

Research Article

# Analysis of the Impact of Load Imbalance on Neutral Current and Power Losses Caused by Neutral Current in Transformer 1, 30 MVA, 70/20 kV at Bungaran Substation

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**Abstract:** Power transformers are crucial in the electrical distribution system, and their operational stability is significantly affected by load imbalance among phases. Load imbalance can lead to the flow of neutral current through the neutral conductor, causing additional power losses in the transformer. This study analyzes the impact of load imbalance on neutral current and power losses at Transformer 1 (30 MVA capacity, 70/20 kV) at the Bungaran Substation. Data such as phase current, neutral current, and power losses were measured at 12:00 and 21:00. At 12:00, the transformer's full-load current was 839.17 A with a loading of 28.44% and a load imbalance of 0.74%, resulting in a neutral current of 4.36 A (1.83% of load current). The power loss due to neutral current was 12.64 W ( $4.36 \times 10^{-5}$  %), and the loss due to neutral current flowing to the ground was 760 W ( $2.62 \times 10^{-3}$  %). At 21:00, the full-load current decreased to 834.46 A, with a loading of 29.36% and a higher load imbalance of 1.36%. This caused a neutral current of 7.94 A (3.24%), with a power loss of 41.90 W ( $1.43 \times 10^{-4}$  %) and a ground power loss of 2.52 W ( $8.60 \times 10^{-3}$  %). The power losses were minimal compared to the transformer's capacity, having little effect on system efficiency. However, maintaining load balance is essential for system efficiency and transformer longevity.

**Keywords:** Imbalance; Load; Neutral Current; Power Losses; Transformer

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## 1. Introduction

Power transformers are one of the main components in the electrical power system, functioning to transmit and distribute electrical energy efficiently from one voltage level to another (Azis et al., 2018). The reliability and efficiency of transformer operation greatly determine the stability and quality of power delivery from substations to consumers. Therefore, transformer operating conditions must always be maintained within safe and standard limits, including ensuring load balance among its phases (Hartono et al., 2025).

Load imbalance among phases is a common issue in power distribution systems. This imbalance occurs when the current or power flowing through each phase is not equal. Such a condition can cause neutral current to flow through the neutral conductor of the transformer, which in turn leads to increased power losses and overheating in the conductors or internal components of the transformer (Aini et al., 2021; Arifin et al., 2023). If allowed to continue, load imbalance can reduce operational efficiency, accelerate insulation aging, and shorten the transformer's lifespan (Wardhana et al., 2024).

In addition, the neutral current resulting from load imbalance can cause extra power losses due to its flow through the resistance of the neutral conductor or into the grounding system (Latupeirissa & Titaley, 2023). Although relatively small, these losses still affect the

overall efficiency of the electrical power system, especially over the long term (Chen et al., 2018; Diao et al., 2025). Therefore, it is important to analyze the degree of load imbalance, neutral current, and the resulting power losses to determine the actual performance condition of the transformer and ensure its operation complies with standards set by PT PLN (PT PLN, 2014).

Bungaran Substation is one of the key substations in the Palembang area, responsible for distributing electrical energy to various regions. This substation houses several power transformers, including Transformer 1 with a capacity of 30 MVA and a voltage of 70/20 kV, which serves as the object of this study. Through the analysis of load imbalance, neutral current, and the resulting power losses in this transformer, it is expected that an accurate overview of transformer performance and efficiency in power delivery can be obtained (Irwansyah et al., 2022; Widagdo et al., 2023).

This study aims to analyze the effect of load imbalance on neutral current and power losses in Transformer 1 at Bungaran Substation. The results of this analysis are expected to serve as a reference for managing and evaluating distribution system loads, as well as a basis for maintenance and operational efficiency improvement, ensuring equipment longevity and reliable, efficient power system operation.

## 2. Literature Review

A transformer is an electrical device that functions to transfer power from high voltage to low voltage or vice versa. A power transformer specifically serves to transmit electrical energy from the transmission system to the distribution system through a substation. This type of transformer plays a vital role in adjusting voltage levels to meet the requirements of the load side system. Typically, power transformers are installed at substations that serve as connection points between transmission and distribution networks (Dendi et al., 2022; Wardhana et al., 2024).

A transformer is an electromagnetic device consisting of two or more coils that are magnetically coupled. When one of the coils, known as the primary winding, is connected to an alternating voltage source, it produces a magnetic flux whose magnitude depends on the voltage and the number of turns in the coil. This magnetic flux then induces another coil, known as the secondary winding, creating a voltage on the secondary side. The induced voltage is proportional to the ratio of the number of turns between the primary and secondary windings (Azis et al., 2018; Latupeirissa & Titaley, 2023).

In a three-phase power transformer with a four-wire system, load imbalance often occurs. This imbalance is caused by uneven load distribution among the secondary phases of the transformer, namely phases *R*, *S*, and *T*. The difference in load among these phases generates a current flowing through the neutral conductor (Aini et al., 2021; Styawan & Rahmawati, 2019).

Figure 1(a) shows a vector diagram of currents under balanced conditions, where the sum of the three current vectors ( $I_R$ ,  $I_S$ ,  $I_T$ ) equals zero, resulting in no neutral current. Conversely, Figure 1(b) illustrates an unbalanced condition where the vector sum is no longer zero, causing a neutral current ( $I_N$ ) to appear. The magnitude of this neutral current depends on the degree of load imbalance (Syahputra, 2019; Widagdo et al., 2023).

