

RESEARCH ARTICLE



Analysis of the Effect of Unbalanced Load on Neutral Current, Power Losses and Efficiency in Distribution Transformer

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Published online: 25 February 2025

Abstract

630 kVA, 20 kV/400 Volt transformer is a distribution transformer that supplies electrical loads at the Aviation Polytechnic of Surabaya. In a distribution transformer if the inter phase load is unbalanced there will be a neutral current flowing in the neutral wire. This load imbalance is caused by single-phase loads on a 220 Volt low voltage network. The current flowing in the neutral of this transformer causes losses, namely due to the presence of neutral current in the neutral conductor of the transformer and losses due to neutral current flowing to the ground. After analyzing the peak load during the day of 79.92% and load imbalance during the day of 12.23%, then there is a neutral current of 181 Amperes and losses due to neutral currents flowing to the ground of 7, 26%, and transformer efficiency at the day of 88.5 %.

Keyword: Unbalanced Load, Neutral Current, Losses, Efficiency

Introduction

In the flow of electricity there is a distribution of loads that are initially evenly distributed but because of the unequal time of use or ignition of these loads, it causes load imbalances in each phase (Phase R, phase S, and phase T) which results in various detrimental things.

For example, the provision of electricity on ships when the load becomes unbalanced, the consumption of fuels also increases, this indicates that there is a waste of fuel oil use (Sarwito, Semin, & Hanif, 2017). Similarly, unbalanced loads can increase the temperature of power transformer oil (Mharakurwa, Nyakoe, & Akumu, 2018).

A distribution transformer is a power transformer where the voltage on the primary and secondary sides of the transformer is the distribution voltage. The transformer in this study the primary voltage is 20 kV and the secondary voltage is 400 Volts. Distribution transformers are used to distribute electrical energy directly to customers (Sulasno, 2009).

State of Balanced Load and Unbalanced Load

Balance is a condition that involves the following characteristics

1. All three voltage vectors are equal
2. The three vectors form an angle of 120° with each other

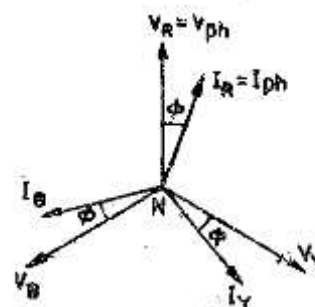


Figure 1 Balanced Load

Meanwhile, an unbalanced condition is a condition where one or both of these conditions are not met. There are three possible unbalanced conditions. These conditions include:

- a. The three vectors are equal but do not form a 120° angle with each other
- b. The three vectors do not have the same size but form an angle of 120° to each other
- c. The third vector is not as large as the other two vectors and does not form an angle of 120° to each other

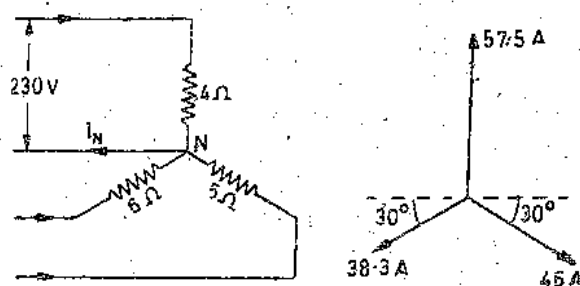


Figure 2 Unbalanced Load

A transformer is an electrical equipment that can move and change electrical energy from one or more electrical circuits to another electrical circuit through a magnetic field and is based on the principle of electromagnetic induction (Zuhal, 1991).

Transformers work based on electromagnetic principles. If the primary coil is connected to an alternating voltage source, alternating flux will appear in the laminated core because the coil forms a closed network and makes the primary current flow. Because of the flux in the primary coil, there is induction in the primary coil and in the secondary coil there is induction due to the induction effect of the primary coil (mutual induction) which causes magnetic flux in the secondary coil and in the secondary current if the secondary circuit is connected to the load so that all electrical energy can be transferred magnetically (Wijaya, 2001).

Table 1 Transformer data at Poltekbang Surabaya

Merk	Trafindo, Indonesai
Type	Ootdoor
Power	630 kVA
Rating oltage	21/20,5/20.19,5/1kV//400 V
Impedance at 75 ° C	4 %
Exciting Current	1,8 %
Cos ϕ	0,85
Trafo	1 x 3 phase

- Transfer electric power from the circuit to another
- It does so without a change of frequency
- It accomplishes this by electromagnetic induction and
- When two electric circuit are in mutual inductive influence or each other

The Transformer on No Load

When the transformer on no-load the primary input current is not wholly reaction. The primary input current under no load conditions has to supply.

