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Research article

Analysis of Voltage Drop Improvement Using Transformer Insertion Method in LG-02 Receiver Lhokseumawe City

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Abstract: The LG-02 Darussalam distribution network, within the operational area of PT. PLN (Persero) ULP Lhokseumawe City, shows low voltage issues at the Gg. Damai and Bakso Pakde substations. According to PT. PLN standards, transformers face adverse loading conditions if usage exceeds 80% capacity. Specifically, Gg. Damai operates at 88.5% capacity and Bakso Pakde at 94.4%, resulting in a voltage drop of 370 Volts from the nominal 400 Volts at end consumer service phases. SPLN T6.001-2013 recommends that voltage differences at supply terminals not exceed ±10% of the system's nominal voltage, allowing a maximum drop of 360 Volts between phases under normal conditions. Failure to address these issues promptly risks further significant voltage drops. To resolve voltage drop and power loss problems, this study proposes a network repair plan using ETAP 19.0.1 software to align consumer-side voltage and transformer loading with PLN standards. Repair measures include installing additional transformers in the low-voltage distribution network. Post-repair assessments indicate a voltage drop reduction of +2.5% or an increase of approximately 10 Volts at both substations.

Keywords: voltage drop, losses, transformer, ETAP

1. Introduction

Lhokseumawe City is experiencing rapid growth across industry, business, and economy, leading to an increasing demand for electrical energy [1]. This surge places transformers at risk of overloading, surpassing their nominal capacities and potentially causing overheating and damage to insulation [2]. Such damage can lead to voltage drops in the electrical network, significantly affecting electricity distribution quality [3]. These drops can disrupt electronics, increase power losses, and interrupt industrial production [4].

Voltage drops can arise from multiple factors including low power factors, losses in conductors and transformers, load imbalances, and non-technical losses such as unauthorised electricity use [5]. A viable solution to address these issues locally is the transformer insertion method, which optimises energy distribution without the need for extensive infrastructure replacement [6]. By strategically placing transformers, the efficiency of energy distribution can be enhanced, ensuring stable voltage levels and minimising drops during energy transfer [7]. This approach is not only effective but also cost-efficient.

Understanding voltage drop as the discrepancy between input and output voltages is crucial [8]. Areas located farther from distribution substations typically experience more significant voltage drops compared to those in closer proximity [9]. Ensuring consistent voltage quality is essential to meet consumer expectations and maintain uninterrupted operations for businesses and the public [10]. Addressing and rectifying voltage drops through comprehensive analysis enhances the reliability and stability of the electrical grid [11]. Advanced simulation tools like ETAP (Electrical Transient and Analysis Program) enable detailed modelling of electrical networks, enabling the evaluation of voltage distribution and prediction of potential drop issues [12].

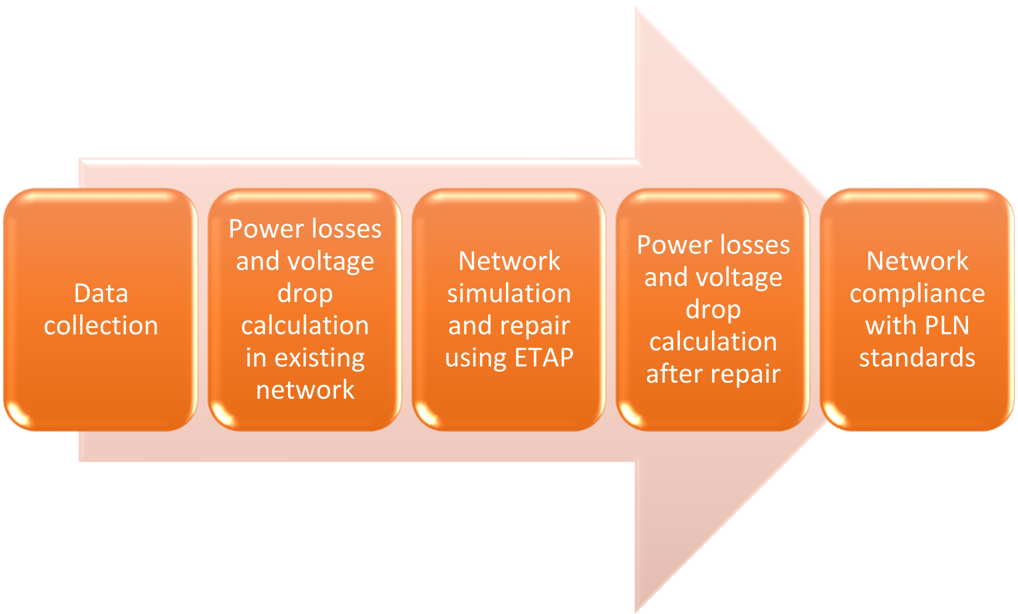
Improving electricity distribution not only enhances system reliability but also contributes to environmental sustainability by optimising energy use and reducing emissions from power generation [13]. Increased efficiency translates to reduced resource consumption to meet energy demands, thus lowering greenhouse gas emissions from power plants [14]. Adherence to standards such as SPLN T6.001-2013, which recommends voltage differences within ±10% of nominal voltage, forms the basis for effective maintenance strategies and rapid responses to maintain voltage stability.

