A COMPARATIVE STUDY OF OPEN DELTA TRANSFORMER AND DELTA TRANSFORMER PERFORMANCE ON LOAD

Sinay, Pelpinus
Jurusan Teknik Elektro
Politeknik Negeri Ambon, Indonesia
nussinay.polnam@gmail.com

Abstract—**The research objective was to carry out a study to compare the performance of open delta transformer and delta transformer on load. The research method used was an experimental method in the laboratory, which included testing on the three-phase transformer of open delta and delta connection on load. The measurement showed that there was a comparison of performance (output) between the average current with loses and efficiency in the open delta transformer connection which had smaller value compared to the delta transformer connection. It was due to the load power capacity supplied in the open delta transformer which was smaller than the delta transformer, with a ratio of V = 0.577 and Δ = 1, the actual power capacity needed or used was 2100 VA.**

Keywords: open delta transformer, delta transformer, on load

I. Introduction

Transformer is a device that can transmit (distribute) and change the amount of electric power from one circuit to another electrical circuit with the same frequency based on the principle of electromagnetic induction. The voltage received can be increased or decreased in accordance with the current in the circuit [1]. The electric power transferred and changed is the voltage and alternating current (AC) [2].

Delta-delta connection is the most effective connection used for low voltages with large load current. This winding connection is also the most widely used winding connection when compared to a variety of other winding connection.

If only two single-phase transformers are available, it is still possible to make a three-phase system using two one-phase transformers or the remaining two windings which can be used to deliver electrical power by using open-delta winding connection [3] [4].

A three-phase open delta connection transformer is a three-phase transformer with two coils or a three-phase transformer consisting of two single phase transformers. The open delta winding connection is closely related to the delta winding connection because the open delta winding connection is a modification of the delta winding connection [4]. Furthermore, the three-phase open delta transformer can be a specific winding connection in the three-phase transformer. If this winding connection is carried out on a delta-connected transformer where one of windings is damaged (broken), then by using the remaining two windings, the three-phase power can continue to be distributed to the load even with a smaller power capacity [5]. Even though the amount of power that can be served must be reduced by a few percent from the kVA branch of the three-phase transformer of open delta connection. This winding connection has a very important role in sending power to the load so that the continuity of electrical power is obtained temporarily, so the system works continuously until the transformer is replaced [5].

In general, the load served by a transformer is balanced. In reality, often the load served by a transformer is not balanced. The unbalance of the load causes the current in each phase to be unbalanced, so that the resultant load current is not equal to zero. As a result, for the same output power (the same load), the unbalanced transformer will have a greater loss and will absorb more power so that the efficiency will be smaller. Unbalance current in each phase can occur because the impedance of the load is not balanced. If the open delta and delta transformers are given unbalanced load, the phase currents will be unbalanced which results in the secondary voltage on the transformer being unbalanced so that reduce the input power (P_{in}) that is supplied to the load. Thus, before it is operated, it needs to be tested. The test is intended to examine the performance of the open delta transformer and delta transformer under load conditions [6] [7] [8].

Based on the background above, therefore, this study has problem definitions as follow:

1. How to show the ratio of power capacity needed to obtain performance in the open delta and delta transformers on load.
2. How to obtain the performance in the open delta and delta transformers on load. Besides, the open delta transformer does not have the same performance as the delta transformer when it is loaded with a balanced load and an equally unequal load.
3. How to implement balanced and unbalanced loads to determine the current and power for each phase in the open delta and delta transformers.

As the study must possess definite scope, the discussion included only on the comparison of the performance between open delta and delta transformers on load, using a set unbalanced load which is connected to three-phase transformer of open delta and delta connections. The main objective of this study is to discuss the comparative study of open delta and delta transformers performance in the average loaded phase current in the given power capacity (VA) when given similar amount of balanced and unbalanced load.

The research is projected to has at least two benefits:

1. Overcoming a long outage of a three-phase delta transformer (Δ), if one of the 3-phase windings is damaged, then using the remaining two windings, connected by open-delta (V) can transfer 3-phase electrical power to the load in time as soon as possible.
2. This open delta connection transformer is very useful for temporary in transferring electrical power to wood processing machines in the company, while waiting for the process of procuring or replacing a new transformer.

