Experiment No. 5a

THREE-PHASE TO TWO-PHASE/ONE-PHASE CONVERSION USING TWO TRANSFORMERS *(Scott Connection)*

INTRODUCTION:

Phase conversion from three to two phase is needed in special cases, such as in supplying 2-phase electric arc furnaces. Scott connection of two-single phase transformers is employed for conversion of a three-phase system to two phase system or vice-versa. Rating of one transformer should be 15% greater than that of the other, but in practical two identical transformers are used for interchangeability and spares. The connection scheme, known as Scott connections is as shown in the figure 1, 50% tap of one transformer (Main transformer) is connected to 86.6% tap of the other transformer (Teaser transformer). The secondaries for balanced supply system have equal number of turns.

AIM:

1) To obtain balanced two-phase supply from three-phase supply by Scott arrangement of two transformers.
2) To perform load test at unity power factor for both balanced and unbalanced loads and compare the test results with predictions.
3) To obtain single-phase supply from three-phase supply by Scott arrangement and perform load test at unity power factor.

THEORY:

Consider the Scott connection of two single-phase transformers with turn's ratio N1:N2 as shown in figure 1. The phase diagram of line voltages on the primary side, V_{AB}, V_{BC}, V_{CA} form an equilateral triangle.

Let,

$$V_{AB} = V \qquad (1)$$

$$V_{BC} = V(-120^\circ) \qquad (2)$$

$$V_{CA} = V(120^\circ) \qquad (3)$$

The secondary voltage of the main transformer is given by,

$$V_b = \frac{N_2 V_{CB}}{N_1} = \frac{N_2}{N_1} V(60^\circ) \qquad (4)$$

The voltage V_{AM} is given by,

$$V_{AM} = V_{AB} + \frac{V_{BC}}{2} \qquad (5)$$

$$=> V_{AM} = V + \frac{V}{2}(-120^\circ)$$

$$=> V_{AM} = V\left(\frac{3}{4} - j\frac{\sqrt{3}}{4}\right)$$

$$=> V_{AM} = \frac{\sqrt{3}}{2} V(-30^{\circ}) \qquad (6)$$

This voltage V_{AM} is across $(\sqrt{3}/2)*N_1$ turns. Therefore, the primary voltage (across N1 turns) of teaser transformer is given by,

$$V_{AA'} = \frac{2}{\sqrt{3}} V_{AM}$$

$$=> V_{AA'} = V(-30^{\circ}) \qquad (7)$$

Hence, the secondary voltage of the teaser transformer is given by,

$$V_a = \frac{N_2}{N_1} V_{AA'}$$

$$=> V_a = \frac{N_2}{N_1} V(-30^{\circ}) \qquad (8)$$

Hence, from equations (4) and (8) we can see that, for a balanced three-phase supply on the primary side, the voltages on the secondary side of the transformers are equal in magnitude but 90 degrees out of phase. Therefore we got a balanced two-phase supply from balanced three-phase supply using Scott connection.

If the secondary load currents are $\mathbf{I_a}$ and $\mathbf{I_b}$, then the primary currents can be obtained as follows,

$$\boldsymbol{I_A} = \frac{2N_2}{\sqrt{3}N_1} \boldsymbol{I_a} \qquad (9)$$

$$\boldsymbol{I_{CB}} = \frac{N_2}{N_1} \boldsymbol{I_b} \qquad (10)$$

$$\boldsymbol{I_B} = -\boldsymbol{I_{CB}} - \frac{\boldsymbol{I_A}}{2} \qquad (11)$$

$$\boldsymbol{I_C} = \boldsymbol{I_{CB}} - \frac{\boldsymbol{I_A}}{2} \qquad (12)$$

The Phasor diagrams for balanced and unbalanced unity power factor load are shown in figure 2. Note that for balanced load, the two secondary currents are equal (I_a=I_b) in magnitude and the three primary currents are also equal (I_A=I_B=I_C) in magnitude.

To get single-phase voltage supply, short negative polarity side of teaser transformer and positive polarity of main transformer on secondary side and take the voltage across positive polarity of teaser transformer and negative polarity of main transformer on secondary side. This single phase voltage is given by,

$$V = \sqrt{V_a^2 + V_b^2} \qquad (13)$$

Since, V_a and V_b are 90 degrees apart.

In case of single-phase configuration, the secondary currents of teaser and main transformer are same i.e.,

$$\boldsymbol{I_a} = \boldsymbol{I_b} \qquad (14)$$

Substituting equation (14) in equations (9), (10), (11) and (12) we can get the currents on primary side.

