1 Experiment No. 10

2 Experiment Title

Three-Phase Transformer using Two Single-Phase Transformers (Open-$\Delta - \Delta$ Connection)

3 Objective

The objectives of this lab are as follows:

- To analyze the performance of a three-phase transformer using an open-Δ connection.
- To calculate and compare the power delivered in the closed-Δ and open-Δ configurations.
- To determine the power ratio and validate the theoretical reduction in power capacity.
- To understand the effects of using an open-Δ connection in terms of power factor and load capacity.

4 Theory

4.1 Open-Delta (V-V) Connection

The open-delta or V-V connection is a method of transforming three-phase power using only two transformers instead of three. It is utilized in the following cases:

1. When the three-phase load is too small to justify the installation of a full three-phase transformer bank.
2. When one transformer in a $\Delta - \Delta$ bank fails, enabling service continuity at reduced capacity.
3. When there is a future expectation of increased load, allowing for the open-delta to be closed later to form a $\Delta - \Delta$ bank.

In a V-V connection, the transformer bank's capacity is reduced compared to the $\Delta - \Delta$ configuration. The ratio of V-V capacity to $\Delta - \Delta$ capacity can be derived as follows:

4.2 Derivation of Capacity Ratio

For a $\Delta - \Delta$ transformer bank, the total capacity is:

$$P_{\Delta-\Delta} = \sqrt{3}\, V_L\, I_L,$$

where V_L is the line voltage, and I_L is the line current. In the case of a V-V connection, the capacity is:

$$P_{\text{V-V}} = 2 \cdot (\text{per-transformer capacity}).$$

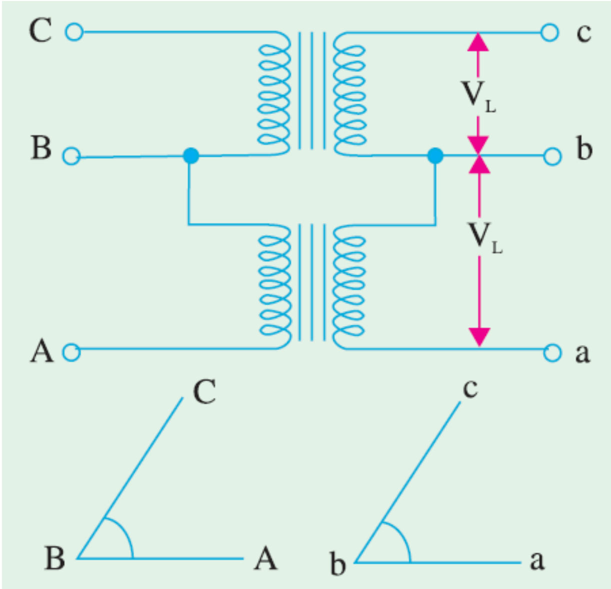

Figure 1: Open-Delta (V-V) Connection

Here, the line current in a V-V connection equals the phase current I_S, so:

$$P_{\text{V-V}} = \sqrt{3}\, V_L\, I_S,$$

and $I_S = I_L/\sqrt{3}$. Substituting this relationship gives:

$$P_{\text{V-V}} = \sqrt{3}\, V_L \left(\frac{I_L}{\sqrt{3}}\right) = V_L\, I_L.$$

The ratio of V-V capacity to $\Delta - \Delta$ capacity is then:

$$\text{Capacity Ratio} = \frac{P_{\text{V-V}}}{P_{\Delta-\Delta}} = \frac{V_L\, I_L}{\sqrt{3}\, V_L\, I_L} = \frac{1}{\sqrt{3}} \approx 0.577.$$

This demonstrates that the V-V connection's capacity is approximately 57.7% of the full $\Delta - \Delta$ capacity.

4.3 Key Properties of V-V Connection

1. **Utility Factor:** The available capacity of a V-V bank is 86.6% of the combined ratings of the two transformers:

$$\text{Utility Factor} = \sqrt{3}/2 \approx 0.866.$$

2. **Load per Transformer:** Each transformer carries 57.7% of the total load:

$$\text{Load per Transformer} = \frac{\text{Total Load}}{2} \times \frac{1}{\sqrt{3}}.$$

3. **Overload in Open-Delta Operation:** If one transformer is removed from a fully-loaded $\Delta - \Delta$ bank, the remaining transformers experience overload:

$$\text{Overload Factor} = \sqrt{3} \approx 1.732\,(\text{or } 73.2\%).$$

4.4 Disadvantages of V-V Connection

1. The average power factor of the V-V bank is lower than the load power factor:

$$\text{Power Factor of V-V Bank} = 0.866 \times \text{Load Power Factor}.$$

2. The secondary terminal voltages become unbalanced as the load increases, even for a balanced load.

4.5 Power Supplied by V–V Bank

When a V–V bank of two transformers supplies a balanced 3-phase load of power factor $\cos\phi$, then one transformer operates at a power factor of $\cos(30° - \phi)$ and the other at $\cos(30° + \phi)$. Consequently, the two transformers will not have the same voltage regulation.

$$P_1 = \text{kVA}\cos(30° - \phi) \quad \text{and} \quad P_2 = \text{kVA}\cos(30° + \phi)$$

Case 1: When $\phi = 0$ (i.e., load p.f. = 1)

Each transformer will have a power factor:

$$\cos 30° = 0.866$$

Case 2: When $\phi = 30°$ (i.e., load p.f. = 0.866)

In this case, one transformer has a power factor:

$$\cos(30° - 30°) = 1$$

and the other has a power factor:

$$\cos(30° + 30°) = 0.866$$

Case 3: When $\phi = 60°$ (i.e., load p.f. = 0.5)

In this case, one transformer will have a power factor:

$$\cos(30° - 60°) = \cos(-30°) = 0.866$$

and the other will have a power factor:

$$\cos(30° + 60°) = 0$$

It means that one of the transformers will not supply any load, whereas the other having a power factor of 0.866 will supply the entire load.

