voltage Profile of the Unsyiah Distribution Feeder

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ABSTRACT

Distributed generation (DG) ha s emerged as an effective solution for improving power quality, enhancing voltage profiles, and reducing power losses in electrical distribution systems. This study investigates the impact of renewable-energy-based DG integration on the voltage profile and power losses of the Unsyiah distribution feeder in Banda Aceh, Indonesia. The distribution network was modeled and analyzed using ETAP 16.0.2, while MATLAB R2021a with the backpropagation artificial neural network (ANN) method was employed to estimate solar radiation intensity and wind speed data for photovoltaic (PV) and wind power plant (WPP) generation. The ANN model was trained using environmental and climate data, producing regression values of 0.84901 for solar radiation prediction and 0.85083 for wind speed prediction, indicating satisfactory predictive performance. Two DG placement scenarios with a penetration level of 20% of the total feeder load (388.4 kW) were evaluated at Bus USK 01 and Bus USK 24. Simulation results demonstrate that DG integration significantly improves the voltage profile, particularly at buses located near the end of the feeder where voltage drops are more severe. The optimal scenario was achieved by placing wind-power-based DG at Bus USK 24, which reduced active power losses from 11.8 kW to 8.1 kW and reactive power losses from 13.1 kVAR to 8.6 kVAR. Overall, the integration reduced active power losses by 31.35% and reactive power losses by 34.35%. The findings confirm that both DG placement location and DG type strongly influence the effectiveness of voltage profile enhancement and power loss reduction in radial distribution systems.

Keywords: Distributed Generation; Voltage; Power Losses, Distribution System, Renewable Energy

ABSTRAK

Distributed generation (DG) menjadi salah satu solusi yang efektif untuk meningkatkan kualitas daya, memperbaiki profil tegangan, dan mengurangi rugi-rugi daya pada sistem distribusi tenaga listrik. Penelitian ini menganalisis pengaruh integrasi DG berbasis energi terbarukan terhadap profil tegangan dan rugi-rugi daya pada penyulang Unsyiah di Banda Aceh, Indonesia. Pemodelan dan analisis jaringan distribusi dilakukan menggunakan ETAP 16.0.2, sedangkan MATLAB R2021a dengan metode jaringan syaraf tiruan (JST) backpropagation digunakan untuk memperkirakan intensitas radiasi matahari dan kecepatan angin sebagai sumber pembangkitan fotovoltaik (PLTS) dan pembangkit listrik tenaga bayu (PLTB). Model JST dilatih menggunakan data lingkungan dan iklim, menghasilkan nilai regresi sebesar 0,84901 untuk prediksi radiasi matahari dan 0,85083 untuk prediksi kecepatan angin, yang menunjukkan kemampuan prediksi yang baik. Penelitian ini mengevaluasi dua skenario penempatan DG dengan tingkat penetrasi sebesar 20% dari total beban penyulang, yaitu sebesar 388,4 kW, pada Bus USK 01 dan Bus USK 24. Hasil simulasi menunjukkan bahwa integrasi DG mampu meningkatkan profil tegangan secara signifikan, terutama pada bus yang berada di ujung penyulang yang mengalami penurunan tegangan lebih besar. Skenario optimal diperoleh pada penempatan DG berbasis PLTB di Bus USK 24, yang mampu menurunkan rugi-rugi daya aktif dari 11,8 kW menjadi 8,1 kW dan rugi-rugi daya reaktif dari 13,1 kVAR menjadi 8,6 kVAR. Secara keseluruhan, integrasi DG berhasil mengurangi rugi-rugi daya aktif sebesar 31,35% dan rugi-rugi daya reaktif sebesar 34,35%. Hasil penelitian menunjukkan bahwa lokasi penempatan dan jenis DG sangat mempengaruhi efektivitas peningkatan profil tegangan dan pengurangan rugi-rugi daya pada sistem distribusi radial.

Kata kunci: Distributed Generation, Profil Tegangan, Rugi-Rugi Daya, Sistem Distribusi, Energi Terbarukan

1. INTRODUCTION

Currently, renewable energy sources are considered a highly promising alternative in modern power systems. Distributed generation (DG) is a technology in the field of electrical power engineering that emphasizes small-scale power generation and utilizes environmentally friendly renewable energy sources. One of the major issues driving the development of DG is the high cost associated with the construction of transmission and distribution lines [1]. In Indonesia, renewable energy sources such as solar and wind energy have gradually been implemented in various regions with considerable renewable energy potential.

