Module 7

Transformer

Lesson 26

Three Phase Transformer

Contents

26.1 Goals of the lesson

Three phase system has been adopted in modern power system to generate, transmit and distribute power all over the world. In this lesson, we shall first discuss how three number of *single phase transformers* can be connected for 3-phase system requiring change of voltage level. Then we shall take up the construction of a 3-phase transformer as a single unit. *Name plate rating* of a three phase transformer is explained. Some basic connections of a 3-phase transformer along with the idea of *vector grouping* is introduced.

Key Words: bank of three phase transformer, vector group.

After going through this section students will be able to answer the following questions.

- Point out one important advantage of connecting a *bank* of 3-phase transformer.
- Point out one disadvantage of connecting a *bank* of 3-phase transformer.
- Is it possible to transform a 3-phase voltage, to another level of 3-phase voltage by using two identical single phase transformers? If yes, comment on the total kVA rating obtainable.
- From the name plate rating of a 3-phase transformer, how can you get individual coil rating of both HV and LV side?
- How to connect successfully 3 coils in delta in a transformer?

26.2 Three phase transformer

It is the three phase system which has been adopted world over to generate, transmit and distribute electrical power. Therefore to change the level of voltages in the system three phase transformers should be used.

Three number of identical single phase transformers can be suitably connected for use in a three phase system and such a three phase transformer is called a *bank of three phase transformer*. Alternatively, a three phase transformer can be constructed as a single unit.

26.3 Introducing basic ideas

In a single phase transformer, we have only two coils namely primary and secondary. Primary is energized with single phase supply and load is connected across the secondary. However, in a 3-phase transformer there will be 3 numbers of primary coils and 3 numbers of secondary coils. So these 3 primary coils and the three secondary coils are to be properly connected so that the voltage level of a balanced 3-phase supply may be changed to another 3-phase balanced system of different voltage level.

Suppose you take three identical transformers each of rating 10 kVA, 200 V / 100 V, 50 Hz and to distinguish them call them as A, B and C. For transformer-A, primary terminals are marked as A_1A_2 and the secondary terminals are marked as a_1a_2. The markings are done in such a way that A_1 and a_1 represent the dot (•) terminals. Similarly terminals for B and C transformers are marked and shown in figure 26.1.

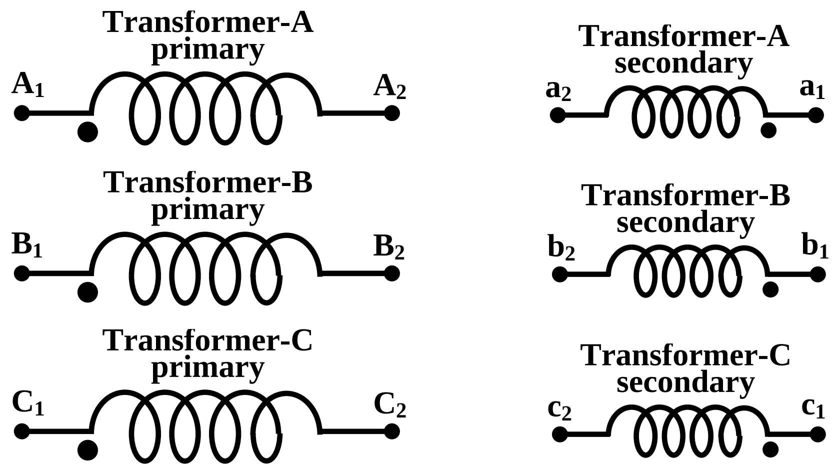


Figure 26.1: Terminal markings along with dots

It may be noted that individually each transformer will work following the rules of single phase transformer i.e, induced voltage in a_1a_2 will be in phase with applied voltage across A_1A_2 and the ratio of magnitude of voltages and currents will be as usual decided by a where $a = N_1/N_2 = 2/1$, the turns ratio. This will be true for transformer-B and transformer-C as well i.e., induced voltage in b_1b_2 will be in phase with applied voltage across B_1B_2 and induced voltage in c_1c_2 will be in phase with applied voltage across C_1C_2.

Now let us join the terminals A_2, B_2 and C_2 of the 3 primary coils of the transformers and no inter connections are made between the secondary coils of the transformers. Now to the free terminals A_1, B_1 and C_1 a balanced 3-phase supply with phase sequence A-B-C is connected as shown in figure 26.2. Primary is said to be connected in star.

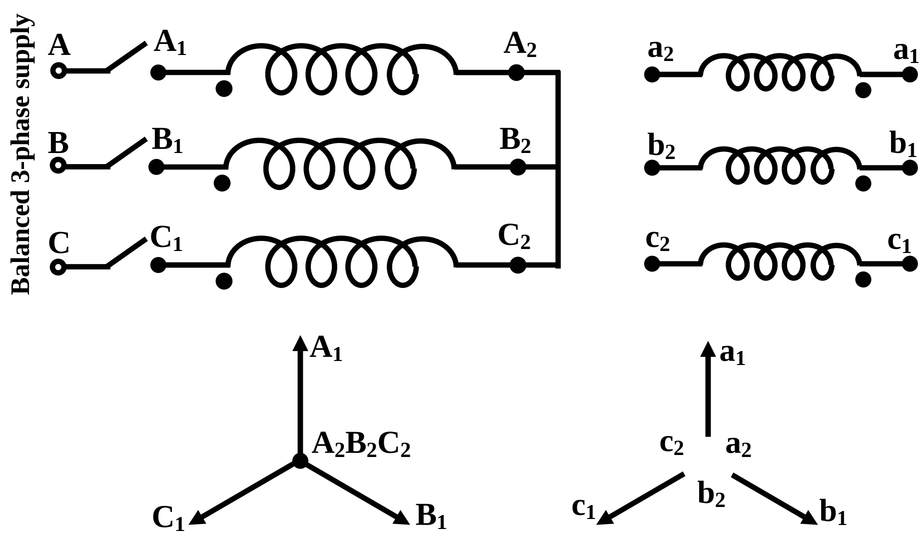


Figure 26.2: Star connected primary with secondary coils left alone.

