Analysis of Load Imbalance in 20 kV/400 V Distribution Transformers at PT PLN (Persero) Siantar Kota ULP Operational Area

Robinson Sinaga, Siti Anisah, Dian Yulis Wulandari

Abstract

Load unbalance in distribution transformers causes increased power losses and degraded voltage quality. This study analyzes the load unbalance level of 623 distribution transformers (20 kV/400 V) in the service area of PT PLN (Persero) ULP Siantar Kota, distributed across twenty-one feeders with seven transformer codes (A, K, L, M, P, S, and T). The Current Unbalance Factor (CUF) method was applied using phase current measurement data under Off-Peak Load (LBP) and Peak Load (BP) conditions in February 2026. Results show that the overall average CUF reached 33.81% (LBP) and 32.32% (BP), far exceeding PLN's 20% tolerance limit. A total of 410 transformers (65.8%) under LBP and 399 transformers (64.0%) under BP fall into the severe unbalance category (CUF ≥ 20%). Substation codes K recorded the highest average CUF of 37.15% (LBP) and 37.76% (BP). Immediate load balancing through the redistribution of customer connections across phases is strongly recommended.

Keywords: load unbalance, distribution transformer, Current Unbalance Factor (CUF), neutral current, ULP Siantar Kota

Robinson Sinaga
[1] Electrical Engineering, Fakultas Sains dan Teknologi, Universitas Pembangunan Panca Budi
e-mail: gerald.naga12@gmail.com,[1]

Siti Anisah[2], Dian Yulis Wulandari[3]
[2,3] Master of Management, Universitas Pembangunan Panca Budi, Indonesia
e-mailsitianisah@dosen.pancabudi.ac.id[2], dianyulis@dosen.pancabudi.ac.id [3]

Introduction

The electric power distribution system plays a strategic role in ensuring the reliability of electricity supply to customers[1] . The 20 kV/400 V distribution transformer is a critical component that connects the medium-voltage network to the low-voltage network to serve residential, commercial, and small industrial customers[2] . One of the commonly encountered is phase-to-phase load imbalance, which occurs when the current distribution across the R, S, and T phases is disproportionate.

Low-voltage networks serving single-phase loads are prone to imbalance, especially when new customers are not added evenly across all three phases. The consequences include the generation of neutral current, increased power losses, accelerated insulation degradation, and a decline in the quality of voltage received by customers[3][4] .

PT PLN (Persero) ULP Siantar Kota operates 623 distribution transformers across twenty-one feeder lines and seven transformer codes in the Pematang Siantar City area. Based on the summary data of transformer load measurements from February 2026, significant load imbalance is indicated in most transformers. This highlights the need for a systematic analysis to identify the degree of imbalance, calculate neutral currents, and determine priorities for mitigation.

The objectives of this study are: (1) to calculate the CUF under LBP and BP conditions; (2) to calculate the theoretical neutral current; (3) to classify transformers based on the level of imbalance per feeder; and (4) to provide technical recommendations for load balancing priorities.

Literature Review

2.1 Distribution Transformers

A distribution transformer is a static electrical device that steps down voltage from a 20 kV medium-voltage network to a 400/231 V low-voltage level for distribution to customers. Transformers operate based on Faraday’s law of induction, whereby an alternating current in the primary winding generates a magnetic flux in the iron core that induces an electromotive force in the secondary winding[5][6] .

According to SPLN D3.002-1:2007, PLN distribution transformers are available in various ratings ranging from 25 kVA to 400 kVA. This standard also stipulates that the load on a distribution transformer must not exceed 80% of its rated capacity under peak load conditions to ensure reliability and optimal operational lifespan[7][8] .

2.2 Load Imbalance in a Three-Phase System

An ideal three-phase electrical power distribution system operates in a balanced state—that is, a state in which the currents in the three phases, R, S, and T, are of equal magnitude and have a phase angle difference of 120°[9] . However, in practice, low-voltage distribution systems serving single-phase loads tend to experience load imbalances. This imbalance can be caused by uneven customer additions, disproportionate load growth, and changes in consumption patterns[10][11][12] .