Efforts to mitigate voltage drops at PT. PLN Lhokseumawe Main Substation can significantly improve energy transmission efficiency, minimise losses due to drops, and potentially reduce operational costs. Effectively managing voltage drops not only enhances service quality but also optimises equipment usage and decreases the need for maintenance and replacement of electrical components affected by prolonged drops. Therefore, initiatives aimed at reducing voltage drops yield both technical improvements and positive impacts on operational economics. This study seeks to explore the voltage drop repair analysis using the transformer insertion method in LG-02 feeder Lhokseumawe City using ETAP simulation, focusing on these critical aspects.

2. Methods

The study workflow is depicted in Figure 1.

Figure 1. Study workflow.



This research discusses planning for voltage drop repairs using the transformer insertion method in the low voltage network distribution system (JTR), calculating the existing transformer loading, power losses, and insert transformer capacity, as well as simulating the conditions before and after the transformer insertion, making comparisons. voltage drop and power loss using ETAP 19.0.1 software. The data collection process in this research was carried out at PT. PLN ULP Lhokseumawe City, on the LG-02 Darussalam feeder with research time in November 2023.

The methodology for this study unfolds through several key stages focused on planning voltage drop repairs using the transformer insertion method within the low voltage network distribution system (JTR). This includes assessing existing transformer loads and power losses, determining insertion transformer capacity, and simulating pre- and post-insertion conditions to compare voltage drops and power losses using ETAP 19.0.1 software. Data collection occurred at PT. PLN ULP Lhokseumawe City, specifically on the LG-02 Darussalam feeder, in November 2023.

Previous studies have explored various strategies to improve voltage drops in electricity distribution networks. For instance, Syakirman et al. examined the impact of wind turbine installation on radial distribution systems in Lhokseumawe City [15], while Marbun et al. investigated methods to reduce power losses and voltage drops in a 380 Volt network through load equalisation [16]. Effendi et al. also explored the effects of integrating Guntung PLTM on voltage drop reduction [17].

To initiate the analysis of voltage drops and power losses, the use of ETAP 19.0.1 software is imperative. Initial steps involve gathering essential data such as the one-line network diagram, cable specifications (length and cross-sectional area), current transformer loading, transformer capacities, end voltage and current profiles, and load types. Descriptive statistics serve as the primary data analysis technique in this research. This approach provides a comprehensive overview of the object under study, facilitating comparisons between network conditions before and after repairs.

Within the LG-02 feeder, the low voltage network employs 3 x 70 mm2 aluminum conductors featuring a cross-sectional resistance of 0.641 Ohm/Km. Table 4.1 provides detailed data on transformer loads across the LG-02 feeder, outlining substation locations, transformer capacities, and power usage.

The study proceeds with the following steps: i) Calculate transformer loading percentage based on base voltage and current using Equation (1) and Equation (2); ii) Compare ETAP simulation results under existing conditions with field data, focusing on voltage and loss values using Equation (3) and Equation (4); iii) Utilise reference field data for guiding voltage repairs in cases of overloaded transformers; iv) Determine transformer overload percentages using Equation (5) and calculate the required load size and insert transformer capacity using Equation (6) and Equation (7); and v) Conduct ETAP simulations to compare voltage drops pre- and post-repair, while also evaluating loss values post-repair against pre-repair metrics using Equation (3) and Equation (4).