If the line voltage of the supply is $V_{LL} = 200\sqrt{3}$ V, the magnitude of the voltage impressed across each of the primary coils will be $\sqrt{3}$ times less i.e., 200 V. However, the phasors $\bar{V}_{A_1A_2}$,

$\bar{V}_{B_1B_2}$ and $\bar{V}_{C_1C_2}$ will be have a mutual phase difference of 120º as shown in figure 26.2. Then from the fundamental principle of single phase transformer we know, secondary coil voltage $\bar{V}_{a_1a_2}$ will be parallel to $\bar{V}_{A_1A_2}$; $\bar{V}_{b_1b_2}$ will be parallel to $\bar{V}_{B_1B_2}$ and $\bar{V}_{c_1c_2}$ will be parallel to $\bar{V}_{C_1C_2}$. Thus the secondary induced voltage phasors will have same magnitude i.e., 100 V but are displaced by 120º mutually. The secondary coil voltage phasors $\bar{V}_{a_1a_2}$, $\bar{V}_{b_1b_2}$ and $\bar{V}_{c_1c_2}$ are shown in figure 26.2. Since the secondary coils are not interconnected, the secondary voltage phasors too have been shown independent without any interconnections between them. In contrast, the terminals A_2, B_2 and C_2 are physically joined forcing them to be equipotential which has been reflected in the primary coil voltage phasors as well where phasor points A_2, B_2 and C_2 are also shown joined. Coming back to secondary, if a voltmeter is connected across any coil i.e., between a_1 and a_2 or between b_1 and b_2 or between c_1 and c_2 it will read 100 V. However, voltmeter will not read anything if connected between a_1 and b_1 or between b_1 and c_1 or between c_1 and a_1 as open circuit exist in the paths due to no physical connections between the coils.

Imagine now the secondary coil terminals a_2, b_2 and c_2 are joined together physically as shown in figure 26.3. So the secondary coil phasors should not be shown isolated as a_2, b_2 and c_2 become equipotential due to shorting of these terminals. Thus, the secondary coil voltage phasors should not only be parallel to the respective primary coil voltages but also a_2, b_2 and c_2 should be equipotential. Therefore, shift and place the phasors $\bar{V}_{a_1a_2}$, $\bar{V}_{b_1b_2}$ and $\bar{V}_{c_1c_2}$ in such a way that they remain parallel to the respective primary coil voltages and the points a_2, b_2 and c_2 are superposed.

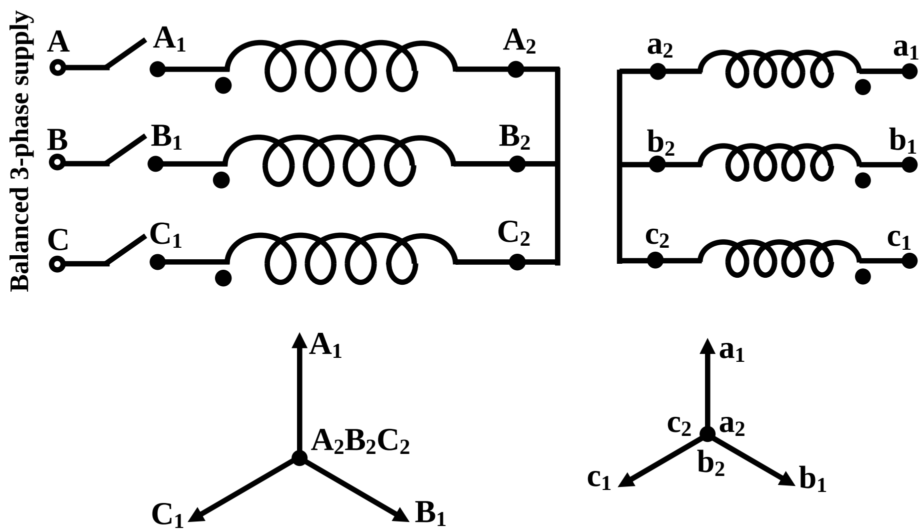


Figure 26.3: Both primary & secondary are star connected.

Here obviously, if a voltmeter is connected between a_1 and b_1 or between b_1 and c_1 or between c_1 and a_1 it will read corresponding phasor lengths a_1b_1 or $b_1\, c_1$ or c_1a_1 which are all equal to $200\sqrt{3}$ V. Thus, $\bar{V}_{a_1b_1}$, $\bar{V}_{b_1c_2}$ and $\bar{V}_{c_2a_1}$ are of same magnitude and displaced mutually by 120º to form a balanced 3-phase voltage system. Primary 3-phase line to line voltage of $200\sqrt{3}$ V is therefore stepped down to 3-phase, $100\sqrt{3}$ V line to line voltage at the secondary. The junction of A_2, B_2 and C_2 can be used as *primary neutral* and may be denoted by N. Similarly the junction of a_2, b_2 and c_2 may be denoted by n for secondary neutral.

26.3.1 A wrong star-star connection

In continuation with the discussion of the last section, we show here a deliberate wrong connection to highlight the importance of proper terminal markings of the coils with dots (•). Let us start from the figure 26.2 where the secondary coils are yet to be connected. To implement star connection on the secondary side, let us assume that someone joins the terminals a_2, b_1 and c_2 together as shown in figure 26.4.