PROCEDURE:

1) Perform polarity test of the two single-phase transformers and find the polarities.
2) Connect the circuit as shown in the figure 1 for three-phase to two-phase conversion.
3) The three-phase balanced supply should be given to the circuit through auto-transformer and switch S1.
4) With switch S2 open, close S1 to supply rated voltage on primary side. Note down the voltages on primary and secondary sides of teaser and main transformers.
5) Start with balanced load on the secondary side ($Z_{L1}=Z_{L2}$). Close S2 and take all the ammeter and voltmeter readings. (Note that for balanced load the two secondary currents are equal and the three primary currents are equal. Else, it implies that the load is unbalanced).
6) Now keep unbalanced load on secondary side and take all the voltmeter and ammeter readings. Repeat this for 3 more sets of unbalanced load.
7) Verify the results with theoretical predictions and draw Phasor diagrams.
8) For three-phase to single-phase conversion, short the negative polarity side of teaser transformer and positive polarity side of main transformer in the previous circuit. Note the load is kept across positive polarity side of teaser and negative polarity side of main transformer. (Note that the single-phase voltage is higher than the secondary voltage in two-phase conversion (equation 13) and connect the load accordingly. If necessary connect two loads in series to maintain the rated voltage of load greater than or equal to single-phase voltage.)
9) Keep load at some value and note down all the voltmeter and ammeter readings.
10) Verify the results with theoretical predictions and draw Phasor diagrams.

