UNIT – VV
TESTING OF TRANSFORMERS

CONTENTS:

- **OC and SC tests**
- **Sumpner'stest**
- **Predetermination of efficiency and regulation**
- **Separation of losses test**
- **Parallel operation with equal and unequal voltage ratios**
- **Auto transformers- equivalent circuit**
- **Comparison with two winding Transformers**

Open Circuit (OC) and Short Circuit (SC) tests:

They are conducted on the transformer to find out the transformer losses and from them to determine the circuit constants that are used to represent the equivalent circuit. From these parameters the transformer efficiency and regulation can also be calculated. These tests are conducted without actually loading the transformer to its full load and hence the power consumed during the test is very small as compared to its full load (rated) power.

Open Circuit or No Load test:

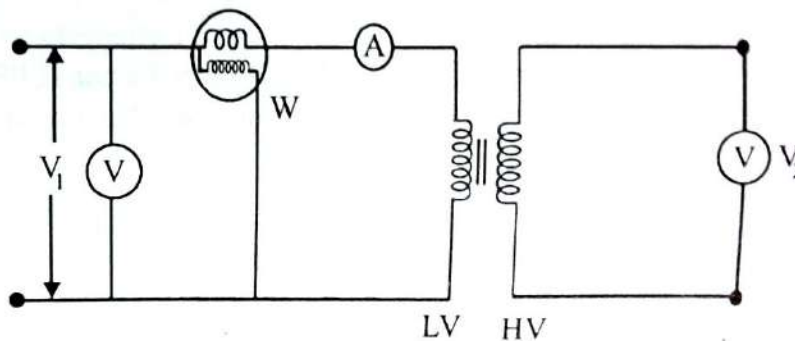The test setup to conduct the OC test is shown in the figure below.

Fig: Test Setup to conduct the Open Circuit or No Load test

Low voltage side is designated as Primary and High voltage side is designated as Secondary. Voltmeter V_1 , Ammeter **A** and wattmeter **W** are connected in the primary as shown . Voltmeter V_2 is connected in the open circuited Secondary. Since the secondary is open circuited a small value of no load current called I_0 flows in the primary and this is measured by the ammeter **A.** The power loss in the transformer is due to core losses and a very small I^2R loss in the primary. There is no I^2R **loss** in the secondary since the secondary is open and there is no secondary current. Since I^2R loss in the primary also is very small the no load current is very small (usually 2 to 5 % of the full load current). The core loss is dependent on the flux which in turn depends on the applied voltage. Since full

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rated voltage is applied to the primary in this test, full rated flux will be set up and the full Core losses will be present. And these core losses will be constant at all loads. Since the I^2R loss in the primary is very small compared to the core losses, they can be ignored and the full power consumed in the primary as read by wattmeter **W** can be regarded as the core losses. With this understanding the readings of the various meters in the OC test are as follows.

- Ammeter reading   : No load current I_0
- Volt meter reading   : Applied rated Primary voltage V_1
- Wattmeter reading   : Input power totally consumed as Core losses P_{CL}

From these measurements the parameters R_C and X_M shown in the equivalent circuit can be computed as shown below.

No load power factor   : **Cos Θ = P_{CL} / $V_1.I_0$ (Since Input power = P_{CL} = $V_1.I_0$. Cos Θ)**

We already know from the equivalent circuit description that I_{CL} is the core loss current corresponding to R_C and I_M is the magnetizing current corresponding to X_M and in terms of the present measurements are given by :
$$I_{CL} = I_0. \text{Cos } \Theta \quad \text{and } I_M = I_0. \text{Sin } \Theta$$

Therefore R_C and X_M are given by :
$$R_C = V_1 / I_{CL} \quad \text{and } X_M = V_1 / I_M$$

Short Circuit test:

The test setup to conduct the SC test is shown in the figure below.