The question is: is it a valid star connection? If not why? To answer this we have to interconnect the secondary voltage phasors in accordance with the physical connections of the coils. In other words, shift and place the secondary voltage phasors so that a_2, b_1 and c_2 overlap each other to make them equipotential. The lengths of phasors $\bar{V}_{a_1a_2}$, $\bar{V}_{b_1b_2}$ and $\bar{V}_{c_1c_2}$ are no doubt, same and equal to 100 V but they do not maintain 120° mutual phase displacement between them as clear from figure 26.4. The magnitude of the line to line voltages too will not be equal. From simple geometry, it can easily be shown that

$$\left|\bar{V}_{a_1b_2}\right| = \left|\bar{V}_{b_2c_1}\right| \neq \left|\bar{V}_{c_1a_1}\right|$$

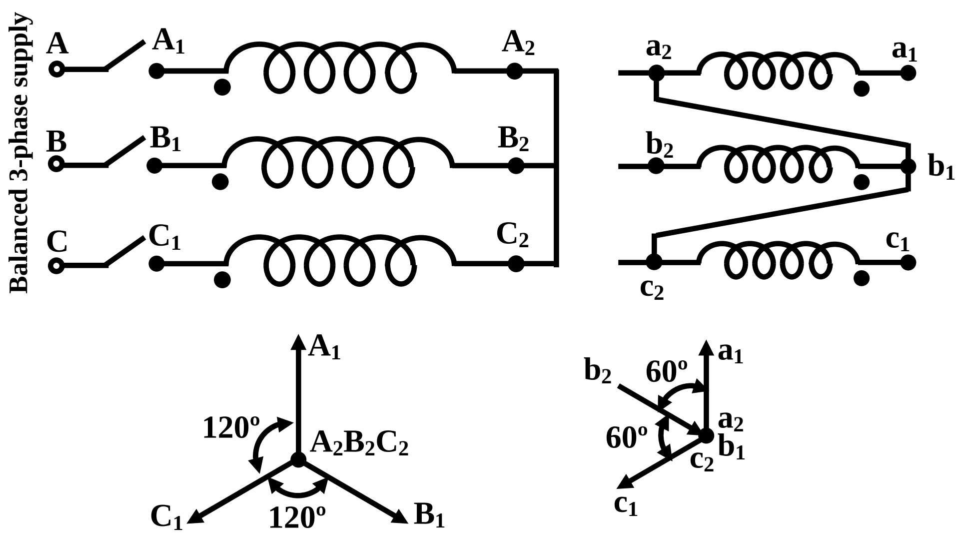


Figure 26.4: Both primary & secondary are star connected.

Thus both the phase as well as line voltages are not balanced 3-phase voltage. Hence the above connection is useless so far as transforming a balanced 3-phase voltage into another level of balanced 3-phase voltage is concerned.

Appropriate polarity markings with letters along with dots (•) are essential in order to make various successful 3-phase transformer connections in practice or laboratory.

26.3.2 Bank of three phase transformer

In the background of the points discussed in previous section, we are now in a position to study different connections of 3-phase transformer. Let the discussion be continued with the same three single phase identical transformers, each of rating 10kVA, 200V / 100V, 50Hz,. These transformers now should be connected in such a way, that it will change the level of a balanced three phase voltage to another balanced three phase voltage level. The three primary and the three secondary windings can be connected in various standard ways such as *star / star* or *star / delta* or *delta / delta* or in *delta / star* fashion. Apart from these, *open delta* connection is also used in practice.

Star-star connection

We have discussed in length in the last section, the implementation of star-star connection of a 3-phase transformer. The connection diagram along with the phasor diagram are shown in figure 26.5 and 26.6.

As discussed earlier, we need to apply to the primary terminals ($A_1B_1C_1$) a line to line voltage of $200\sqrt{3}$ V so that rated voltage (200 V) is impressed across each of the primary coils of the individual transformer. This ensures 100 V to be induced across each of the secondary coil and the line to line voltage in the secondary will be $100\sqrt{3}$ V. Thus a 3-phase line to line voltage of $200\sqrt{3}$ V is stepped down to a 3-phase line to line voltage of $100\sqrt{3}$ V. Now we have to calculate how much load current or kVA can be supplied by this bank of three phase transformers without over loading any of the single phase transformers. From the individual rating of each transformer, we know maximum allowable currents of HV and LV windings are respectively I_{HV} = 10000/200 = 50A and I_{LV} = 10000/100 = 100A. Since secondary side is connected in star, line current and the winding currents are same. Therefore total kVA that can be supplied to a balanced 3-phase load is $\sqrt{3}V_{LL}I_L = \sqrt{3}\left(\sqrt{3}100\right)100 = 30\,\text{kVA}$. While solving problems, it is not necessary to show all the terminal markings in detail and a simple and popular way of showing the same star-star connection is given in figure 26.7.

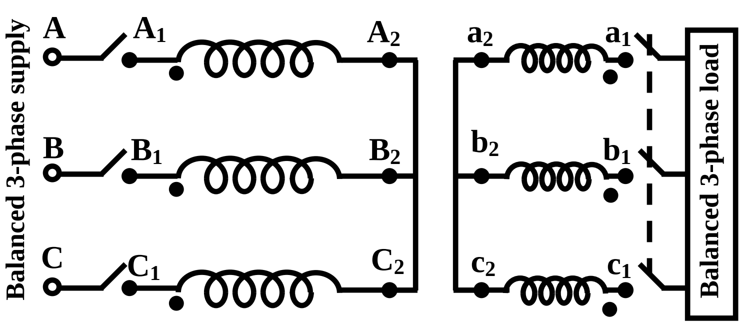


Figure 26.5: Star/star Connection.

