Analysis of Overloading Impact on Harmonic Content and Loss of Life in Distribution Transformers

[1]Kartika Tresya M, [2]Alex Fernandes. [3]Welly Okke, [4]Nurmiati Pasra, [5]Samsurizal, [6]Tony Koerniawan
[1,2,3,4,5,6]Institut Teknologi PLN, Jl. Lingkar Luar Barat Duri Kosambi, Cengkareng Jakarta Barat, 11750
[1]kartika@itpln.ac.id, [2]alex.fernandes@itpln.ac.id, [3]welly1811026@itpln.ac.id, [4]nurmiati@itpln.ac.id, [5]samsurizal@itpln.ac.id, [6]tony.koerniawan@itpln.ac.id

Abstract - ***In the wake of Indonesia's accelerating power infrastructure growth, maintaining distribution system integrity is essential to meet the increasing electricity demand from both residential and industrial sectors. This study investigates the operational performance of the PGCE distribution transformer at the Lemah Abang Customer Service Unit (ULP), which experienced severe overloading with a peak loading of 113.82%, exceeding the maximum allowable loading limit of 80% specified in SE No. 0017.E/DIR/2014. The overload condition resulted in excessive thermal stress and a 17% voltage drop, exceeding the permissible service voltage variation specified in SPLN 1:1995. To address these problems, a load-splitting strategy was implemented through the installation of an SNTR insertion transformer. A comparative quantitative (before–after) analysis was conducted using field measurement data to evaluate transformer loading, voltage drop, and transformer loss of life before and after the technical intervention. The results show that the loading of the PGCE distribution transformer was reduced to approximately 76–77%, restoring its operation to within the recommended loading limit. In addition, the voltage drop decreased from 17% to 4.5%, satisfying the service voltage requirement of +5% to −10%. The reduction in transformer loading also lowered thermal stress on the winding insulation, thereby reducing the transformer loss of life and improving asset reliability. These findings demonstrate that load splitting combined with the installation of an insertion transformer is an effective engineering solution for mitigating transformer overloading, improving voltage quality, and extending transformer service life. The proposed approach provides practical guidance for distribution asset management and overload mitigation in rapidly growing electrical distribution networks.***

Keywords — Distribution Transformer, Overload Mitigation, Load Splitting, Voltage Drop, Loss of Life.

I. Introduction

The rapid development and growth of power generation in Indonesia demand facilities and infrastructure to support adequate electricity availability [1]. Currently, electricity is a primary necessity for the Indonesian people, leading to a continuous increase in the number of consumers and electrical loads [2]. Household and industrial appliances rely heavily on electricity because this energy is easily converted into other forms [3]. Reliable and sustainable power quality is an absolute requirement to meet the needs of power distributed to customers [4], [5]. The Indonesian power system consists of three main parts: generation, transmission, and distribution [6]. Among these, the distribution system holds a critical role as it connects directly to electricity users [7]. The primary function of a distribution substation is to step down the voltage to a low-voltage level of 220 V/380 V [8].

In the case of the Customer Service Unit (ULP) in the Lemah Abang area, specifically the transformers at the Pasir Gombong (PGCE) substation, transformer loads have increased alongside population growth, often exceeding standard limits. Based on PT PLN (Persero) SE No. 0017.E/DIR/2014 [9], the maximum allowable load for a distribution transformer is 80% [10]. Overload conditions occur when the load exceeds the nominal capacity, causing the transformer to overheat and the conductors to be unable to withstand the load [11], [12]. This creates heat that increases the winding temperature, which can damage the insulation [13], [14]. Consequently, overloading negatively affects power quality, leading to voltage drops at the network ends and a significant reduction in the transformer's service life [15], [16].

Several previous studies have addressed the impact of overloading [17]. Research by Susanto in 2020 [18] indicated that the load percentage after transformer uprating reached 64.8%. A study by Wahyudi Widiatmika et al. in 2018 [17] regarding the DB0244 transformer utilized an insertion transformer to mitigate overload, achieving a load percentage of 68.3%. Furthermore, research by Pebrisasvian et al. in 2013 [19] demonstrated that installing a distribution transformer could correct overload conditions from 124.17% to 46.646% and improve voltage drops from 12% to 8.2%.