$$kVA\ load = (I_r \cdot V_{R-N}) + (I_s \cdot V_{S-N}) + (I_t \cdot V_{T-N}) \tag{1}$$

$$\%loading = \frac{kVA\ load}{kVA\ transformer} \times 100\% \tag{2}$$

In Equation (1), I_r, I_s, and I_t represent the currents in the primary (r), secondary (s), and tertiary (t) windings of the transformer, respectively, while $V_{R\text{-}N}$, $V_{S\text{-}N}$, and $V_{T\text{-}N}$ represent the voltages between phases (R-N, S-N, T-N) in each winding.

$$R = r \cdot L \tag{3}$$

$$P_{losses} = I^2 \cdot R \tag{4}$$

In Equation (3) and (4), *R* is the resistance of the conductor, *r* is the material resistivity, and *L* is the length of the conductor. P_{losses} represents the power losses and *I* is the current flow through the conductor.

$$\%Overload = \%Load - \%Load\ Health\ Index \tag{5}$$

$$Load = \frac{\%Overload}{100\%} \times Original\ Transformer\ Rating \tag{6}$$

$$Transformer\ Capacity = \frac{Load}{0.8} \tag{7}$$

These methodological steps are essential for comprehensively assessing and addressing voltage drop issues within the LG-02 feeder of Lhokseumawe City, utilising both theoretical insights and practical field data to guide effective network improvements.

3. Results and Discussion

3.1. Existing Condition

Table 1 and 2 shows transformer load data and base load data in November 2023 at LG-02 Darussalam.

Table 1. LG-02 transformer loading data in November 2023.

Substation Name	Rated Power (kVA)	Main Load Currents				Power Used	
		R	S	T	N	kVA	%
Gg. Damai	100	121	167	93	78	88.50	88.5
PLTD Hagu I	200	122	100	98	35	71.87	35.9
Depan Sma .I.	100	71	55	50	32	40.88	40.9
Sp.Malikussaleh	200	181	106	127	117	92.98	46.5
Panti Asuhan	100	97	86	122	50	67.97	68.0
Gg. Aman Darussalam	250	117	205	124	127	100.94	40.4
Darussalam Sma-1	100	116	82	76	63	63.64	63.6
Depan Sma - 1 (3)	50	65	48	60	35	40.12	80.2
Rs. Bunda	160	104	62	59	42	51.05	31.9
Bakso Pakde	50	66	73	75	39	47.20	94.4
Sp. Tp Teurendam	100	57	102	91	75	56.72	56.7
PLTD Hagu 2	160	61	72	61	29	44.02	27.5
Mesjid Baiturrahman	100	89	108	92	17	63.24	63.2
Gang Amal Darussalam	100	100	54	44	54	45.92	45.9
Lancang Garam/bejee	100	22	42	32	38	21.95	21.9
Dpn Asia Mart	100	28	6	50	36	19.50	19.5
Man Lhokseumawe	50	21	9	15	22	10.44	20.9
Rs. Abby 1	200	35	29	62	50	29.24	14.6
Depan Sma 1 (S2)	100	95	42	37	61	40.42	40.4
Depan Sma 1 (S3)	100	77	90	106	46	63.41	63.4

Table 2. LG-02 base load data in November 2023.

Substation Name	Base Voltage					
	R-S	R-T	S-T	R-N	S-N	T-N
Gg. Damai	400	403	404	224	223	222
PLTD Hagu I	389	389	389	223	223	223
Depan SMA I	404	402	401	228	229	227
Sp.Malikussaleh	389	389	389	224	224	224
Panti Asuhan	386	386	386	223	223	223
Gg. Aman Darussalam	392	392	392	226	226	226
Darussalam SMA-1 S1	400	403	404	224	223	222
Depan SMA-1 (3)	401	401	403	227	228	227
RS. Bunda	393	393	393	224	224	224
Bakso Pakde	382	382	382	223	223	223
Sp. Tp Teurendam	393	393	393	223	223	223
PLTD Hagu 2	393	393	393	225	225	225
Mesjid Baiturrahman	394	349	394	227	227	227
Gang Amal Darussalam	400	402	403	223	223	223
Lancang Garam/Bejee	396	396	396	227	227	227
Dpn Asia Mart	402	402	402	233	233	233
MAN Lhokseumawe	401	400	404	228	226	229
RS. Abby 1	402	402	402	233	233	233
Depan SMA 1 S2	400	403	404	224	223	222
Depan SMA 1 S3	400	403	404	224	223	222

By analysing the voltage and current profiles of each substation, we can determine the substation's percentage loading. This involves using equation (1) to calculate the kVA load and equation (2) to find the percentage loading of each transformer. Based on these calculations, it is determined that the transformer at Gg. Damai is loaded at 84.991%. Using the equation mentioned earlier, the loading percentage for each transformer is as Table 3.