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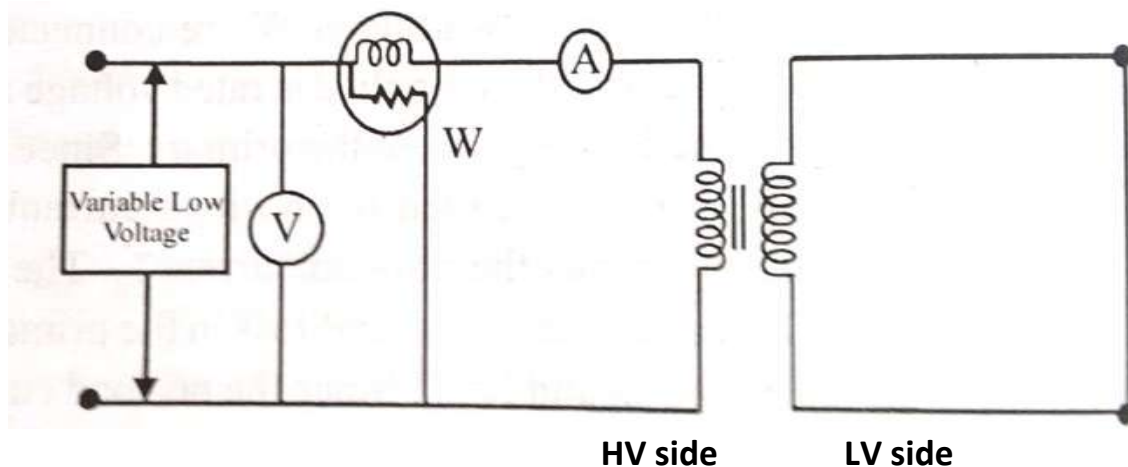
HV side   **LV side**

Fig: Test Setup to conduct the Short Circuit test

In this test high voltage side is designated as Primary (where an input voltage is applied) and the low voltage side is designated as Secondary which is usually short-circuited by a thick conductor(or sometimes through an Ammeter to read additionally the secondary load current).Voltmeter **V**, Ammeter **A** and wattmeter **W** are connected in the primary as shown.

A very low voltage through a Variac (Variable auto transformer) is applied to the primary gradually from zero Volts to about 5 to 10 % of the rated primary value till the primary current is just equal to the rated primary current. Since the secondary is short circuited we will get rated primary current with a low value of voltage itself. Since the applied voltage is very low the flux produced is also very low. Hence the core losses also will be low and can be neglected. Now since the rated currents are flowing in both the Primary and the secondary the input power will be mostly consumed as copper losses. Since the secondary is short circuited the secondary voltage is zero and the entire input voltage V_1 drops in the total equivalent impedance Z_{EQP} of the transformer reflected to the primary.

$$\text{i.e.} \quad V_1 = I_{PSC} \cdot Z_{EQP}$$

The readings in the short circuit test are as follows:

- Ammeter reading   : Primary current I_{PSC}(with secondary short circuited)
- Volt meter reading   : Applied Primary voltage V_1
- Wattmeter reading   :   Input power totally consumed as Copper losses P_{CUL}

With this notation the power factor **Cos Θ_{SC}**   in this test is given by:

$$P_{CUL} = V_1. I_{PSC} . Cos\ \Theta_{SC}$$

From the above readings and the governing equations we can calculate the Equivalent Resistance, Equivalent Impedance and Equivalent Reactance parameters of the transformer referred to the primary as below.

Equivalent Resistance: $R_{EQP} = P_{CUL} / I^2_{PSC}$

Equivalent Impedance: $Z_{EQP} = V_1 / I_{PSC}$

Equivalent Reactance   : $X_{EQP} = \sqrt{Z^2_{EQP} - R^2_{EQP}}$

Sumpner's Test :

Sumpner's test or back to back test on transformer is another method for determining transformer efficiency, voltage regulation and heating under loaded conditions. Short circuit and open circuit tests on transformer can give us parameters of equivalent circuit of transformer, but they cannot help us in finding the heating information. Unlike O.C. and S.C. tests, actual loading is simulated in Sumpner's test. Thus the Sumpner's test gives more accurate results of regulation and   efficiency   than   O.C.   and   S.C.   tests.