Previous studies on distribution transformer overloading have primarily focused on loading analysis or voltage quality assessment as separate issues. Limited research has comprehensively evaluated the combined impact of transformer overloading on voltage drop and transformer loss of life, while simultaneously assessing the effectiveness of load splitting and the installation of an insertion transformer under actual distribution network operating conditions. Furthermore, studies based on real operational data from PT PLN (Persero) distribution systems remain limited.

To address this gap, this research comprehensively analyzes the impact of overloading on the operational performance of the PGCE distribution transformer by integrating transformer loading analysis, voltage drop evaluation, and transformer loss-of-life assessment before and after the implementation of load splitting and the installation of the SNTR insertion transformer. The novelty of this study lies in the use of a comparative before–after analysis based on actual field measurements to evaluate the effectiveness of these technical interventions in improving power quality, restoring transformer loading to the recommended operating range, and extending transformer service life. The findings provide practical recommendations for distribution asset management and overload mitigation strategies in similar electrical distribution networks.

II. Research Method

This research was conducted on a distribution transformer coded PGCE, located on Jalan Lemah Abang Raya, Kampung Rawa Lintah, Mekarmukti, North Cikarang District, Bekasi Regency, West Java 17530, Indonesia. The study was carried out over a period of three months, from March to May 2022. The selected transformer was identified as experiencing a high loading condition, making it suitable for evaluating the impact of overloading on transformer performance and service life.

Figure 1. Distribution Transformer coded PGCE

Figure 1 shows the PGCE distribution transformer, which served as the object of this study. The transformer is a pole-mounted distribution transformer supplying electrical power to residential and commercial consumers in the Lemah Abang service area. Based on preliminary field observations and operational records from PT PLN (Persero), the transformer had experienced a sustained overload condition, making it an appropriate case study for evaluating the effects of excessive loading on transformer performance. Therefore, this transformer was selected to investigate the impact of overloading on transformer loading, voltage drop, and transformer loss of life, as well as to assess the effectiveness of load splitting and the installation of an SNTR insertion transformer as corrective measures.

Prior to the technical analysis, the condition of the transformer was evaluated using the Matrix Online Assessment Tier-1, which is a preliminary assessment instrument adopted by PT PLN (Persero) for evaluating distribution transformer conditions. The assessment consists of two major characteristic groups, namely Visual Inspection and Load Reading and Profiling. Each parameter is classified into four condition levels (Good, Fair, Poor, and Bad) according to predefined technical criteria. The assessment is intended to identify operational deficiencies and determine whether further technical analysis is required. The complete assessment criteria are presented in Table 1.

Table 1. Matrix Online Assessment Tier-1 for Distribution Transformer Assessment

Characteristic Group	**Characteristic**	**Good**	**Fair**	**Poor**	**Bad**
Visual Inspection	Transformer Oil Leakage	Clean	Cracked gasket	Cracked/oily gasket	Oil seepage/dripping
	Transformer Physical Condition	Smooth/intact	Minor fin defects	Major fin defects	Swollen/deformed
	Transformer Grounding	< 1.7 Ω	1.7 Ω – < 5 Ω	5 Ω – < 10 Ω	≥ 10 Ω
	LV Fuse Current Rating Compliance	Meets standard	One level above standard	Two levels above standard	LV fuse unavailable (bypassed)
	Low Voltage Switch Board (LVSB) Condition	Clean enclosure, neat installation	Dirty enclosure, neat installation	Corroded enclosure, neat installation	Leaking enclosure, poor installation
Load Reading and Profiling	Transformer Current Loading (% of Outlet Current	< 60%	60% – < 80%	80% – < 100%	≥ 100%

Characteristic Group	Characteristic	Good	Fair	Poor	Bad
	Carrying Capacity)				
	Phase Current Unbalance	< 10%	10% – < 20%	20% – < 25%	≥ 25%
	Transformer Neutral Current (% of Transformer Load Current)	< 10%	10% – < 15%	15% – < 20%	≥ 20%
	Transformer Loading (% of Rated Capacity)	< 60%	60% – < 80%	80% – < 100%	≥ 100%

After the preliminary assessment, the research proceeded through several systematic stages, as illustrated in Figure 2. The study began with collecting transformer operational data, including load measurements, electrical parameters, and the Single Line Diagram (SLD) of the distribution network. These data were used to identify the existing operating condition of the transformer before any corrective actions were implemented.