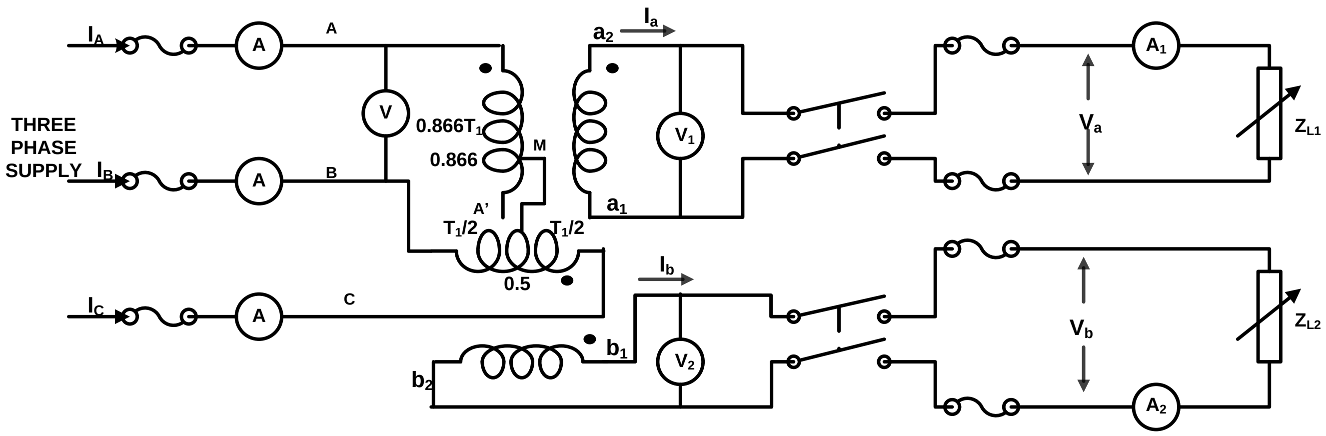

Fig. 1: Connection for load test with Scott connected transformers

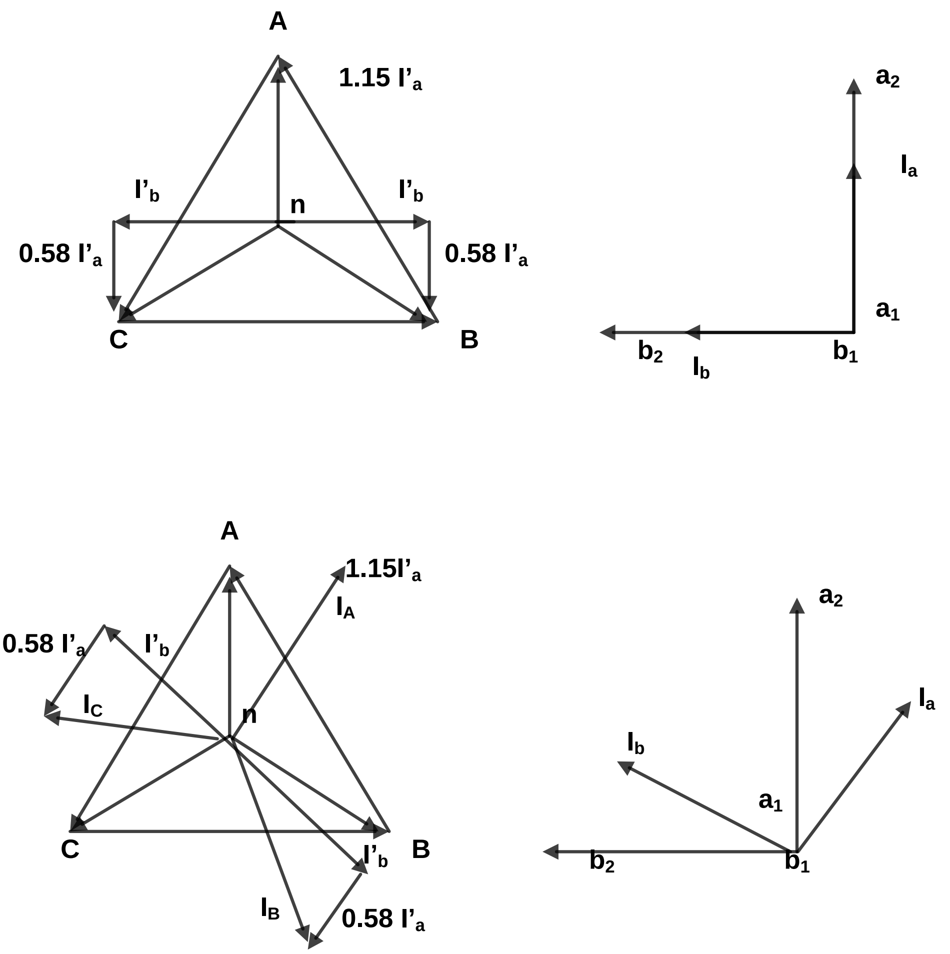

Fig. 2: Phasor diagrams (a) Balanced unity power factor load and (b) Unbalanced load

Experiment No. 5b

THREE PHASE CONNECTION OF SINGLE-PHASE TRANSFORMERS

(*Vector Groups*)

Introduction

Advantages of dealing with three-phase power instead of single-phase power are well known. The requirements of three-phase transmission/distribution system make it necessary to employ three-phase voltage transformation at the sending end as well as the receiving end. Three single-phase transformers are often used for this purpose instead of a single three-phase unit. This reduces the cost of spare and also installation/transportation becomes easier. The single-phase transformers may be connected in different ways to suit specific requirements. For equal transformation ratio of the phase windings (i.e. the individual single-phase units), the ratio of the line voltages and their phase relations depend on the mode of connection of the transformers.

Objective

The main objectives of the experiment are listed below:

1. To connect three single-phase transformers in (a) Star/star, (b) Star/delta, (c) Delta/star, (d) Delta/delta, and to obtain the no-load line voltage ratios and phase relations for each connection.
2. To study the voltage and/or current waveforms for different connections.
3. To obtain triple-frequency components of exciting currents, or triple-frequency induced voltages that appear owing to different phase connections.

Theory

From an economic point of view, a transformer is designed to operate in the saturation region of the magnetic core. This makes the exciting current non-sinusoidal [1, 2]. The exciting current contains the fundamental and all odd harmonics, third one being the predominant one. Thus, for all practical purposes, harmonics greater than third can be neglected. This section describes how these harmonics are generated in various connections and ways to limit their effect. The ratio of line quantities and phase relations for each connection is also described.