Syiah Kuala University is one of the public universities in Aceh that still requires reliable electrical power distribution. The location of power plants far from the load center within the university area results in significant power losses and poor voltage profiles. These problems can be minimized by integrating small-scale generators located close to the load center, commonly known as distributed generation (DG) [2].

This study focuses on the effect of DG integration on voltage profiles and power losses in the Unsyiah feeder distribution network. ETAP 16.0.2 software was used for distribution network modeling and load flow analysis, while MATLAB R2021a was utilized to determine DG capacity using the Artificial Neural Network (ANN) method [3].

Previous studies have shown that distributed generation integration in distribution systems can significantly improve voltage profiles and reduce power losses [4], [5], [14], [15]. A similar study conducted by Fitrizawati et al. [6] on distribution networks also demonstrated voltage profile improvement after DG installation. Several studies have further reported that optimal DG placement provides more significant improvements in voltage stability and power loss minimization [7], [16], [17].

This study contributes to the development of previous research through a specific case study on the Unsyiah feeder using actual data obtained from PT PLN. The main contribution of this research lies in evaluating the effect of renewable-energy-based distributed generation on voltage profiles and power losses using actual Unsyiah feeder data combined with ETAP simulation and artificial neural network prediction. The proposed approach is expected to provide a technical reference for distributed generation integration planning in distribution systems, particularly in the Aceh region.

2. THEORETICAL BACKGROUND

2.1. Distributed Generation (DG)

Distributed Generation (DG) is a power generation method in which generating units are connected directly to the distribution network or directly to consumer loads. DG is not concentrated at a single centralized location but is distributed along the distribution network.

Power losses without DG can be calculated using the following equation [2]:

$$P_{loss}^{base} = \frac{P_{load}^2 + Q_{load}^2}{U^2} R \tag{1}$$

After DG is integrated into the system, the power losses become:

$$P_{loss}^{DG} = \frac{(P_{load} - P_{DG})^2 + (Q_{load} - Q_{DG})^2}{U^2} R \tag{2}$$

Thus, the change in power losses can be expressed as:

$$\Delta P_{loss} = \frac{P_{DG}(P_{DG} - 2P_{load})}{U^2} R \tag{3}$$

If PDG<2Pload, the power losses will decrease. In DG integration, three important aspects that must be considered are penetration, location, and dispersion [8]. Optimal DG penetration is generally reported in the range of 10–20% of feeder loading depending on network characteristics and operating conditions [9], [14], [18].

2.2. Solar Energy (PLTS) and Wind Energy (PLTB)

The output power of a solar panel can be calculated using the following equation [10]:

$Pout = I \times A \times E_p \times E_i$

where I is the solar radiation intensity (W/m^2), A is the panel area (m^2), E is the panel efficiency, and E_i is the inverter efficiency. The average solar radiation intensity in Indonesia ranges from 5.0–6.8 kWh/m^2/day [1].

According to the Meteorology Climatology and Geophysics Agency Blang Bintang station, the wind potential in Banda Aceh ranges from 1.0–5.0 m/s, which still satisfies the minimum operating limit of wind turbines at 2.5 m/s [5]. The power generated by a wind turbine can be calculated using the following equation:

$$P=21\times\rho\times3\times A$$

where ρ is the air density (kg/m^3) and v is the wind speed (m/s) [11].

2.3. Artificial Neural Network (ANN) – Backpropagation

Artificial Neural Network (ANN) is a computational system inspired by biological neural cells. The architecture used in this study is backpropagation, which consists of three phases: forward propagation, backward propagation, and weight adjustment. Training is considered successful when the regression value (R) approaches 1 [12]. The input data for solar irradiance simulation include ambient temperature, sky brightness index, time, and humidity. For wind speed simulation, the input data consist of temperature, air pressure, time, and humidity [13].