Sumpner's test or back to back test can be employed only when two identical transformers are available. Both transformers are connected to supply such that one transformer is loaded on another. Primaries of the two identical

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transformers are connected in parallel across a supply. Secondaries are connected in series opposition such that their e.m.f's are opposite to each other. Another low voltage supply is connected in series with secondaries to get the readings, as shown in the circuit diagram shown below.
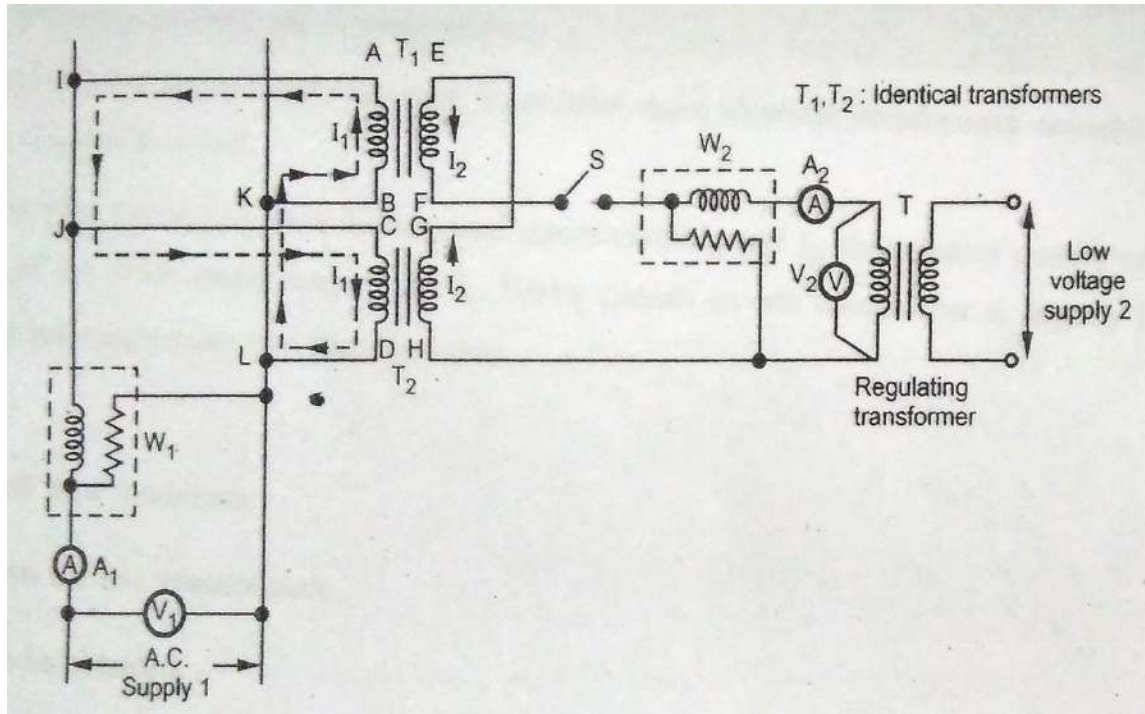

Figure : Sumpner's Test setup

In the above diagram, T_1 and T_2 are identical transformers. Their secondaries are connected in voltage opposition, i.e. both the emf's E_{EF} and E_{GH} cancel each other, as transformers are identical. In this case, as per superposition theorem, no current flows through secondary. And thus the no load test is simulated. The current drawn from V_1 is $2I_0$, where I_0 is equal to no load current of each transformer. Thus , input power measured by wattmeter W_1 is equal to iron losses of both the transformers.

i.e. Iron loss per transformer $P_i = W_1/2$.

Now, a small voltage V_2 is injected into secondary with the help of a low voltage transformer. The voltage V_2 is adjusted such that, the rated current I_2 flows through the secondary. In this case, both primaries and secondaries carry rated current. Thus short circuit test is simulated and wattmeter W_2 shows total full load copper losses of both transformers. i.e. Copper loss per transformer $P_{Cu} = W_2/2$.

From above test results, the **full load efficiency of each transformer** can be given as:

$$\text{\% full load efficiency of each transformer} = \frac{\text{output}}{\text{output} + \frac{W_1}{2} + \frac{W_2}{2}} \times 100$$

And Output = kVA rating x Cos θ (power factor)

Predetermination of efficiency and regulation:

Calculation of efficiency:

We have obtained Iron losses P_i as the input power W_0 from the OC test and then Full load (or at any load) copper losses P_{cu} as the input power P_{sc} from the SC test.

Using this data we can predetermine efficiency and regulation at any load and power factor as shown below.

