EXPERIMENT NO. 3

Objective

To connect three single phase transformers into three-phase transformers banks and study the waveforms for various configurations.

Theory

Three phase transformers are required both at generation and distribution ends of a power system network to transform three phase power from one voltage level to another level. The primary and secondary windings of three phase transformers can be connected in a number of ways such as Star, Mesh (Delta), Zigzag or Vee connections. However the most common ones are the Star-Star, Star-Delta and Delta-Delta connections. Their principal features have been described below.

Polarity:

Before any of the transformer connections are made, it is absolutely necessary to determine the polarity of each single phase transformer unit. Each of the two primary terminals of a transformer is alternately positive and negative with respect to the other. Same is true with secondary terminals. When two terminals, one from the primary and the other from the secondary are either both positive or both negative, simultaneously, are said to have same polarity. A pair of terminals having same polarity is usually symbolized by dots.

Star-Star Connection:

Star connection is formed on each side of a transformer bank by connecting together undotted terminals on both sides of the bank as shown in Fig. 3.2 This connection provides zero degree phase shift between the corresponding line voltages/currents on the primary and secondary sides. For this reason it is called a 0° connection. However if the winding connection on the secondary side is reversed i.e. dotted ends are connected together, the corresponding line voltages/currents become out of phase resulting in 180° connection. Further if the phase transformation ratio of each single phase unit is x:l, the line transformation ratio of the bank is also x:l.

This is the most economical connection for small, high voltage transformers, as number of turns per phase and the amount of insulation required is minimal. 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. Sometimes the tertiary winding can also be used to feed auxiliary loads of the sub-stations/power stations.

Star-Delta Connection:

Star-Delta connection is formed as shown in Fig. 3.3A. If connected with correct polarity, the phasor diagram should reveal that the sum of voltages around delta is zero. This is a must as otherwise a closed delta would mean a short circuit. This connection can provide ±30° and 180±30° connections depending on how the secondary windings are connected. 0° connection is not possible here. Further if the phase transformation ratio of each single phase unit is x:1, the line transformation ratio of the bank is $\sqrt{3}$x:1.

This is the most common arrangement for power supply transformers. It has the advantage of a star point for mixed loading and a delta winding to carry third harmonic currents, which stabilizes the star point potential.

Delta-Delta Connection:

Delta-Delta connection is formed as shown in Fig. 3.4. The 0° or 180° connection is possible here. Further if the phase transformation ratio of each single phase unit is x : l, the line transformation ratio of the bank is x : 1.

This is an economical connection for a large low voltage transformer in which insulation problem is not important, as it increases the number of turns per phase and reduces the necessary sectional area of conductors. Large unbalance of loads may be met without difficulty, while the closed mesh serves to damp out third harmonic voltage. This, however, is not usually practicable with three-phase units as the absence of a star point may be disadvantageous.

Harmonics in 3-phase Transformer banks:

From an economic point of view, a transformer is designed to operate in the saturating region of the magnetic core. This makes the exciting current non-sinusoidal [1]. 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 (fifth, seventh, ninth, etc.) in the exciting current can be neglected. This section describes how these harmonics are generated in various connections of the three-phase transformer and ways to limit their effect [2].

Consider the system shown in Fig. 3.3. The primary windings are connected in star and the neutral point of the supply is available. The secondary windings can be connected in delta. Consider now the following cases:

Case 1: SW 1 CLOSED, SW2 OPEN

Because SW2 is open, no current flows in secondary windings. The currents flowing in the primary are the exciting currents. It is assumed that the exciting currents contain only fundamental and third harmonic currents.

$$i_A = I_{m1}\sin wt + I_{m3}\sin 3wt$$
$$i_B = I_{m1}\sin(wt - 120^\circ) + I_{m3}\sin 3(wt - 120^\circ)$$
$$i_C = I_{m1}\sin(wt - 240^\circ) + I_{m3}\sin 3(wt - 240^\circ)$$

The current in the neutral line is

$$I_{NN} = i_A + i_B + i_C = 3I_{m3}\sin 3wt$$

Note that fundamental currents in the winding are phase shifted by I20° from each other while third harmonic currents are all in phase (*co-phasal*). The neutral line carries only the third harmonic current.

Because the exciting current is non-sinusoidal, the flux in the core and hence the induced voltages in the windings will be sinusoidal. The secondary windings are open and therefore the voltage across a secondary winding will represent the induced voltage.