3. RESEARCH METHODOLOGY

This research was conducted through several interrelated stages, as illustrated in Figure 1. In general, the research stages consisted of: (1) literature review; (2) collection of network, environmental, and climate data; (3) modeling of the Unsyiah feeder using ETAP 16.0.2; (4) load flow analysis and identification of locations with the highest power losses; (5) artificial neural network (ANN) training for solar radiation intensity and wind speed prediction using MATLAB R2021a; (6) conversion of prediction results into photovoltaic (PV) and wind power plant output power; and (7) simulation and analysis of the effect of DG injection on the feeder.

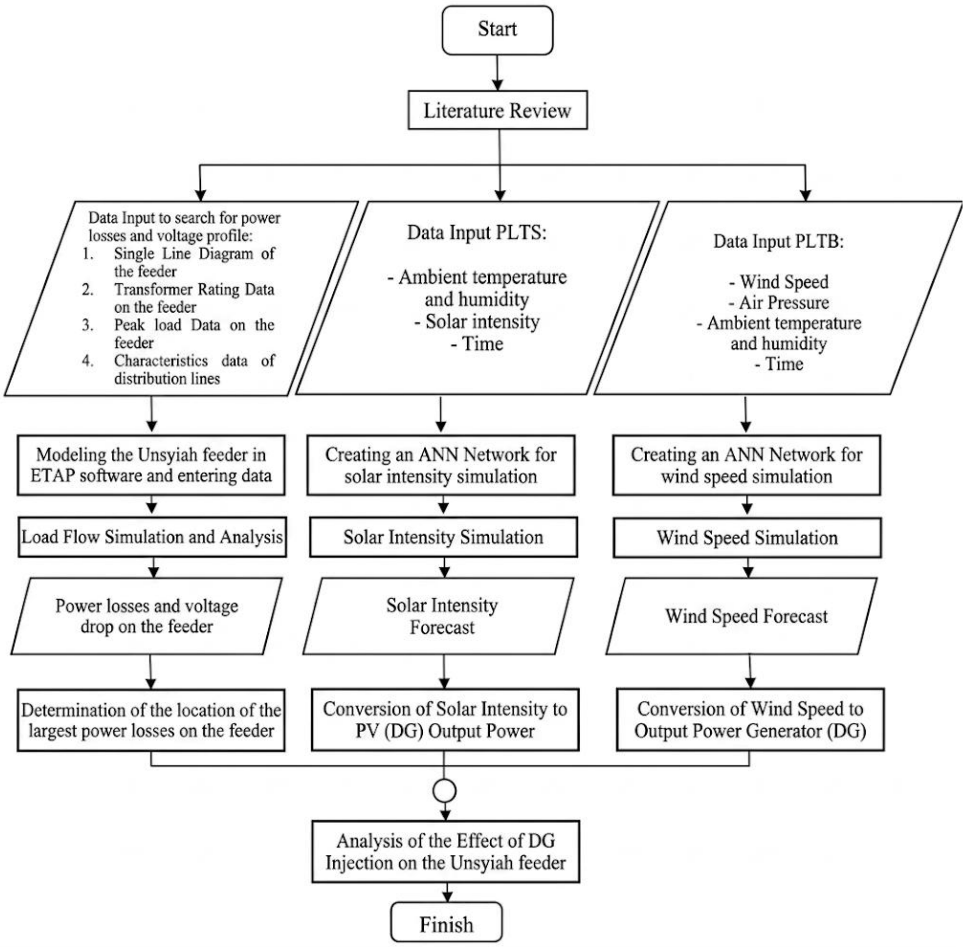

Figure 1. Research Flowchart

3.1. Data Collection

Network data, including the single-line diagram, transformer ratings, peak load, and cable specifications, were obtained from PT PLN. Climate data, including temperature, wind speed, humidity, and air pressure, were obtained from weather forecasting websites. Solar radiation intensity and sky clearness index data were measured directly by the authors using a Solar Power Meter in Darussalam during the period of 1–30 November 2020.

3.2. ETAP Modeling and Simulation

The Unsyiah feeder distribution network, which has a radial configuration, was modeled using ETAP 16.0.2 based on actual data obtained from PT PLN, including 39 distribution transformers with ratings ranging from 50–250 kVA and a 20 kV system voltage. Load Flow Analysis was performed to obtain the voltage profile and losses report for each feeder branch.