II. THEORETICAL BASIS

A. Definition of Performance Comparison

Studying the previous studies, there has been no explanation approaching the research on comparative studies of open delta and delta transformer performance on load, so that the definition of performance comparison can be explained as follows:

Performance is the visible work, response, characteristic or output of a system. Whereas, the comparison of performance is similar to the output of a system that needs to be compared between systems in the three-phase open delta connection transformer and the three-phase delta connection transformer on load. The output of the open delta connection transformer and delta connection transformer namely; in the form of average load phase current, active power loss and efficiency. Comparison of performance (comparison of outputs) in the average load phase current of the power capacity (VA) given in the open delta transformer and delta transformer on load with balanced or unbalanced loads with equal loads. The ratio of power capacity between the three-phase open delta connection and delta connection transformer relations obtained by Equation (1).

$$V = \frac{1}{\sqrt{3}} = 0.577;\ \Delta = 1 \quad (1)$$

The relation in Equation (1) is similar to Equation (2).

$$V = 0.66;\ \Delta = 1 \quad (2)$$

B. Working Principle of Transformer under the Load

Transformer is considered to be under the load if the secondary coil is connected to load Z_L, as shown in Figure 1

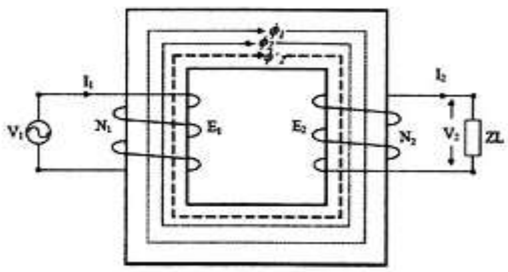

Figure 1 Transformer under the load.

If secondary coil is connected to load Z_L, there will be an I_2 current secondary coil, where $I_2 = {}^{V_2}/_{Z_L}$ with work factor of $\cos\varphi$ which is work factor of the load [6].

The load current I_2 will cause the magnetic motion force $N_2 \cdot I_2$ which tends to oppose the flux (Φ) that already exists due to magnetic currents [2]. Thus, the joint flux does not change in value and the primary coil must have current I_2, which counters the flux generated by the load current I_2, until the overall current flowing in the primary coil becomes Equation (3).

$$I = I_0 + I_1' \quad (3)$$

If the core loss component of current (I_c) is ignored, then $I_0 = I_m$, therefore the Equation (4) takes effect.

$$I = I_m + I_1' \quad (3)$$

C. Three Phase Delta Connection Transformer

This delta has three windings and each of them has the same rating as shown in Figure 2.

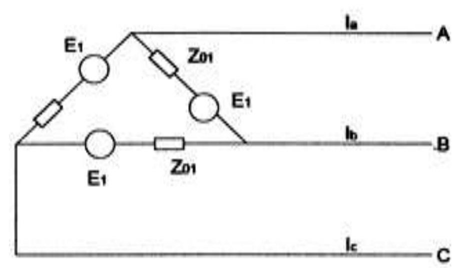

Figure 2 Delta connection transformer.

The relation between currents in Figure 2 is explained in Equation (4) and Equation (5), given the condition as in Equation (6) and Equation (7) [1].

$$I_A = I_L \neq I_{ph} \quad (4)$$

$$I_L = \sqrt{3} \cdot I_{ph} \quad (5)$$

$$V_{AB} = V_{BC} = V_{CA} = V_{L-L} \quad (6)$$

$$V_{L-L} = V_{ph} = V_f = E_1 \quad (7)$$

By taking a reference voltage and zero phase angle, another phase angle can be determined in the three-phase system. The voltage of the three-phase transformer with the coil is delta connected, while V_{AB}, V_{BC}, and V_{CA} are 120° different, so that it is zero a balanced state.

In a delta-connected transformer, the grid voltage is the same as the phase voltage.

$$V_L = V_f \quad (7)$$

The connection of grid current and phase current can be seen in Figure 2, that current in each line is the difference vector of two phase currents that flow through the line.