The increasing demand for electrical energy has resulted in higher loading levels on many distribution transformers. When transformer loading exceeds its recommended operating limit, excessive temperature rise occurs, accelerating insulation aging, increasing voltage drop, reducing transformer efficiency, and shortening transformer service life. Therefore, evaluating transformer loading and its operational impacts is essential for maintaining distribution system reliability.

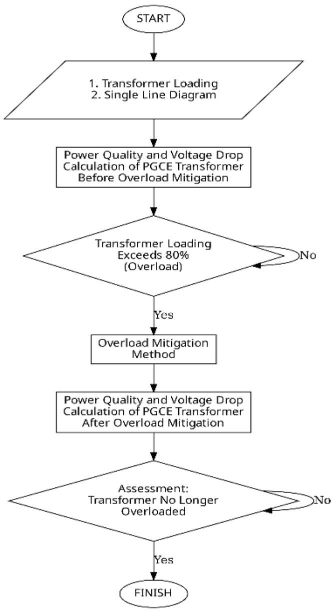

Figure 2. Research Flowchart

Figure 2 illustrates the overall research workflow adopted in this study. The process begins with the collection of transformer loading data and the Single Line Diagram (SLD) of the PGCE distribution transformer to identify its initial operating condition. The collected data are then used to calculate the transformer loading percentage, voltage drop, and power quality parameters before any technical intervention is implemented. If the transformer loading exceeds the maximum allowable limit of 80%, overload mitigation is performed through load splitting and the installation of an SNTR insertion transformer. Subsequently, the transformer loading, voltage drop, and transformer loss of life are recalculated under the improved operating condition. Finally, the post-improvement results are evaluated to verify that the transformer is no longer operating under overload conditions and that the implemented mitigation successfully improves transformer performance and power quality.

In the calculation phase, references were gathered from literature, journals, and previous studies, including national and utility standards such as the Indonesian National Standard (SNI) and the State Electricity Company Standard (SPLN). Data processing involved calculating the loading percentage of the transformer both before and after technical improvements. To obtain the data required for calculations, measurements were taken from the PGCE substation, which was identified as experiencing an overload. Based on the regulations in PT PLN (Persero) SE No. 0017.E/DIR/2014, the maximum allowable loading for a transformer is set at 80% [9]. Overload conditions cause the voltage quality received by customers to deviate from standard criteria. According to the SPLN Series 1 Year 1995, the service voltage variation is set at a maximum of +5% and a minimum of −10% of the nominal voltage [17].

Table 2. Service Voltage Variations

Nominal Voltage (V)	Service Voltage Variation (%)
230/400 400/690 1.000	+5%. -10%

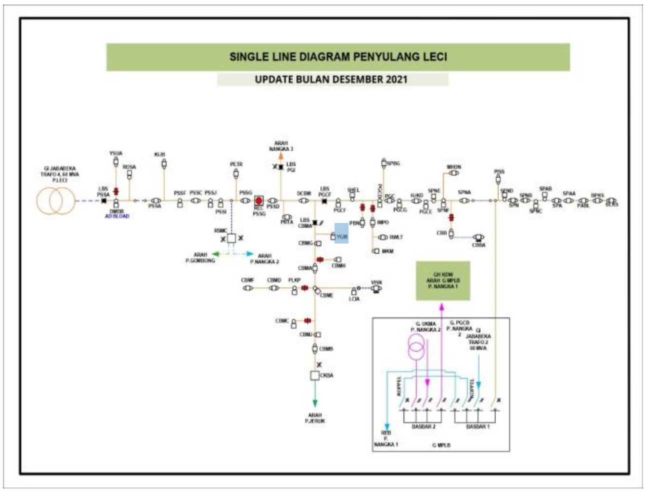

Figure 3. Single Line Diagram Before Improvement

This study employs a quantitative research approach because the analysis is based on numerical data obtained from field measurements and engineering calculations [20]. The research applies a comparative quantitative analysis (before–after study) to evaluate the impact of technical improvements on the operational performance of the PGCE distribution transformer. The comparison focuses on key performance indicators, including transformer loading, voltage drop, and transformer loss of life before and after the improvement. This approach enables an objective assessment of the effectiveness of the implemented corrective actions in reducing transformer loading, improving voltage quality, and extending the transformer's expected service life [21].