% η at full (rated load) = [{Rated KVA x cos Θ} / { Rated KVA x cos Θ + P_i + P_{sc} }]

x 100

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Similarly at any load which is a fraction of full load we can predetermine the efficiency

% η at any load =   [{n x Rated KVA x cos Θ} / { n x Rated KVA x cos Θ + P_i + $n^2 P_{sc}$ }] x 100

Calculation of Regulation:

We know that % Regulation @FL is defined as: % Regulation@FL =[(Input – output at FL)/Input] x100

= [{Drop across the equivalent resistance R_{EQ} and equivalent X_{EQ} @FL}/Input] x 100

From the SC test we can obtain the equivalent circuit parameters. We shall use the following designation and get the expression for regulation by using the circuit parameters referred to both primary and secondary.

V_P = rated primary voltage I_P = rated primary current (FL)

V_S = rated secondary voltage I_S = rated secondary current (FL)

R_{EQP} = Equivalent resistance referred to primary R_{EQS} = Equivalent resistance referred to secondary X_{EQP} = Equivalent reactance referred to primary X_{EQS} = Equivalent reactance referred to secondary

Then

% Regulation (referred to primary)@FL = [{I_P (R_{EQP} x Cos Θ + X_{EQP} x Sin Θ) /V_P }] x 100

% Regulation (referred to secondary)@FL = [{I_S (R_{EQS} x Cos Θ + X_{EQS} x Sin Θ) /(V_P/a)}] x 100

Where '**a**' is the transformer turns ratio

Regulation at any other load can be calculated using the same relation as above except that the currents **Ip** and **Is** are to be multiplied by the corresponding load fractions **'n'** and the relations will become

% Regulation (referred to primary)@any fractional FL = [{nI_P (R_{EQP} x Cos Θ + X_{EQP} x Sin Θ) /V_P }] x 100

% Regulation (referred to secondary)@any fractional FL = [{nI_S (R_{EQS} x Cos Θ + X_{EQS} x Sin Θ) /(V_P/a)}] x 100

Transformer equivalent circuits (Both Complete and simplified) referred to both Primary and secondary are appended below again for a quick reference :
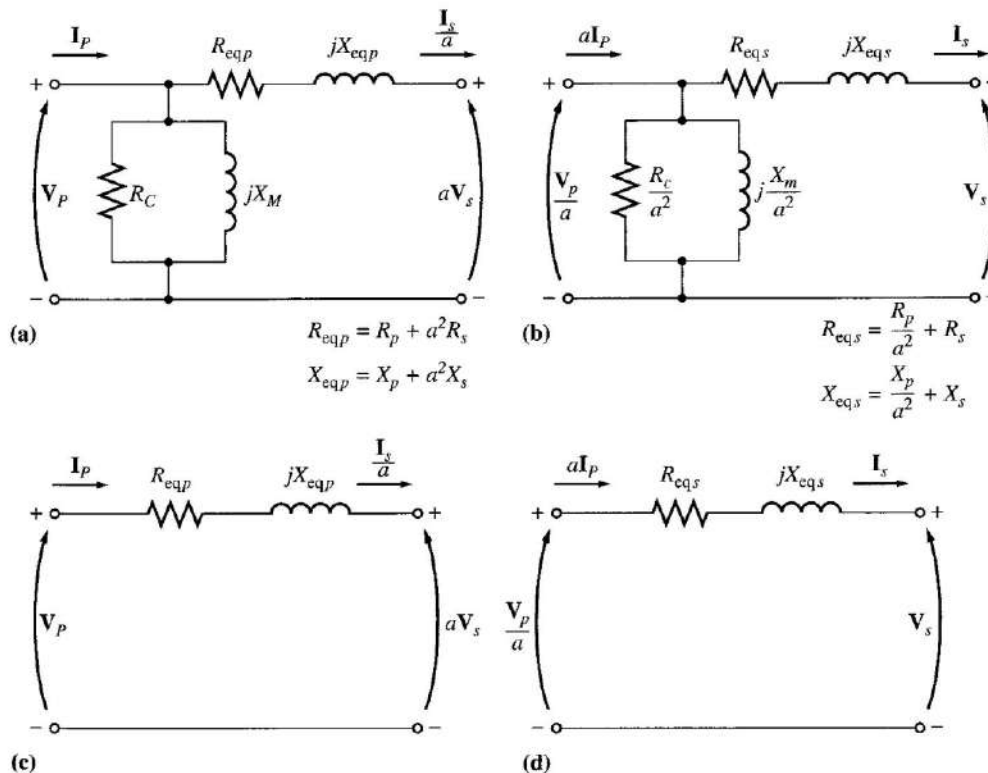
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$$R_{eqp} = R_p + a^2 R_s$$
$$X_{eqp} = X_p + a^2 X_s$$

$$R_{eqs} = \frac{R_p}{a^2} + R_s$$
$$X_{eqs} = \frac{X_p}{a^2} + X_s$$

Fig: Simplified equivalent circuits (a) Referred to the primary side (b) Referred to the secondary side
(c) With no excitation branch, referred to the primary side (d) With no excitation branch, referred to the secondary side