Current in line A can be obtained by calculating vector I_{AB} and I_{AC}, which are the opposite of vector I_{AC} (or $-I_{CA}$), and diagonal from the parallelogram showed the amount of current of line I_A. The angle between I_{AB} and the opposite of I_{CA} is 60°.

$$I_A = I_{AB} - I_{CA} = 2 \cdot I_f \cdot \cos\frac{60°}{2} = \sqrt{3} \cdot I_f \quad (7)$$

$$I_B = I_{BC} - I_{AB} = 2 \cdot I_f \cdot \cos\frac{60°}{2} = \sqrt{3} \cdot I_f \quad (8)$$

$$I_C = I_{CA} - I_{BC} = 2 \cdot I_f \cdot \cos\frac{60°}{2} = \sqrt{3} \cdot I_f \quad (9)$$

$$I_L = I_A = I_B = I_C = \sqrt{3} \cdot I_f \quad (10)$$

Equation (7), Equation (8), and Equation (9) show that current in line A equals to current in line B and line C. It leads to the conclusion as shown in Equation (10).

$$P = I_f \cdot V_f \cdot \cos\varphi \quad (11)$$

$$P_{tot} = 3 \cdot I_f \cdot V_f \cdot \cos\varphi \quad (12)$$

Power of each phase can be determined as in Equation (11), while the total power in three phases is shown as Equation (12).

Given Equation (10) into Equation (12), then the three-phase power for delta connection is shown in Equation (13).

$$P_{tot} = \sqrt{3} \cdot I_L \cdot V_L \cdot \cos\varphi \quad (13)$$

D. Three-Phase Open Delta Connection Transformer

The open delta transformer as a resource is the same as the star transformer (Y). The three-phase star connection (Y) excludes neutral, as shown in Figure 3 [9].

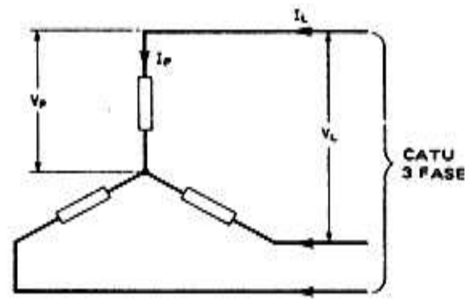

Figure 3 Three-phase star connection transformer.

For clarity, the grid notation (V_L, I_L) and phase (V_L, I_L) is only shown for one phase. where $I_L = I_P$, that is, in this star connection the net current is the same as the phase current. So, the power from the open delta transformer is obtained as in Equation (14), Equation (15), and Equation (16).

$$\frac{\frac{1}{2} \cdot V_L}{V_P} = \cos 30° \quad (14)$$

$$\frac{1}{2} \cdot V_L = V_P \cdot \frac{1}{2}\sqrt{3} \quad (15)$$

$$V_L = \sqrt{3} \cdot V_P \quad (16)$$

The net current is $\sqrt{3}$ times of phase current. On balanced load, the common formula for the three-phase is shown in Equation (17).

$$P = \sqrt{3} \cdot V \cdot I \cdot \cos\varphi \quad (17)$$

Generally, the power in open delta transformer is shown in Figure 4 [10].

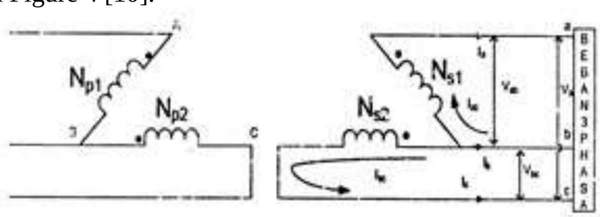

Figure 4 Open delta transformer on load..

The phase angle of voltage in such open delta transformer is determined in Equation (18).

$$V_{CA} = -V_{AB} - V_{BC} = -V\angle 120° - V\angle 0° = V\angle 120° \quad (18)$$

The relation between phase current and line current is determined in Equation (19).

$$I_A = I_{AB};\ I_C = I_{BC};\ I_B = -I_{AB} - I_B \quad (19)$$

Therefore, the amount of power in open delta transformer is shown in Equation (20), Equation (21), and Equation (22).

$$P = V_P \cdot I_P \cdot \cos\varphi \quad (20)$$

$$P_1 = V_P \cdot I_P \cdot \cos(-30°) = \frac{1}{2} \cdot \sqrt{3} \cdot V_P \cdot I_P \quad (21)$$

$$P_2 = V_P \cdot I_P \cdot \cos(30°) = \frac{1}{2} \cdot \sqrt{3} \cdot V_P \cdot I_P \quad (22)$$

As the result, the capacity of three-phase open delta connection is shown in Equation (23).

$$P = P_1 + P_2 = \sqrt{3} \cdot V_P \cdot I_P \quad (23)$$

E. *Balanced and Unbalanced Three Phase Load Circuit of Delta Connection*

It is considered in balance condition if:

1. Three current or voltage vector has the same amount.
2. Each of the three vectors create 120°.

It is considered unbalance of there is a condition where one or two of the requirements of the balanced condition is not fulfilled. The possibility of the unbalanced condition are:

1. Three current or voltage vector do not have the same amount.
2. Each of the three vectors does not create 120°.

The circuit of three-phase delta connection (Δ) can be seen in Figure 5.