5 Required Apparatus

1. **Transformer**
   (a) Power (P): 760 VA
   (b) Primary Voltage (U_1): 230 V
   (c) Secondary Voltage (U_2): 400 – 230 V
   (d) Frequency (f): 50 Hz
   (e) Primary Current (i_1): 3.7 A
   (f) Secondary Current (i_2): 1 – 1.7 A
2. **Voltmeter:** 500 V AC rms MAX
3. **Ammeter:** 5 A MAX
4. **Digital Multimeter Display**
5. **Connecting Wires**
6. **Variable Three Phase AC Line:**
   (a) **Voltage:** 430V
   (b) **Current:** 3A
7. **Variable Resistor:**
   (a) **Resistance:** $3 \times 50\,\Omega$
   (b) **Current:** $3 \times 3.16\,\text{A}$

6 Circuit Diagrram

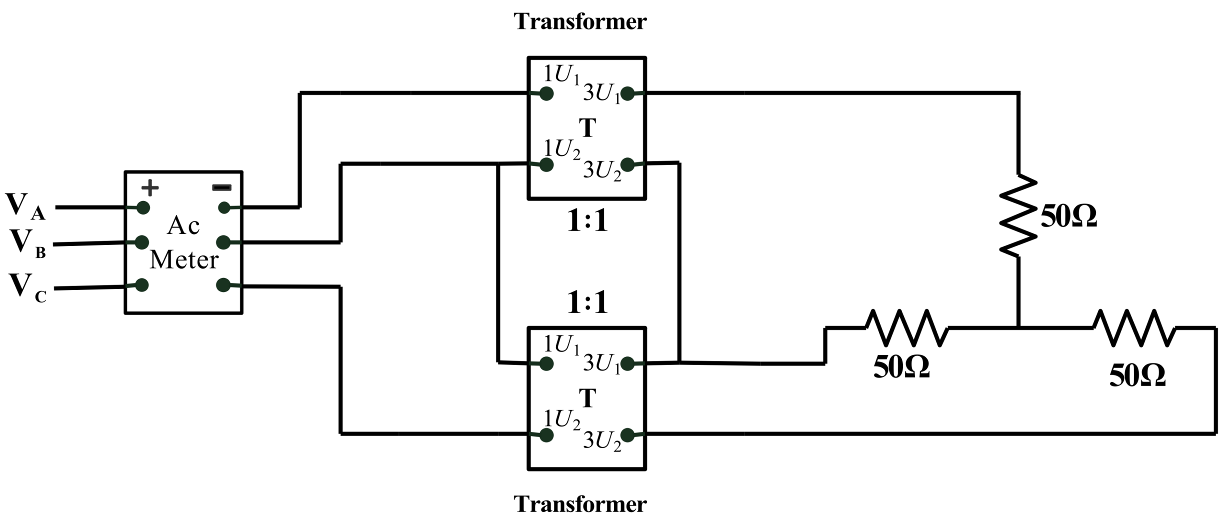

Figure 2: Connection for Three-Phase Transformer using Two Single-Phase.

7 Data Table

V_A (V)	V_B (V)	V_C (V)	I_a (A)	I_b (A)	I_c (A)	P_{open} (W)	P_{close} (W)
						106.0	
165.1	163.1	157.7	1.69	1.73	1.67	267.2	824.541
						110.0	

Table 1: Measured Values and Power for Three-Phase System

8 Calculations

Using the measured data in Table 1, the following calculations are performed:

1. **Closed-Circuit Power, P_{closed}:** The total closed-circuit power is calculated as:

$$P_{\text{closed}} = V_A \cdot I_a + V_B \cdot I_b + V_C \cdot I_c$$

Substituting the values from the table:

$$P_{\text{closed}} = (165.1 \cdot 1.69) + (163.1 \cdot 1.73) + (157.7 \cdot 1.67)$$

Performing the calculations:

$$P_{\text{closed}} = 279.019 + 282.163 + 263.359 = 824.541\,\text{W}$$

2. **Open-Circuit Power, P_{open}:** The open-circuit power is the sum of the individual measurements:

$$P_{\text{open}} = (106.0 + 267.2 + 110.0)\,\text{W}$$

Adding the values:

$$P_{\text{open}} = 483.2\,\text{W}$$

3. **Required Ratio:** The ratio of open-circuit power to closed-circuit power, expressed as a percentage, is calculated as:

$$\text{Required Ratio} = \left(\frac{P_{\text{open}}}{P_{\text{closed}}}\right) \times 100\%$$

Substituting the values:

$$\text{Required Ratio} = \left(\frac{483.2}{824.541}\right) \times 100\%$$

Performing the division:

$$\text{Required Ratio} \approx 58.6\%$$

9 Discussion

The experiment was successfully conducted to analyze the performance of a three-phase transformer using two single-phase transformers in an open-Δ connection. It was found that the power delivered in the open-Δ configuration was approximately 58.6% of the power delivered in the closed-Δ configuration. This reduction in power was consistent with theoretical expectations, where the power delivered in an open-Δ system is approximately 57.7%.
The measured closed-circuit power was found to be $P_{\text{closed}} = 824.541\,\text{W}$, and the open-circuit power was $P_{\text{open}} = 483.2\,\text{W}$, resulting in a power ratio of $\approx 58.6\%$. This confirmed the theoretical reduction in capacity when one transformer was removed from the system.
It was concluded that the open-Δ connection can be used to continue service at reduced capacity, but with a significant drop in power delivery compared to the full closed-Δ system. The variation in power factor across the transformers highlighted the importance of careful load management in such configurations.