Parallel operation of transformers:

Need for Parallel operation of transformers:

When the load outgrows the capacity of an existing transformer, it may be economical to install another one in parallel with it rather than replacing it with a single larger unit. Also, sometimes in a new installation, two units in parallel, though more expensive, may be preferred over a single unit for reasons of reliability—half the load can be supplied with one unit out. Further, the cost of maintaining a spare is less with two units in parallel. However, when spare units are maintained at a central location to serve transformer installations in a certain region, single-unit installations would be preferred. It is, therefore, seen that

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parallel operation of the transformer is quite important and desirable under certain circumstances.

Conditions for successful parallel operation of transformers:

The satisfactory and successful operation of transformers connected in parallel on both sides requires that they fulfill the following conditions:

(i) The transformers must be connected properly as far as their polarities are concerned so that the net voltage around the local loop is zero. A wrong polarity connection results in a dead short circuit.

(ii) Three-phase transformers must have zero relative phase displacement on the secondary sides and must be connected in a proper phase sequence. Only the transformers of the same phase group can be paralleled. For example, Y/Y and Y/D transformers cannot be paralleled as their secondary voltages will have a phase difference of 30°. Transformers with +30° and −30° phase shift can, however, be paralleled by reversing the phase-sequence of one of them.

(iii) The transformers must have the same voltage-ratio to avoid no-load circulating current when transformers are in parallel on both primary and secondary sides. Since the leakage impedance is low, even a small voltage difference can give rise to considerable no-load circulating current and extra I^2R loss.

(iv) There should exist only a limited disparity in the per-unit impedances (on their own bases) of the transformers. The currents carried by two transformers (also their kVA loadings) are proportional to their ratings if their ohmic impedances (or their pu impedances on a common base) are inversely proportional to their ratings or their per unit impedances on their own ratings are equal. The ratio of equivalent leakage reactance to equivalent resistance should be the same for all the transformers. A difference in this ratio results in a divergence of the phase angle of the two currents, so that one transformer will be operating with a higher, and the other with a lower power factor than that of the total output; as a result, the given active load is not proportionally shared by them.

Parallel Transformers on No-load:

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The parallel operation of transformers can be easily conceived on a per phase basis. Figure below shows
two transformers paralleled on both sides with proper polarities but on no-load.
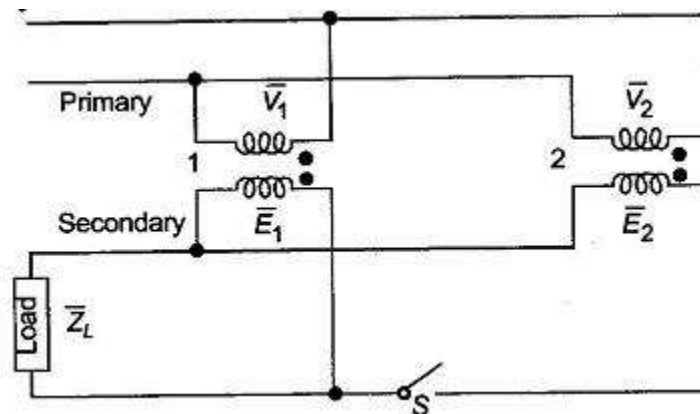

Fig: Two transformers connected in parallel

The primary voltages V_1 and V_2 are obviously equal. If the voltage-ratio of the two transformers are not identical, the secondary induced emf's, E_1 and E_2 though in phase will not be equal in magnitude and the difference $(E_1 - E_2)$ will appear across the switch S. When secondaries are paralleled by closing the switch, a circulating current appears even though the secondaries are not supplying any load. The circulating current will depend upon the total leakage impedance of the two transformers and the difference in their voltage ratios. Only a small difference in the voltage-ratios can be tolerated.