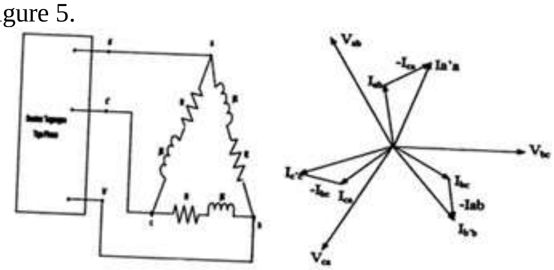

Figure 5 Load of three phase connection Δ and the phasor diagram.

The statement for balanced load current for connection (Δ), line current is not the same as phase current and can be defined into Equation (24).

$$I_{ab} = \frac{V_{ab}}{Z_{ab}};\ I_{bc} = \frac{V_{bc}}{Z_{bc}};\ I_{ca} = \frac{V_{ca}}{Z_{ca}} \quad (24)$$

Current of line $I_{a'a}$ is obtained by implementing the current of Kirchhoff formula as of Equation (25), Equation (26), and Equation (27).

$$I_{a'a} = I_{ab} + I_{ac} = I_{ab} - I_{ca} \quad (25)$$

$$I_{b'b} = I_{ba} + I_{bc} = I_{bc} - I_{ab} \quad (26)$$

$$I_{c'c} = I_{ca} + I_{cb} = I_{ca} - I_{bc} \quad (27)$$

In unbalanced condition (Δ), the impedance load of each phase does not have the same amount, so that it is explained as of Equation (28), Equation (29), and Equation (30).

$$I_{a'a} = I_a = \frac{V_{ab}}{Z_a} \quad (28)$$

$$I_{b'b} = I_b = \frac{V_{bc}}{Z_b} \quad (29)$$

$$I_{c'c} = I_c = \frac{V_{ca}}{Z_c} \quad (30)$$

Line current in unbalanced load I_a, I_b, and I_c are the same to balanced load current (Δ), but there is a shifting in the current phase angle, and the voltage is not as bus and does not create 120° to one another.

$$I_{a'a} = I_a = I_{ab} + I_{ac} = I_{ab} - I_{ca} \quad (31)$$

$$I_{b'b} = I_b = I_{ba} + I_{bc} = I_{bc} - I_{ab} \quad (32)$$

$$I_{c'c} = I_c = I_{ca} + I_{cb} = I_{ca} - I_{bc} \quad (33)$$

F. *Average Unbalanced Load Phase Current*

If the load is in balanced, the amount of the delta connected load power in this experiment is shown in Equation (17). For the same power but with an unbalanced state, the amount of the load phase currents can be expressed by the coefficients as in Equation (34).

$$[I_{AB}] = a[I];\ [I_{BC}] = b[I];\ [I_{CA}] = c[I] \quad (34)$$

If the power factors in all three phases are the same even though the amount of current is different, the magnitude of the power can be expressed as in Equation (35), so that Equation (36) applies, and Equation (37) takes into effect as the average current.

$$P = (a + b + c) \cdot V \cdot I \cdot \cos\varphi \quad (35)$$

$$a + b + c = 3 \quad (36)$$

$$\bar{I} = \frac{|a-1| + |b-1| + |c-1|}{3} \quad (37)$$

As a result, where in a balanced condition, Equation (38) takes effect.

$$a = b = c = 1 \quad (38)$$

III. Research Methods

A. *Framework of the Research*

The diagram of this research framework can be seen in Figure 6. This research scope is limited to the performance of open delta transformer and delta transformer on load, which focuses on average current, losses, and efficiency of both unbalanced 3-phase load. The analysis can be done by investigating the current and power parameters.