Load imbalance is a systemic problem in low-voltage distribution networks[13][14] . Load imbalance in 20 kV distribution transformers has a significant impact on power losses and efficiency. This gap highlights the need for a comprehensive analysis of the 623 transformers in the Siantar Kota ULP.

2.3 Current Unbalance Factor (CUF)

The Current Unbalance Factor (CUF) is a standard parameter used to measure the degree of current unbalance in a three-phase system. According to the NEMA MG-1 standard [4], the CUF is defined as the percentage of the maximum phase current deviation relative to the three-phase average current, calculated as follows:

$$\bar{I} = (I_R + I_S + I_T) / 3 \quad (1)$$

$$CUF\ (\%) = [(I_{max} - \bar{I}) / \bar{I}] \times 100\% \quad (2)$$

IEEE Std. 1159-2019 [7] recommends a maximum current imbalance limit of 10% for distribution systems. PLN's operational standards set a CUF tolerance limit of 20%, with the following classifications: mild (CUF < 10%), moderate (10% ≤ CUF < 20%), and severe (CUF ≥ 20%) [5].

2.4 Neutral Current in an Unbalanced Three-Phase System

In a three-phase, four-wire system, load imbalance causes a current to flow in the neutral wire. The theoretical neutral current can be calculated using the following phasor equation [6]:

$$I_N = \sqrt{I_R^2 + I_S^2 + I_T^2 - I_R \cdot I_S - I_S \cdot I_T - I_T \cdot I_R} \quad (3)$$

A large neutral current has negative effects: (1) additional power losses in the neutral wire; (2) overheating that accelerates insulation degradation; (3) the occurrence of neutral-to-ground voltage; and (4) interference with protection systems [3].

Research Methodology

3.1 Type and Research Approach

This study employs a quantitative approach using descriptive-analytical methods to analyze load imbalance in 20 kV/400 V distribution transformers within the operational area of PT. PLN (Persero) ULP Siantar Kota. The study is classified as applied research, utilizing secondary data—specifically, summary data from distribution transformer load measurements—as the basis for analysis.

The research approach employs historical data analysis using mathematical calculations based on the Current Unbalance Factor (CUF) formula and power loss calculations. This study is descriptive and evaluative in nature, analyzing the actual load imbalance conditions across all distribution transformers in the ULP Siantar Kota service area to provide data-driven recommendations for improvement.

3.2 Research Location and Time

The study was conducted in the service area of PT. PLN (Persero) ULP Siantar Kota, located on Jalan MH. Sitorus, Pematang Siantar City, North Sumatra. The ULP Siantar Kota service area covers twenty-one 20 kV distribution network feeders and seven transformer codes sourced from the Pematang Siantar Substation, with a total of 623 distribution transformers.

The research period lasted 4 months, encompassing the data collection, processing, and analysis stages, through to the preparation of the report. The data analyzed consisted of summary records of distribution transformer load measurements at ULP Siantar Kota, recorded in February 2026, which serve as representative data of the current network loading conditions.

3.3 Required Research Data

The research data consists of several comprehensive technical categories. First, transformer identification and technical specification data, including transformer code, installation location, installed capacity (kVA), number of phases, and transformer brand. Second, phase current measurement data, which includes current values (Amperes) for each phase (R, S, T) and the neutral current (N) at the transformer's incoming point as well as on tap 1 and tap 2, for both Off-

Peak Load (OPL) and Peak Load (PL) conditions. This data is the primary data used to calculate the CUF.