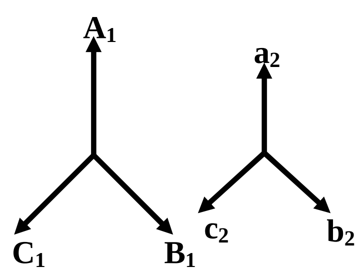


Figure 26.6: Phasor diagram.

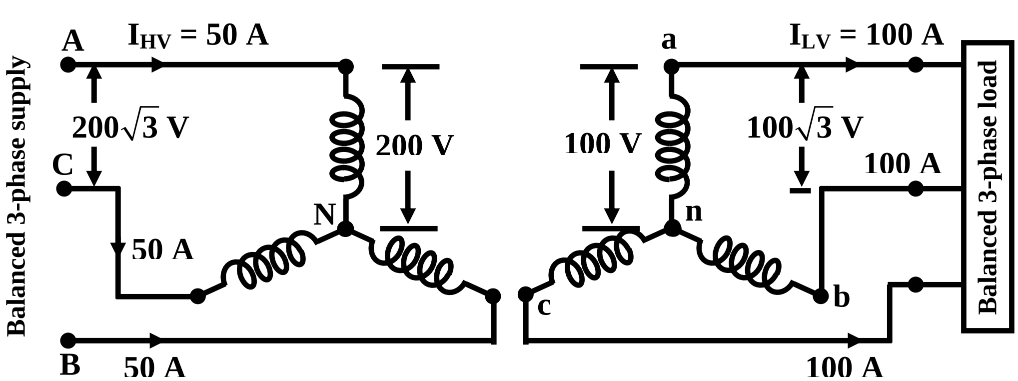


Figure 26.7: Simplified way of showing star-star connection

Star-delta connection

To connect windings in delta, one should be careful enough to avoid dead short circuit. Suppose we want to carry out star / delta connection with the help of the above single phase transformers. HV windings are connected by shorting A_2, B_2 and C_2 together as shown in the figure 26.8. As we know, in delta connection, coils are basically connected in series and from the junction points, connection is made to supply load. Suppose we connect quite arbitrarily (without paying much attention to terminal markings and polarity), a_1 with b_2 and b_1 with c_1. Should we now join a_2 with c_2 by closing the switch S, to complete the delta connection? As a rule, we should not join (i.e., put short circuit) between any two terminals if potential difference exists between the two. It is equivalent to put a short circuit across a voltage source resulting into very large circulating current. Therefore before closing S, we must calculate the voltage difference between a_2 with c_2. To do this, move the secondary voltage phasors such that a_1 and b_2 superpose as well as b_1 with c_1 superpose – this is because a_1 and b_2 are physically joined to make them equipotential; similarly b_1 and c_1 are physically joined so as to make them equipotential. The phasor diagram is shown in figure 26.9. If a voltmeter is connected across S (i.e., between a_2 and c_2), it is going to read the length of the phasor $\bar{V}_{a_2c_2}$. By referring to phasor diagram of figure 26.9, it can be easily shown that the voltage across the switch S, under this condition is $V_{a_2c_2} = 100 + 2\cos 60^{o} 100 = 200\text{V}$. So this connection is not proper and the switch S should not be closed.

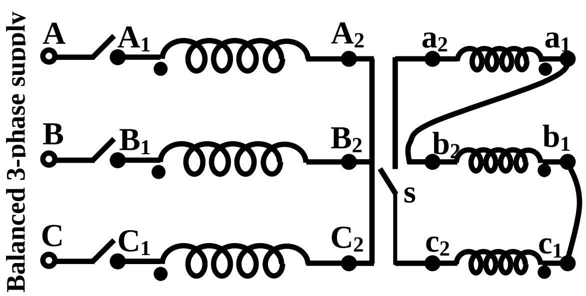


Figure 26.8: Incomplete Connection.

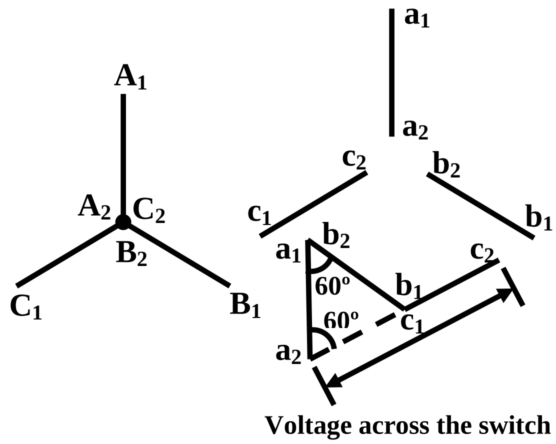


Figure 26.9: Phasor diagram.

Another alternative way to attempt delta connection in the secondary could be: join a_1 with b_2 and b_1 with c_2. Before joining a_2 with c_1 to complete delta connection, examine the open circuit voltage $\bar{V}_{a_2c_1}$. Following the methods described before it can easily be shown that $\bar{V}_{a_2c_1}$ = 0, which allows to join a_2 with c_1 without any circulating current. So this, indeed is a correct delta connection and is shown in figure 26.10 where a_1 is joined with b_2, b_1 is joined with c_2 and c_1 is joined with a_2. The net voltage acting in the closed delta in this case is zero. Although voltage exists in each winding, the resultant sum becomes zero as they are 120° mutually apart. The output terminals are taken from the junctions as *a*, *b* and *c* for supplying 3-phase load. The corresponding phasor diagram is shown in figure 26.11.