3.3. ANN Training and Power Conversion

Eighteen days of data (November 1–18, 2020) were used to train a backpropagation neural network (ANN) in MATLAB R2021a. After the regression value (R) approached 1, the network was used to predict solar intensity and wind speed for the next 15 days (November 16–30, 2020). The prediction results were then converted into output power using the solar power plant (PLTS) and wind power plant (PLTB) equations.

Assumed DG specifications: (a) PLTS: Canadian Superpower CS6K-MS panel (18% efficiency), Fronius Galvo 3.1-1 inverter (95.4% efficiency), land area 14,000 m^2, installed capacity 1,500 kWp; (b) PLTB: Rexco RC-500 Horizontal turbine (propeller diameter 2.14 m, generator efficiency 92%), installed at a height of 10 m, number of units 2,800 units, installed capacity 800 kWp. DG injection is set at 20% of the total feeder load (1,942 MW), which is 388.4 kW, carried out on two buses: Bus USK 01 (location of the smallest power loss) and Bus USK 24 (distance 2/3 of the feeder length) [9].

4. RESULTS AND DISCUSSION

4.1. Load Flow Modeling and Analysis of the Unsyiah Feeder

The modeling of the Unsyiah feeder distribution network using ETAP 16.0.2 successfully represented all network components accurately according to the actual field data. The load flow analysis results under peak load conditions (Figure 2) indicate that almost all nodes operated at a voltage level of approximately ±380 V in a 400 V three-phase system. ETAP detected several under-voltage alerts at a number of buses, particularly those located at the end of the feeder (Bus USK 24 to Bus USK 39), with the lowest voltage reaching 19.758 kV (98.79% of the nominal 20 kV voltage). One transformer (UNS 17-00) was identified in an overload condition at 222.6%. The losses report showed total power losses of 53 kW and 114.7 kVAR throughout the feeder..

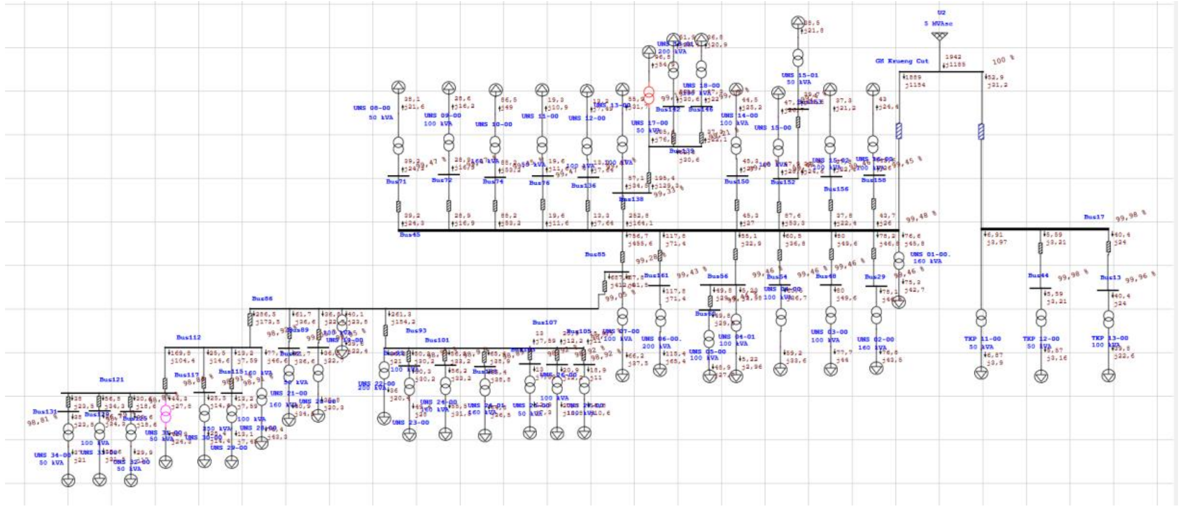

Figure 2. Load Flow Analysis Results of the Unsyiah Feeder in ETAP 16.0.2

4.2. Load Flow Modeling and Analysis of the Unsyiah Feeder

The backpropagation ANN training for solar radiation simulation produced a regression value of R = 0.84901, while the ANN training for wind speed simulation yielded an R value of 0.85083. Both values are close to 1, indicating that the network is sufficiently capable of learning the data patterns and is ready for predictive simulation.

