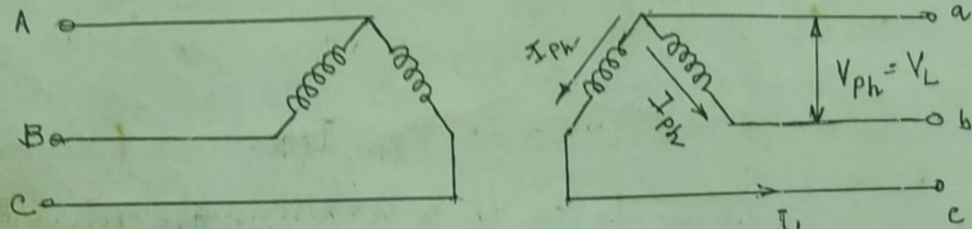
open-delta or V-connection:-

In a delta/delta connection if one of the transformers is disconnected, the resulting connection is known as open-delta or V-connection. In a open-delta or V-connection, the power can still be supplied, though at a reduced level.



V-connection:

KVA delivered by open delta :-

let V_{ph} = rated phase voltage, in each of the three transformer secondaries.

I_{ph} = rated phase current in each of the three transformer secondaries.

When all the three transformers are connected in closed delta, then

line voltage, V_L = Phase voltage, V_{ph}

line current, $I_L = \sqrt{3}\, I_{ph}$.

$\therefore$ VA rating of the bank of three transformers in delta

$$S_{delta} = \sqrt{3}\, V_L I_L = \sqrt{3}\, V_{ph} (\sqrt{3}\, I_{ph}) = 3\, V_{ph} I_{ph}.$$

When one transformer is entirely removed from the closed delta,

then for an open-delta,

line voltage, V_L = Phase voltage, V_{ph} as before.

line current, I_L = Phase current, I_{ph}.

$\therefore$ VA rating of the open delta connection,

$$S_{open\text{-}delta} = \sqrt{3}\, V_L\, I_L$$
$$= \sqrt{3}\, V_{ph}\, I_{ph}.$$

$$\therefore \frac{\text{open delta VA or KVA rating, } S_{open\text{-}delta}}{\text{closed delta VA or KVA rating, } S_{delta}}$$

$$= \frac{\sqrt{3}\, V_{ph}\, I_{ph}}{3\, V_{ph}\, I_{ph}} = \frac{1}{\sqrt{3}}$$

$$\frac{S_{open\text{-}delta}}{S_{delta}} = \frac{1}{\sqrt{3}} = 0.58$$

Thus the open delta connection has a VA or KVA rating of $\frac{1}{\sqrt{3}} = 0.58$ of the rating of the normal delta/delta connection.

It may be noted that open-delta operates at a lower KVA capacity ($= \sqrt{3}\, V_p I_{ph} \times 10^{-3}$) compared with the sum of the individual transformer KVA capacities ($= 2 V_{ph} I_{ph} \times 10^{-3}$).

The ratio $\dfrac{\text{Actual available KVA}}{\text{Sum of the KVA ratings of the transformers installed.}}$,

is called the utilisation, or rating, factor for a particular type of connections.

For open-delta connection, the utilisation factor is $\frac{\sqrt{3}\, V_{ph} I_{ph}}{2\, V_{ph} I_{ph}} = 0.866$.

and for a closed delta, the utilisation factor is unity.

Uses :- The open delta connection is used on transmission ~~or~~ lines or distribution systems, which have been recently put into Service. In doing, so, the cost of one transformer unit is saved and provision is also made for further raising the system KVA capacity in future. The capacity of the open delta should be sufficient enough to meet the growth of load, at least for some years more. When the load demand exceeds the installed KVA capacity in open delta, the third transformer is added to form the closed delta, thereby augmenting the capacity of the system from $\sqrt{3}\, V_{ph} I_{ph}$ to $3\, V_{ph} I_{ph}$. Its further use is to maintain the continuity of supply to 3-phase loads, though at reduced level, in the case of damage to one transformer.