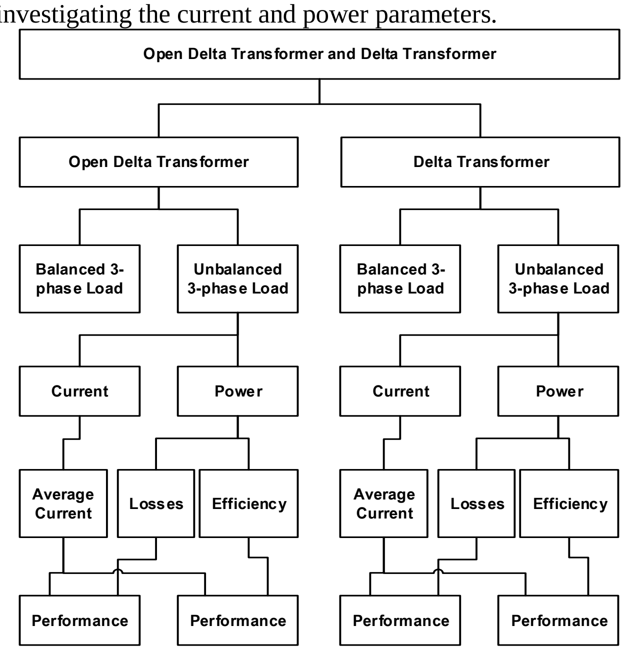

Figure 6 Diagram of research framework.

B. *Methods of the Research*

The research methodology used in this study was the method of measurement and analysis, namely testing in the laboratory to obtain test data. The steps of the research methodology carried out in this study are shown in the flowchart as in Figure 7.

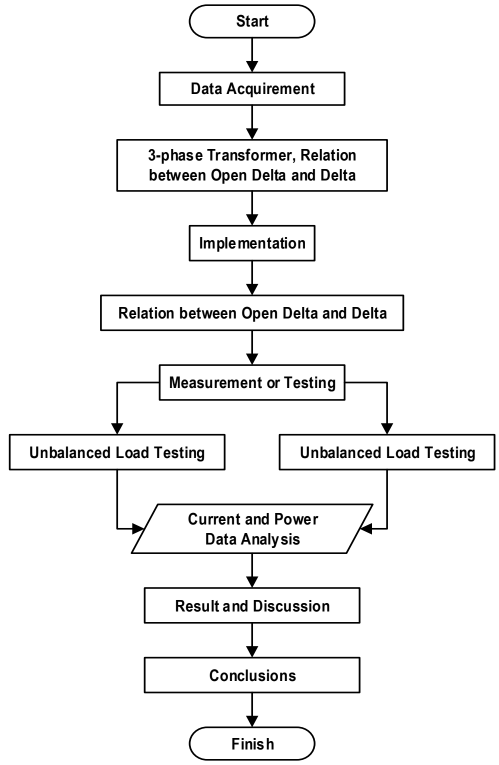

Figure 7 Flowchart of research methodology.

IV. Results and Discussions

The three-phase delta connection transformer ($\Delta-\Delta$) is the most effective connection used for low voltages with large load currents. This delta transformer is very closely related to the open delta transformer ($V-V$). If in a delta transformer one of the windings is damaged, then this transformer can be transformed into an open delta transformer.

The three-phase open delta connection transformer is a special winding relationship, with lower power capacity compared to the delta transformer, using two windings of the three-phase power which can be transferred to the load.

This research was intended to obtain a comparative study of the performance of open delta and delta transformers under the load.

A. *The Equations Used in the Testing of Three-Phase Transformer under the Load*

The equation used in analyzing the performance (characteristics or output) of the three-phase open delta and delta transformers was the same as analyzing the characteristics of a single-phase transformer, only the amount was replaced by a three-phase magnitude.

This experiment aimed to get the performance (characteristic or output) of the three-phase open delta and delta transformers. The equation used to obtain the characteristics of the three-phase transformer in load, to obtain power on the primary and secondary sides and the power factor on each phase as in Equation (39), while Equation (40) for the three-phase delta connection.

$$P = V \cdot I \cdot \cos\varphi \tag{39}$$

$$P = \sqrt{3} \cdot V_L \cdot I_L \cdot \cos\varphi \tag{40}$$

The efficiency of the transformer is given by Equation (41), and the average current is determined in Equation (42).

$$\eta = \frac{P_{out}}{P_{in}} \cdot 100\% \tag{41}$$

$$\bar{I} = \frac{|a-1|+|b-1|+|c-1|}{3} \tag{42}$$

The comparison between the power capacity of open delta transformer and delta transformer is $0.577 : 1$.