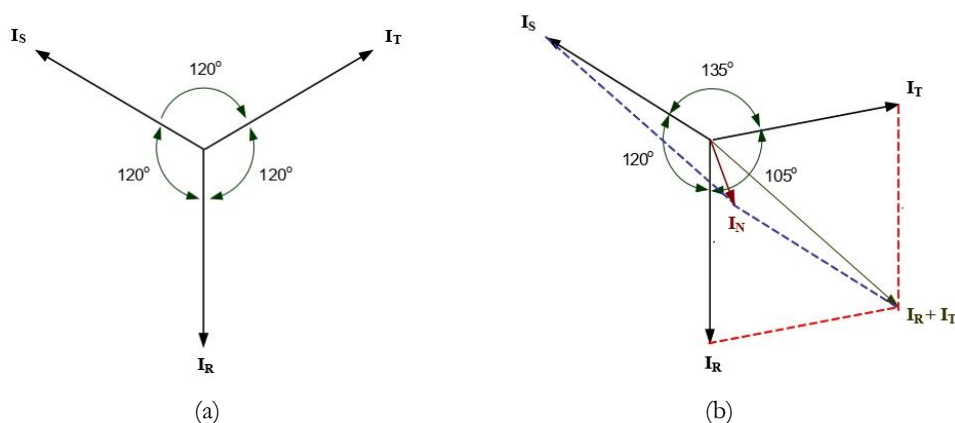


Figure 1. Current Vector Diagram.

The presence of this neutral current can cause power losses in the transformer. One of the common issues in three-phase power systems at substations is load imbalance, which usually occurs due to dominant loading on one particular phase. When the loads among phases are not evenly distributed, current flows through the neutral conductor, and the phase angles among the three phases deviate from the ideal  $120^\circ$  separation (Chen et al., 2018; Diao et al., 2025).

The balanced condition shown in Figure 1(a) is defined as a state where (Syahputra, 2019; Rizal et al., 2024):

- The three current or voltage vectors have equal magnitudes.
- The three vectors form an angle of  $120^\circ$  with each other.

Meanwhile, the unbalanced condition shown in Figure 1(b) occurs when one or both of these conditions are not met. There are three possible forms of load imbalance (Aini et al., 2021; Styawan & Rahmawati, 2019):

- The three vectors have equal magnitudes but do not form an angle of  $120^\circ$  with each other.
- The three vectors differ in magnitude but still form an angle of  $120^\circ$ .
- The three vectors differ in both magnitude and angle, not forming a  $120^\circ$  separation.

### 3. Research Methodology

#### 3.1. Research Location

The research was conducted at PT PLN (Persero) P3B Sumatera UPT Palembang, Bungaran Substation, located at Kelurahan 8 Ulu, Jakabaring District, Palembang City, South Sumatra 30267. The object of this research is Transformer 1 with a capacity of 30 MVA and a voltage level of 70/20 kV at the Bungaran Substation. The research was carried out from May to June 2024.

#### 3.2. Research Stages

The data used in this research are secondary data, obtained through observations at the research site. The secondary data consist of the specification data and load data of Transformer 1, 30 MVA 70/20 kV. The collected data were then analyzed and processed to be used in the research stages. The stages of this research are as follows:

##### 3.2.1. Full Load Current of Transformer

The transformer power, when viewed from the secondary voltage side, can be determined using the following equation (Irwansyah et al., 2022):

$$S = \sqrt{3} V I \quad (1)$$

Hence, the magnitude of the full-load current in the transformer can be determined using the following equation (Liliana et al., 2024):

$$I_{FL} = \frac{S}{\sqrt{3} V} \quad (2)$$

Description:

$S$  = Transformer power (kVA)

$V$  = Secondary voltage of transformer (kV)

$I_{FL}$  = Full load current (A)

##### 3.2.2. Transformer Loading Percentage

The loading of a transformer under unbalanced load conditions is equal to the magnitude of the average current. The average current in the transformer can be determined using the following equation (Arifin et al., 2023):

$$I_{average} = \frac{I_R + I_S + I_T}{3} \quad (3)$$

Thus, the transformer loading percentage can be determined using the following equation (Rizal et al., 2024):

$$I_{loading} (\%) = \frac{I_{average}}{I_{FL}} \times 100\% \quad (4)$$

Description:

$I_{average}$	= Average current (A)
$I_R$	= Phase R current (A)
$I_S$	= Phase S current (A)
$I_T$	= Phase T current (A)
$I_{loading}$ (%)	= Transformer loading percentage (%)

### 3.2.3. Load Imbalance Percentage

As an example, let a power  $P$  be transmitted through a line that has a neutral conductor. If the currents in each phase are balanced, the transmitted power can be expressed by the following equation (Latupeirissa & Titaley, 2023):

$$P = 3 V I \cos \theta \quad (6)$$

Description:

$P$	= Power on the sending side (W)
$V$	= Voltage on the sending side (V)
$\cos \theta$	= Power factor

If  $I$  represents the phase current under balanced conditions, then under unbalanced conditions, the phase currents can be expressed with coefficients  $a$ ,  $b$ , and  $c$  as follows (Widagdo & Andriawan, 2023):

$$I_R = a \times I_{average} \text{ maka } a = \frac{I_R}{I_{average}} \quad (7)$$

$$I_S = b \times I_{average} \text{ maka } b = \frac{I_S}{I_{average}} \quad (8)$$

$$I_T = c \times I_{average} \text{ maka } c = \frac{I_T}{I_{average}} \quad (9)$$