III. Results and Discussion

A. Results Before Improvement

Single Line Diagram of Leci Feeder

It is essential to understand the single line diagram of the PT. PLN ULP Lemah Abang distribution network to simplify the understanding of the electrical system, particularly on the Leci feeder. This single line diagram consists of 55 substations, including pole-mounted and portal substations. The Leci feeder is distributed from the Jababeka Main Substation Transformer 4, which has a capacity of 60 MVA.

One of the substations in the low-voltage network of the Leci Feeder experienced a problem in the form of an excessive load or overload. The substation experiencing this overload is the PGCE distribution transformer.

Specification of PGCE Distribution Transformer

The specifications of the distribution transformer experiencing the overload are necessary for calculating the loading and power quality before and after the addition of a new substation and load splitting. The specifications of the PGCE distribution transformer are as follows:

Table 3. Specification of PGCE Distribution Transformer

No.	Description	Specification
1	Substation Name	PGCE
2	Feeder	Leci
3	Serial Number	163306475
4	Brand	Trafoindo
5	Transformer Type	Hermetic
6	Substation Type	Pole-Mounted Substation
7	Frequency	50 Hz
8	Transformer Capacity	160 kVA
9	Primary Transformer Voltage	20 kV
10	Secondary Transformer Voltage	400 V
11	Primary Transformer Current	4.62 A
12	Secondary Transformer Current	230.94 A

Load Current Conditions of PGCE Distribution Transformer

The PGCE distribution transformer is one of the transformers on the Leci feeder at PT. PLN (Persero) ULP Lemah Abang that experienced an overload. Overloading causes the transformer to heat up and the conductors to no longer be able to withstand the load, leading to a rise in winding temperature and potential damage. Data was collected during peak load periods over 14 days, from March 5, 2022, to March 18, 2022.
The full load current (I_{FL}) of the PGCE distribution transformer was calculated using the following formula based on its specification However, the actual measurements showed that the average currents far exceeded this capacity. The percentage of transformer loading was calculated to determine the severity of the overload. Based on the calculations, the loading percentage ranged from 109% to 117%.

Table 4. Percentage of PGCE Distribution Transformer Load Current Before Improvement

No	Date	I Average (A)	I Loading (%)
1	5-Mar-22	434.807	109%
2	6-Mar-22	435.383	109%
3	7-Mar-22	438.267	110%
4	8-Mar-22	438.267	110%
5	9-Mar-22	440.573	110%
6	10-Mar-22	445.763	111%

7	11-Mar-22	446.917	112%
8	12-Mar-22	453.837	113%
9	13-Mar-22	455.567	114%
10	14-Mar-22	456.720	114%
11	15-Mar-22	463.063	116%
12	16-Mar-22	461.910	115%
13	17-Mar-22	464.793	116%
14	18-Mar-22	466.523	117%

Based on these results, the loading percentage of the distribution transformer is significantly above the maximum allowable limit of 80% as regulated by SPLN No. 17 of 2014. If left unaddressed, this condition causes excessive heat, which leads to a decrease in power quality and eventual damage to the electrical distribution system.

Load Imbalance of PGCE Distribution Transformer

Load imbalance in a distribution system often occurs due to uneven single-phase loads among the three phases (R, S, T). This imbalance results in neutral currents, leading to losses and decreased transformer efficiency. Calculations for the PGCE transformer before improvement showed imbalance percentages ranging from 2% to 4%.