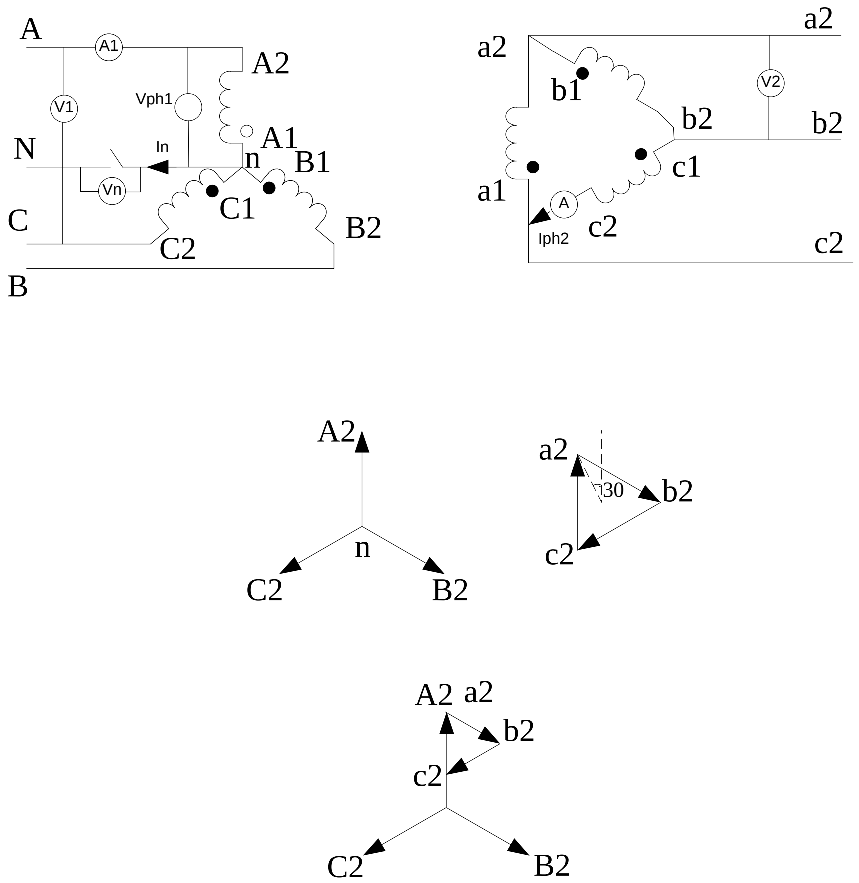

Fig. 3(a) Star-Delta Connection of Three Phase Transformers

Star/delta connection: Consider the system shown in Fig. 3(a). The primary windings are connected in star and the neutral point of the supply is available. The secondary windings are connected in delta. To start with, let us consider that the secondary delta is not closed (say, one arm is open). If the neutral of the primary star is connected to the system ground, the exciting currents of the three phases are given as

$$
\begin{aligned}
i_a &= \sqrt{2}I_{ph_1}\sin(\omega t-\varphi)+\sqrt{2}I_{ph_3}\sin 3(\omega t-\varphi)\\
i_b &= \sqrt{2}I_{ph_1}\sin(\omega t-\varphi-120^\circ)+\sqrt{2}I_{ph_3}\sin 3(\omega t-\varphi-120^\circ)\\
&= \sqrt{2}I_{ph_1}\sin(\omega t-\varphi-120^\circ)+\sqrt{2}I_{ph_3}\sin 3(\omega t-\varphi)\\
i_c &= \sqrt{2}I_{ph_1}\sin(\omega t-\varphi+120^\circ)+\sqrt{2}I_{ph_3}\sin 3(\omega t-\varphi+120^\circ)\\
&= \sqrt{2}I_{ph_1}\sin(\omega t-\varphi+120^\circ)+\sqrt{2}I_{ph_3}\sin 3(\omega t-\varphi)
\end{aligned}
$$

Where, I_{ph_1} and I_{ph_3} are the r.m.s. values of the fundamental and the third harmonic phase currents respectively and φ is the power factor angle. It can be noted that the fundamental currents in the windings are phase shifted by 120° from each other, while the third harmonic currents are all in phase (co-phasal). The neutral line carries the sum of the three third harmonic currents, i_n, but no fundamental.

$$
i_n = 3\sqrt{2}I_{ph_3}\sin 3(\omega t-\varphi)
$$

As the exciting current is non-sinusoidal, the flux in the core and hence the induced voltages in both the windings will be sinusoidal.

Next, consider the case when the neutral of the primary is kept isolated and the secondary continues to be open delta. The third harmonic currents cannot flow in the primary windings; hence the primary currents are essentially sinusoidal. The flux will be non-sinusoidal because of nonlinear *B-H* characteristics of the magnetic core, and it contains third harmonic components (higher order harmonics neglected as before). This will induce third harmonic voltage in the windings. The phase voltages are therefore non-sinusoidal, containing the fundamental and third harmonic voltages.

$$v_a = \sqrt{2}V_{ph_1}\sin\omega t + \sqrt{2}V_{ph_3}\sin 3\omega t$$

$$v_b = \sqrt{2}V_{ph_1}\sin(\omega t - 120°) + \sqrt{2}V_{m_3}\sin 3(\omega t - 120°)$$

$$v_c = \sqrt{2}V_{ph_1}\sin(\omega t + 120°) + \sqrt{2}V_{ph_3}\sin 3(\omega t + 120°)$$

Where, V_{ph_1} and V_{ph_3} are the r.m.s. value of the fundamental and the third harmonic components of phase voltage respectively. The r.m.s. value of the net phase voltage, V_{ph} is given by

$$V_{ph} = \sqrt{V_{ph_1}^2 + V_{ph_3}^2}$$

The line voltage is given by

$$v_{ab} = v_a - v_b = \sqrt{2}V_{ph_1}\sin\omega t - \sqrt{2}V_{ph_1}\sin(\omega t - 120°)$$

Note that although the phase voltages have third harmonic components, the line voltages do not. Therefore, the ratio of line voltages of primary and secondary is $\sqrt{3}\,N_1/N_2 : 1$, where N_1 and N_2 are the number of turns of primary and secondary winding respectively.

The open delta voltage of the secondary is

$$v_{\Delta_0} = v_a + v_b + v_c = 3\sqrt{2}V_{ph_3}\sin 3\omega t$$

The voltage across the open delta is the sum of the three third harmonic voltages induced in the secondary windings. Now, under this condition, if the delta is closed then the net third harmonic voltage will give rise to a third harmonic current which will circulate in the delta connected windings. This will partly provide the missing third harmonic component of the primary exciting current and consequently the flux and induced voltage will be close to sinusoidal [2].