Here,  $I_R$ ,  $I_S$ , and  $I_T$  are the currents in phases  $R$ ,  $S$ , and  $T$ , respectively. The power factor ( $\cos \theta$ ) of the three phases is assumed to be the same even though the current magnitudes differ. Therefore, the transmitted power can be expressed as follows (Latupeirissa & Titaley, 2023):

$$P = (a + b + c) V I \cos \theta \quad (10)$$

If equations (9) and (5) represent the same power, then the coefficients  $a$ ,  $b$ , and  $c$  must satisfy  $a + b + c = 3$  for the unbalanced condition, while under balanced conditions, the coefficients are  $a = b = c = 1$ . Furthermore, the percentage of load imbalance can be expressed as follows (Listiwati & Andini, 2023):

$$I_{load\ imbalance}(\%) = \frac{\{|a-1|+|b-1|+|c-1|\}}{3} \times 100\% \quad (11)$$

### 3.2.4. Neutral Current Due to Load Imbalance

For the three-phase currents of an unbalanced system, the analysis can be solved using the symmetrical component method. Using the same notation as for voltages, the phase current equations can be expressed as follows (Hartono et al., 2025):

$$I_R = I_1 + I_2 + I_0 \quad (12)$$

$$I_S = a^2 I_1 + a I_2 + I_0 \quad (13)$$

$$I_T = a I_1 + a^2 I_2 + I_0 \quad (14)$$

By applying the same procedure used to determine the positive, negative, and zero-sequence voltages, the sequence currents can also be determined as follows (Pan et al., 2019):

$$I_1 = \frac{1}{3}(I_R + a I_S + a^2 I_T) \quad (15)$$

$$I_2 = \frac{1}{3}(I_R + a^2 I_S + a I_T) \quad (16)$$

$$I_0 = \frac{1}{3}(I_R + I_S + I_T) \quad (17)$$

Here, the zero-sequence current ( $I_0$ ) represents one-third of the neutral current, or it becomes zero if the system operates under a perfectly balanced three phase four wire configuration. In such a system, the sum of the line currents equals the neutral current returning through the neutral conductor (Febrianti, 2018):

$$I_N = I_R + I_S + I_T \quad (18)$$

By substituting equation (17) into equation (18), the following relationship is obtained (Pan et al., 2019; Rizal et al., 2024):

$$\begin{aligned} I_N &= 3I_0 \\ I_N &= I_R + I_S + I_T \\ I_N &= [I]\{a + b \cos(-120) + j b \sin(-120) + c \cos(-120) + j c \sin(120)\} \\ I_N &= [I]\{a + b(-\frac{1}{2}) + j b(-\frac{\sqrt{3}}{2}) + c(-\frac{1}{2}) + j c(\frac{\sqrt{3}}{2})\} \\ I_N &= [I]\left\{a - \frac{b+c}{2} + j \frac{(c-b)\sqrt{3}}{2}\right\} \\ I_N &= [I_{average}]\left\{a - \frac{b+c}{2} + j \frac{(c-b)\sqrt{3}}{2}\right\} \end{aligned} \quad (19)$$

The percentage of neutral current relative to the transformer load current is given by (Irwansyah et al., 2022):

$$I_N (\%) = \frac{I_N}{I_{average}} \times 100\% \quad (20)$$

Description:

$I_N$  = Current flowing through the neutral conductor (A)

$I_N (\%)$  = Percentage of neutral current relative to transformer load current (%)

### 3.2.5. Power Losses Due to Neutral Current

As a result of unbalanced loading on each phase, current will flow through the neutral conductor. When the neutral conductor has a resistance value and is carrying current, a voltage drop will occur along it, causing an imbalance in the transformer voltage. The current flowing through the neutral conductor leads to power losses along the neutral path, which can be expressed as follows (Siboro et al., 2024):

$$\Delta P_N = I_N^2 R_N \quad (21)$$

Hence, the percentage of power losses caused by the neutral current is given by (Listiwati & Andini, 2023):

$$\Delta P_N (\%) = \frac{\Delta P_N}{P} \times 100\% = \frac{\Delta P_N}{S \cos \theta} \times 100\% \quad (22)$$

Description:

$\Delta P_N$  = Power loss due to neutral current (W)

$R_N$  = Resistance of the neutral conductor ( $\Omega$ )

$\Delta P_N (\%)$  = Percentage of power losses caused by neutral current (%)

### 3.2.6. Power Losses Due to Neutral Current Flowing to Ground

This type of power loss occurs because of the neutral current flowing to the ground. The magnitude of this power loss can be calculated using the following equation (Syahputra, 2019):

$$\Delta P_G = I_G^2 R_G \quad (23)$$

Furthermore, the percentage of power loss caused by the neutral current flowing to the ground can be expressed as follows (Rizal et al., 2024):

$$\Delta P_G (\%) = \frac{\Delta P_G}{P} \times 100\% = \frac{\Delta P_G}{S \cos \theta} \times 100\% \tag{24}$$

Description:

$\Delta P_G$  = Power loss due to neutral current flowing to ground (W)

$I_G$  = Neutral current flowing to ground (A)

$R_G$  = Grounding resistance of the transformer neutral ( $\Omega$ )

$\Delta P_G (\%)$  = Percentage of power loss caused by neutral current flowing to ground (%)

### 3.2.7. Transformer Loading Standards

Table 1 presents the transformer loading standards established based on the Edaran Direksi PT PLN (Persero) Nomor: 0017.E/DIR/2014. These standards are used as a reference to assess the health and performance of transformers based on parameters such as the percentage of transformer current loading relative to nominal capacity, current imbalance between phases, and the magnitude of the neutral current as a percentage of the load current. The transformer condition is classified into four categories: Good, Fair, Poor, and Bad to facilitate decision-making regarding maintenance and optimal operation.