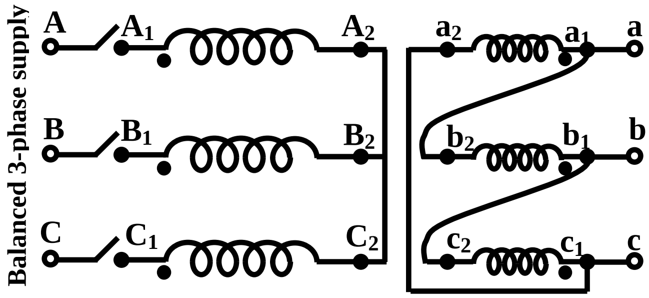


Figure 26.10: Star/delta Connection.

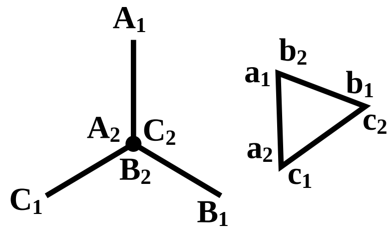


Figure 26.11: Phasor diagram.

Here also we can calculate the maximum kVA this star / delta transformer can handle without over loading any of the constituents transformers. In this case the secondary line to line voltage is same as the winding voltage i.e., 100V, but the line current which can be supplied to the load is $100\sqrt{3}$. Because it is at this line current, winding current becomes the rated 100A. Therefore total load that can be supplied is $\sqrt{3}V_{LL}I_L = \sqrt{3}\ 100\left(\sqrt{3}\,100\right)\text{VA} = 30\text{kVA}$. Here also total kVA is 3 times the kVA of each transformer. The star-delta connection is usually drawn in a simplified manner for problem solving and easy understanding as shown in figure 26.12.

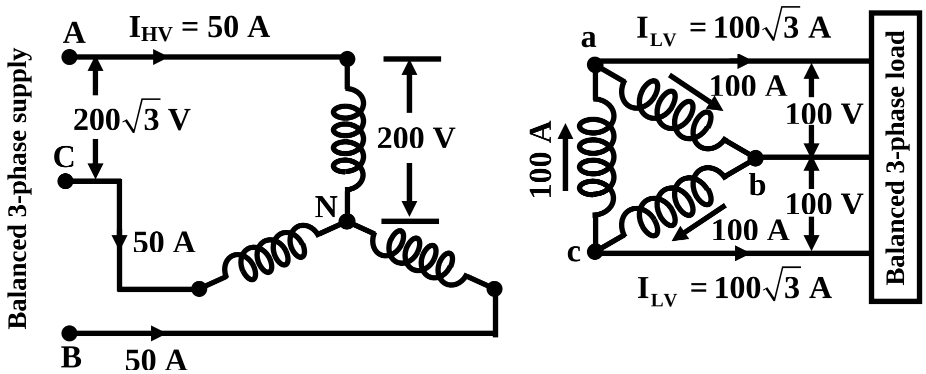


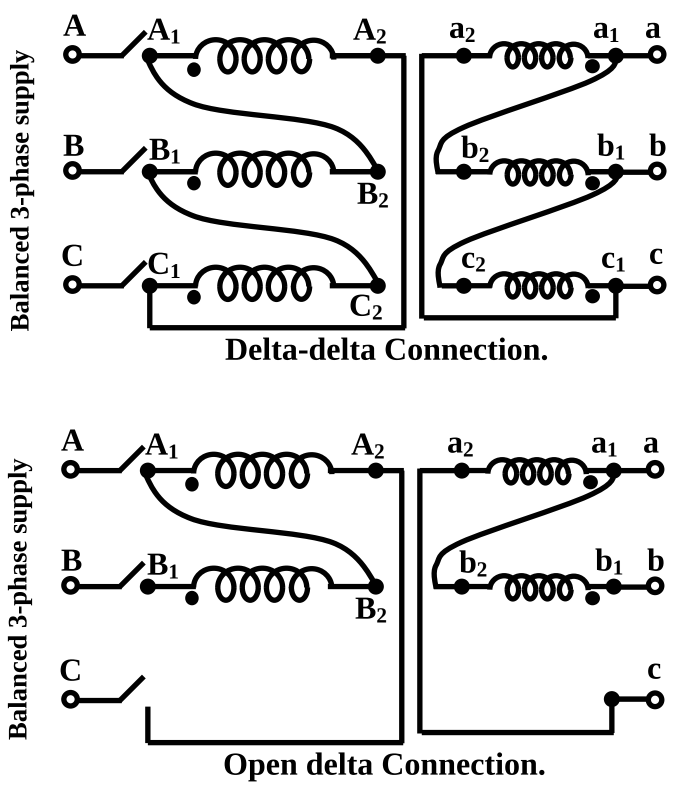
Figure 26.12: Simplified way of showing star-star connection

Another valid delta connection on the LV side is also possible by joining a_2 with b_1, b_2 with c_1 and c_2 with a_1. It is suggested that the reader tries other 3-phase connections and verify that the total KVA is 3-times the individual KVA of each transformer. However, we shall discuss about delta / delta and open delta connection.

Delta / delta and open delta connection

Here we mention about the delta/delta connection because, another important and useful connection namely open delta connection can be understood well. Valid delta connection can be implemented in the usual way as shown in the figure 26.13. The output line to line voltage will be 100V for an input line voltage of 200V. From the secondary one can draw a line current of $100\sqrt{3}$ A which means a total of 30 kVA can be supplied without overloading any of the individual transformers. A simplified representation of the delta-delta connection is shown in figure 26.15 along with the magnitude of the currents in the lines and in the coils of HV and LV side.