Table 3. Transformer loading calculation percentage.

Substation Name	Transformer Loading %
Gg. Damai	84.99
PLTD Hagu I	35.68
Depan SMA I	40.133
Sp.Malikussaleh	46.368
Panti Asuhan	68.015
Gg. Aman Darussalam	40.318
Darussalam SMA-1 S1	61.142
Depan SMA-1 (3)	78.638
RS. Bunda	31.5
Bakso Pakde	95.44
Sp. Tp Teurendam	55.75
PLTD Hagu 2	27.281
Mesjid Baiturrahman	65.602
Gang Amal Darussalam	44.154
Lancang Garam/Bejee	21.792
Dpn Asia Mart	41.707
MAN Lhokseumawe	20.514
RS. Abby 1	14.679
Depan SMA 1 S2	38.86
Depan SMA 1 S3	60.85

Based on Table 3, two substations have a loading percentages exceeding 80%:

1. **Gg. Damai** Substation: The transformer here is operating at 84.99% capacity. This indicates significant overload, necessitating careful attention to prevent performance degradation or transformer damage.
2. **Bakso Pakde** Substation: The transformer at this location is operating at 94.4% capacity, indicating an extremely high loading condition. Immediate action is crucial to prevent potential serious damage to the transformers.

Although Table 1 initially indicated three transformers with loading percentages above 80%, further precise calculations using the formula revealed that the transformer Depan SMA-1 (3) has a loading percentage of 78.638%. Therefore, this transformer does not fall into the overload category based on accurate calculations. As a result, the focus of repair and overload management efforts should be directed towards the transformers at Gg. Damai and Bakso Pakde substations.

Table 4 displays the end voltage profiles of each substation on the LG-02 Darussalam feeder as of November 2023. The primary concern lies with the voltage drop observed at Gg. Damai and Bakso Pakde substations, in addition to their transformers experiencing overload. The significant voltage decrease between phases (R-S, R-T, S-T) at these locations is likely influenced by several factors, including overloaded transformers. When a transformer operates beyond its recommended capacity, its efficiency declines, and the transformer's temperature rises due to overload. This elevated temperature not only reduces the transformer's operational efficiency but also increases power losses. To address this issue, the proposed solution involves installing an additional transformer at the overloaded substations. Introducing an additional transformer will distribute the load more evenly, alleviating pressure on each transformer and potentially mitigating voltage drops and efficiency issues.

Table 4. LG-02 end voltage data in November 2023.

Substation Name	End Voltage					
	R-S	R-T	S-T	R-N	S-N	T-N
Gg. Damai	371	372	371	214	214	215
PLTD Hagu I	377	377	377	216	216	216
Depan SMA I	392	390	389	221	222	220
Sp.Malikussaleh	377	377	377	217	217	217
Panti Asuhan	374	374	374	216	216	216
Gg. Aman Darussalam	380	380	380	219	219	219
Darussalam SMA-1 S1	388	391	392	217	216	215
Depan SMA-1 (3)	371	371	371	214	216	214
RS. Bunda	381	381	381	217	217	217
Bakso Pakde	370	371	370	213	212	213
Sp. Tp Teurendam	381	381	381	216	216	216
PLTD Hagu 2	381	381	381	218	218	218
Mesjid Baiturrahman	382	339	382	220	220	220
Gang Amal Darussalam	388	390	391	216	216	216
Lancang Garam/Bejee	384	384	384	220	220	220
Dpn Asia Mart	390	390	390	226	226	226
MAN Lhokseumawe	389	388	392	221	219	222
RS. Abby 1	390	390	390	226	226	226
Depan SMA 1 S2	388	391	392	217	216	215
Depan SMA 1 S3	388	391	392	217	216	215

3.2. Simulation of Existing Conditions

Before adding an additional transformer, the existing conditions at the Gg Damai substation include an inter-phase voltage of 371 Volts. The transformer at this substation is currently overloaded at 88.5%. Upon installing an additional transformer, the load will be distributed between the existing and new transformers, effectively reducing the load on the original transformer.