**Table 1.** Transformer Loading Standards According to Edaran Direksi PT PLN (Persero) Nomor: 0017.E/DIR/2014.

Characteristic Group	Characteristic	Health Index			
		Good	Fair	Poor	Bad
Load Reading and Profilling	Transformer Current Loading (% to KHA outlet)	< 60%	60% - < 80%	80% - < 100%	$\geq$ 100%
	Phase Current Imbalance	< 10%	10% - < 20%	20% - < 25%	$\geq$ 25%
	Transformer Neutral Current (% to transformer load current)	< 10%	10% - < 15%	15% - < 20%	$\geq$ 20%

## 4. Results and Discussion

### 4.1. Research Data

#### 4.1.1. Transformer Data

The specification data of Transformer 1, 30 MVA 70/20 kV at Bungaran Substation are as follows:

**Table 2.** Specification Data of Transformer 1, 30 MVA 70/20 kV at Bungaran Substation.

Specification	Description
Brand	PAUWELS
Capacity	30 MVA
Number of Phases	3
Frequency	50 Hz
Impedance	12.45%
Primary Voltage	70 kV
Secondary Voltage	20 kV
Neutral Resistance	0,665 $\Omega$
NGR	40 $\Omega$



**Figure 2.** Transformer 1, 30 MVA 70/20 kV at Bungaran Substation, Palembang.

#### 4.1.2. Transformer Load Data

The load data of Transformer 1, 30 MVA 70/20 kV at Bungaran Substation Palembang for April 2024 is shown in Table 3.

**Table 3.** Transformer 1 Load Data (30 MVA, 70/20 kV) at Bungaran Substation Palembang for April 2024.

Time	$I_R$ (A)	$I_S$ (A)	$I_T$ (A)	$V_R$ (kV)	$V_S$ (kV)	$V_T$ (kV)	P (MW)	Q (MVAR)	Cos $\theta$
00.00	195	195	195	20,8	20,8	20,8	6,77	1,58	0,9738
01.00	190	190	190	20,7	20,7	20,7	6,68	1,57	0,9734
02.00	190	190	190	20,7	20,7	20,7	6,61	1,56	0,9731
03.00	189	189	189	20,7	20,7	20,7	6,55	1,59	0,9719
04.00	188	188	188	20,7	20,7	20,7	6,51	1,57	0,9721
05.00	189	189	189	20,7	20,7	20,7	6,46	1,60	0,9706
06.00	191	191	191	20,6	20,6	20,6	6,56	1,63	0,9706
07.00	198	198	198	20,6	20,6	20,6	6,81	1,75	0,9685
08.00	208	208	208	20,6	20,6	20,6	7,11	1,84	0,9681
09.00	221	221	221	20,6	20,6	20,6	7,57	1,97	0,9679
10.00	231	231	231	20,5	20,5	20,5	7,87	2,04	0,9681
11.00	236	234	238	20,6	20,5	20,7	8,05	2,06	0,9689
12.00	239	236	241	20,6	20,5	20,7	8,18	2,13	0,9678
13.00	237	235	239	20,6	20,5	20,7	8,17	2,13	0,9676
14.00	236	236	236	20,6	20,6	20,6	8,10	2,12	0,9673
15.00	228	228	228	20,7	20,7	20,7	7,80	2,27	0,9603
16.00	221	220	222	20,7	20,7	20,7	7,60	2,75	0,9403
17.00	218	217	220	20,7	20,6	20,8	7,56	2,13	0,9626
18.00	226	225	227	20,6	20,5	20,7	7,78	2,41	0,9551
19.00	231	230	232	20,6	20,5	20,7	7,98	1,66	0,9791
20.00	226	225	228	20,7	20,6	20,8	7,83	2,05	0,9674
21.00	246	240	249	20,8	20,7	20,9	7,67	1,65	0,9777
22.00	209	208	212	20,8	20,7	20,9	9,56	1,61	0,9861
23.00	199	199	199	20,8	20,8	20,8	6,95	1,57	0,9753
24.00	192	192	192	20,8	20,8	20,8	6,65	1,56	0,9737

#### 4.2. Results

In this study, the calculation of the effect of load imbalance on neutral current and power losses in Transformer 1, 30 MVA 70/20 kV at Bungaran Substation was analyzed based on the following conditions:

- Off-Peak Load Period between 22:00 and 18:00, where the peak load occurs at 12:00.

- Peak Load Period between 18:00 and 22:00, where the peak load occurs at 21:00.

#### 4.2.1. Full Load Current of the Transformer

Transformer 1 has a rated power of 30 MVA, so the full load current is calculated as follows:

- At 12:00

$$I_{FL} = \frac{S}{\sqrt{3} V} = \frac{30.000}{\sqrt{3} \times 20,6} = 839,1719 \text{ A}$$

- At 21.00

$$I_{FL} = \frac{S}{\sqrt{3} V} = \frac{30.000}{\sqrt{3} \times 20,8} = 834,4552 \text{ A}$$

#### 4.2.2. Transformer Loading Percentage

The loading percentage of Transformer 1 under unbalanced load conditions is as follows:

- At 12.00

$$I_{average} = \frac{I_R + I_S + I_T}{3} = \frac{239+237+241}{3} = 238,6667 \text{ A}$$

Thus, the transformer loading percentage is:

$$I_{loading} (\%) = \frac{I_{average}}{I_{FL}} \times 100\% = \frac{239}{839,1719} \times 100\% = 28,4407\%$$

- At 21.00

$$I_{average} = \frac{I_R + I_S + I_T}{3} = \frac{246+240+249}{3} = 245 \text{ A}$$

Thus, the transformer loading percentage is:

$$I_{loading} (\%) = \frac{I_{average}}{I_{FL}} \times 100\% = \frac{245}{834,4552} \times 100\% = 29,3605\%$$

#### 4.2.3. Percentage of Transformer Load Imbalance

Under unbalanced load conditions, the current magnitude in each phase of Transformer 1 can be expressed by coefficients *a*, *b*, and *c*.