Validation was carried out by comparing the simulated data with the measured data during 16–18 November 2020 (Figures 3 and 4). The results show that the simulation curves closely follow the trend of the actual data. The observed differences are caused by random weather fluctuations.

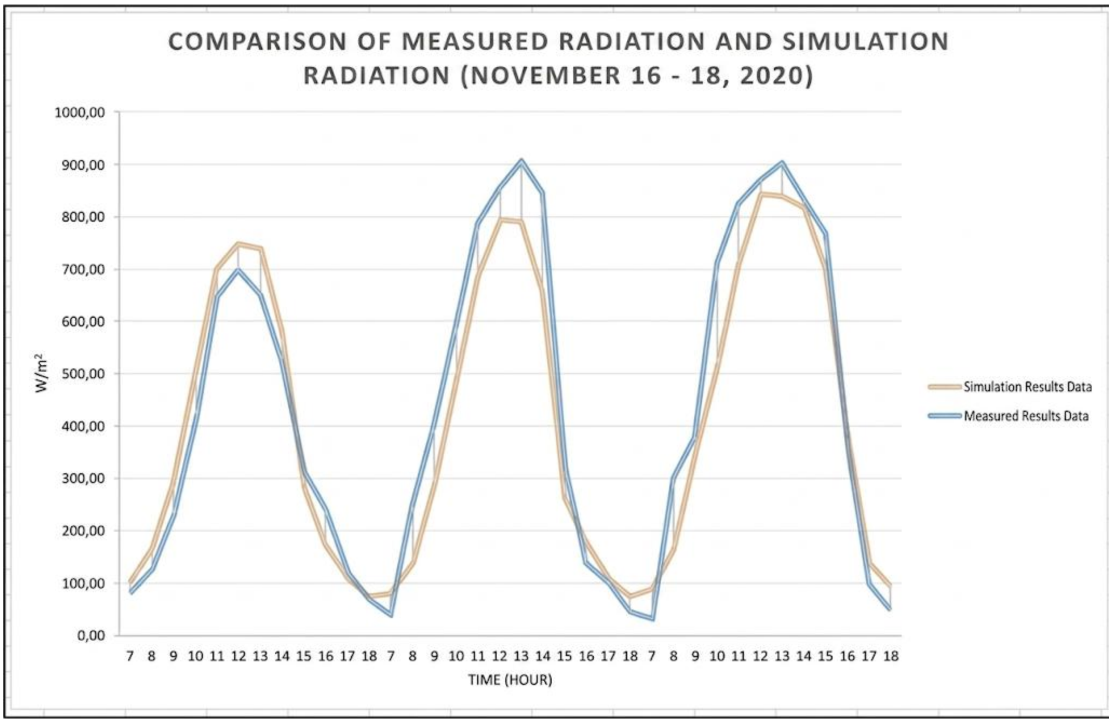

Figure 3. Comparison of Simulated Radiation Intensity and Measurement Results (November 16–18, 2020)