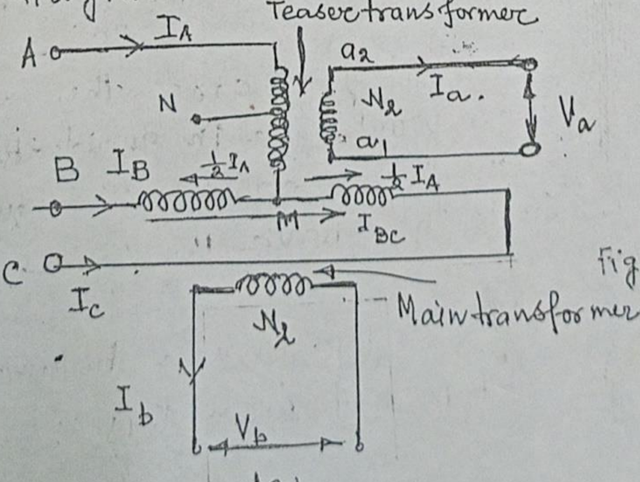
Three/Two-phase ~~conver~~ conversion (Scott Connection):

At present three-phase energy system are by far the most common, but for certain specialized applications two-phase supplies are essential. For example two-phase energy system is required to feed power to

(I) single-phase arc furnaces.
(II) low voltage single-phase rural supplies
(III) electrified tracks in electric traction
(IV) two phase control motors

Charles F. Scott converted ~~three~~ two-phase to ~~two~~ three-phases at Niagara Falls and this arrangement used by him is known as Scott-connection, in his honour.

Scott connection is used to obtain three to two-phase transformation, and vice-versa. The underlying principle is based on the three-phase balanced voltage ~~phasor~~ triangle diagram, as shown in Fig. (b)



(a)

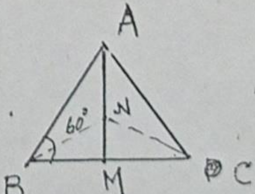


Fig. (b)

(c)

In which, it can be seen that (a) the perpendicular from the vertex A on BC at a point M gives, $BM = MC$.

(b) $AM = AB \sin 60^\circ = \frac{\sqrt{3}}{2} AB = 0.866 AB$

Thus, if a two single-phase transformers I and II in Fig (a) are so chosen that

(a) Transformer I (known as main transformer) has N_1 turns in the primary with a mid-point tap at M.

(b) Transformer II (known as teaser transformer) has $0.866 N_1$ turns in the primary and

(c) both transformers have equal turns N_2 in the secondary, and the primaries are connected as shown in Fig (a), applications of balanced three-phase voltage across A, B and C will result in a

(a) induced counter voltage in BC and AM are in quadrature with each other.

(b) counter voltage in $AM = 0.866$ times that in BC.

~~Thus.~~ That is, the voltage across the secondaries windings would be in quadrature with each other with their magnitudes equal to each other (since they have the same no. of turns).

In other words, two-phase balanced outputs will be obtained from this connection.

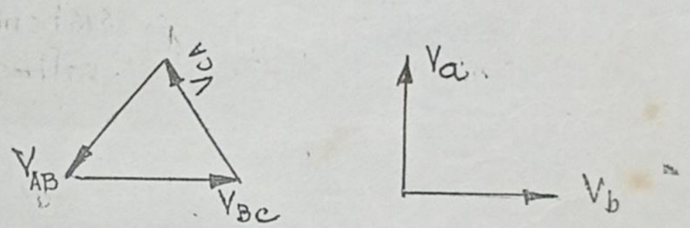
The neutral point on the 3-phase side, if required, could be located at the point N. Which divides the primary winding of the tertiary transformer in the ratio 1:2

[Since $AN = V/\sqrt{3}$ and $AM = \frac{\sqrt{3}}{2}V$

$$\therefore MN = AM - AN = \frac{\sqrt{3}}{2}V - \frac{V}{\sqrt{3}}$$

$$= \frac{3-2}{2\times\sqrt{3}}V = \frac{1}{2\sqrt{3}}V$$

$$\therefore MN : AN = \frac{V}{2\sqrt{3}} : \frac{V}{\sqrt{3}} = \frac{1}{2} : 1 = 1:2 \text{]}$$



Voltage-phasor diagram.

Load Analysis :-

If the secondary load currents are $\bar{I}_a$ and $\bar{I}_b$, the currents on the 3-phase side can be found ~~out~~ by balancing primary and secondary ampere turns.