Third, transformer load data in kVA and the percentage of load relative to nominal capacity for both Off-Peak Load (OPL) and Peak Load (PL) conditions, which are used to evaluate utilization levels and identify transformers that are approaching or exceeding their nominal capacity. Fourth, Single Line Diagram (SLD) data for the 20 kV ULP Siantar Kota feeder as of February 2026, used as a reference for the network topology and to identify the location of each transformer within the distribution system.

3.4 Data Processing and Analysis Techniques

Data processing was performed using Microsoft Excel software for mathematical calculations and data visualization. Raw data from the measurement summary first underwent validation and data cleaning to ensure data consistency and completeness before analysis. This study employed a secondary data analysis approach and did not conduct direct field measurements.

The data analysis steps are as follows. First, the Current Unbalance Factor (CUF) is calculated for each transformer under LBP and BP conditions using the incoming phase currents R, S, and T based on Equations (1) and (2). Second, transformers were classified based on their imbalance level into three categories: mild (CUF < 10%), moderate (10% ≤ CUF < 20%), and severe (CUF ≥ 20%). Third, the theoretical neutral current was calculated and compared with the measured value to validate the imbalance level using Equation (3). Fourth, an analysis of power losses due to load imbalance is performed using the formula for neutral conductor losses ($P = I_n^2 \times R_n$). Fifth, priority transformers requiring load balancing measures are identified based on the highest CUF values and load levels.

The analysis results are presented in the form of: (1) a summary table of load imbalance per transformer and per feeder; (2) a graph of the CUF distribution for all transformers; (3) a map of transformer distribution based on imbalance categories with reference to the 20 kV feeder SLD; and (4) prioritized technical recommendations for load balancing based on urgency and technical impact.

3.5 Measurement Data Samples by Substation Code

Table 1 presents a sample of phase current measurement data (LBP and BP) from two representative transformers for each Transformer Code, selected based on capacity variations (large and small) to reflect the diversity of loading conditions within the Siantar Kota ULP service area.

Table 1. Sample Phase Current Measurement Data by Transformer Code (February 2026)

Pnyl	Transformer Code	Location	kVA	IR LBP	IS LBP	IT LBP	IR BP	IS BP	IT BP	Source
A	A.14-1	Jl. Hok. Salamudin	250	193	159	161	194	150	134	ULP Siantar Kota Transformer Load Measurement Data, Feb 2026
	A.104-1	Asahan Road, Km VI	25	30	14	15	34	6	17	
K	K.24-1	Jl. Capt.	400	71	67	41	72	97	25	Ibid.

		MH. Sitorus								
	K.101-1	Wahidin St. / Tower	25	23	4	4	25	8	10	
L	L.3-1	Dalil Tani St.	315	83	100	81	76	88	71	Ibid.
	L.36-1	Farel Pasaribu St., Jambu Intersection	25	2	2	11	3	3	9	
M	M.1-1	Ahmad Yani St.	250	180	242	219	210	249	232	Ibid.
	M.113-1	Jl. Medan, Kr. Sari Intersection	25	3	2	10	4	4	12	
P	P.1-1	Church St., Simpang 4	250	170	138	103	130	128	83	Ibid.
	P.13-1	Suka Mulia Village	16	131	110	108	181	170	187	
S	S.24-1	SM Raja St., in front of USI	250	127	148	139	114	152	116	Ibid.
	p. 13-1	Tengkoh St.	25	38	34	7	38	92	37	
T	T.34-1	Jl. Raya Simp. Silimakuta	250	25	50	80	48	72	99	Ibid.
	T.63-1	Handayani St.	25	13	9	17	42	25	28	

3.6 Network Topology (Single-Line Diagram)

Figure 1 presents the Single Line Diagram (SLD) of the 20 kV feeder at the Siantar Kota ULP, which is used as a reference for the network topology. The SLD depicts all 623 transformers distributed across twenty-one feeders sourced from three power transformers at the Pematang Siantar Substation (TD.01 30 MVA, TD.02 60 MVA, TD.03 60 MVA), surveyed and approved by PT PLN (Persero) UP3 Pematang Siantar in February 2026.