- At 12.00

The values of coefficients *a*, *b*, and *c* for each phase of Transformer 1 are as follows:

$$a = \frac{I_R}{I_{average}} = \frac{239}{238,6667} = 1,0014$$

$$b = \frac{I_S}{I_{average}} = \frac{236}{238,6667} = 0,9888$$

$$c = \frac{I_T}{I_{average}} = \frac{241}{238,6667} = 1,0098$$

Thus, the percentage of load imbalance is:

$$\begin{aligned} I_{load\ imbalance} (\%) &= \frac{\{|a-1|+|b-1|+|c-1|\}}{3} \times 100\% \\ &= \frac{\{|1,0014-1|+|0,9888-1|+|1,0098-1|\}}{3} \times 100\% \\ &= \frac{0,0223}{3} \times 100\% = 0,7449\% \end{aligned}$$

- At 21.00

The values of coefficients *a*, *b*, and *c* for each phase of Transformer 1 are as follows:

$$a = \frac{I_R}{I_{average}} = \frac{246}{245} = 1,0041$$

$$b = \frac{I_S}{I_{average}} = \frac{240}{245} = 0,9796$$

$$c = \frac{I_T}{I_{average}} = \frac{249}{245} = 1,0163$$

Thus, the percentage of load imbalance is:

$$\begin{aligned} I_{load\ imbalance} (\%) &= \frac{\{|a-1|+|b-1|+|c-1|\}}{3} \times 100\% \\ &= \frac{\{|1,0041-1|+|0,9796-1|+|1,0163-1|\}}{3} \times 100\% \\ &= \frac{0,0408}{3} \times 100\% = 1,3605\% \end{aligned}$$

#### 4.2.4. Neutral Current Due to Unbalanced Load

The neutral current resulting from the unbalanced load condition in Transformer 1 is calculated as follows:

- At 12.00

$$\begin{aligned} I_N &= [I_{average}] \left\{ a - \frac{b+c}{2} + j \frac{(c-b)\sqrt{3}}{2} \right\} \\ &= [238,6667] \left\{ 1,0014 - \frac{0,9888+1,0098}{2} + j \frac{(1,0098-0,9888)\sqrt{3}}{2} \right\} \\ &= [238,6667] \{0,0021 + j0,0181\} \\ &= 0,5000 + j4,3301 = 4,3589 \angle 83,4132^\circ \end{aligned}$$

Thus, the percentage of neutral current relative to the transformer load current is:

$$I_N (\%) = \frac{I_N}{I_{average}} \times 100\% = \frac{4,3589}{238,6667} \times 100\% = 1,8264\%$$

- At 21.00

$$\begin{aligned} I_N &= [I_{average}] \left\{ a - \frac{b+c}{2} + j \frac{(c-b)\sqrt{3}}{2} \right\} \\ &= [245] \left\{ 1,0041 - \frac{0,9796+1,0163}{2} + j \frac{(1,0163-0,9796)\sqrt{3}}{2} \right\} \\ &= [245] \{0,0061 + j0,0318\} \\ &= 1,5000 + j7,7942 = 7,9373 \angle 79,1066^\circ \end{aligned}$$

Thus, the percentage of neutral current relative to the transformer load current is:

$$I_N (\%) = \frac{I_N}{I_{average}} \times 100\% = \frac{7,9373}{245} \times 100\% = 3,2397\%$$

#### 4.2.5. Power Losses Due to Neutral Current

The power losses due to the presence of neutral current in Transformer 1 are as follows:

- At 12.00

$$\Delta P_N = I_N^2 R_N = 4,3589^2 \times 0,665 = 12,6350 \text{ W}$$

Thus, the percentage of power losses caused by the neutral current is:

$$\Delta P_N (\%) = \frac{\Delta P_N}{S \cos \theta} \times 100\% = \frac{7,8850}{30 \times 10^6 \times 0,9670} \times 100\% = 4,3552 \times 10^{-5}\%$$

- At 21.00

$$\Delta P_N = I_N^2 R_N = 7,9373^2 \times 0,665 = 41,8950 \text{ W}$$

Thus, the percentage of power losses caused by the neutral current is:

$$\Delta P_N (\%) = \frac{\Delta P_N}{S \cos \theta} \times 100\% = \frac{7,8850}{30 \times 10^6 \times 0,9773} \times 100\% = 1,4289 \times 10^{-4}\%$$

#### 4.2.6. Power Losses Due to Neutral Current Flowing to Ground

The power losses due to the neutral current flowing to ground in Transformer 1 are as follows:

- At 12.00

$$\Delta P_G = I_G^2 R_G = 4,3589^2 \times 40 = 760 \text{ W}$$

Thus, the percentage of power losses due to the neutral current flowing to ground is:

$$\Delta P_G (\%) = \frac{\Delta P_G}{S \cos \theta} \times 100\% = \frac{760}{30 \times 10^6 \times 0,9670} \times 100\% = 2,6197 \times 10^{-3}\%$$