B. *Name Plate Data of Three-Phase Open Delta and Delta Connection Transformer*

The name plate data mentioned in transformer body was as follows:

Transformer Capacity : 2100 VA
Frequency : 50 Hz
Voltage of Primary Side : 50 V to 64 V
Current of Primary Side : 22 A
Voltage of Secondary Side : 110 V to 220 V
Current of Secondary Side : 10 A

The transformer was made into a three-phase transformer of open delta and delta connection with step-up settings, therefore obtained parameters of open delta connection are:

Transformer Capacity : 1212 VA
Frequency : 50 Hz
Voltage of Primary Side : 55 V
Current of Primary Side : 12.7 A
Voltage of Secondary Side : 220 V
Current of Secondary Side : 3.2 A

On the other side, for the delta connection, the obtained parameters are:

Transformer Capacity : 2100 VA
Frequency : 50 Hz
Voltage of Primary Side : 55 V
Current of Primary Side : 22 A
Voltage of Secondary Side : 220 V
Current of Secondary Side : 5.3 A

C. *The Calculation and Analysis of Three-Phase Open Delta Connection Transformer under the Load*

With the regulation of $V_1 = 55\,V$, measurement data of unbalanced load with two balanced phases, while another phase unloaded, in open delta connection transformer, is described in **Error! Reference source not found.**.

Table I MEASUREMENT DATA OF UNBALANCED LOAD WITH TWO BALANCED PHASES WHILE ANOTHER PHASE UNLOADED IN OPEN DELTA CONNECTION TRANSFORMER

No	Primary Current (A)			Input Power (W)			Voltage (V)	Secondary Current (A)			Output Power (W)		
	I_1	I_2	I_3	P_1	P_2	P_3	V_2	I_4	I_5	I_6	P_4	P_5	P_6
1	9.6	9.8	11.1	343	350	391	190.75	3	3	0	490.5	490.5	0
2	11.2	9.6	9.8	391	343	350	190.35	3	0	3	489.5	0	489.5
3	9.8	11.3	9.6	345	396	343	190.55	0	3	3	0	490	490

After the measurement conducted, the input power, output power, losses, and efficiency of each measurement item can be determined, as shown in Table II .

Table II DATA RESULT OF UNBALANCED LOAD WITH TWO BALANCED PHASES WHILE ANOTHER PHASE UNLOADED IN OPEN DELTA CONNECTION TRANSFORMER

No	Input power (watt)	Output power (watt)	Loses (watt)	Efficiency (%)
1	1084	981	103	90,49
2	1084	979	105	90,31
3	1084	980	104	90,40

The data result from table can be summarized as described in Table III.

Table III SUMMARY OF UNBALANCED LOAD WITH TWO BALANCED PHASES WHILE ANOTHER PHASE UNLOADED IN OPEN DELTA CONNECTION TRANSFORMER

Average current (%)	Loses (watt)	Efficiency (%)
66,66	103	90,49
50	94,83	91,25
33,33	85,33	92,02
0	64	93,87

Finally, from the summary in Table III, the characteristics of connection between average load current and loses can be seen in Figure 8.

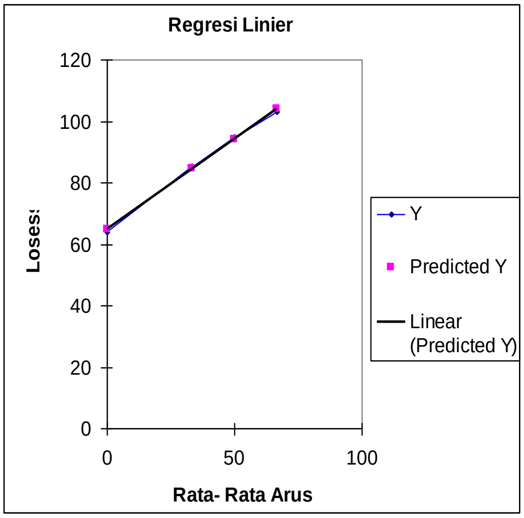

Figure 8 Characteristics of connection between average load current and losses of unbalanced load with two balanced phases while another phase unloaded in open delta connection transformer.

In addition, from the results of the unbalanced measurement data analysis results table, the performance (characteristic) of connection between average load current and efficiency of the three-phase open delta connection transformer was obtained in the Figure 9.