It can be seen from the emf phasor diagram that if the transformers are connected in Yd11 and A_2 and a_2 are joined, the following conditions hold

$$\left|V_{C_2} - V_{c_2}\right| = \left|V_{B_2} - V_{c_2}\right|$$

$$\left|V_{C_2} - V_{b_2}\right| > \left|V_{B_2} - V_{b_2}\right|$$

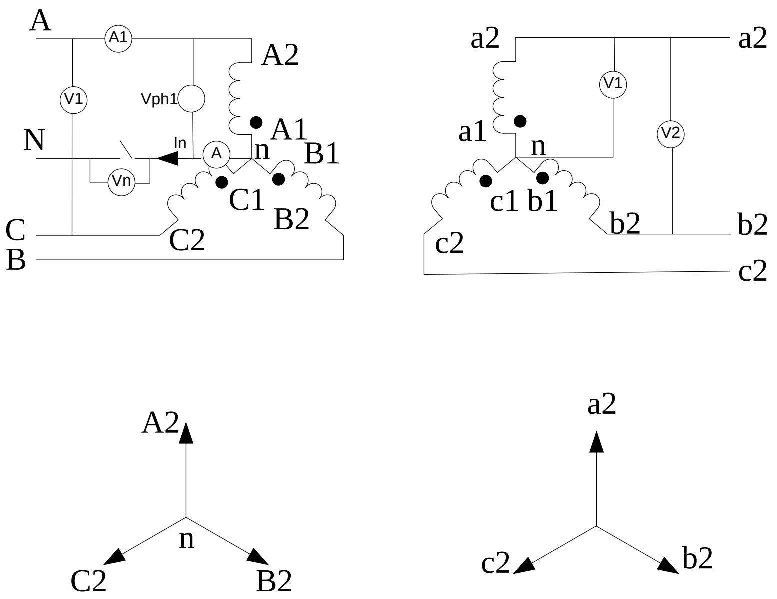

Fig. 3(b) Star-Star Connection of Three Phase Transformers

Star/star connection (Fig. 3(b)): Similar to the Star/delta connection with no neutral and open delta, the triple frequency components of the excitation currents are suppressed thereby causing large triple frequency components in flux variation. Triple frequency component will be present in the phase voltages of both the windings, but these will not appear in the line voltages. For such connections the ratio of line voltages of primary and secondary is $N_1/N_2 : 1$. The neutral point voltage will be

$$v_{Y_0} = 3\sqrt{2}V_{ph_3} \sin 3\omega t$$

With the neutral connection (4 wire system), the triple frequency components will disappear from the induced voltages in all the windings as the exciting currents of the primary will contain all the harmonics. Phase difference between the primary and secondary emfs for the connection is zero i.e., the connection is Yy0. If A_2 and a_2 are joined, the following conditions hold

$$\left|V_{C_2} - V_{c_2}\right| < \left|V_{C_2} - V_{b_2}\right|$$

$$\left|V_{B_2} - V_{b_2}\right| < \left|V_{B_2} - V_{c_2}\right|$$

Star-star connected transformers are normally provided with a tertiary winding connected in delta. This winding helps in minimizing the third harmonic content in line currents and stabilizing the neutral of the fundamental frequency voltage.