- Iron losses in the core i.e. hysteresis loss and eddy current loss
- A very small amount of copper loss in primary (there being no Cu loss in secondary as it is open).

Hence the no load primary input current I_0 is not 90° behind V_1 but lags it by an angle $\phi < 90^\circ$ (Theraja & Theraja, 1995)..

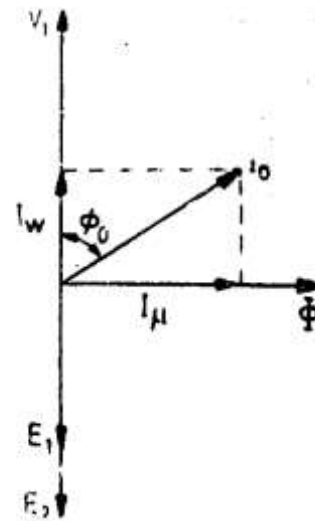


Figure 3 Transformator on No Load Condition (Theraja & Theraja, 1995).

$$\text{No load input power } W_0 = V_1 I_0 \cos \phi \dots\dots\dots (1)$$

$$\text{Primary Cu loss } I_w = I_0 \cos \phi \dots\dots\dots (2)$$

$$\text{Magnetizing component } I_\mu = I_0 \sin \phi \dots\dots\dots (3)$$

The transformer On Load

When the secondary is loaded, the secondary current I_2 is set up. The magnitude and phase of I_2 with respect to V_2 is determined by the characteristics of the load. Current I_2 is in phase V_2 if load is non inductive, it lags if load is inductive and it leads if load is capacitive.

Hence, when transformer is on load, the primary winding has two current in it; one is I_0 and the other is I'_2 which is phase with I_2 and K times in magnitude. The total primary current is the vector sum of I_0 and I'_2 .

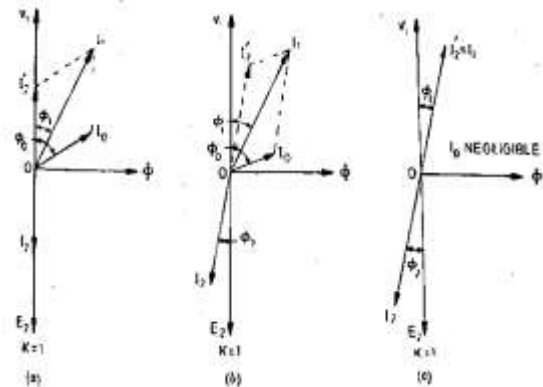


Figure 4 Transformator On Load Condition (Theraja & Theraja, 1995).

In Fig. 4 are shown the vector diagram for a loaded transformer, when load is non-inductive and when it is inductive (a similar diagram could be drawn for capacitive load). When the secondary is loaded, the secondary current I_2 is set up. The magnitude and phase of I_2 with respect to V_2 is determined by the characteristics of the load. Current I_2 is in phase V_2 if load is non inductive, it lags if load is inductive and it leads if load is capacitive (Theraja & Theraja, 1995)..

1.2.3. Neutral Current due to Unbalanced Load

Neutral Current in the power distribution system is known as the current flowing on the neutral wire in the three phase four wire low voltage distribution system. The current flowing on the neutral wire is the vector sum of the three phase currents in symmetrical components.

For the three-phase current of an unbalanced system, it can also be solved using the symmetrical component method. By using the same notations as for the voltage, the equations for the phase currents will be obtained as follows:

$$I_a = I_1 + I_2 + I_0 \quad (4)$$

$$I_b = a \cdot I_1 + a^2 \cdot I_2 + I_0 \quad (5)$$

$$I_c = a^2 \cdot I_1 + a \cdot I_2 + I_0 \quad (6)$$

Similarly, the sequence currents can also be determined in the same way so as to get

$$I_1 = 1/3 (I_a + a \cdot I_b + a^2 \cdot I_c) \quad (7)$$

$$I_2 = 1/3 (I_a + a^2 \cdot I_b + a \cdot I_c) \quad (8)$$

$$I_0 = 1/3 (I_a + I_b + I_c) \quad (9)$$

In a three-phase four-wire system the sum of the line current is equal to the neutral current returning through the neutral wire, then

$$I_N = I_a + I_b + I_c \quad (10)$$

By subsuming the equation, it is obtained: (Stevenson & Idris, 1994).

$$I_N = 3 \cdot I_0 \quad (11)$$

1.2.4. Calculation of Full Load Current and Short Circuit Current (Sudirham, 1991)

Distribution transformer power in terms of high voltage (primary) side can be formulated as follows:

$$S = \sqrt{3} \cdot V \cdot I \quad (12)$$

Where:

S: transformer power (kVA)

V: transformer primary side voltage (kV)

I: mesh current (A)

Thus, to calculate the full load current (IFL) can be calculated using the formula: (Sudirham, 1991)

$$IFL = S / \sqrt{3} \cdot V \quad (13)$$

As for calculating the short circuit current in the transformer using the formula:

$$ISC = (S \cdot 100) / (\%Z \cdot \sqrt{3} \cdot V) \quad (14)$$

ISC = Short circuit current (A)

S = Power of Transformer (kA)

V = Voltage skunder side Transformer (kV)

%Z = Percent Impedance Transformer

Method

Data Source

The data used in this study are measurement data at the distribution transformer at the Aviation Polytechnic of Surabaya. The data contains data on transformer loads R, S, T, N by using Digital Earth Clamp Tester Kyoritsu 4200, Tank Ampere Kyoritsu 2055, Avometer Sanwa CD 800 and Power Meter Easy Logic PM 2200 Schneider was carried out from June 22, 2024 to September 9, 2024 on the scondary side of the transformer at the Politeknik Penerbangan Surabaya.

Research Method

In conducting this research, the stages carried out are arranged systematically, broadly speaking, the research flow chart can be described as follows:

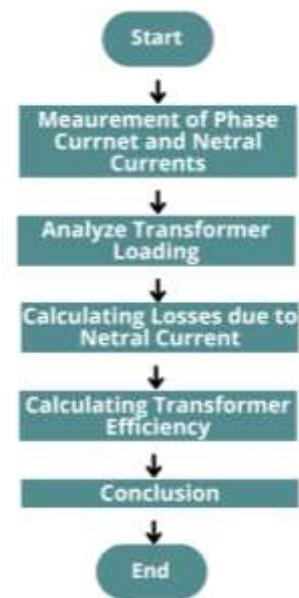


Figure 5 Research Flowchart

Discussion

After observing the neutral current value from June 22, 2024 to September 9, 2024, the highest I_N value measurement was obtained on August 16, 2024 at 02.00 PM with $I_N = 181$ Amperes (daytime) and the lowest $I_N = 32,6$ A value measurement on July 10, 2024 at 03.00 AM (nighttime).

Table 2 Measurement of Phase Current and Neutral Current

Time	I_R (A)	I_S (A)	I_T (A)	Current			R_G (Ω)	Vph (V)
				I_N (A)	I_0 (A)			
Noon	860.8	648.1	673.9	181	90	4,8		230
Night	428.6	399.5	450.1	32.6	14,6	4,8		230

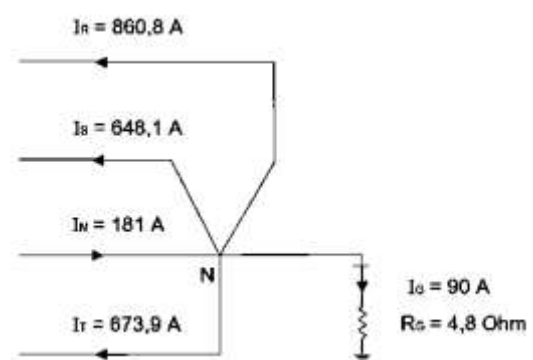


Figure 6 Schematic of current flow on the transformer secondary side at highest I_N (noon)

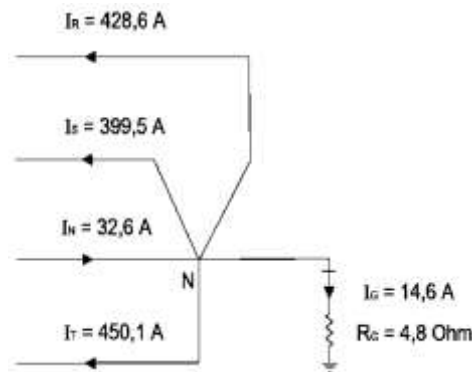


Figure 7. Schematic of current flow on the secondary side of the transformer at the lowest IN (night)

Peak Load Analysis

In this load analysis it is necessary to know in advance the full load current using equation (13).

$$I_{Full\ Load} = \frac{S}{\sqrt{3} \cdot V} = \frac{630.000}{\sqrt{3} \times 400} = \frac{630.000}{692} = 910,4 \text{ Amperre}$$

$$I_{average\ during\ the\ day} = \frac{I_R + I_S + I_T}{3} = \frac{860,8 + 648,1 + 673,9}{3} = \frac{2182,8}{3} = 727,6 \text{ A}$$

$$I_{average\ at\ night} = \frac{I_R + I_S + I_T}{3} = \frac{428,6 + 399,5 + 450,1}{3} = \frac{1278,2}{3} = 426 \text{ A}$$

a. Load during the day

$$= \frac{I_{average\ during\ the\ day}}{I_{Full\ Load}} \times 100\% \\ = \frac{727,6}{910,4} \times 100\% = 79,92\%$$

b. Load at night

$$= \frac{I_{average\ at\ night}}{I_{Full\ Load}} \times 100\% \\ = \frac{426}{910,4} \times 100\% = 46,79\%$$

The results obtained show that the peak load during the day is 79.92%.