- At 21.00

$$\Delta P_G = I_G^2 R_G = 7,9373^2 \times 40 = 2.520 \text{ W}$$

Thus, the percentage of power losses due to the neutral current flowing to ground is:

$$\Delta P_G (\%) = \frac{\Delta P_G}{S \cos \theta} \times 100\% = \frac{2.520}{30 \times 10^6 \times 0,9773} \times 100\% = 8,5951 \times 10^{-3}\%$$

#### 4.3. Discussion

Table 3 presents the results of the calculations of transformer loading, load imbalance, neutral current, power losses due to neutral current, and power losses due to neutral current flowing to ground at two different measurement times, namely at 12:00 and 21:00.

**Table 3.** Calculation Results.

Time	Full Load Current (A)	Transformer Loading (%)	Load Imbalance (%)	$I_N$ (A)	$I_N$ (%)	$\Delta P_N$ (W)	$\Delta P_N$ (%)	$\Delta P_G$ (W)	$\Delta P_G$ (%)
12.00	839,1719	28,4407	0,7449	4,3589	1,8264	12,6350	$4,3552 \times 10^{-5}$	760	$2,6197 \times 10^{-3}$
21.00	834,4552	29,3605	1,3605	7,9373	3,2397	41,8950	$1,4289 \times 10^{-4}$	2.520	$8,5951 \times 10^{-3}$

##### 4.3.1. Transformer Loading

Transformer 1 at Bungaran Substation has a power capacity of 30 MVA with a voltage rating of 70/20 kV. Based on the calculation results, the full load current of this transformer reaches 839.1719 A at 12:00 p.m. and 834.4552 A at 9:00 p.m., with loading levels of 28.4407% and 29.3605% of its nominal capacity at those respective times. According to the loading standard set by Edaran Direksi PT PLN (Persero) Nomor 0017.E/DIR/2014, loading below 60% is categorized as Good, indicating that this transformer operates within safe and efficient limits.

This relatively low loading indicates that the transformer operates well below its maximum capacity, thereby minimizing the risk of overheating, insulation degradation, and damage due to overcurrent. The transformer's operating temperature tends to remain stable, power losses are minimal, and system efficiency remains high. The relatively balanced loading between day and night also suggests that the network load is evenly distributed without significant fluctuations that could stress the equipment.

With the loading still far below its maximum capacity, the transformer retains a substantial reserve margin to accommodate future load increases without compromising operational reliability. However, regular monitoring remains essential to ensure operational stability, particularly in anticipating changes in load patterns and phase imbalance, which can affect performance and power losses.

Overall, the transformer at Bungaran Substation operates under excellent conditions, maintaining high efficiency, operational safety, and optimal equipment lifespan. The consistently low loading level reflects the reliability and readiness of the transformer to handle future load growth, provided that periodic supervision continues to be conducted to maintain system stability and performance.

### **4.3.2. Load Imbalance**

Based on the calculation results shown in Table 3, the load imbalance on Transformer 1 at Bungaran Substation exhibits very low values 0,7449% at 12:00 p.m. and slightly increasing to 1,3605% at 9:00 p.m. According to Edaran Direksi PT PLN (Persero) Nomor 0017.E/DIR/2014, a load imbalance below 10% falls within the Good category. Therefore, it can be concluded that the phase loads of this transformer are very well balanced.

This low imbalance value indicates that the currents in the three phases are almost equal. Such a condition is highly beneficial, as it helps reduce excessive neutral current, which, if too large, could lead to increased power losses, higher operating temperatures, and potential insulation or transformer component damage. Although there is a slight increase in imbalance at 9:00 p.m., the value remains well below the tolerance limit and does not negatively affect the transformer's performance.

Good load balance reflects optimal power distribution efficiency and effective load management within the distribution network. This condition also contributes to overall power system stability, reducing thermal and mechanical stress, and extending the operational lifespan of the transformer.

In summary, the very minimal load imbalance on Transformer 1 at Bungaran Substation indicates that the transformer operates in an excellent, efficient, and reliable condition. To maintain this performance, regular monitoring is recommended to ensure that the imbalance value consistently remains within the Good category as defined by PLN standards, thereby supporting the stability and efficiency of the power system's ongoing operation.

### **4.3.3. Neutral Current Due to Unbalanced Load**

Neutral current in a transformer primarily arises from load imbalance among the phases on the secondary side of the transformer. Based on the calculation results in Table 3 for Transformer 1 at Bungaran Substation, the neutral current was recorded at 4,3589 A (1,8264% of load current) at 12:00 p.m. and increased to 7,9373 A (3,2397% of load current) at 9:00 p.m. These values indicate that although there is a slight load imbalance among the phases, the magnitude of the resulting neutral current remains very small and is well below the 10% maximum limit stipulated in Edaran Direksi PT PLN (Persero) Nomor 0017.E/DIR/2014, thereby classifying it within the Good condition category.

The neutral current resulting from load imbalance can cause power losses in the transformer's neutral conductor. This occurs because the neutral current flows through the neutral resistance of the transformer, leading to power dissipation in the form of heat (losses). The increase in neutral current during peak load hours, although still within safe limits, indicates a rise in power losses that should be considered to maintain the efficiency and operational lifespan of the transformer.