For the teaser transformer :-

$$\bar{I}_A \times \frac{\sqrt{3}}{2} N_1 = \bar{I}_a N_2$$

$$\text{or } \bar{I}_A = 1.15\,\bar{I}_a \frac{N_2}{N_1} = 1.15\,\bar{I}_a \quad (\text{for } N_2/N_1 = 1)$$

For the main transformer :-

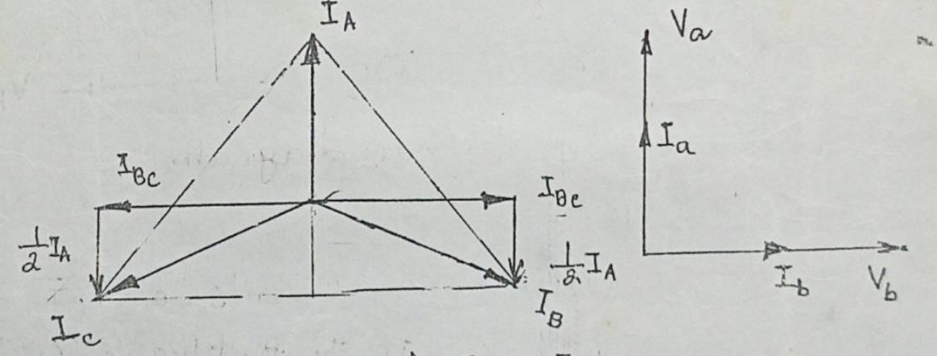
$$\bar{I}_{BC} \times N_1 = \bar{I}_b \times N_2$$

$$\bar{I}_{BC} = \bar{I}_b \times \frac{N_2}{N_1} = \bar{I}_b \quad \left(\text{for } \frac{N_2}{N_1} = 1\right)$$

$$\therefore \quad \bar{I}_B = \bar{I}_{BC} - \frac{1}{2}\bar{I}_A$$

$$\bar{I}_C = -\bar{I}_{BC} - \frac{1}{2}\bar{I}_A$$

The corresponding phasor diagram for balanced Secondary side load of unity p.f. is drawn in Fig. . from which it is obvious that the currents drawn from the 3-phase system are balanced and cophasal with star voltages.



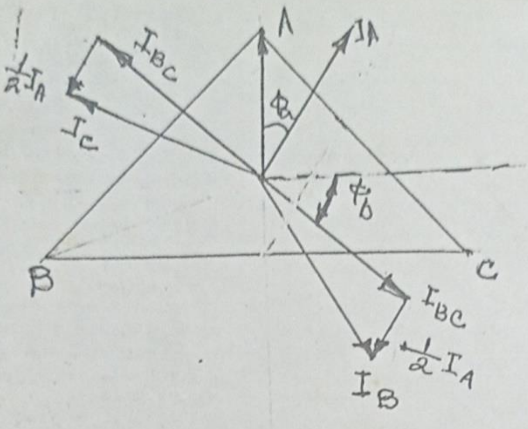
For a balanced load, $I_a = I_b$

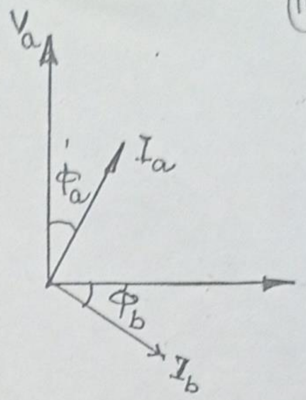
$$\therefore \quad I_A = 1.15\, I_a,$$

$$I_B = \sqrt{(I_{BC})^2 + \left(\frac{1}{2} I_A\right)^2} = \sqrt{I_a^2 + \left(\frac{1}{2} \times 1.15\, I_a\right)^2}$$