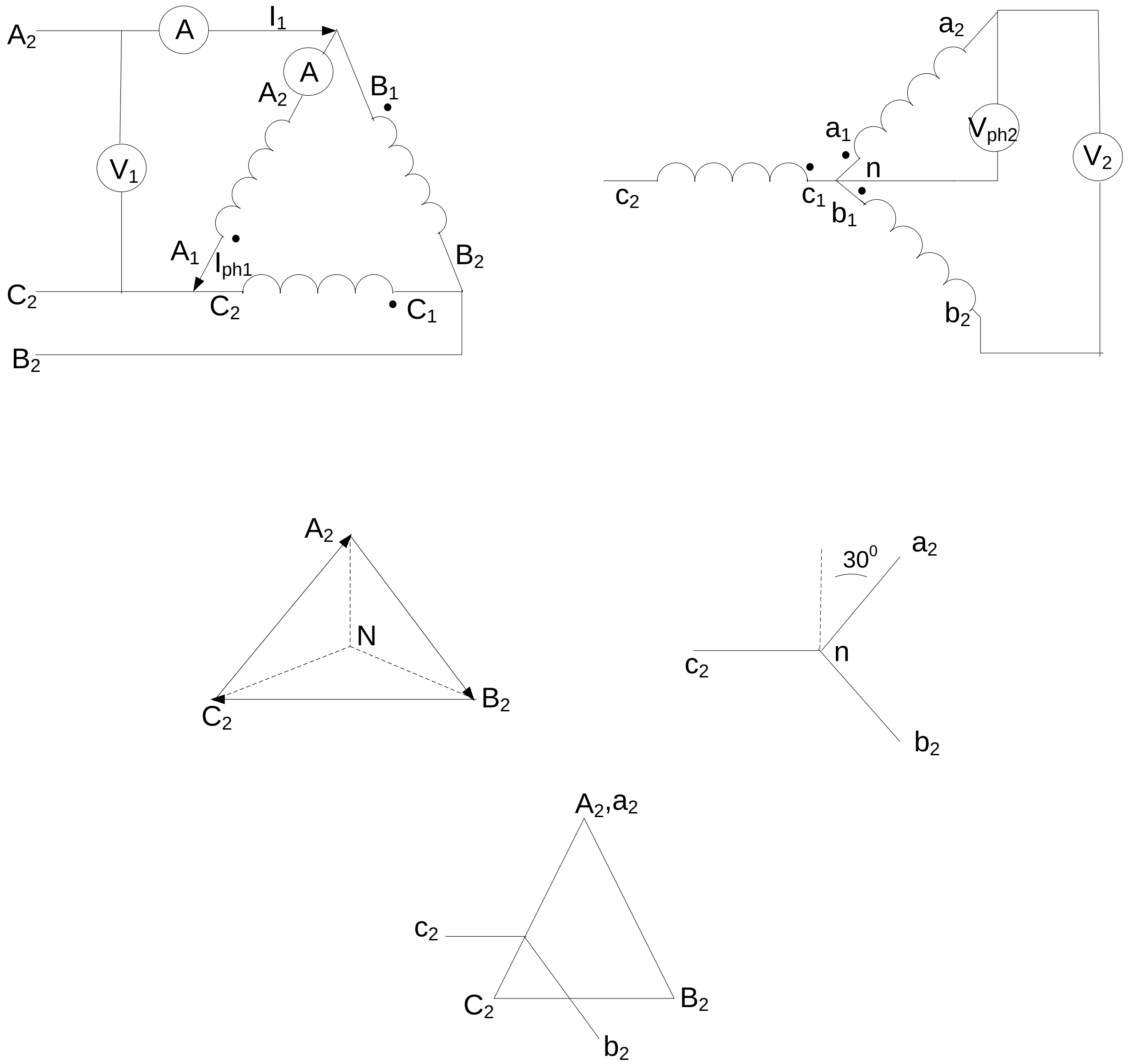

Fig. 3(c) Delta-Star Connection of Three Phase Transformers

Delta/star connection: The connection and the corresponding phasor diagram for fundamental component of induced voltages are shown in Fig. 3(c). It is obvious that the ratio of primary line voltage to secondary line voltage is $1:\sqrt{3}\,N_1/N_2$. As explained earlier, triple frequency current in each of the primary windings being in phase, the delta connection will provide a closed path for these harmonics to flow, and therefore, they will be absent from the line current. Thus the line magnetizing current will carry only the fundamental frequency component. As a consequence, r.m.s. values of the line and phase exciting currents will not be related by $\sqrt{3}$. The fundamental component phase current (I_{ph_1}) can be related to the line current (I_L) and the third harmonic component of phase current (I_{ph_3}) by the expression

$$I_{ph_1} = \sqrt{\left(\frac{I_L}{\sqrt{3}}\right)^2 + I_{ph_3}^2}$$

Triple frequency current being present, flux variation will almost be sinusoidal and the line and phase voltages on the secondary side will be related by $\sqrt{3}$. For the connection shown in the figure, it can be observed that the secondary induced e.m.f. lags the primary induced e.m.f. by 30° (Dy1) for the phase sequence ABC. If A_2 and a_2 are joined, the following conditions hold