The relatively low neutral current level signifies that the power distribution system operates with a well-balanced load and good load management. However, regular monitoring of the neutral current is crucial to prevent an increase in imbalance that could cause premature equipment damage or a decline in distribution efficiency. Corrective actions should be taken if the neutral current shows a significant upward trend beyond the standard limits.

Overall, the neutral current due to unbalanced load in Transformer 1 at Bungaran Substation remains at a safe level, supporting stable and efficient operation of the transformer with minimal power losses resulting from load imbalance.

### **4.3.4. Power Losses Due to Neutral Current**

Power losses caused by neutral current are one form of energy loss that occurs in a transformer when the phase loads are unbalanced. Based on the calculation results for Transformer 1 at Bungaran Substation, the neutral current resulting from load imbalance was 4,3589 A at 12:00 p.m. and increased to 7,9373 A at 9:00 p.m. This neutral current causes power losses in the transformer's neutral conductor of 12,6350 W ( $4,3552 \times 10^{-5}$  %) at 12:00 p.m., increasing to 41,8950 W ( $1,4289 \times 10^{-4}$  %) at 9:00 p.m. These power loss values are very small compared to the transformer's capacity of 30 MVA, and therefore do not significantly affect the overall system efficiency.

Technically, power losses due to neutral current occur because the flow of current through the neutral conductor's resistance generates heat proportional to the square of the current. The greater the phase load imbalance, the larger the neutral current, and consequently, the power losses in the neutral conductor increase. Although the magnitude of

these losses in this transformer remains within safe limits and is relatively small, this phenomenon still requires attention, as an increase could lead to local heating in the neutral conductor and reduce the operational efficiency of the transformer.

In conclusion, the power losses caused by neutral current in Transformer 1 at Bungaran Substation are within a safe range and do not have a significant impact on system efficiency. However, regular monitoring of the neutral current and neutral conductor temperature is necessary to ensure stable operating conditions. Efforts to balance the phase loads are also recommended to minimize neutral current losses, enabling the transformer to operate at high efficiency while maintaining the longevity of its equipment.

#### **4.3.5. Power Losses Due to Neutral Current Flowing to Ground**

Power losses caused by neutral current flowing to the ground are a form of energy loss that occurs when the neutral current resulting from load imbalance flows through the grounding resistance in the transformer's neutral system. Based on the calculation results for Transformer 1 at Bungaran Substation, the neutral current resulting from load imbalance was 4,3589 A at 12:00 p.m. and increased to 7,9373 A at 9:00 p.m. This neutral current causes power losses to ground of 760 W ( $2,6197 \times 10^{-3} \%$ ) at 12:00 p.m. and 2,520 W ( $8,5951 \times 10^{-3} \%$ ) at 9:00 p.m.

Although the percentage of power loss due to neutral current flowing to ground relative to the transformer's nominal capacity (30 MVA) is very small, it still indicates that phase load imbalance directly contributes to increased energy losses in the grounding system. The power losses in the neutral-to-ground path are generally dissipated as heat in the Neutral Grounding Resistor (NGR). If allowed to increase continuously, this can lead to overheating and accelerate the degradation of grounding components.

Operationally, the power losses due to neutral current flowing to ground in this transformer remain within safe limits and are considered very small, indicating that the grounding system is functioning properly and the phase loads are relatively balanced. Nevertheless, regular monitoring of neutral current and NGR conditions is necessary, especially during peak load periods, to ensure that there is no excessive temperature rise or current that could compromise system stability.

### **5. Conclusion**

Overall, Transformer 1, 30 MVA 70/20 kV at Bungaran Substation demonstrates good operating conditions, with low loading levels, minimal phase load imbalance, and very small power losses due to neutral current and current flowing to ground. This indicates that the transformer operates under optimal conditions, with high efficiency and reliable system performance. The low neutral current and minimal load imbalance signify that the phase loads are well-managed, thereby minimizing the risk of overcurrent, overheating, and insulation damage.

Furthermore, the small power losses both in the neutral conductor and in the grounding system indicate that the electrical energy lost due to load imbalance remains within very safe limits and does not significantly affect the overall efficiency of the power system. This condition reflects an efficient and stable distribution system capable of maintaining good power quality.

Transformer 1 at Bungaran Substation can be categorized as having optimal performance, a long service life, and is suitable for continued operation without requiring major corrective actions. Nevertheless, regular monitoring of load currents, phase imbalance, and neutral current is still necessary to ensure stable operating conditions, maintain transformer efficiency, and guarantee that the power system operates reliably, safely, and in accordance with PT PLN (Persero) standards.

### **References**

- Aini, Z., Mutari, E., Liliana, L., & Candra, O. (2021). Analysis of imbalance loads and losses based on the largest loading by 3 units of 3-phase distribution transformer. *JTEV (Jurnal Teknik Elektro dan Vokasional)*, 7(1), 69-77. <https://doi.org/10.24036/jtev.v7i1.111965>
- Arifin, M. Z., Amiruddin, M., & Margono, M. (2023). Power losses caused by load imbalance in the central building of PGRI Semarang University. *Advance Sustainable Science, Engineering and Technology*, 5(1), 0230103. <https://doi.org/10.26877/asset.v5i1.13854>
- Azis, A., Nurdiana, N., & Lathifatun Nisa, U. (2018). Rugi-rugi daya pada transformator U. 019 PT. PLN (Persero) WS@ JB Rayon Ampera akibat ketidakseimbangan beban. *Jurnal Ampere*, 3(1), 177-184. <https://doi.org/10.31851/ampere.v3i1.3475>