Let us now imagine that the third transformer C be removed from the circuit as shown in the second part of the figure 26.13. In effect now two transformers are present. If the HV sides is energized with three phase 200V supply, in the secondary we get 3-phase balanced 100V supply which is clear from the phasor diagram shown in figure 26.14. Although no transformer winding exist now between A_2 & B_1 on the primary side and between a_2 & b_1 on the secondary side, the voltage between A_2 & B_1 on the primary side and between a_2 & b_1 on the secondary side exist. Their phasor representation are shown by the dotted line confirming balanced 3-phase supply. But what happens to kVA handling capacity of the open delta connection? Is it 20 kVA, because two transformers are involved? Let us see. The line current that we can allow to flow in the secondary is 100A (and not $100\sqrt{3}$ as in delta / delta connection). Therefore total maximum kVA handled is given by $\sqrt{3}V_{LL}I_L = \left(\sqrt{3}\ 100\ 100\right)\ \text{VA} = 17.32\ \text{kVA}$, which is about 57.7% of the delta connected system. This is one of the usefulness of using bank of 3-phase transformers and connecting them in delta-delta. In case one of them develops a fault, it can be removed from the circuit and power can be partially restored.



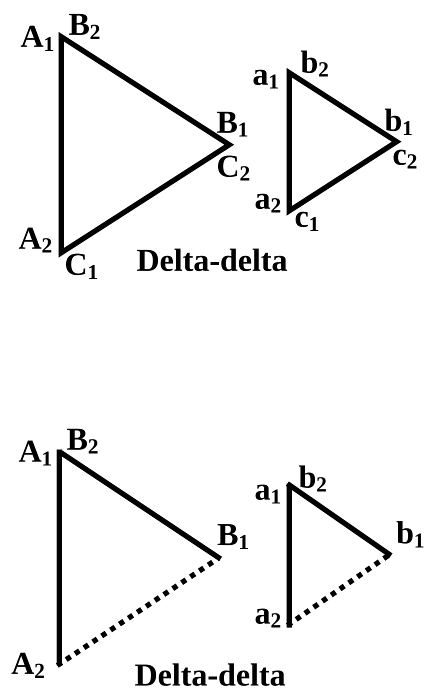


Figure 26.13: Delta/delta and open delta connection. Figure 26.14: Phasor diagram

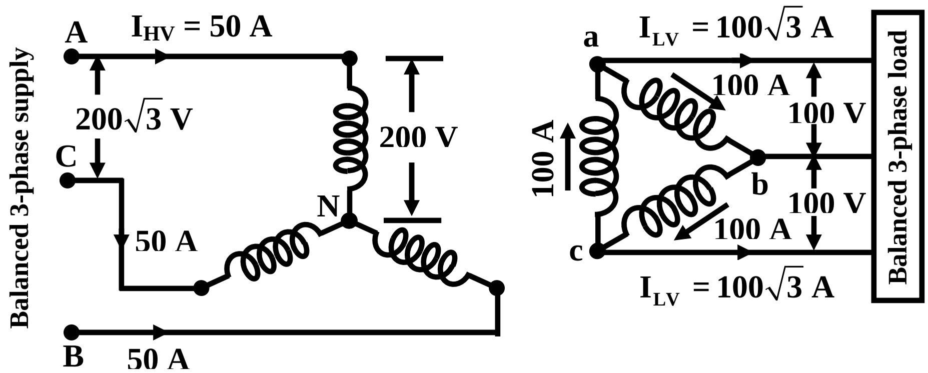


Figure 26.15: Simplified way of showing delta-delta connection

26.3.3 3-phase transformer- a single unit

Instead of using three number of single phase transformers, a three phase transformer can be constructed as a single unit. The advantage of a single unit of 3-phase transformer is that the cost is much less compared to a bank of single phase transformers. In fact all large capacity transformers are a single unit of three phase transformer.

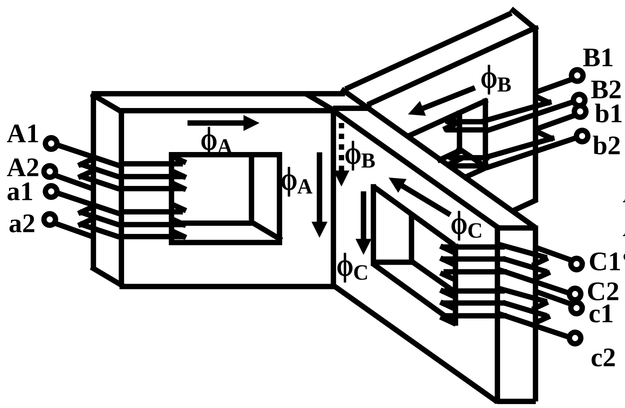


Figure 26.16: A conceptual three phase transformer.

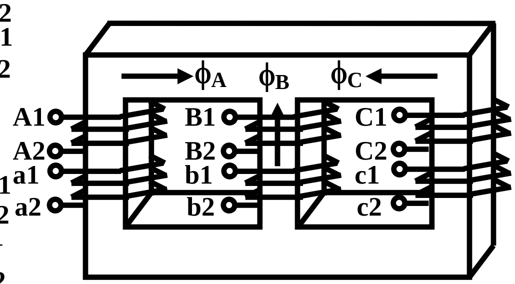


Figure 26.17: A practical core type three phase transformer.