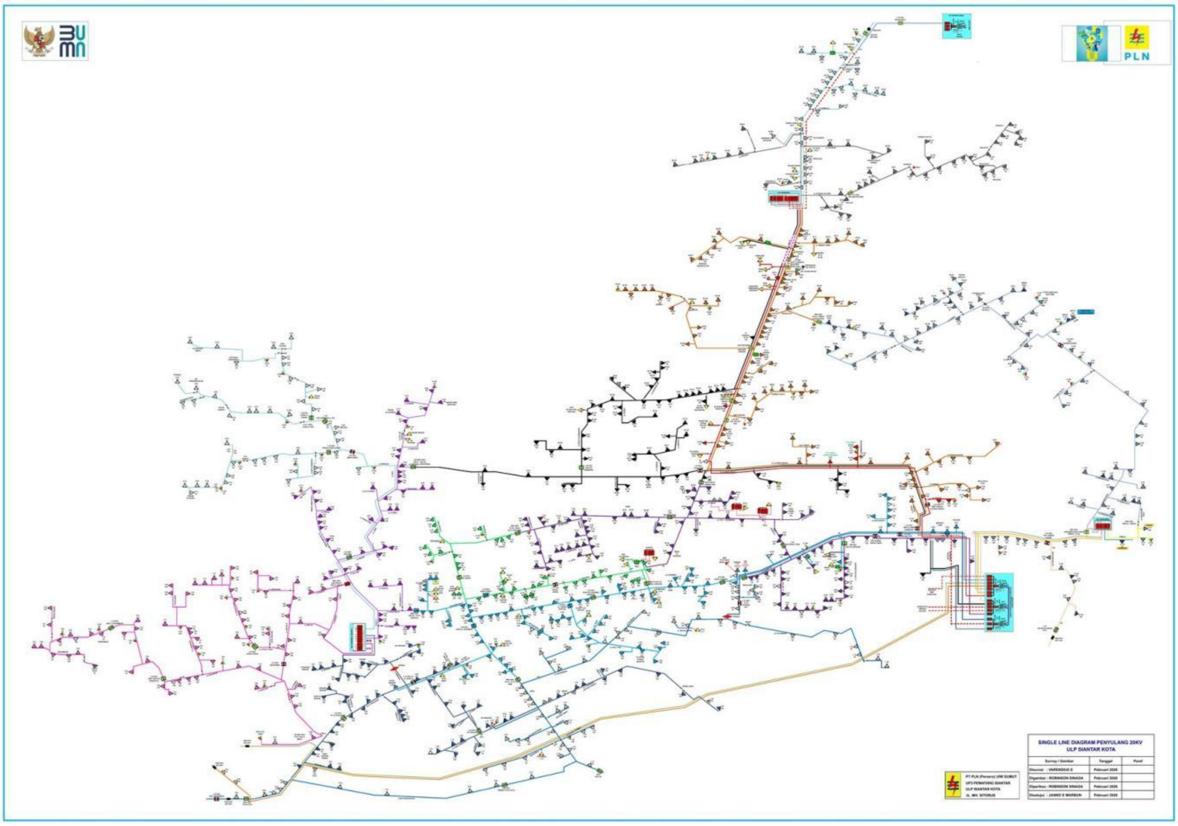

Figure 1. Single-Line Diagram of the 20 kV Feeder at the Siantar Kota Substation (Source: PT PLN (Persero) UP3 Pematang Siantar, February 2026).

Results and Discussion

4.1 Load Imbalance Statistics by Transformer Code

Table 2 presents a summary of the CUF calculation results for all 623 transformers based on substation code. The results show that all transformer codes have an average CUF that far exceeds the 20% tolerance limit.