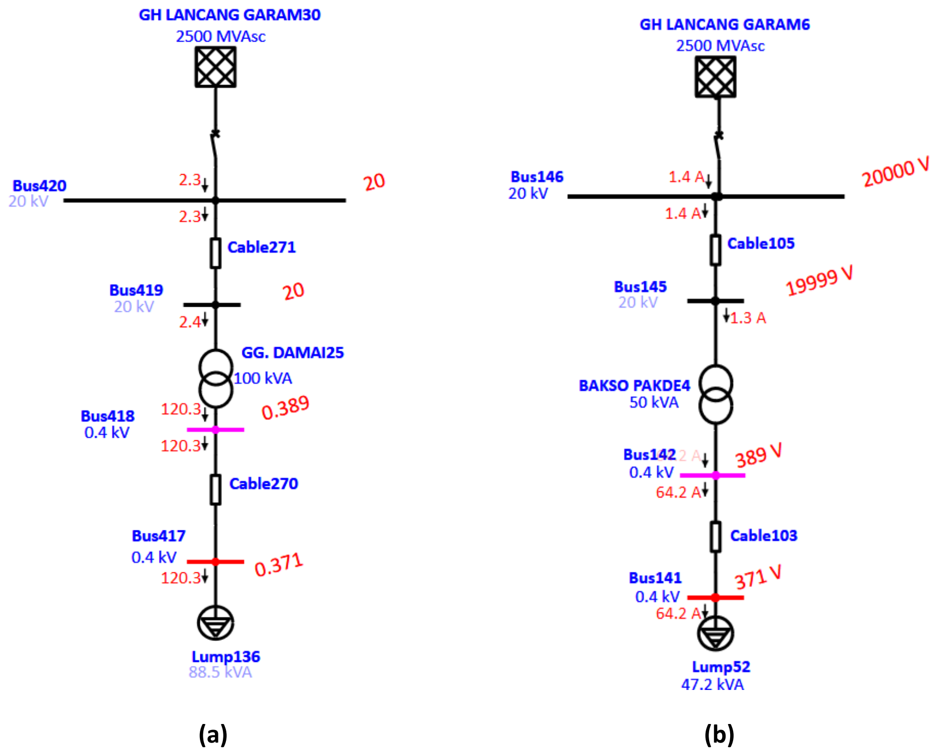


Figure 2. ETAP simulation of existing conditions: **(a)** Gg. Damai, **(b)** Bakso Pakde substation

The existing condition at BS-147 Bakso Pakde shows the transformer is overloaded at 94.4%, with the voltage at the BS end measured at 371 Volts. An additional transformer will be inserted at this substation to alleviate the overload and observe its impact on the end voltage. At the Gg. Damai substation, the existing losses amount to 5.5 kW. Meanwhile, at the Bakso Pakde substation, the losses are recorded at 2.9 kW.

3.3. Calculating Additional Transformer Capacity

According to PT PLN (Persero) regulations outlined in SE No. 0017.E/DIR/2014 on Distribution Transformer Maintenance Methods based on Asset Management Principles, transformers should not exceed 80% of their rated capacity. At Gg. Damai, the transformer is currently overloaded at 88.5% of its 100 kVA capacity, resulting in an overload of 8.5%. To address this overload, calculations were conducted using equations (5), (6), and (7). These calculations determined that an additional load of 8.5 kVA needs to be shifted. Considering the maximum permissible loading of 80%, the required capacity for the new transformer was calculated to be 10.625 kVA. Based on the transformer capacities available on the market, a 25 kVA transformer is suitable for installation at Gg. Damai to manage the load effectively. Similarly, calculations indicate that a 25 kVA transformer is also required to manage the load effectively for the Bakso Pakde substation. These steps ensure that the transformers operate within safe limits and maintain reliability in the distribution network.

3.4. Simulation of Additional Transformer

After calculating the capacity requirements for the inserted transformer, the next step is to install it according to the required specifications.