To understand, how it is constructed let us refer to figure 26.16. Here three, single phase transformers are so placed that they share a common central limb. The primary and the secondary windings of each phase are placed on the three outer limbs and appropriately marked. If the primary windings are connected to a balanced 3-phase supply (after connecting the windings in say star), the fluxes $\phi_A(t)$, $\phi_B(t)$ and $\phi_C(t)$ will be produced in the cores differing in time phase mutually by 120°. The return path of these fluxes are through the central limb of the core structure. In other words the central limb carries sum of these three fluxes. Since instantaneous sum of the fluxes, $\phi_A(t)+ \phi_B(t)+ \phi_C(t) = 0$, no flux lines will exist in the central limb at any time. As such the central common core material can be totally removed without affecting the working of the transformer. Immediately we see that considerable saving of the core material takes place if a 3-phase transformer is constructed as a single unit. The structure however requires more floor area as the three outer limbs protrudes outwardly in three different directions.

A further simplification of the structure can be obtained by bringing the limbs in the same plane as shown in the figure 26.17. But what do we sacrifice when we go for this simplified structure? In core structure of figure 26.16, we note that the reluctance seen by the three fluxes are same, Hence magnetizing current will be equal in all the three phases. In the simplified core structure of figure 26.17, reluctance encountered by the flux ϕ_B is different from the reluctance encountered by fluxes ϕ_A and ϕ_C, Hence the magnetizing currents or the no load currents drawn will remain slightly unbalanced. This degree of unbalanced for no load current has practically no influence on the performance of the loaded transformer. Transformer having this type of core structure is called the *core type* transformer.

26.4 Vector Group of 3-phase transformer

The secondary voltages of a 3-phase transformer may undergo a *phase shift* of either +30° leading or -30° lagging or 0° i.e, no phase shift or 180° reversal with respective line or phase to neutral voltages. On the name plate of a three phase transformer, the vector group is mentioned. Typical representation of the vector group could be Yd1 or Dy11 etc. The first capital latter Y indicates that the primary is connected in star and the second lower case latter d indicates delta connection of the secondary side. The third numerical figure conveys the angle of phase shift based on *clock convention.* The minute hand is used to represent the primary phase to neutral voltage and always shown to occupy the position 12. The hour hand represents the secondary phase to neutral voltage and may, depending upon phase shift, occupy position other than 12 as shown in the figure 26.18.

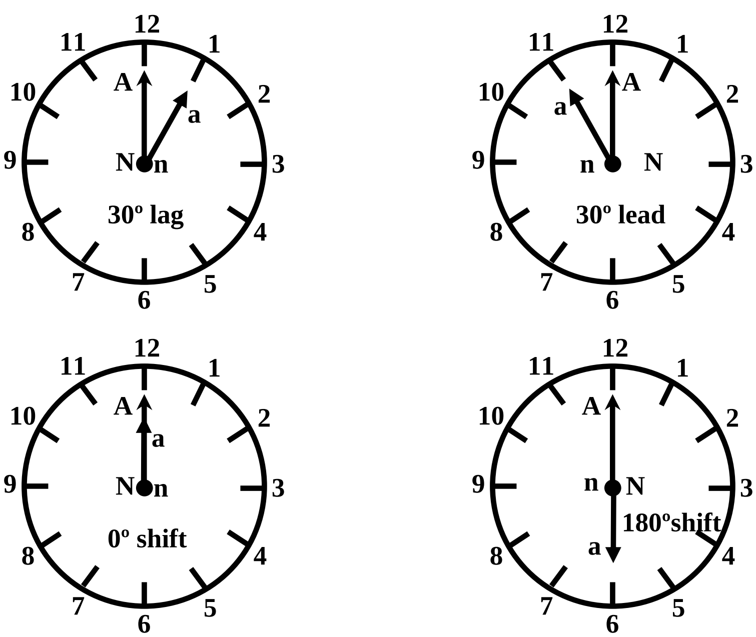


Figure 26.18: Clock convention representing vector groups.

The angle between two consecutive numbers on the clock is 30°. The star-delta connection and the phasor diagram shown in the figures 26.10 and 26.11 correspond to Yd_1. It can be easily seen that the secondary *a* phase voltage to neutral *n* (artificial in case of delta connection) leads the *A* phase voltage to neutral N by 30°. However the star delta connection shown in the figure 26.19 correspond to Yd_{11}.

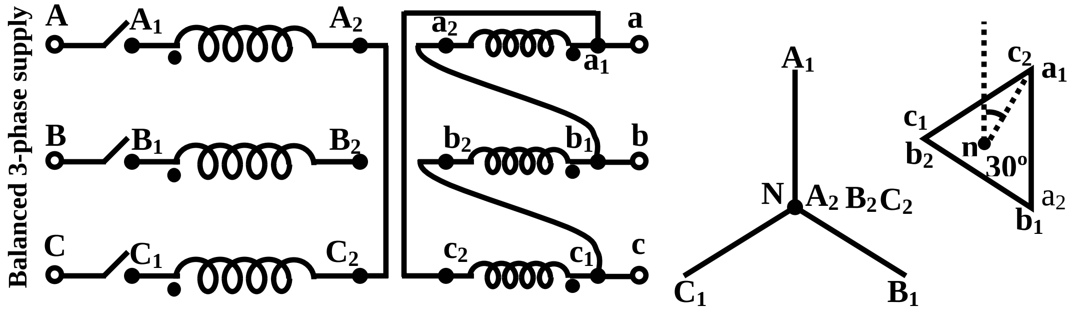


Figure 26.19: Connection and phasor diagram for *Y d11*.