Parallel Operation of Two Ideal Transformers:

Now we will consider ideal case of two transformers having the same voltage ratio and their voltage triangles are equal in size and shape.i.e. apart from their impedances being same, their X/R ratios are also same. The circuit shown in the figure below consists of two transformers in parallel.
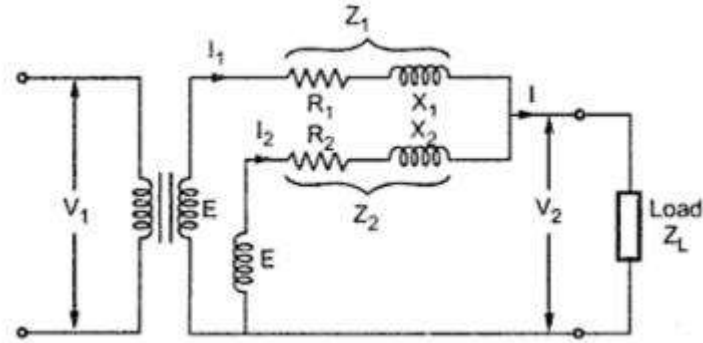
Fig: Two ideal transformers connected in parallel

The corresponding phasor diagram is shown in the figure below.

As seen from this figure the impedance voltage triangles of both the transformers are same. I_1 and I_2 are the currents flowing through transformers 1 and 2 which are in parallel. These currents are in phase with the load current and are inversely proportional to the respective impedances.
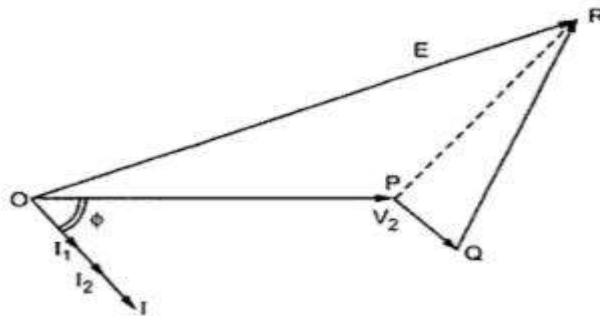

Fig: Phasor diagram of two ideal transformers connected in parallel

Current sharing : Let us now find out the distribution of the given load current for this condition between the two transformers. Let **I** be the total current and **I_1** and **I_2** be the currents shared by the two transformers.

Then applying KCL to the transformer secondaries ,

$I = I_1 + I_2$

Secondary voltage,

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$$V_2 = E - I_1 Z_A = E - I_2 Z_2$$

Also $I_1 Z_1 = I_2 Z_2$

$$I_1 / I_2 = Z_2 / Z_1$$

Applying current divider formulae we get

$$I_1 = I Z_2 / (Z_1 + Z_2)$$

and $I_2 = I Z_1 /(Z_1 + Z_2)$

Parallel Operation of Transformers with Equal Voltage Ratios:

Let us now consider the case of two transformers connected in parallel having equal voltage ratios. The two transformers are having no load secondary voltage same. i.e. $E_1 = E_2 = E$. These voltages are in phase with each other. This is possible if the magnetizing currents of the two transformers are not much different. With this case the primaries and secondaries of the two transformers can be connected in parallel and no current will circulate under no load condition. This is represented in the figure below.
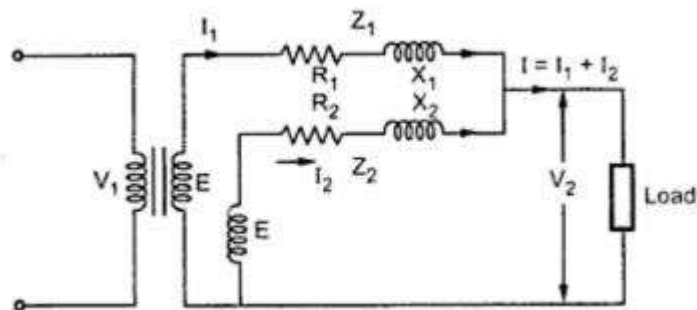

Fig: Two transformers with equal voltage ratios connected in parallel

If we neglect magnetizing components, the two transformers are represented as shown in the figure below .
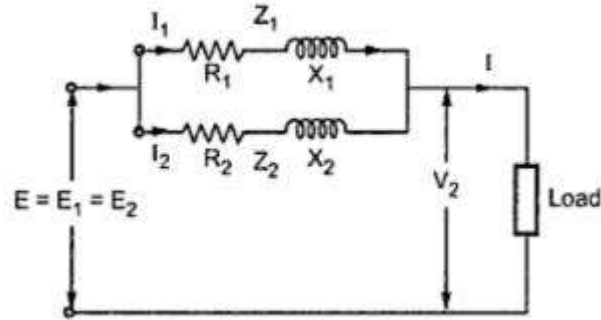
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Fig: Simplified equivalent circuit neglecting the magnetizing componenets

The phasor diagram under this case is shown in the figure below .