Table 2. Summary of CUF by Transformer Code

No	Transformer Code	No. of Transformers	Avg CUF LBP (%)	Avg. CUF BP (%)	LBP Weight	Medium LBP	Light LBP	Severe BP	Moderate+Mild BP
1	A	105	30.61	27.23	67	22	16	65	40
2	K	83	37.15	37.76	54	21	10	52	31
3	L	68	34.04	30.85	46	14	8	45	23
4	M	190	36.29	34.00	133	37	20	126	64
5	P	41	31.48	27.84	25	9	7	20	21
6	S	70	30.24	33.65	40	15	15	44	26
7	T	66	32.60	31.59	45	13	8	47	19
Total			**623**	**33.81**	**32.32**	**410**	**133**	**80**	**399**

Transformer Code K recorded the highest average CUF for both LBP (37.15%) and BP (37.76%). Substation Code M has the largest number of transformers (190 units), with 133 transformers classified as heavily overloaded in the LBP. Although Substation Code A has the lowest average CUF (30.61%), this figure still far exceeds the tolerance limit, indicating a systemic problem across the entire service area.

4.2 Load Imbalance Classification

Overall, under LBP conditions, there are 410 transformers (65.8%) classified as severe, 133 transformers (21.3%) as moderate, and 80 transformers (12.8%) as mild. Under BP conditions, there were 399 transformers (64.0%) in the severe category, 143 transformers (23.0%) in the moderate category, and 81 transformers (13.0%) in the mild category. The high proportion of transformers in the severe category indicates that the distribution of single-phase load to customers was not evenly planned across all three phases.

4.3 Transformers with the Highest Imbalance

Table 3 presents the five transformers with the highest BP CUF values, which are the top priority for remediation.

Table 3. Priority Transformers for Remediation (Highest CUF BP)

Transformer Code	Location	Rated Power (kVA)	CUF LBP (%)	CUF BP (%)	I_N BP (A)	BP Load (%)
L.57-1	Jl. Bahkora	100	112.31	110.99	101.73	39.9
K.71-1	Jl. Sriwijaya Simp. Muntilan	50	82.14	108.70	13.23	10.1
A.136-1	Jl. Asahan Aspol (Tower)	25	88.89	104.00	13.00	21.9
S.79-1	Jl. Rajamin Purba	100	13.64	103.67	57.61	23.9
M.202-1	Jl. Maranatha	100	200.00	200.00	107.00	23.5

Transformer L.57-1 (100 kVA, Jl. Bahkora) has a CUF BP of 110.99% with a neutral current of 101.73 A. Transformer S.79-1 shows a drastic change from LBP (13.64%) to BP (103.67%), indicating the presence of a very large single-phase peak load. Transformer M.202-1 recorded the highest neutral current of 107 A under BP conditions.

4.4 Calculation Example for Transformer Code K

Transformer Code K was selected as a calculation example because it has the highest average CUF. Table 4 presents sample current measurement data and CUF calculation results for 10 representative transformers from Feeder K.

Table 4. Sample Measurement Data and CUF Results for Transformer Code K

No	Transformer Code	Power (kVA)	IR LBP	IS LBP	IT LBP	IR BP	IS BP	IT BP	CUF LBP (%)	CUF BP (%)

1	K.1/A-1	315	229	266	185	264	275	176	17.35	15.38
2	K.10-1	160	115	67	96	48	84	65	24.10	27.92
3	K.13-1	250	165	129	90	81	104	33	28.91	43.12
4	K.22-1	160	70	62	120	92	67	127	42.86	33.22
5	K.26-1	200	126	135	122	123	168	153	5.74	13.51
6	K.37-1	100	22	37	78	30	43	101	70.80	74.14
7	K.42-1	160	21	62	21	20	80	22	78.85	96.72
8	K.71-1	50	4	7	17	1	6	16	82.14	108.70
9	K.76-1	50	57	58	19	102	71	38	29.85	45.02
10	K.109-1	160	93	92	69	115	116	115	9.84	0.58