Voltage Level Quality of PGCE Distribution Transformer

Voltage drop calculations are necessary to ensure that the receiving end voltage maintains quality according to applicable standards. The conductor used is a low-voltage twisted cable with a size of 3x70+1x50 mm² over a distance of 0.25 km. According to the engineering design criteria in SPLN 64 of 1985 [8], the characteristics of this aluminum conductor are as follows:

Table 5. Characteristics of Aluminum JTR Conductors

Conductor		KHA (A)	Conductor Resistance at 20°C (Ω/km)		Reactance at f = 50 Hz (Ω/km)
Type	Size		Phase	Neutral	
Twisted Cable	3x35+1x50 mm^2	125	0,867	0,581	0,3790
	3x50+1x50 mm^2	154	0,641	0,581	0,3678
	3x70+1x50 mm^2	196	0,443	0,581	0,3572
	3x90+1x50 mm^2	242	0,308	0,581	0,3449

Calculations revealed that the voltage drop reached up to 17%. According to SPLN series 1 of 1995, the service voltage variation is set at a maximum of +5% and a minimum of -10% [3]. Thus, the PGCE transformer not only experienced an overload but also a voltage drop that significantly exceeded the standard.

B. Results After Improvement

Implementation of Load Splitting and SNTR Insertion Transformer

To address the overload condition on the PGCE transformer, PT. PLN (Persero) ULP Lemah Abang implemented a technical intervention by installing an insertion transformer (SNTR) and performing load splitting. This process involved moving a portion of the load from the PGCE transformer to a newly installed transformer to ensure both operate within safe loading limits.

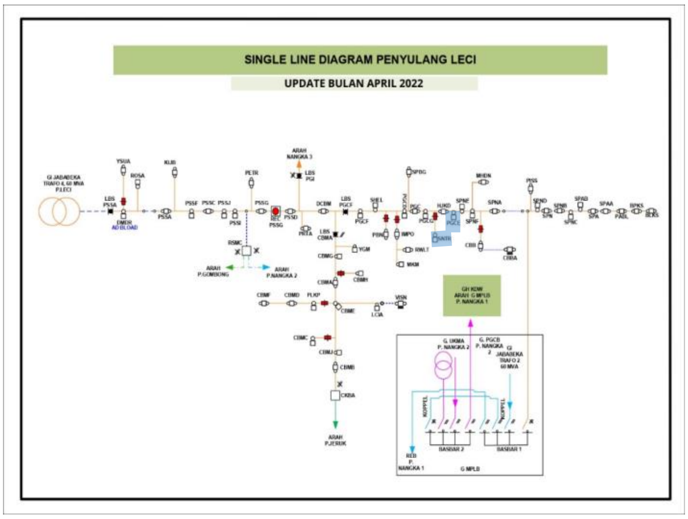

Figure 5. Single Line Diagram After Improvement

Loading Percentage After Improvement

After the installation of the SNTR insertion transformer and the implementation of load splitting, transformer loading was monitored over a 14-day observation period to evaluate the effectiveness of the improvement. Before the improvement, the PGCE distribution transformer operated under severe overload conditions, reaching a peak loading of **113.82%**, which exceeded the maximum allowable loading limit of **80%** specified by PT PLN (Persero). Following the implementation of load splitting, the **average loading of the PGCE transformer** decreased to **48.74%**, indicating that the transformer had returned to an acceptable operating condition. The installation of the SNTR insertion transformer enabled part of the load to be transferred from the PGCE transformer, thereby relieving the overload condition.

Table 6. Percentage of PGCE Distribution Transformer Load Current After Improvement

No	Date	IAverage (A)	Loading(%)
1	19-Mar-22	302.750	76%
2	20-Mar-22	303.327	76%
3	21-Mar-22	303.327	76%

No	Date	IAverage (A)	Loading(%)
4	22-Mar-22	302.750	76%
5	23-Mar-22	303.327	76%
6	24-Mar-22	304.480	76%
7	25-Mar-22	306.210	77%
8	26-Mar-22	303.903	76%
9	27-Mar-22	306.787	77%
10	28-Mar-22	303.327	76%
11	29-Mar-22	305.633	76%
12	30-Mar-22	304.480	76%
13	31-Mar-22	305.633	76%
14	1-Apr-22	303.327	76%

This reduction ensures that the transformer operates below the 80% maximum limit regulated by SE No. 0017.E/DIR/2014 [2]. By maintaining the load at this level, the risk of overheating and insulation damage is significantly minimized.