Load Imbalance Analysis

If the phase currents are in balance then the power can be calculated by the formula.

$$P = 3 \cdot [V] \cdot [I] \cdot \cos \varphi \quad (15)$$

If [I] is the magnitude of the phase current in the power distribution of P in a balanced state, then at the same power distribution but with an unbalanced state, the magnitude of the phase currents can be expressed by the coefficients a, b and c as follows:

$$[I_R] = a [I]$$

$$[I_S] = b [I] \quad (16)$$

$$[I_T] = c [I]$$

With I_R , I_S , I_T respectively is the current in phase R, S, T.

If the power factor in the three phases is considered the same even though the magnitude of the current is different, the amount of power supplied can be expressed as

$$P = (a + b + c) \cdot [V] \cdot [I] \cdot \cos \varphi \quad (17)$$

If equations (17) and (15) express the same amount of power, then from these two equations, the requirements for the coefficients a, b, c can be obtained, namely

$$a + b + c = 3$$

where in a balanced state the value of $a = b = c = 1$

From the above data it can be seen that the load is in an unbalanced state. The amount of load imbalance that occurs is known by using the following equation:

$$I_R = a \cdot I, \text{ so } a = \frac{I_R}{I_{average}}$$

$$I_S = b \cdot I, \text{ so } b = \frac{I_S}{I_{average}}$$

$$I_T = c \cdot I, \text{ so } c = \frac{I_T}{I_{average}}$$

3.2.1. Load imbalance during the day

$$a = \frac{I_R}{I_{average}} = \frac{860,8}{727,6} = 1,183$$

$$b = \frac{I_S}{I_{average}} = \frac{648,1}{727,6} = 0,89$$

$$c = \frac{I_T}{I_{average}} = \frac{673,9}{727,6} = 0,926$$

$$\text{Average imbalance} = (a+b+c)/3 = (1,183+0,89+0,926)/3 = 0,999$$

So the percentage of Unbalanced Load (UL) is

$$UL = ((a-1)+(b-1)+(c-1))/3 \times 100\% = ((1,183-1)+(0,89-1)+(0,926-1))/3 \times 100\%$$

$$UL = 12,23\%$$

3.2.2. Load imbalance at night

$$a = \frac{I_R}{I_{average}} = \frac{428,6}{426} = 1,006$$

$$b = \frac{I_S}{I_{average}} = \frac{399,5}{426} = 0,937$$

$$c = \frac{I_T}{I_{average}} = \frac{450,1}{426} = 1,056$$

$$\text{Average imbalance} = (a+b+c)/3 = (1,006+0,937+1,056)/3 = 1,01$$

So the percentage of unbalanced load (UL) is

$$UL = ((a-1)+(b-1)+(c-1))/3 \times 100\% = ((1,006-1)+(0,937-1)+(1,056-1))/3 \times 100\%$$

$$UL = 4,16\%$$

From the results of the above calculations, it can be seen that the average load imbalance is greater during the day than at night, which is 12.23%.

Power Losses Analysis

The wire size for the neutral conductor of the transformer is 70 mm² with $R = 0.5049 \Omega / \text{km}$

3.3.1. During the day

The power loss due to the current flowing in the transformer neutral is

$$P_N = I_N^2 \cdot R_N = (181)^2 \times 0.5049 = 16,541 \text{ Watt} = 16,54 \text{ kW}$$

Where is the active power of the transformer (P)

$$P = S \cdot \cos \varphi \text{ where the } \cos \varphi \text{ used is } 0.85$$

$$P = 630 \cdot 0.85 = 535.5 \text{ kW}$$

So that the percentage of losses due to neutral current in the neutral conductor of the transformer is

$$\% P_N = \frac{P_N}{P} \times 100\% = \frac{16,54}{535,5} \times 100\% = 3,09\%$$

Losses due to neutral currents flowing to the ground can be calculated:

$$P_G = I_G^2 \cdot R_G = (90)^2 \cdot 4.8 = 38,880 \text{ Watt} = 38.88 \text{ kW}$$