- Chen, J., Zhu, R., Liserre, M., & O'Donnell, T. (2018, May). Neutral current reduction control for smart transformer under the imbalanced load in distribution system. In *2018 13th IEEE Conference on Industrial Electronics and Applications (ICIEA)* (pp. 2381-2386). IEEE. <https://doi.org/10.1109/ICIEA.2018.8398108>
- Dendi, D., Azis, A., & Perawati, P. (2022). Analisa pengaruh pembebanan terhadap susut umur transformator daya 150 kV di PLTGU Keramasan Palembang. *TEKNIKA: Jurnal Teknik*, *9*(1), 28-41. <https://doi.org/10.35449/teknika.v9i1.198>
- Diao, G., Ni, H., Si, W., Gu, Y., & Yang, J. (2025). Multi-physics numerical research in oil-immersed three-phase transformer under load unbalance. *Energies*, *18*(5), 1217. <https://doi.org/10.3390/en18051217>
- Febrianti, I. K. (2018). Analisa sistem pentanahan transformator. *Jurnal Ampere*, *3*(1), 185-201. <https://doi.org/10.31851/ampere.v3i1.2146>
- Hartono, H., Sudjoko, R. I., Hariyadi, S., & Sukomardojo, T. (2025). Analysis of the effect of unbalanced load on neutral current, power losses and efficiency in distribution transformer. *Journal of Research in Social Science and Humanities*, *5*(1). <https://doi.org/10.47679/jrss.v5i1.370>
- Irwansyah, D., Yandi, W., Sunanda, W., & Zakri, A. A. (2022). Distribution transformer load imbalance analysis at Universitas Bangka Belitung. *Journal of Innovation and Technology*, *3*(1), 6. <https://doi.org/10.31629/jit.v3i1.4333>
- Latupeirissa, H. L., & Titaley, G. V. (2023). Analysis of the effect of load imbalance on neutral current and power losses in distribution transformer Bglwy1036 substation Rumah Tiga. *International Journal of Multi Science*, *3*(04), 178-190. <https://multisciencejournal.com/index.php/ijm/article/view/343/278>
- Liliana, L., Aini, Z., & Bandri, S. (2024). Estimated cost of power losses due to imbalance, no-load and on-load on transformers in 2023-2033. *Jurnal Edukasi Elektro*, *8*(1), 45-54. <https://doi.org/10.21831/jee.v8i1.65224>
- Listiawati, D., & Andini, A. N. (2023). Analysis of the influence of load unbalance on the neutral current power loss in substation KP10 PT. PLN (Persero) UP3 Teluk Naga. *International Journal of Advanced Multidisciplinary*, *2*(3), 690-702. <https://doi.org/10.38035/ijam.v2i3.354>
- Pan, B., Zhang, Y., Gui, X., Wan, Y., & Wang, G. (2019, April). Analysis and research of three-phase unbalance in distribution transformers. In *IOP Conference Series: Earth and Environmental Science* (Vol. 252, No. 3, p. 032196). IOP Publishing. <https://doi.org/10.1088/1755-1315/252/3/032196>
- PT PLN. (2014). Edaran Direksi PT PLN (Persero) Nomor: 0017. E/DIR/2014 Tentang Metode Pemeliharaan Trafo Distribusi Berbasis Kaidah Manajemen Aset. [https://caridokumen.com/queue/pt-pln-persero-edaran-direksi-pt-pln-persero-5a46cb27b7d7bc7b7a1f4c7e.pdf?queue\\_id=-1](https://caridokumen.com/queue/pt-pln-persero-edaran-direksi-pt-pln-persero-5a46cb27b7d7bc7b7a1f4c7e.pdf?queue_id=-1)
- Rizal, M., Azis, A., Emidiana, I. K. P., Al Amin, M. S., Nurdiana, N., & Perawati, Y. I. (2024). Analysis of load imbalance in Tarakan distribution transformer of PT PLN (Persero) Sukarami customer service unit. <https://doi.org/10.47191/etj/v9i05.12>
- Siboro, D. A. S., Arsyad, M. I., & Junaidi, J. (2023). Analysis of transformer loading imbalance at the Faculty of Engineering, Tanjungpura University. *Journal of Electrical Engineering, Energy, and Information Technology (J3EIT)*, *12*(2), 385-395. <https://doi.org/10.26418/j3eit.v12i2.77061>
- Styawan, T. A., & Rahmawati, Y. (2021). Load impact analysis towards power loss in distribution substation in Wlingi District. <http://dx.doi.org/10.17977/um049v1i1p27-33>
- Syahputra, R. (2019, June). Study of the effect of load balance in 500 kVA distribution transformers in complex Pt. Perta Arun Gas area of 17 Dumai branch Lhokseumawe City. In *IOP Conference Series: Materials Science and Engineering* (Vol. 536, No. 1, p. 012053). IOP Publishing. <https://doi.org/10.1088/1757-899X/536/1/012053>
- Wardhana, W., Azis, A., & Irwansi, Y. (2024). Analisa penurunan umur transformator akibat pengaruh pembebanan dan temperatur di PT PLN (Persero) P3B Sumatera UPT Palembang Gardu Induk Keramasan. *Jurnal Surya Energy*, *9*(1), 46-57. <https://doi.org/10.32502/jse.v9i1.283>
- Widagdo, R. S., & Andriawan, A. H. (2023). Analysis of losses due to load unbalance in a 2000 kVA transformer at Supermall Mansion 2 Tower Tanglin Surabaya. *Journal of Engineering and Scientific Research*, *5*(2), 78-84. <https://doi.org/10.23960/jesr.v5i2.144>