Case 2: SW1 OPEN, SW2 OPEN

In this case the third harmonic currents cannot flow in the primary windings. Therefore the primary currents are essentially sinusoidal. If the exciting current is sinusoidal, the flux is non-sinusoidal because of nonlinear B-H characteristics of the magnetic core, and it contains third harmonic components. This will induce third harmonic voltage in the windings. The phase voltages are therefore non-sinusoidal, containing the fundamental and third harmonic voltages.

$$v_A = v_{A1} + v_{A3}$$
$$v_B = v_{B1} + v_{B3}$$
$$v_C = \underbrace{v_{C1}}_{\text{fundamental voltages}} + \underbrace{v_{C3}}_{\text{third harmonics voltages}}$$

The line-to-line voltage is

$$\begin{aligned} v_{AB} &= v_A - v_B \\ &= v_{A1} - v_{B1} + v_{A3} - v_{B3} \end{aligned}$$

Because v_{A3} and v_{B3} are in phase and have same magnitude,

$$v_{A3} - v_{B3} = 0$$

Therefore,

$$v_{AB} = v_{A1} - v_{B1}$$

Note that although phase voltages have third harmonic components, the line-to-line voltages do not. The open delta voltage of the secondary is

$$\begin{aligned} v_{\Delta 0} &= v_a + v_b + v_c \\ &= (v_{a1} + v_{b1} + v_{c1}) + (v_{a3} + v_{b3} + v_{c3}) \\ &= 3v_{a3} \end{aligned}$$

The voltage across the open delta is the sum of the three third harmonic voltages induced in the secondary windings.

Case 3: SW 1 OPEN, SW2 CLOSED

If SW2 is closed the voltage $v_{\Delta 0}$ will drive a third harmonic current around the secondary delta. This will provide the missing third harmonic component of the primary exciting current and consequently the flux and induced voltage will be essentially sinusoidal.

Laboratory Work

I.) Determination of polarity: Arbitrarily assign a dot to one of the HV terminals of a transformer unit and connect as shown in Fig. 3.1. Switch on the supply. The voltmeter would read either V_1+V_2 (additive polarity) or V_1~V_2 (subtractive polarity), where V_1 and V_2 are primary and secondary rated voltages respectively. In case the voltmeter reads V_1~V_2, the secondary terminal connected to the primary dotted terminal is marked dotted. Otherwise the other terminal is marked dotted. Similarly obtain the dots for the other two transformer units.

II.) Star-Star connection:

Step l: Make the connections as per Fig 3.2 and apply an ac voltage of 400 Volts line to line by Variac with S open and measure line-to-line and line-to-neutral voltages on both primary and secondary sides. Connect the current probe to channel 1 of DSO to record the no-load current waveform in phase winding 'A' and connect the voltage differential probe on channel 2 across phase winding 'A' to record the no load phase voltage. Record both the waveforms on a same graph. Now connect channel 2 across any line-to-line terminals and just observe & record the waveform. Is it sinusoidal or non-sinusoidal? Comment on your observation.

Step2: Re-connect voltage differential probe across phase-winding 'A' and Close switch "S", record the phase voltage and phase current waveforms on the same graph. Disconnect current probe from step 1 and measure the current through ground point E and observe & record the waveform and determine its frequency. Switch off the supply.

III.) Star-Delta Connection:

Step 1: Make the Star-Delta connections as in Fig. 3.3A keeping S closed but **do not** close the delta in the secondary. Connect a high range voltmeter across the open delta terminals as shown in fig.3.3B. Note the voltmeter reading. If the connection is made as per the polarity markings, voltmeter should be reading zero. If the reading on the voltmeter is not zero, can you explain why it is so? Reverse one of the secondary coils and again measure the voltage across open delta terminals. Also record the wave shape of the no load primary current. Is it different from the no load current of a single phase transformer?

Step 2: Make the circuit on the delta side such that the voltmeter reads zero. Open S and note down the new voltmeter reading. Does it still remain zero? Why? Connect the DSO across voltmeter terminals and record the waveform. Determine its frequency. What do you infer? Switch off the supply.

Step 3: Close the delta and again record the no load current waveform on primary side. Is it similar to one observed in step 1 or step 2? Why? Switch off the supply and set the variac to zero volts.

IV.) Delta-Delta Connection:

Now connect the primary windings with correct polarity as per Fig. 3.4. Apply **reduced voltage**, **i.e. 230 V line to line by variac**. Secondary is also to be connected in delta as in previous part. Introduce an ammeter in series with any one phase winding and another in the line and record the no load winding current i.e., phase current and no load line current. Record the wave shape of current in secondary of a closed delta as given in Fig. 3.4.