Voltage Quality and Voltage Drop After Improvement

The reduction in the total current flowing through the low-voltage network directly affected the voltage drop. With the load being split, the current (I) decreased, which in turn reduced the voltage drop (Delta V) across the conductors. Calculation results indicate that the voltage drop at the customer end was improved from 17% to 4.5%.

Table 7. Voltage Drop Before Improvement

No	Δ Voltage Drop (V)			Voltage Drop (%)		
	R	S	T	R	S	T
1	34.38	37.82	35.81	15%	16%	15%
2	34.67	37.68	34.67	15%	16%	15%
3	34.95	37.68	34.95	15%	16%	15%
4	35.38	37.68	35.38	15%	16%	15%
5	35.53	38.11	35.53	15%	16%	15%
6	35.81	38.68	35.81	15%	17%	15%
7	36.10	38.68	36.10	15%	17%	16%
8	36.96	38.96	36.96	16%	17%	16%
9	37.25	38.68	37.25	16%	17%	16%
10	37.53	38.68	37.53	16%	17%	16%
11	37.25	39.39	37.25	16%	17%	16%
12	37.53	39.25	37.53	16%	17%	16%
13	37.53	39.68	37.53	16%	17%	16%
14	37.68	39.82	37.68	16%	17%	16%

Table 7. Voltage Drop After Improvement

No	PGCE Transformer After Improvement						SNTR Insertion Transformer					
	Voltage Drop (V)			Voltage Drop (%)			Voltage Drop (V)			Voltage Drop (%)		
	R	S	T	R	S	T	R	S	T	R	S	T
1	9.74	10.03	10.31	4%	4%	5%	7.99	8.85	7.56	4%	4%	3%
2	9.74	10.03	10.37	4%	4%	5%	7.99	8.85	7.48	4%	4%	3%
3	9.74	10.03	10.37	4%	4%	5%	7.99	8.85	7.48	4%	4%	3%
4	9.80	9.97	10.31	4%	4%	5%	7.91	8.94	7.56	3%	4%	3%
5	9.86	9.91	10.37	4%	4%	5%	7.82	9.02	7.48	3%	4%	3%
6	9.86	9.86	10.54	4%	4%	5%	7.82	9.11	7.22	3%	4%	3%
7	9.80	10.08	10.54	4%	4%	5%	7.91	8.77	7.22	3%	4%	3%
8	9.80	10.08	10.31	4%	4%	5%	7.91	8.77	7.56	3%	4%	3%
9	9.91	10.14	10.43	4%	4%	5%	7.74	8.68	7.39	3%	4%	3%
10	9.74	9.97	10.43	4%	4%	5%	7.99	8.94	7.39	4%	4%	3%
11	9.86	9.97	10.54	4%	4%	5%	7.82	8.94	7.22	3%	4%	3%
12	9.80	10.03	10.43	4%	4%	5%	7.91	8.85	7.39	3%	4%	3%
13	9.91	10.08	10.37	4%	4%	5%	7.74	8.77	7.48	3%	4%	3%
14	9.74	10.03	10.37	4%	4%	5%	7.99	8.85	7.48	4%	4%	3%

This improvement ensures that the power quality delivered to consumers meets the standards of SPLN 1 of 1995, which requires service voltage variations to remain within 5% and -10% of the nominal voltage [3].

Analysis of Transformer Loss of Life

The service life of a distribution transformer is determined by the quality of its insulation, which degrades over time due to thermal stress caused by loading. Overloading causes the transformer's internal temperature (hottest-spot temperature) to rise, accelerating the aging process. According to the IEEE Std C57.91 standard [9], the relative aging rate doubles for every 6°C increase in temperature above the reference point.

Based on the calculations for the PGCE transformer, the loss of life before improvement was significantly higher than the normal rate. However, after the load splitting and reduction in loading percentage to 48.74%, the estimated loss of life returned to a normal range. This intervention effectively extended the transformer's operational duration and prevented premature failure.