The two impedances Z_1 and Z_2 are in parallel. The values of Z_1 and Z_2 are with respect to secondary. The impedances Z_1 and Z_2 are equal in magnitude but not in phase. i.e. the ratios X_1/R_1 and X_2/R_2 are not equal.
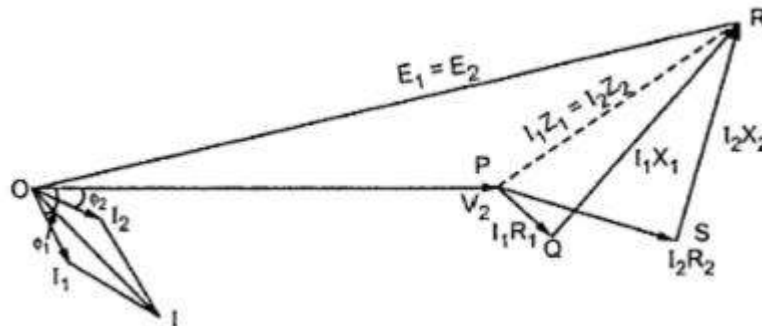

Fig: Phasor diagram of the two transformers with equal voltage ratios connected in parallel

Current distribution:

Z_1 and Z_2 are in parallel therefore the equivalent impedance is given by,

$$1/Z_{eq} = 1/Z_1 + 1/Z_2 \qquad Z_{eq} = Z_1 Z_2 /(Z_1 + Z_2)$$

As seen from the phasor diagram

$$I_1 Z_1 = I_2 Z_2 = I Z_{eq}$$
$$I_1 = I Z_{eq}/ Z_1 = I Z_2 /(Z_1 + Z_2)$$

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$I_2 = I \, Zeq/ = I \, Z_1/(Z_1 + Z_2$

Multiplying both terms of above equation by voltage V_2,

$V_2 I_1 = V_2 I \, Z_2 /(Z_1 + Z_2)$

$V_2 I_2 = V_2 I \, Z_1/(Z_1 + Z_2)$

But **$V_2 I \times 10^{-3}$ is Q** i.e. the combined load in KVA

From this , the KVA carried by each transformer is calculated as,

$$Q_1 = Q \cdot \frac{Z_2}{Z_1 + Z_2} = Q \cdot \frac{1}{1 + \frac{Z_1}{Z_2}}$$

and

$$Q_2 = Q \cdot \frac{Z_1}{Z_1 + Z_2} = Q \cdot \frac{1}{1 + \frac{Z_2}{Z_1}}$$

The above expressions are useful in determining the values of Q_1 and Q_2 in magnitude and in phase.

The two transformers work at different power factor. One operates at high p.f. while the other at low p.f. If the impedances Z_1 and Z_2 are equal both in magnitude and quality i.e. ($X_1/ R_1 = X_2/R_2$), then both transformers operate at the same p.f. which is the p.f. of the load.

Parallel Operation of Transformers with Unequal Voltage Ratios:

Now we will consider the case of two transformers working in parallel and having unequal voltage ratio. This is shown in the figure below. The voltage ratios of the two transformers are not equal. The parallel operation under this case is still possible. But as seen previously there would be a circulating current under no load condition.
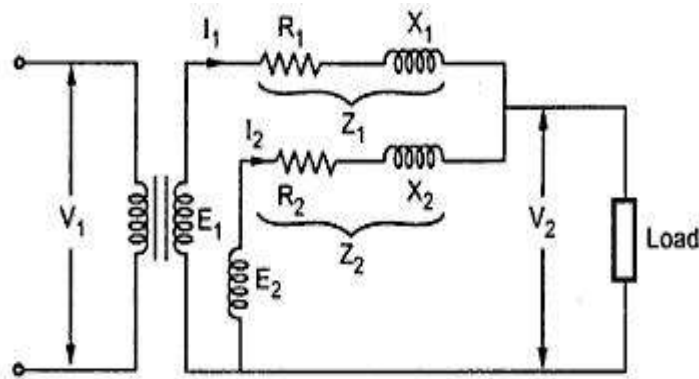
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Fig: Two transformers with unequal voltage ratios connected in parallel