Thus the percentage of losses is

$$\% P_G = \frac{P_G}{P} \times 100\% = \frac{38,8}{535,5} \times 100\% = 7.26\%$$

At night

Losses due to neutral current flowing can be calculated

$$P_N = I_N^2 \cdot R_N = (32.6)^2 \times 0.5049 = 536,58 \text{ Watt} = 0,536 \text{ kW}$$

The percentage of losses due to neutral current in the transformer neutral conductor is:

$$\% P_N = \frac{P_N}{P} \times 100\% = \frac{0,536}{535,5} \times 100\% = 0.1\%$$

Losses due to neutral currents flowing to the ground can be calculated

$$P_G = I_G^2 \cdot R_G = (14.6)^2 \cdot 4.8 = 1,023.16 \text{ Watts} = 1 \text{ kW}$$

Percentage of losses due to neutral current flowing to the ground

$$\% P_G = \frac{1}{535.5} \times 100\% = 0.18\%$$

From the calculation of power losses above, it can be seen that the greater the load imbalance that occurs, the greater the power loss in the transformer

Efficiency Analysis

To find out the amount of efficiency is to use the equation, namely

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

3.4.1. During the day

$$\begin{aligned} P_{out} &= (a + b + c) \cdot V_{ph} \cdot I_{avg} \cdot \cos \phi \\ &= (1,183 + 0,89 + 0,926) \cdot 230 \cdot 727,6 \cdot 0,85 \\ &= 426,595.15 \text{ Watts} = 426,6 \text{ kW} \end{aligned}$$

So the efficiency during the day is

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{P_{out}}{P_{out} + \text{losses}} \times 100\%$$

$$\eta = 426.6 / (426.6 + 16.54 + 38.88) \times 100\% = 88,5\%$$

3.4.2. At night

$$\begin{aligned} P_{out} &= (a + b + c) \cdot V_{ph} \cdot I_{avg} \cdot \cos \phi \\ &= (1,006 + 0,937 + 1,056) \cdot 230 \cdot 426 \cdot 0,85 \end{aligned}$$

$$P_{out} = 249,765.7 \text{ Watt} = 249,765 \text{ kW}$$

So the efficiency at night

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{P_{out}}{P_{out} + \text{losses}} \times 100\%$$

$$\eta = 249.765 / (249.765 + 0.536 + 1) \times 100\%$$

$$\eta = 99,38\%$$

Table 3 Load, Unbalanced oad, Losses (PN), Losses (PG), Efficiency in present

	LOAD (%)	UL (%)	P _N (%)	P _G (%)	η(%)
At noon	79,92	12,23	3,09	7,26	88,5
At night	46,79	4,16	0,1	0,18	99,38

Limitation Of The Study

This study has several limitations that should be acknowledged. First, the analysis was conducted using data obtained from a single distribution transformer at the Aviation Polytechnic of Surabaya. As such, the findings may not be fully generalizable to other transformers with different capacities, configurations, or operational environments. Second, the study relied on observational data during peak load periods without conducting simulations or controlled experiments that could further validate the observed effects of unbalanced loads. Third, environmental factors such as temperature variations, humidity, or harmonic distortions, which could influence transformer efficiency and power losses, were not extensively considered in the analysis. Finally, this study did not evaluate long-term effects or maintenance implications related to

persistent unbalanced loads on transformer performance. Future research should address these limitations by incorporating a broader dataset, experimental validation, and additional influencing variables.

Conclusions and Recommendations

There is an imbalance in the load of the 630 kVA distribution transformer at the Surabaya Aviation Polytechnic where because activities are carried out during the day, the use of electric loads is greater during the day than at night.

The load imbalance results in the flow of the maximum neutral current during the day amounting to 181 A and the minimum occurs at night amounting to 32,6 A.

Peak load occurs during the day at 79.92% with an average phase current of 727,6 A. Load imbalance occurs during the day by 12, 23% and at night by 4, 16%. As a result of the load imbalance, power losses occur during the day, namely losses due to current flowing in the neutral wire of 16,54 kW (3,09 %) and losses due to neutral current flowing to the ground of 38.88 kW (7.26%).

Load imbalance at night is smaller than during the day, namely losses due to current flowing to the neutral wire of 0,536 kW (0.1%) and losses due to neutral current flowing to the ground as large as 1 kW (0.18%).

Because the load imbalance at night is smaller at night, at night there is a greater distribution transformer efficiency during the night, which is as large as 99.38% compared to the distribution transformer efficiency during the day of 88,5 %.

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