$$\left|V_{B_2} - V_{b_2}\right| < \left|V_{B_2} - V_{c_2}\right|$$

$$\left|V_{C_2} - V_{c_2}\right| = \left|V_{C_2} - V_{b_2}\right|$$

In the case of 30° lead (Dy11), the relation will be

$$\left|V_{B_2} - V_{b_2}\right| = \left|V_{B_2} - V_{c_2}\right|$$

$$\left|V_{C_2} - V_{c_2}\right| < \left|V_{C_2} - V_{b_2}\right|$$

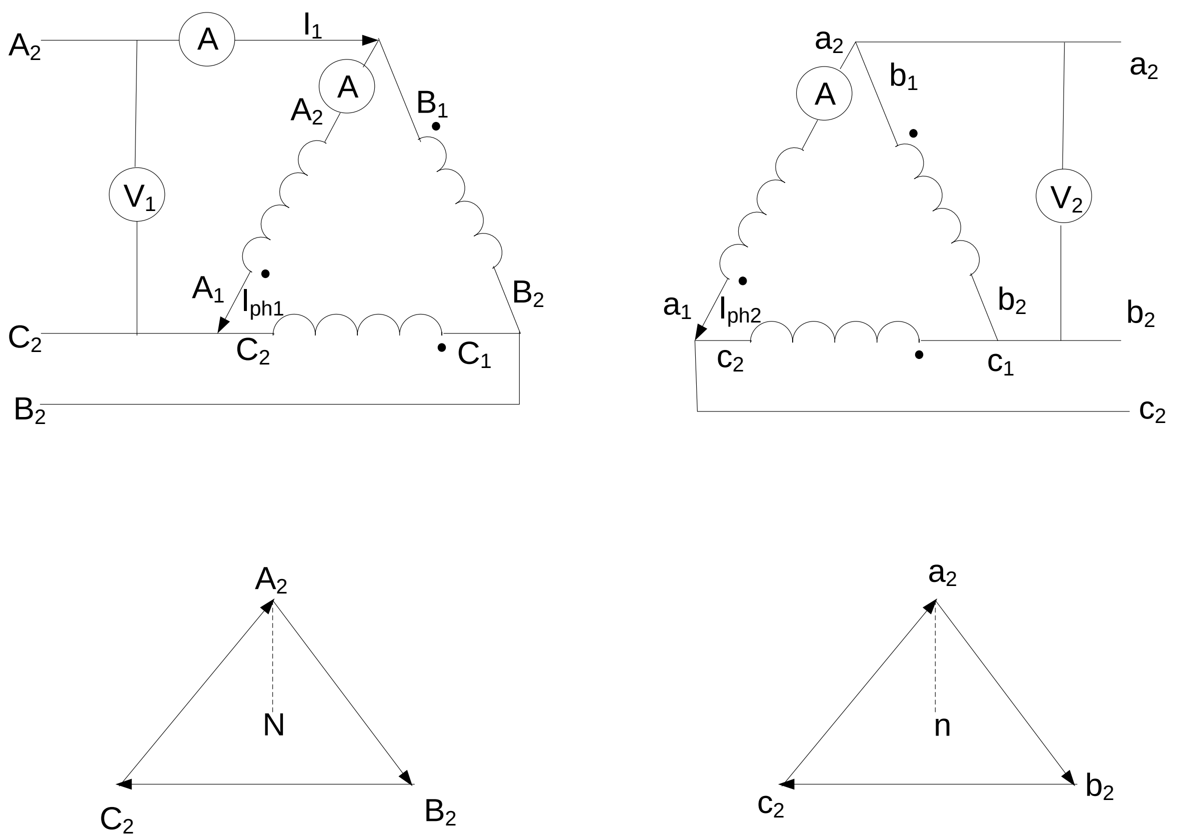

Fig. 3(d) Delta-Delta Connection of Three Phase Transformers

Delta/delta connection: The delta-delta method of connection is shown in Fig. 3(d) along with its e.m.f. phasor diagram for balanced supply voltage. It can be seen that the (primary to secondary) transformation ratio for line as well as phase voltage is $N_1/N_2 : 1$. For the reasons described before, delta-delta connection will cause the triple frequency currents to circulate, making the resultant flux variation almost sinusoidal. Owing to circulating triple frequency current, primary line and phase currents will not be related by $\sqrt{3}$. It is clear from the phasor diagram that there is no phase difference between the primary and secondary induced e.m.f.s and the connection is Dd0. If A_2 and a_2 are joined, the following will be observed

$$\left|V_{C_2} - V_{c_2}\right| < \left|V_{C_2} - V_{b_2}\right|$$

$$\left|V_{B_2} - V_{b_2}\right| < \left|V_{B_2} - V_{c_2}\right|$$

With this connection, large unbalance of loads may be met without difficulty while the closed mesh serves to damp out third harmonic voltage.