Report

1. Draw the pharos diagram for the three connections. Follow general principles to construct the phasor diagrams:
   a) The voltages of primary and secondary windings on the same link are in phase i.e. the phase voltages are always in phase despite any connection.
   b) The e.m.f.s induced in the three windings are equal, balanced, displaced mutually one third period in time and have definite sequence.
2. Record the phase and line values of currents and voltages for each of the connections and comment on your observations.
3. Comment on the nature of wave shapes recorded as above for the three connections.

Precautions

1. Before switching on the 3-phase power supply, you must ensure that the variac kept in the 0 (zero voltage) position.

2. While giving the supply to the Delta-Delta connection do not exceed the line-to-line voltage above 230V.
3. Do not press unnecessary buttons/knobs of DSO.

4. Chose the correct setting of voltage differential/ current Probes.

References:

[1] I J Nagrath, D P Kothari, Electric Machines. New Delhi, India: Tata McGraw-Hill Publishing Company Limited, 1981.
[2] P C Sen, Principles of Electric Machines and Power Electronics, New York, USA., John Wiley & Sons Inc., 1997.

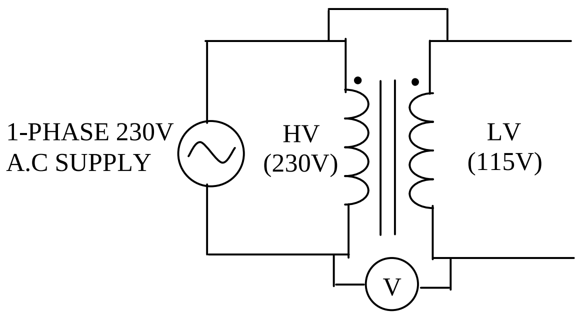


FIG 3.1 Connections for Polarity testing

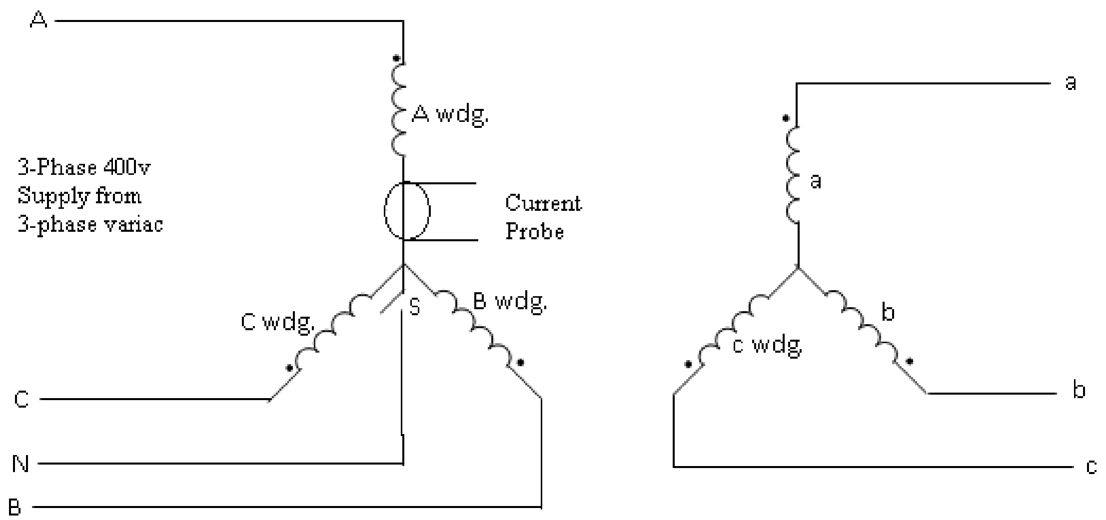


FIG. 3.2 Star Star Connection

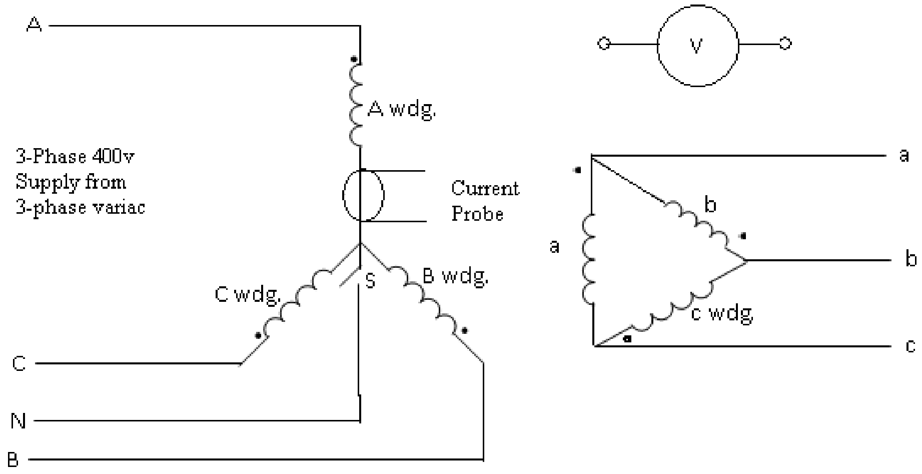
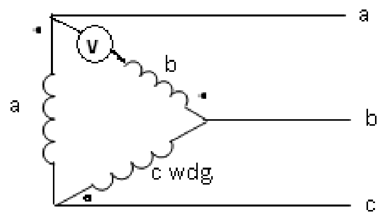


FIG.3.3 A Star Delta Connection



3.3 B Delta close through Voltmeter

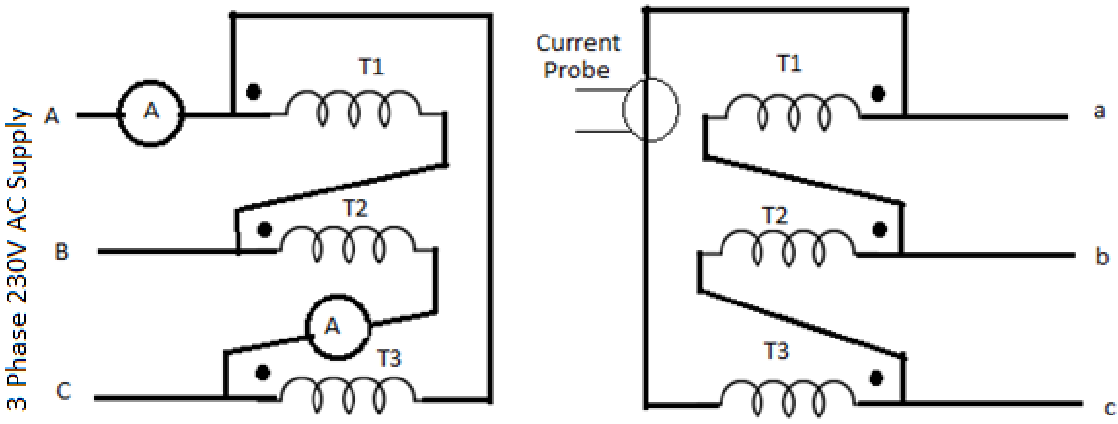


Fig. 3.4 Delta - Delta Connection

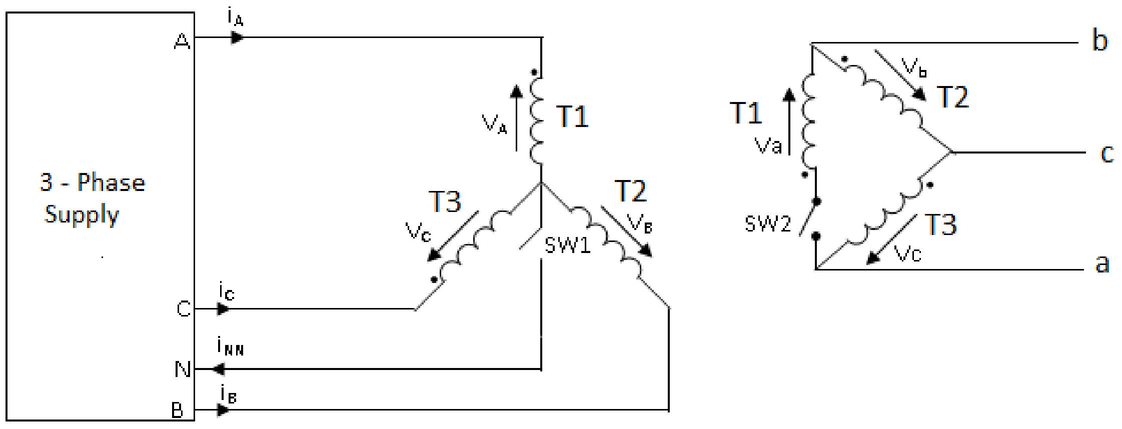


Fig. 3.5 Star - Delta connection for studying Harmonics