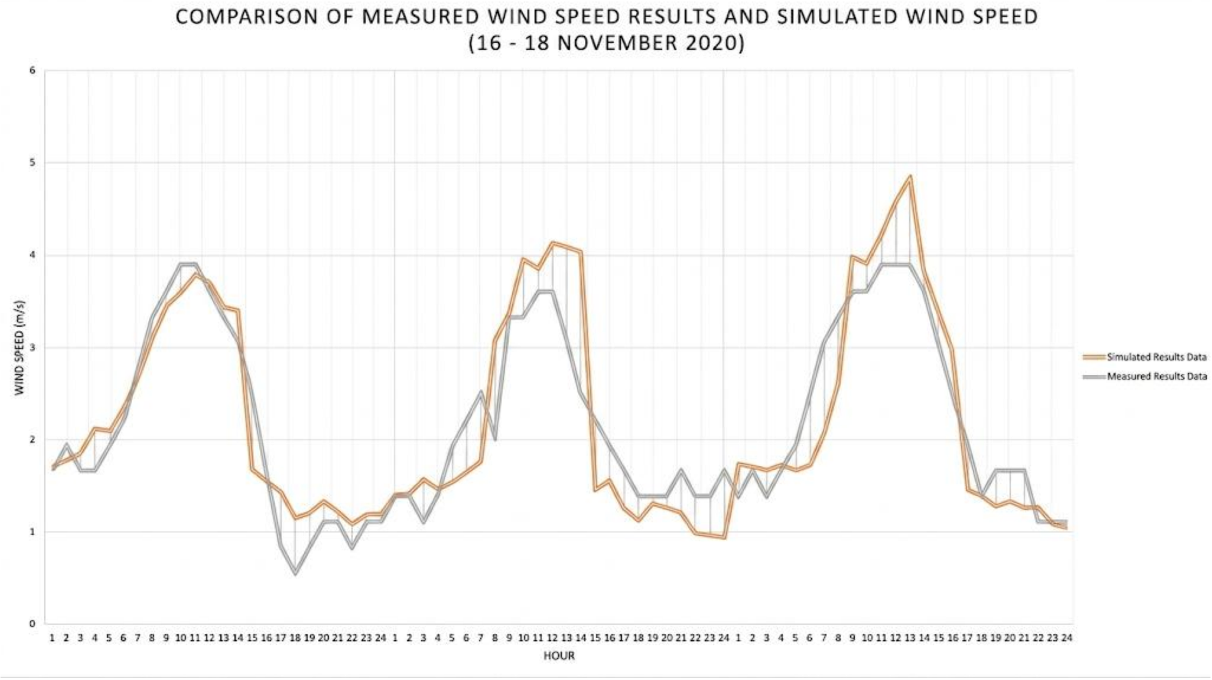

Figure 4. Comparison of Simulated and Measured Wind Speed (16–18 November 2020)

4.3. DG Output Power Potential

Based on the ANN simulation results obtained during the 15-day period (16–30 November 2020), the average hourly power potential generated by the 1,500 kWp photovoltaic power plant (PV) and the 800 kWp wind power plant (WPP) is presented in Tables 1 and 2, respectively.

Table 1. Average Hourly Power Potential of a 1,500 kWp PV System (16–30 November 2020)

Hour	Average Radiation (W/m^2)	Conversion Power (kW)
7	79.84	191.94
8	131.68	316.57
9	250.27	601.67
10	404.68	972.88
11	572.82	1.377,11
12	625.91	1.504,74
13	589.32	1.416,77
14	469.76	1.129,34
15	354.16	851.43
16	237.60	571.21
17	147.64	354.94
18	88.49	212.74

Table 2. Average Hourly Power Potential of an 800 kWp Wind Power Plant (16–30 November 2020) – Peak Hours

Hour	Average Wind District (m/s)	Conversion Power (kW)
08	2.010	200.09
09	2.508	388.71
10	2.726	499.14
11	3.110	741.18
12	3.175	788.63
13	3.108	739.75
14	2.636	451.31
15	2.121	235.11

The maximum output power of the photovoltaic power plant (PV) was achieved at 12:00 WIB, reaching 1,504.74 kW with an average solar radiation intensity of 625.91 W/m^2. Meanwhile, the maximum output power of the wind power plant (WPP) was also achieved at 12:00 WIB, reaching 788.63 kW with an average wind speed of 3.175 m/s. The wind potential in Darussalam is relatively low, with an average daily wind speed of 1.8 m/s; therefore, a large number of small-capacity wind turbines (2,800 units) is required to achieve the targeted generation capacity.

4.4. Analysis of the Impact of DG Injection on Voltage Profile

A Distributed Generation (DG) injection of 388.4 kW (20% of a 1.942 MW load) was carried out in two scenarios: (1) DG 1 installed at Bus USK 01, and (2) DG 2 installed at Bus USK 24. Table 3 presents a comparison of the voltage profile before and after DG injection at buses experiencing significant voltage drops.