3.4.1. BS-03 Gg. Damai

Based on the calculations, BS-03 Gg. Damai requires an inserted transformer with a capacity of 25 kVA. Several factors influence the selection of the transformer rating. The substation is centrally located in a rapidly growing city area, necessitating a transformer capacity that can accommodate future load increases. When determining the capacity of the inserted transformer, it is crucial to adhere to PLN standards, which specify a maximum load percentage typically not exceeding 80%. Selecting a transformer capacity below this threshold ensures optimal performance. In this instance, a 50 kVA transformer was chosen. The single line diagram of Gg. Damai Substation after repair is seen in Fig. 3.

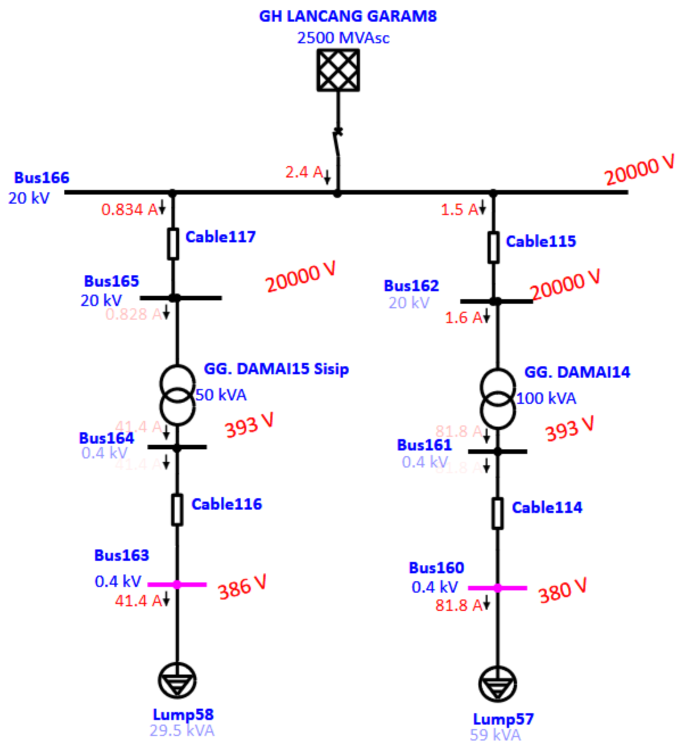


Figure 3. BS-03 Gg. Damai substation after repair.

The next step involves testing whether the addition of this transformer affects voltage levels. Observations showed that after installation, the transformer loading percentage decreased significantly. Initially at 88.5%, it reduced to 59%, well below the 80% limit, indicating optimal operation according to the Health Index. Voltage measurements before and after installation indicate a decrease from 371 Volts to 386 Volts on the inserted transformer and 380 Volts on the original transformer. The original voltage experienced a drop of 7.25% from a source voltage of 400 Volts, reducing to 381 Volts after installation, indicating a 4.75% decrease.

Specifically, in the Gg. Damai area, the voltage drop decreased by 2.50%. Furthermore, the loss value at GI Gg. Damai reduced from 5.5 kW in the existing condition to 3.3 kW after the transformer installation and adjustments. These steps demonstrate how the installation of an additional transformer not only optimized transformer loading but also improved voltage stability and reduced losses in the distribution network. Table 5 shows the simulation results before and after adding a newly inserted transformer at Gg. Damai, while Figure 4 depicted the load and voltage drop at Gg. Damai.

Table 5. Gg. Damai substation repair results.

Substation	Before		After	
	Load Percentage (%)	Voltage (V)	Load Percentage (%)	Voltage (V)
Gg. Damai	88.5	371	59	380
Additional transformer	-	-	59	386