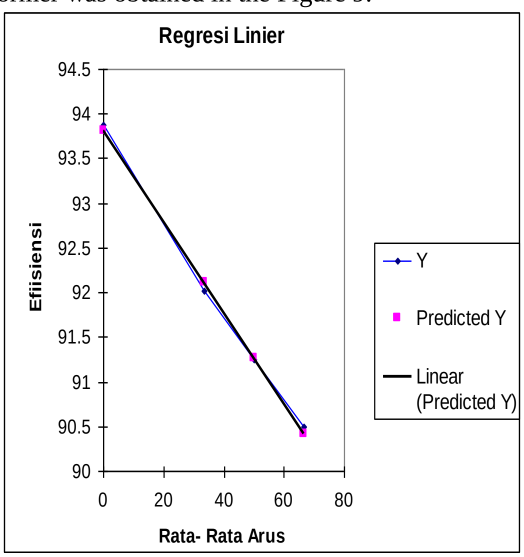

Figure 9 Characteristics of connection between average load current and efficiency of unbalanced load with two balanced phases while another phase unloaded in open delta connection transformer.

D. *The Calculation and Analysis of Three-Phase Delta Connection Transformer under the Load*

With the regulation of $V_1 = 55\,V$, measurement data of unbalanced load with two balanced phases, while another phase unloaded, in delta connection transformer, is described in Table IV.

Table IV MEASUREMENT DATA OF UNBALANCED LOAD WITH TWO BALANCED PHASES WHILE ANOTHER PHASE UNLOADED IN DELTA CONNECTION TRANSFORMER

No	Primary Current (A)			Input Power (W)			Voltage (V)	Secondary Current (A)			Output Power (W)		
	I_1	I_2	I_3	P_1	P_2	P_3	V_2	I_4	I_5	I_6	P_4	P_5	P_6
1	17,2	19,1	17,3	665	738	669	190,75	8	8	0	983	983	0
2	19,2	17,2	17,3	741	664	667	190,35	8	0	8	981	0	981
3	17,3	19,3	17,2	667	743	662	190,55	0	8	8	0	982	982

After the measurement conducted, the input power, output power, losses, and efficiency of each measurement item can be determined, as shown in Table V.

Table V DATA RESULT OF UNBALANCED LOAD WITH TWO BALANCED PHASES WHILE ANOTHER PHASE UNLOADED IN DELTA CONNECTION TRANSFORMER

No	Input power (watt)	Output power (watt)	Loses (watt)	Efficiency (%)
1	2072	1966	106	94,88
2	2072	1962	110	94,69
3	2072	1964	108	94,78

The data result from table can be summarized as described in Table VI.

Table VI SUMMARY OF UNBALANCED LOAD WITH TWO BALANCED PHASES WHILE ANOTHER PHASE UNLOADED IN DELTA CONNECTION TRANSFORMER

Average current (%)	Loses (watt)	Efficiency (%)
100	106	94,88
50	98,83	95,20
33,33	97,33	95,66
0	73	96,41

Finally, from the summary in Table III, the characteristics of connection between average load current and loses can be seen in Figure 10.

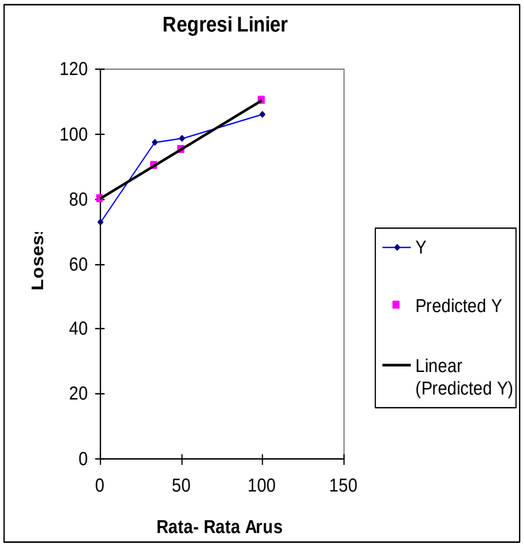

Figure 10 Characteristics of connection between average load current and losses of unbalanced load with two balanced phases while another phase unloaded in delta connection transformer.

In addition, from the results of the unbalanced measurement data analysis results table, the performance (characteristic) of connection between average load current and efficiency of the three-phase delta connection transformer was obtained in the Figure 11.