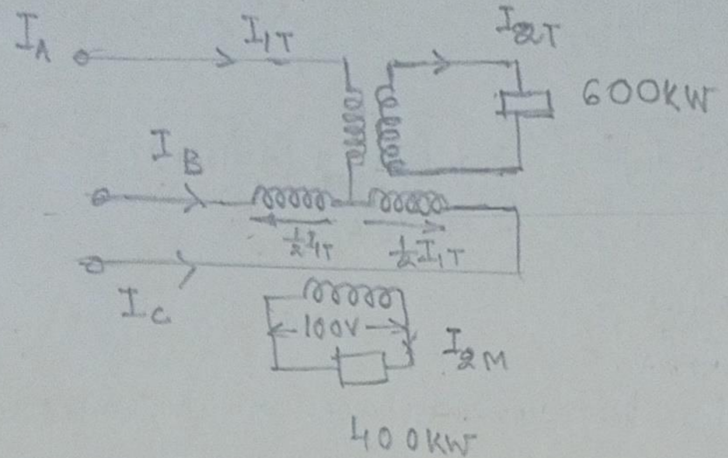
$$= 1.15\, I_a.$$

Also, $I_C = 1.15\, I_a$


A
B
C
I_A
I_{BC}
$\frac{1}{2}I_A$
I_C
ϕ_a
ϕ_b
I_{BC}
$\frac{1}{2}I_A$
I_B


V_a
I_a
ϕ_a
ϕ_b
I_b

Two 100-V single phase transformers take loads of 600 KW , 400 KW respectively at unity p.f and are supplied from 6.6 kV; 3-phase mains through scott-connection. Calculate the currents in the 3-phase lines. Neglect transformer losses.



Secondary teaser current, $I_{2T} = \dfrac{600\times10^3}{100} A = 6000 A$

Secondary main current, $I_{2M} = \dfrac{400\times10^5}{100} A = 4,000 A$.

Now the main primary current is given by the equation $I_{1M} \times T_1 = I_{2M} T_2$

or $I_{1M} = \dfrac{T_2}{T_1} \times I_{2M} = \dfrac{V_2}{V_1} \times I_{2M} = \dfrac{100}{6600} \times 4000 A$

$= 60.6 A$

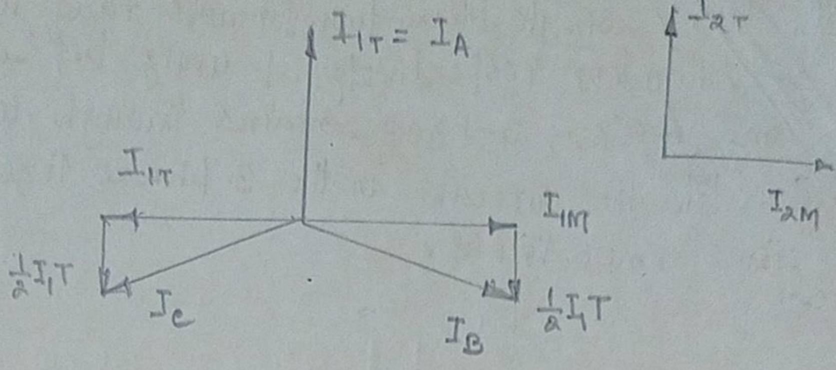
∴ Similarly teaser primary current is given by $I_{1T} \times 0.866 \times T_1 = I_{2T} T_2$

or $I_{1T} = \dfrac{T_2}{T_1} \times \dfrac{1}{0.866} \times I_{2T}$

$= \dfrac{V_2}{V_1} \times \dfrac{1}{0.866} \times I_{2T} = \dfrac{100}{6600} \times \dfrac{1}{0.866} \times 600$

$= 104.97 A$

Now currents in the three phase lines are obtained from the phasor diagram as shown.



$$I_B = \sqrt{I_{1M}^2 + \left(\frac{1}{2} I_{1T}\right)^2} = \sqrt{60.6^2 + \left(\frac{1}{2} \times 104.97\right)^2} \text{ A}$$

$$= 80.16 \text{ A}$$

$I_B = I_c = 80.16 \text{A}$

$I_A = I_1 T = 104.97 \text{A}$.

So, the three phase line currents are 80.16 A, 80.16 A and 104.97 A.

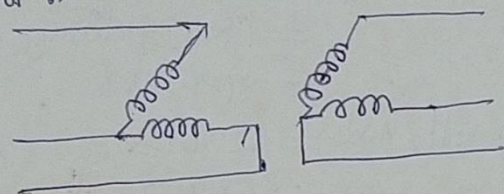
The primary and secondary windings of two transformers, each rated 250 KVA, 11/2KV and 50HZ, are connected in open delta.

Find

(a) the KVA load that can be supplied from this connection.

(b) currents on the h.v side of a delta connected 3-phase load 250 KVA, 0.8 pf lag, 2 kV is connected to the LV side r connection.

Solⁿ :-



(a) KVA rating of each transformer

$= 250\ KVA$

KV.A rating of closed delta connection

$= 3 \times 250\ KVA = 750\ KVA$.