Table 3. Comparison of Voltage Profile Before and After DG Injection (kV)

Bus ID	Without DG	DG1 PLTS	DG1 PLTB	DG2 PLTS	DG2 PLTB
Bus USK 1	19.896	19.908	19.909	19.909	19.910
Bus USK 8	19.856	19.867	19.869	19.878	19.880
Bus USK 15	19.843	19.855	19.851	19.855	19.856
Bus USK 23	19.810	19.822	19.823	19.846	19.849
Bus USK 24	19.786	19.798	19.799	19.843	19.847
Bus USK 27	19.778	19.790	19.791	19.834	19.839
Bus USK 36	19.769	19.781	19.782	19.805	19.808
Bus USK 38	19.758	19.770	19.771	19.794	19.797

From Table 3, it can be observed that DG injection in all scenarios successfully improves the voltage profile across all buses. The most significant improvement occurs at the downstream buses of the feeder (Bus USK 23 to USK 38) when DG is placed at Bus USK 24 (DG 2). This is due to the local power supply from DG 2, which directly reduces the current flow from the main source, thereby effectively minimizing voltage drop along the long distribution lines. These results are consistent with recent studies reporting that DG placement near the end of radial feeders significantly improves voltage profiles and reduces voltage drops [16], [17].

4.5. Analysis of the Impact of DG Injection on Power Losses

Table 4 presents a comparison of power losses in the main feeder lines before and after DG injection.

Table 4. Comparison of Main Line Power Losses Before and After DG Injection

Line	Without DG P(kW)	Without DG Q(kVAR)	DG1 PLTS P	DG1 PLTS Q	DG1 PLTB P	DG1 PLTB Q	DG2 PLTB P	DG2 PLTB Q
Line Unsyiah	8.1	8.7	6.1	6.6	5.9	6.3	6.0	6.3
Line USK 7	1.1	1.7	1.1	1.7	1.1	1.7	0.5	0.7
Line USK 22	1.2	1.5	1.2	1.5	1.2	1.5	0.5	0.6
TOTAL	11.8	13.1	9.8	11.0	9.6	10.7	8.1	8.6

The highest power losses occur in the Line Unsyiah feeder (2.18 km in length), which serves as the main interconnection line from the Krueng Cut Switching Station to the distribution feeder network. Without DG, the losses in this line reach 8.1 kW and 8.7 kVAR. The most significant reduction in power losses occurs when wind power-based DG (PLTB) is injected at Bus USK 24 (DG 2). In this case, the total feeder power losses are reduced by 3.7 kW (31.35%) for active power and 4.5 kVAR (34.35%) for reactive power compared to the base case without DG. Conversely, the smallest reduction is observed when solar PV-based DG (PLTS) is injected at Bus USK 01, with reductions of 2.0 kW (16.95%) and 2.1 kVAR (16.03%). This indicates that DG placement closer to the end-load buses results in a more significant reduction in power losses [7].

The significant reduction in power losses on the Line Unsyiah feeder is consistent with the theory that DG reduces the magnitude of current flowing from the main source, thereby decreasing resistive (I^2R) losses. In contrast, short inter-transformer distribution lines exhibit negligible losses even without DG, which is associated with their very low impedance values. The reduction in power losses obtained in this study is also in agreement with recent investigations on the integration of renewable distributed generation in radial distribution systems [14], [18].

5. CONCLUSION

Based on the simulation results and analysis conducted on the Unsyiah distribution feeder, it can be concluded that the integration of distributed generation (DG) significantly improves the performance of the distribution system. The study demonstrates that line impedance strongly influences both the voltage profile and the magnitude of power losses along the feeder. The implementation of renewable-energy-based DG, particularly photovoltaic (PV) and wind power plant (WPP) systems, successfully improved the voltage profile at several buses, especially those located near the end of the feeder where voltage drops were more critical. In addition, DG integration effectively reduced both active and reactive power losses in the distribution network. The optimal scenario was achieved when wind-power-based DG was installed at Bus USK 24, resulting in a reduction of active power losses by 31.35% and reactive power losses by 34.35% compared to the condition without DG. The results also indicate that the type and placement location of DG have a major impact on the effectiveness of voltage profile enhancement and power loss reduction. Therefore, proper planning of DG placement is essential to maximize the operational performance and efficiency of radial distribution systems.

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