DISCUSSION

The results demonstrate that the PGCE distribution transformer experienced a severe overload condition before the implementation of the technical improvement. As presented in Table 4, the transformer loading continuously increased during the 14-day observation period, ranging from 109% to 117%, with a peak loading of 117%. This operating condition exceeded the maximum loading limit of 80% specified by PT PLN (Persero), indicating that the transformer was operating beyond its recommended capacity. Prolonged operation under such conditions increases winding temperature, accelerates insulation deterioration, and reduces transformer reliability.

The overload condition also had a direct impact on the voltage quality supplied to customers. Based on the voltage-drop calculation presented in Table 7 (Before Improvement), the voltage drop reached 17% on the S phase, while the R and T phases experienced voltage drops of approximately 15–16%. These values exceeded the allowable service voltage variation of +5% to −10% specified in SPLN 1:1995 [3]. The excessive voltage drop was caused by the high load current flowing through the low-voltage distribution conductors, resulting in greater voltage losses along the feeder and reducing the quality of electrical power delivered to consumers.

To overcome these operational problems, PT PLN (Persero) implemented a load-splitting strategy by installing the SNTR insertion transformer, as illustrated in Figure 5. The additional transformer redistributed part of the electrical load from the PGCE transformer, thereby reducing the loading on the original transformer and balancing the feeder load. This technical intervention represents a practical solution for improving transformer operating conditions without replacing the existing transformer.

The effectiveness of the load-splitting strategy is confirmed by the loading data presented in Table 6. Following the installation of the SNTR insertion transformer, the loading of the PGCE transformer decreased to approximately 76–77% throughout the 14-day observation period. This loading level is below the maximum allowable limit of 80%, indicating that the overload condition was successfully eliminated. Maintaining transformer loading within the recommended operating range reduces thermal stress on the transformer windings and improves operational reliability.

The improvement in transformer loading also resulted in better voltage quality. As shown in Table 7 (After Improvement), the voltage drop of the PGCE transformer decreased to approximately 4–5% on all phases, while the newly installed SNTR transformer exhibited voltage drops of approximately 3–4%. These results comply with the service voltage requirements specified in SPLN 1:1995 [3]. The reduction in voltage drop demonstrates that decreasing transformer loading effectively reduced the current flowing through the conductors, thereby minimizing voltage losses along the distribution network.

From the perspective of transformer asset management, reducing transformer loading also contributes to extending transformer service life. Lower operating currents reduce winding temperature and hottest-spot temperature, thereby slowing insulation aging in accordance with the thermal aging principles described in IEEE Std C57.91 [9]. Consequently, the risk of premature transformer failure decreases, maintenance requirements can be reduced, and the long-term reliability of the distribution system can be improved.

Overall, the comparison between the operating conditions before and after the implementation of load splitting demonstrates that the installation of the SNTR insertion transformer effectively mitigated transformer overloading, improved voltage quality, and enhanced the operational performance of the PGCE distribution transformer. These findings indicate that load splitting is an effective engineering solution for distribution transformers experiencing sustained overload conditions, particularly in areas where electricity demand continues to increase.

IV. Conslusion

Based on the analysis results, the following conclusions can be drawn:

1. The PGCE distribution transformer was initially operating under severe overload conditions, reaching a peak loading of 113.82%, which exceeded the 80% loading limit specified by PT PLN (Persero) standards. This condition resulted in a voltage drop of 17% and accelerated transformer insulation aging.
2. The implementation of load splitting and the installation of an SNTR insertion transformer successfully reduced the average transformer loading to 48.74%, thereby restoring the loading level to within the acceptable operating limits.
3. The applied technical interventions improved the voltage profile of the distribution system, reducing the voltage drop from 17% to 4.5%, in accordance with the requirements of SPLN 1:1995.
4. The reduction in transformer loading also mitigated the accelerated loss of life of the transformer insulation, contributing to improved asset reliability and extended service life.
5. Overall, the load splitting and SNTR insertion strategies proved effective in enhancing power quality, maintaining transformer performance, and ensuring the long-term reliability of the distribution network on the Leci feeder.
6. Periodic monitoring of transformer loading and voltage profiles should be conducted to prevent future overload conditions.
7. Similar load redistribution and transformer insertion strategies can be considered for other distribution transformers experiencing high loading levels.
8. Future studies may evaluate the economic feasibility and long-term reliability impacts of transformer insertion programs across a wider distribution network.

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