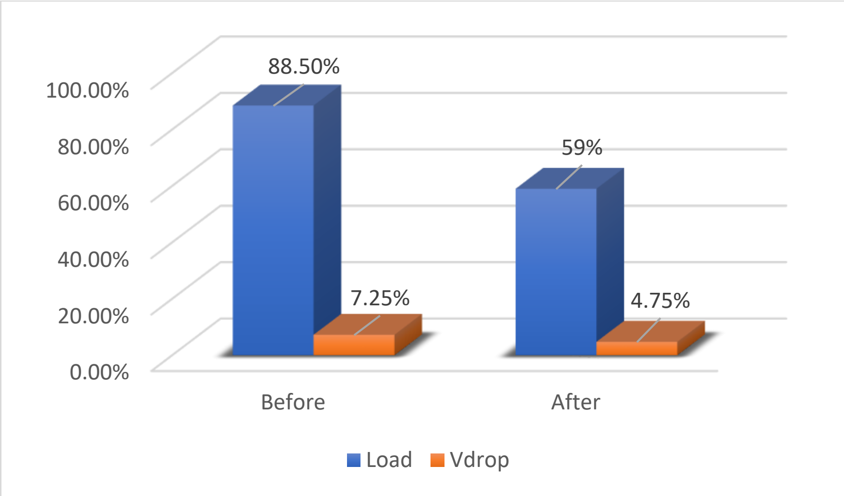


Figure 4. Load and voltage drop at Gg. Damai substation.

3.4.2. BS-147 Bakso Pakde

Based on the calculations conducted, BS-14 Bakso Pakde requires the addition of an inserted transformer with a capacity of 25 kVA. Currently, the transformer operates at 50 kVA capacity. Upon inserting the 25 kVA transformer, the load will be redistributed, with 15.73 kVA transferred to the new transformer, leaving 31.47 kVA on the existing transformer. After the insertion of the new transformer, voltage measurements showed an increase from 371 Volts to 386 Volts on the inserted transformer and 380 Volts on the existing transformer. This increase can be attributed to the dynamic response of the transformer to load changes and incoming voltage fluctuations. Additionally, normal operational conditions can alter impedance in the circuit, leading to voltage variations across different points in the network. The single line diagram of Bakso Pakde Substation after repairing is seen in Figure 5.

Following the transformer installation, the percentage of transformer loading decreased significantly, from the previous 88.5% to 59%, a reduction of 29.5%. This reduction ensures that the transformers operate within safe limits, well below the maximum allowable loading of 80%, and aligns with optimal operational standards according to the Health Index. Table 6 shows the simulation results.

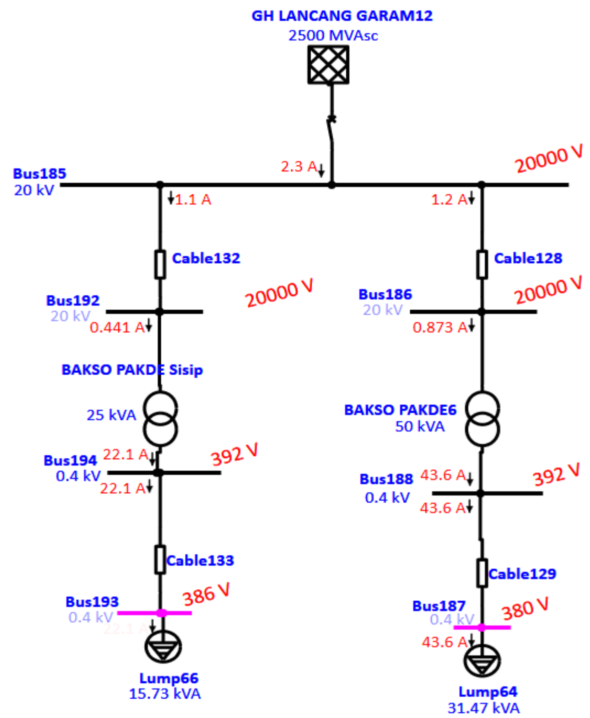


Figure 5. BS-147 Bakso Pakde substation after repair.

Table 6. Bakso Pakde substation repair results.

Substation	Before		After	
	Load Percentage (%)	Voltage (V)	Load Percentage (%)	Voltage (V)
Bakso Pakde	94.4	370	62.94	380
Additional transformer	-	-	62.94	386

Regarding voltage stability, the original voltage dropped by 7.50% from a source voltage of 400 Volts, measuring 370 Volts initially. Post-installation, the voltage drop reduced to 5%, measuring 381 Volts. This decrease indicates improved voltage stability in the Bakso Pakde area, with a reduction of 2.50% in voltage drop. Additionally, at GI Bakso Pakde, the loss value decreased from 2.9 kW in the initial condition to 1.8 kW after the transformer adjustments, reflecting improved efficiency and reduced power losses. These results illustrate how strategic transformer additions can enhance network performance, mitigate overload risks, and improve voltage stability in distribution systems. Figure 6 shows the load and voltage drop at Bakso Pakde Substation before and after inserting new transformer.