Then the KVA load that can be supplied from open delta connection

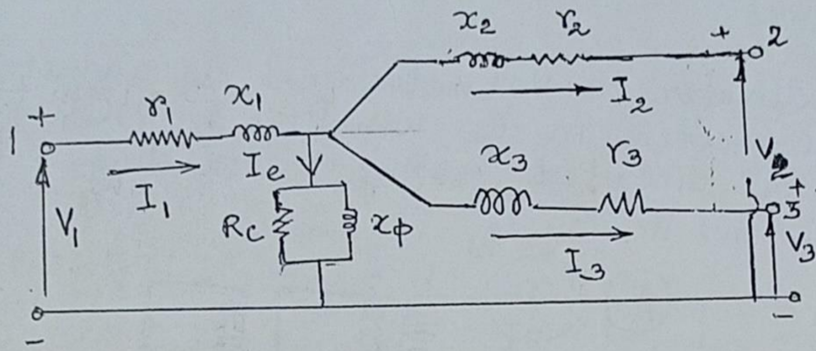
$= \frac{1}{\sqrt{3}} \times$ closed delta KVA rating.

$= \frac{1}{\sqrt{3}} \times 750\ KVA = 433\ KVA.$

(b) currents on h.v. side of a delta connected 3-phase load $= \frac{250 \times 10^3}{11 \times 10^3} = 22.73\ A.$

Equivalent circuit of a 3-Winding transformer

Star equivalent Circuit of a 3-winding transformer is shown in Fig.



r_1, r_2, r_3 = resistances of the windings 1, 2 & 3 respectively.

x_1, x_2, x_3 = equivalent leakage reactances of the windings, 1, 2 & 3 respectively.

x_ϕ = magnetising reactance.

R_e = core resistance.

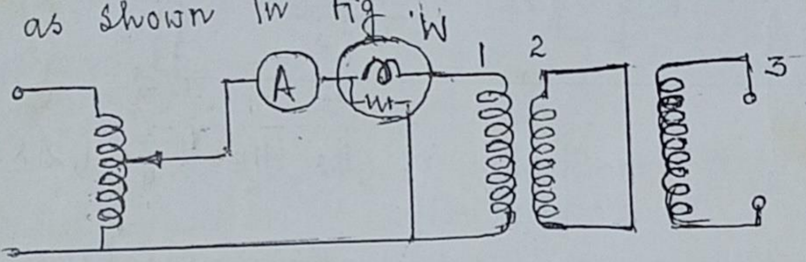
Z_1, Z_2 and Z_3 = equivalent leakage impedances of the windings 1, 2 & 3 respectively.

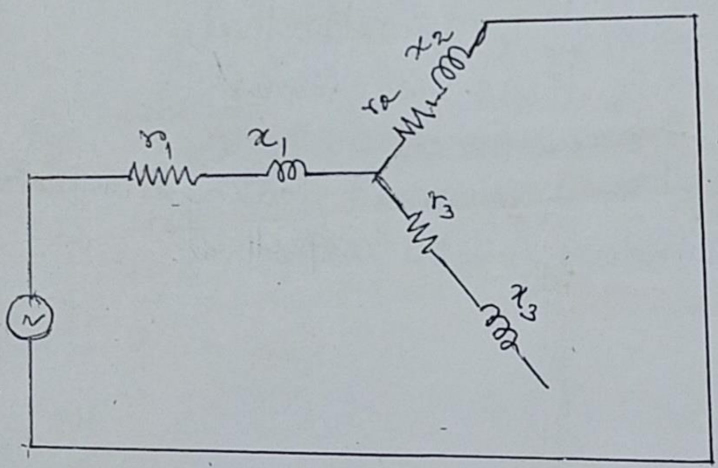
Determination of equivalent circuit parameters:-

(a) Short-Circuit test:-

Three-short circuit tests are to be performed In order to determine the equivalent leakage impedances.

1. A Wattmeter, a voltmeter and a ammeter are connected in the winding 1, Winding 2 is short circuited keeping the winding 3 open as shown in Fig.





Let the voltmeter, Wattmeter and ammeter readings are V_1, W_1 and I_1 respectively

Then the magnitude of ~~Short~~ equivalent or short circuit impedance Z_{12} of the winding 1 and 2 is given by

$$Z_{12} = \frac{V_1}{I_1}$$

equivalent resistance $r_{12} = \frac{W_1}{I_1^2}$

and equivalent leakage reactance,

$$x_{12} = \sqrt{z_{12}^2 - r_{12}^2}$$

From the above fig.

$$z_{12} = r_{12} + j x_{12} = z_1 + z_2.$$

$$r_{12} = r_1 + r_2.$$

where $z_1 = r_1 + j x_1$, $z_2 = r_2 + j x_2$.