26.5 Tick the correct answer

1. The secondary line to line voltage of a star-delta connected transformer is measured to be 400 V. If the turns ratio between the primary and secondary coils is 2 : 1, the applied line to line voltage in the primary is:

   (A) 462 V (B) 346 V (C) 1386 V (D) 800 V

2. The secondary line to line voltage of a delta-delta connected transformer is measured to be 400 V. If the turns ratio between the primary and secondary coils is 2 : 1, the applied line to line voltage in the primary is:

   (A) 462 V (B) 346 V (C) 1386 V (D) 800 V

3. The secondary line to line voltage of a delta-star connected transformer is measured to be 400 V. If the turns ratio between the primary and secondary coils is 2 : 1, the applied line to line voltage in the primary is:

   (A) 800 V (B) 500 V (C) 1386 V (D) 462 V

4. The secondary line current of a star-delta connected transformer is measured to be 100 A. If the turns ratio between the primary and secondary coils is 2 : 1, the line current in the primary is:

   (A) 50 A (B) 28.9 A (C) 57.7 A (D) 60 A

5. The secondary line current of a delta-star connected transformer is measured to be 100 A. If the turns ratio between the primary and secondary coils is 2 : 1, the line current in the primary is:

   (A) 86.6 A (B) 50 A (C) 60 A (D) 57.7 A

6. The primary line current of an open delta connected transformer is measured to be 100 A. If the turns ratio between the primary and secondary coils 2 : 1, the line current in the primary is:

   (A) 173.2 A (B) 200 A (C) 150 A (D) 50 A

7. Two single-phase transformers, each of rating 15 kVA, 200 V / 400 V, 50 Hz are connected in open delta fashion. The arrangement can supply safely, a balanced 3-phase load of:

   (A) 45 kVA (B) 25.9 kVA (C) 30 kVA (D) 7.5 kVA

8. In figure 26.20 showing an incomplete 3-phase transformer connection, the reading of the voltmeter will be:

   (A) 0 V (B) 173.2 V (C) 346.4 V (D) 300 V

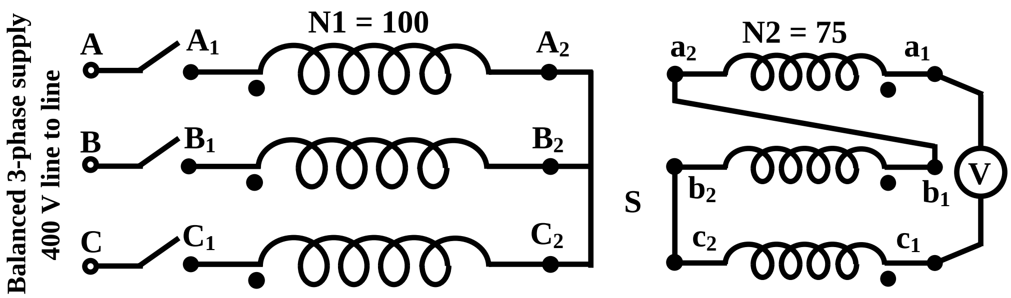


Figure 26.20:

26.6 Problems

1. Three number of single phase *ideal* transformers, each of rating. 10kVA, 200V / 100V, 50Hz is connected in star/delta fashion to supply a balanced three phase 20 kW, 0.8 power factor load at 100V(line to line). Draw a circuit diagram for this. Calculate (i) what line to line voltage should be applied to the primary side? (ii) Calculate the line and phase currents on the secondary and primary sides and indicate them on the diagram.

2. How two identical single phase transformers each of rating 5kVA, 200V/100V, 50Hz be used to step down a balanced 3-phase, 200V supply to a balanced 3-phase, 100V supply? Explain with circuit and phasor diagrams. Calculate also the maximum kVA that can be supplied from this connection.

3. A balanced 3-phase load of 20kW, 0.8 power factor lagging is to be supplied at a line to line voltage of 110V. However, a balanced 3-phase voltage of 381V (line to line) is available. Using three numbers of identical single phase ideal transformers each of rating 10kVA, 220V/110V, 50Hz make an arrangement such that the above load can be supplied. Draw the circuit diagram and show the magnitude of currents in the *lines* and in the *windings* of the transformers on both LV and HV side.

4. Refer to the following figure 26.21 which shows the windings of a 3-phase transformer. Primary turns per phase is 250. Each phase has got two *identical* secondary windings each having 100 turns. The primary windings are connected in star by shorting A_2, B_2 and C_2 and supplied from a balanced 3-phase 1000 V (line to line), 50 Hz source.

   a) If the secondary coils are connected by joining a_2 with b_3 and b_4 with c_1 then calculate $V_{a_1c_1}$.

   b) All the 6 coils are connected in series in the following way:

a_2 joined with b_2	b_1 joined with c_2
c_1 joined with c_4	c_3 joined with b_4
b_3 joined with a_3	

   Draw the phasor diagram and calculate the voltage $V_{a_1a_4}$

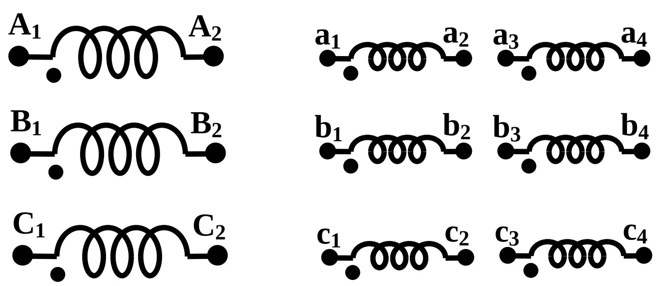


Figure 26.21: 3-phase transformer with two secondary coils per phase