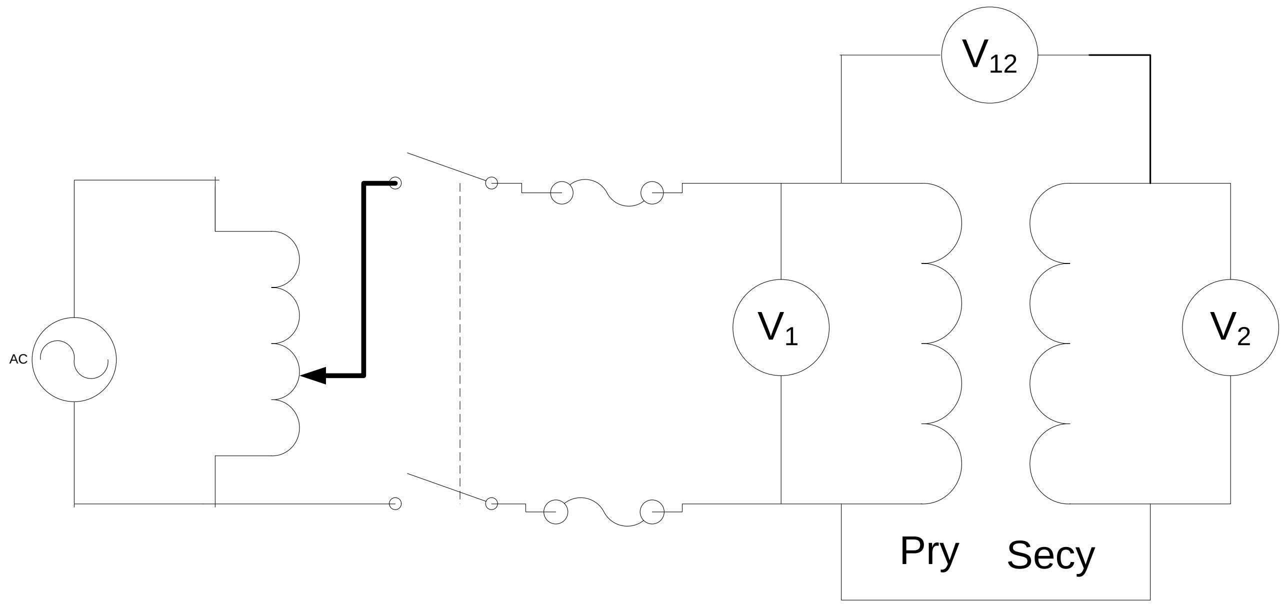

Fig. 4. Circuit Diagram for Polarity Test

<u>Procedure</u>

Step I: Refer to Fig. 4 for identification of the corresponding terminals (polarities) of the primary and the secondary windings. Join one terminal of the primary winding to any one of the terminals of the secondary winding and apply a small voltage to the primary winding. Measure the voltage V_{12} between the remaining two terminals of the windings as well as the secondary terminal voltage V_2. If V_{12} closely equals the difference between the primary applied voltage V_1 and the secondary induced voltage V_2, the terminals to which the voltmeter is connected are the corresponding terminals (or terminals with same polarity). If not then the secondary terminal joined with primary terminal is to be changed.

Step II: With due regard to the polarities of the windings, connect the primaries and the secondaries of the transformers in the manner indicated in Fig. 1. For balanced applied voltage note down the readings of the ammeters and voltmeters and enter them in the appropriate columns of Table 1 and Table 2. In the case of star connected primary take the readings both with and without neutral connection to the system neutral.

Step III: Using a Digital Storage Oscilloscope (DSO) observe the waveforms of the voltages and currents mentioned below for different connections. Using Fast Fourier Transform (FFT), find the percentages of 3^{rd}, 5^{th} and 7^{th} harmonics with respect to the fundamental.

Star/star

(i) Line voltage, phase voltage and line current of the primary when neutral is not grounded.
(ii) Line voltage, phase voltage and line current of the primary when neutral is grounded. Also observe the current through the neutral-ground connection wire.
(iii) Line voltage and phase voltage of the secondary with (a) primary neutral isolated and (b) primary neutral grounded.
(iv) Connect A_2 and a_2, connect neutral of primary to ground and observe the voltage between neutrals of the two windings.

Star/delta

(i) Line voltage, phase voltage and line current of the primary when *neutral is isolated and the secondary delta is open*. Also measure and observe the voltage between the open points of the delta connected secondary.
(ii) Line voltage and phase voltage of the primary, line voltage of the secondary and the current flowing in the delta of the secondary when *the primary neutral is still isolated but the secondary delta is closed*.
(iii) Now make *the neutral grounded but the secondary delta open*. Measure and observe the voltage between the open points of the delta connected secondary.

Delta/star

(i) Phase and line current and phase voltage of the primary.
(ii) Phase and line voltage of the secondary.

Delta/delta:

(i) Line current and phase current of the primary.
(ii) Phase current of the secondary.

Discussion

1. Comment on the observed line-voltage ratios for different transformer connections and their deviations from the name plate information.
2. Comment on the observations on the neutral voltages and currents with star connected primary.
3. Compare the probable third harmonic voltages and currents in a three-limb transformer compared with those in a three-phase bank of single-phase transformers with similar connections.

Questions

1. What do the polarities of the transformer windings mean?
2. What are the relative merits and demerits of different three phase connections?

3. Supply to one terminal of a delta/star connected transformer fails. What would be the line-to-neutral and line-to-line voltages on the secondary side?
4. Terminal markings of a three-phase three limb transformer are missing. How could you identify all the terminals (A_1-A_2, B_1-B_2, C_1-C_2, a_1-a_2, b_1-b_2, and c_1-c_2) of the windings?