Similarly other tests are performed with the following connections :-

2. Instruments are ~~a~~ connected in the winding 1, winding 3 is shorted circuited and winding 2 is open circuited. Then the short circuit impedance z_{13} of the windings 1 and 3 can be determined as before from the voltmeter, wattmeter and ammeter readings,

$$z_{13} = r_{13} + j x_{13} = z_1 + z_3$$

$r_{13} = r_1 + r_3$; where $z_1 = r_1 + j x_1$ and $z_3 = r_3 + j x_3$

3. Instruments are connected in the winding 2, ~~windind~~ winding 3 is short-circuited and winding 1 is open circuited. Then the short circuit impedance z_{23} of the winding 2 and 3 can be determined as before from the voltmeter, wattmeter and ammeter readings.

$$z_{23} = r_{23} + j x_{23} = z_2 + z_3$$

$$r_{23} = r_2 + r_3,$$

$\therefore \quad Z_{12} = r_{12} + j\,x_{12} = Z_1 + Z_2$

$Z_{13} = r_{13} + j\,x_{13} = Z_1 + Z_3$

$Z_{23} = r_{23} + j\,x_{23} = Z_2 + Z_3.$

Solving the above equations, we get,

$Z_1 = \frac{1}{2}\left(Z_{12} + Z_{13} - Z_{23}\right)$

$Z_2 = \frac{1}{2}\left(Z_{12} + Z_{23} - Z_{13}\right)$

$Z_3 = \frac{1}{2}\left(Z_{13} + Z_{23} - Z_{12}\right)$

Again, $r_{12} = r_1 + r_2$

$r_{13} = r_1 + r_3$

$r_{23} = r_2 + r_3$

Solving,

$r_1 = \frac{1}{2}\left(r_{12} + r_{13} - r_{23}\right)$

$r_2 = \frac{1}{2}\left(r_{12} + r_{23} - r_{13}\right)$

$r_3 = \frac{1}{2}\left(r_{13} + r_{23} - r_{12}\right)$

Parallel operation of three-phase transformers:

The need for parallel operation of three-phase transformers arises more frequently, since the generation, transmission and distribution of power is almost always three-phase.

The various conditions that must be fulfilled for successful parallel operation of three-phase transformers are as follows:

(a) The line voltage ratios of the transformers must be the same.

(*b*) The transformers should have equal per unit leakage impedances.

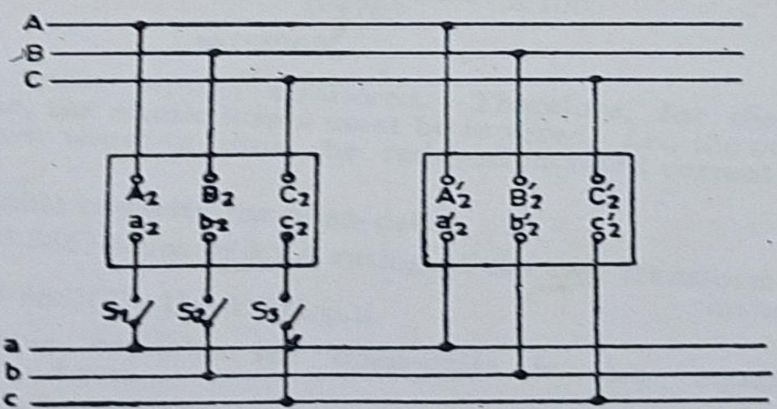
(*c*) The ratio of equivalent leakage reactance to equivalent resistance should be same for all the transformers.

(*d*) The transformers should have the same polarity.