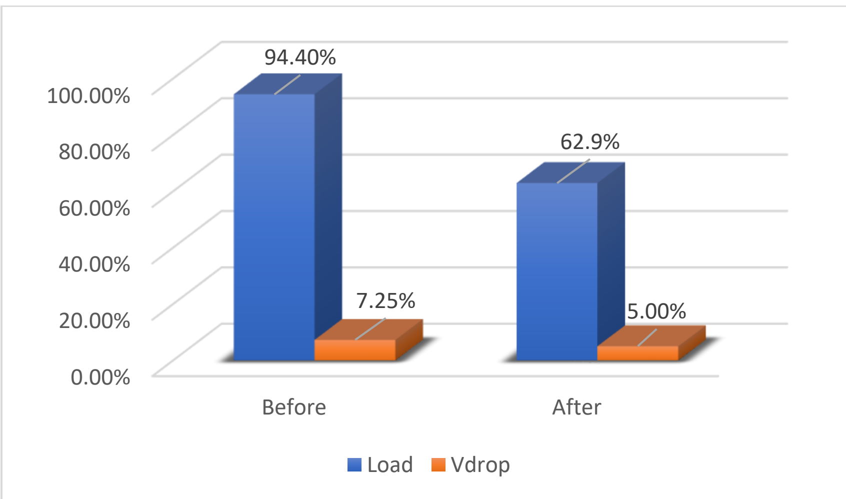


Figure 6. Load and voltage drop at Bakso Pakde substation.

3.5. Study Limitation

This study faces several limitations that should be acknowledged. Firstly, data limitations pose a significant obstacle. The accuracy and availability of data used in the simulation may not fully reflect actual field conditions. Historical data on feeder load and conditions can change, potentially impacting the accuracy of simulation results. Secondly, limitations in the simulation process itself must be considered. Using ETAP for simulation involves simplifications and assumptions, such as uniform load distribution and ideal equipment operating conditions, which may not entirely represent real-world complexities. Additionally, parameters in the electrical system that are difficult to measure or predict accurately, such as dynamic network impedance or unexpected disturbances, can affect simulation outcomes.

Thirdly, the generalizability of the study's findings is limited. This research is specific to the LG-02 feeder in Lhokseumawe City, and applying these results to other regions or electrical systems requires caution due to differences in infrastructure, operational conditions, and environmental factors. Fourthly, practical implementation of the transformer insertion method may encounter technical and financial challenges. Costs associated with installation, maintenance, and adjustments to existing infrastructure could be prohibitive. Scaling these solutions to larger or more complex distribution networks may pose further challenges. Lastly, external factors such as changes in government policies, regulations in the energy distribution sector, and advancements in electricity technologies can influence the applicability and relevance of the proposed solution. Acknowledging these limitations is essential for interpreting and applying the study's findings appropriately. Further research is recommended to address these limitations and strengthen the robustness of the study's conclusions.

4. Conclusions

Based on this research, the conclusion drawn is that the insertion of additional transformers reduces voltage drops and operational losses in the distribution network. For instance, at Gg. Damai, the voltage improved from 371 V to 381 V after the transformer insertion, indicating a 2.5% decrease in voltage drop. Similarly, at Bakso Pakde, the voltage increased from 370 V to 380 V, also reducing the voltage drop by 2.5% from previous conditions. Moreover, the implementation of transformer inserts resulted in reduced operational losses. At Gg. Damai, losses decreased from 5.4 kW to 3.3 kW, while at Bakso Pakde, losses reduced from 2.9 kW to 1.8 kW after the transformers were inserted.

Transformers operating under overload conditions can cause voltage drops, as observed in this study, where transformers in the Gg. Damai and Bakso Pakde areas experienced voltage drops due to overload. By introducing distribution transformer inserts, the load on existing transformers is shared, thereby reducing the load percentage. At Gg. Damai, the load decreased from 88.5% to 59% after inserting the transformer. Similarly, at Bakso Pakde, the load decreased from 94.4% to 62.94% post-insertion. In summary, the insertion of transformers effectively mitigates voltage drops, reduces operational losses, and optimises the load distribution across the network, enhancing overall performance and reliability.

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Data Availability Statement: Due to privacy restrictions, the data of this study is unavailable.

Conflicts of Interest: The authors declare no conflicts of interest.

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