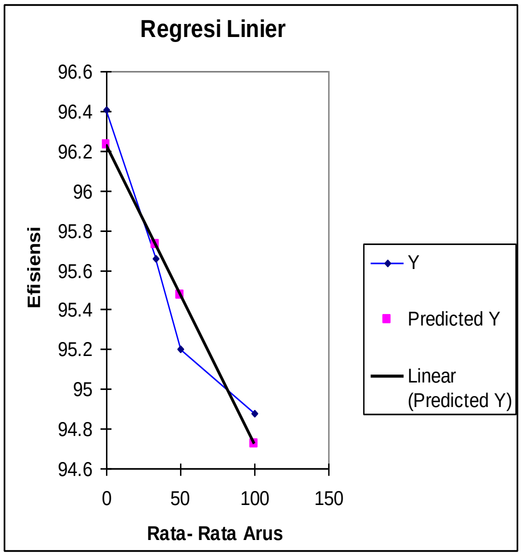

Figure 11 Characteristics of connection between average load current and efficiency of unbalanced load with two balanced phases while another phase unloaded in delta connection transformer.

V. Conclusion

The conclusions that can be taken from this research are:

1. From the description, it is obtained that the open delta transformer was unable to take the same load as the load taken by the delta transformer, because the power capacity ratio between the open delta transformer (V) and the delta transformer (Δ) is V = 0.577: Δ = 1, from power capacity used.
2. Comparison of performance (output) based on data analysis obtained from the open delta transformer and delta transformer experiments shows that the average load current for each phase on the open delta transformer was 66.6%, with the power capacity for the open delta transformer 0.577 of capacity active power used. Whereas, in the delta transformer an average load current of 100% was obtained, with the power capacity for the open delta 1 transformer of the active power capacity used.
3. Open delta transformer did not have the same performance as delta transformer on load with balanced and unbalanced load. It was caused by the increased current in each unbalanced phase, resulting in an increase in input power absorbed by unbalanced loads which caused greater power loses with reduced efficiency.

VI. Future Scope

The propositions of the future research are:

1. To avoid the increase in the power loss, it is necessary to balance the load on each phase, for the open delta and delta connection.
2. Although the open delta connection can be operated, the delta connection transformer must be repaired immediately so that the system can operate normally.

VII. References

[1] R. Panjaitan, Lampu Listrik dan Penggunaannya, Bandung: Tarsito, 1989.

[2] A. Malvino and D. Bates, Electronic Principles, 8 ed., New York: McGraw-Hill, 2016.

[3] A. Kadir, Pengantar Teknik Tenaga Listrik, Jakarta: Lembaga Penelitian, Pendidikan, dan Penerangan Ekonomi dan Sosial, 1983.

[4] G. Mil, Dasar-dasar Teknik Listrik, Jakarta: Penerbit Erlangga, 2002.

[5] H. Saadat, Power System Analysis, New York: Milwaukee School of Engineering, 1999.

[6] Zuhal, Dasar Tenaga Listrik, Bandung: ITB, 1991.

[7] L. Trevor, Instalasi Listrik, Jakarta: Penerbit Erlangga, 2004.

[8] M. H. Rashid, Circuits, Devices, and Applications, Pensacola: Electrical and Computer Engineering, University of West Florida, 2011.

[9] M. Neidle, Teknologi Instalasi Listrik, Jakarta: Penerbit Erlangga, 1999.

[10] Soemarwanto dan H. Purnomo, Mesin Elektrik I, Jakarta: Penerbit Erlangga, 2000.

[11] C. Cekdin, Sistem Tenaga Listrik, Yogyakarta: Andi Offset, 2006.

[12] J. S. Setiadji, T. Machmudsyah dan Y. Isnanto, "Pengaruh Ketidakseimbangan Beban Terhadap Arus Netral dan Losses pada Trafo Distribusi," *Jurnal Teknik Elektro,* vol. 6, 2006.

[13] Markoni, Teknik Tenaga Listrik, Yogyakarta: Penerbit Graha Ilmu, 2014.

[14] M. Budiono, Dasar Teknik Elektro, Malang: Penerbit Bayumedia, 2006.

[15] M. Ramdhani, Rangkaian Listrik, Jakarta: Penerbit Erlangga, 2008.

[16] S. Sudaryatno, Analisis Rangkaian Listrik, Bandung: ITB, 2002.

[17] B. L. Tobing, Teknik Pengujian Tegangan Tinggi, Jakarta: Penerbit Erlangga, 2017.