The above four conditions are also applicable for the successful parallel operation of single-phase transformers. In addition to these four conditions, two more *essential* conditions that must be fulfilled for the parallel operation of three-phase transformers are as follows :

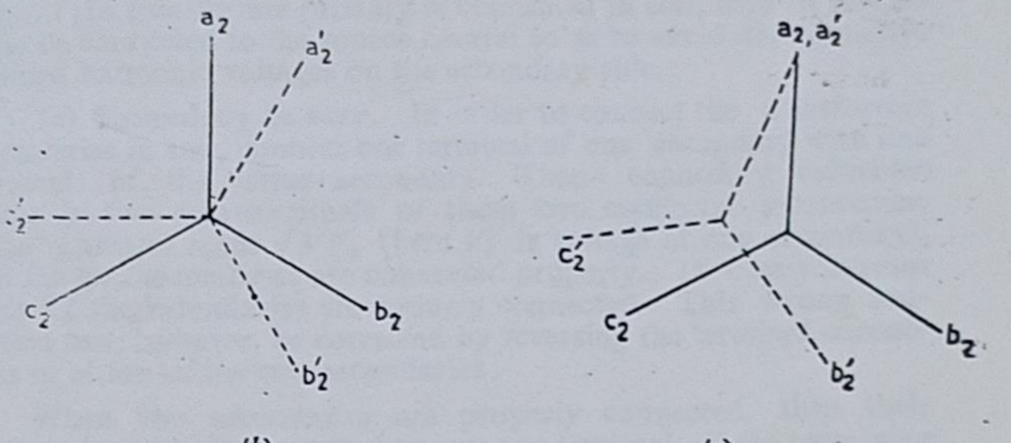
(*e*) **Relative-phase displacement.** The relative-phase displacement between the secondary line voltage of all the transformers must be zero ; *i.e.* the transformers to be connected in parallel, must belong to the same group number. For example, $Yy0$ and $Dd0$ belong to group number 1, these can, therefore, be operated in parallel.

What would happen if transformers of different group numbers are connected in parallel ? In order to examine this, consider



(*a*)

two, 3-phase transformers of different group numbers connected to the same source of supply as shown in Fig. 8·19 (*a*). The secondary line voltages of these two transformers are not in phase as shown in Fig. 8·19 (*b*). In this figure, the phasors joining a_2, a_2' ; b_2, b_2' and c_2, c_2' represent the voltages across switches S_1, S_2 and S_3 respectively. Any one of the three switches can be closed without any danger. For example, if S_1 is closed, there will be no circulating current because the secondary circuit is not complete. The effect of closing the switch S_1 is to bring a_2 and a_2' together so that these overlap each other as shown in Fig. 8·19 (*c*). Now the voltage across switches S_2 and S_3 will be equal to the phasors joining b_2b_2' and c_2c_2' respectively in Fig. 8·19 (*c*). After closing S_1, if S_3 is also closed, voltage b_2b_2' would send a large circulating current in phases A and B which may be damaged. Hence, for successful parallel operation, the voltage across switches S_1, S_2 and

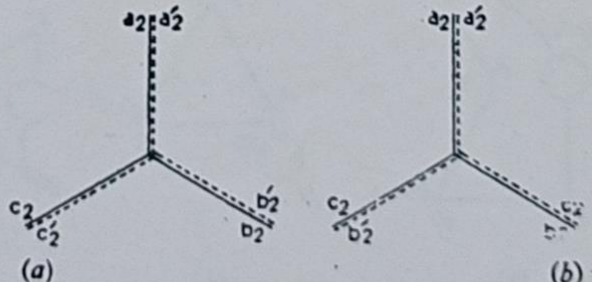


(b) (c)

Fig. 8·19. Parallel operation of three-phase transformers with different group numbers.

S_3 (or across S_2 and S_3 if S_1 is closed), should be zero. In other words, it is essential that the transformers belong to the same group number so that the relative-phase displacement between the secondary line voltages is zero. However, transformers of group numbers 3 and 4 can be successfully operated in parallel as explained in Example 8·1.

(*f*) **Phase-sequence.** If the secondary line voltages are of the same phase sequence as shown in Fig. 8·20 (*a*), then the voltage across switches S_1, S_2 and S_3 of Fig. 8·19 (*a*) would be zero and the parallel operation is possible. However, an improper phase sequence as shown in Fig. 8·20 (*b*), would give zero voltage across switch S_1 and line voltages across switch S_2 and S_3. Consequently the parallel operation is not possible. Hence, it is essential that the secondary line voltages are of proper phase sequence.



(a) (b)

Fig. 8·20. Pertaining to the phase sequence of three-phase transformers.

The computations, pertaining to the parallel operation of three-phase transformers under balanced conditions, can be carried out by reducing a 3-phase problem to an equivalent single-phase problem. For this purpose, equivalent circuits and various relations, derived for the parallel operation of single-phase transformers, can be used.