The following presents a detailed calculation example for transformer K.71-1 (50 kVA, Jl. Sriwijaya, Simp. Gg. Muntilan) as the transformer with the highest BP CUF in Feeder K.

a) Off-Peak Load Conditions (LBP): I_R = 4 A, I_S = 7 A, I_T = 17 A

$\bar{I} = (4 + 7 + 17) / 3 = 9.33\ A$

$I_{max} = I_T = 17\ A$

$CUF_{LBP} = [(17 – 9.33) / 9.33] \times 100\% = 82.21\% \rightarrow HEAVY\ Category$

$I_N = \sqrt{(16 + 49 + 289 – 28 – 119 – 68)} = \sqrt{139} = 11.79\ A$

b) Peak Load (PL) Conditions: I_R = 1 A, I_S = 6 A, I_T = 16 A

$\bar{I} = (1 + 6 + 16) / 3 = 7.67\ A$

$I_{max} = I_T = 16\ A$

$CUF_{BP} = [(16 – 7.67) / 7.67] \times 100\% = 108.61\% \rightarrow HEAVY\ Category$

$I_N = \sqrt{(1 + 36 + 256 – 6 – 96 – 16)} = \sqrt{175} = 13.23\ A$

Phase T carries a much larger load than phase R (16:1), so the imbalance worsens under peak load conditions. The theoretical neutral current of 13.23 A matches the measured neutral current of 13 A, confirming the validity of the calculation.

Table 5. Summary of CUF Classification for Substation Code K

Classification	Criteria	No. of LBP	% of LBP	No. of BP	% BP
Mild	CUF < 10%	10	12.0%	13	15.7%
Moderate	10% ≤ CUF < 20%	21	25.3%	18	21.7%
Heavy	CUF ≥ 20%	52	62.7%	52	62.7%
Total		**83**	**100%**	**83**	**100%**

4.5 Neutral Current and Technical Implications

Neutral current is a direct indicator of the magnitude of load imbalance. Transformers with high CUF generate significant neutral current, which results in: (1) increased power losses in the neutral conductor; (2) overheating of the neutral winding; (3) potential harmonic interference; and (4) the risk of damage to customer equipment due to neutral-to-ground voltage.

According to SPLN D3.002-1:2007 and IEEE Std. 1159-2019, load imbalances exceeding 20% must be addressed immediately. Data shows that 64–65.8% of transformers in the Siantar Kota ULP have exceeded this threshold, necessitating a structured and comprehensive load balancing program.

Conclusion

Based on the analysis of load imbalance in 623 units of 20 kV/400 V distribution transformers at PT PLN (Persero) Siantar Kota ULP, the following conclusions were drawn:

The overall average CUF reached 33.81% (LBP) and 32.32% (BP), far exceeding the 20% tolerance limit. The imbalance problem is systemic across the entire service area of the Siantar Kota ULP.

A total of 410 transformers (65.8%) in the LBP and 399 transformers (64.0%) in the BP were classified as severe cases. Substation Code K had the highest average CUF (37.15% LBP; 37.76% BP) with 52 transformers classified as severe cases.

Calculations for transformer K.71-1 (50 kVA) show an LBP CUF of 82.21% and a BP CUF of 108.61% with a theoretical neutral current of 13.23 A, confirming extreme imbalance due to the T phase load being significantly larger than the R and S phases.

Technical recommendations include redistributing customer connections across phases on transformers classified as “heavy,” starting with the transformer having the highest neutral current, accompanied by periodic monitoring every three months.

Role Conflict significantly mediates the effect of Job Satisfaction on Employee Performance. This means that Job Satisfaction not only directly influences Employee Performance but also influences it through Role Conflict as an intervening variable.

Role Conflict is able to significantly mediate the effect of Teamwork on Employee Performance. Thus, although Teamwork does not have a significant direct effect on Employee Performance, this influence can occur through Role Conflict as an intervening variable.

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