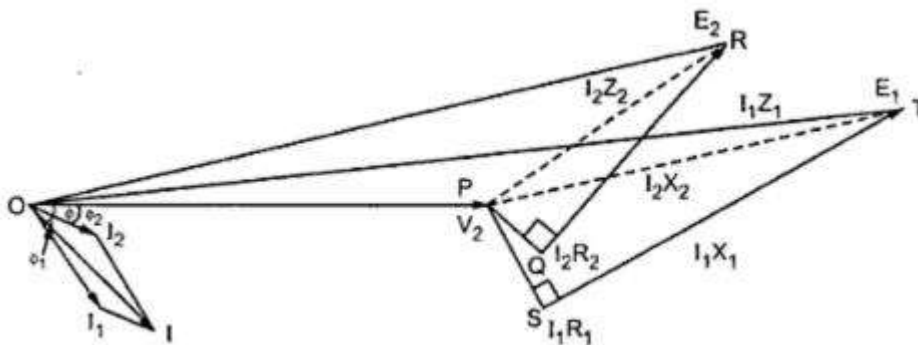The phasor diagram of this transformer is shown below:

Fig: Phasor diagram of two transformers with unequal voltage ratios connected in parallel

As can be seen the two transformers apart from having unequal output voltages E_1 and E_2 , their impedances Z_1 and Z_2 and their **X/R** ratios are also unequal. Φ_1 and Φ_2 are the power factor angles of these two transformers and Φ is the combined p.f. angle.

Current distribution (Load sharing):

Let us consider that the voltage ratio of transformer-1 is slightly more than that of transformer-2. So the induced e.m.f E_1 is greater than E_2. Thus the resultant

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terminal voltage will be $(E_1 - E_2)$ which will cause a circulating current I_c under no load condition.

$$I_c = (E_1 - E_2)/(Z_1 + Z_2)$$

From the circuit diagram we have,

$$E_1 = V_2 + I_1 Z_1$$

$$E_2 = V_2 + I_2 Z_2$$

Also,

$$I_L = I_1 + I_2$$

$$V_2 = I_L Z_L = (I_1 + I_2) Z_L$$

$$E_1 = (I_1 + I_2) Z_L + I_1 Z_1 \qquad \text{......... (1)}$$

$$E_2 = (I_1 + I_2) Z_L + I_2 Z_2 \qquad \text{......... (2)}$$

Subtracting equation (b) from (a) we have,

$$E_1 - E_2 = I_1 Z_1 - I_2 Z_2 \quad \text{from which we get}$$

$$I_1 = [(E_1 - E_2) + I_2 Z_2] /Z_1 \qquad \text{...........(3)}$$

and

$$I_2 = [I_1 Z_1 - (E_1 - E_2)]/Z_2 \qquad \text{..........(4)}$$

Substituting the value of I_1 from (3) in equation (2) we get :

$$E_2 = I_2 Z_2 + \left[\left\{ \frac{(E_1 - E_2) + I_2 Z_2}{Z_1} \right\} + I_2 \right] Z_L$$

From which we get: $\quad$ **$I_2 = [E_2 Z_1 - (E_1 - E_2)Z_L) / (Z_1 Z_2 + Z_L (Z_1 + Z_2)]$ .... (5)**

Similarly by Substituting the value of I_2 from equation (4) in equation (1) we get :

$$E_1 = I_1 Z_1 + [I_1 + \{I_1 Z_1 - (E_1 - E_2)\}/Z_2] Z_L$$

From which we get: $\quad$ **$I_1 = [E_1 Z_2 + (E_1 - E_2)Z_L)/ (Z_1 Z_2 + Z_L (Z_1 + Z_2)]$ .... (6)**

If impedances Z_1 and Z_2 are small in comparision with load impedance Z_L then the product $Z_1 Z_2$ in the above equations **(6)** and **(5)** for currents I_1 and I_2 may be neglected so that finally we get the current distribution between the two transformers as,

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$$I_1 = \frac{E_1 Z_2}{Z_L (Z_1 + Z_2)} + \frac{E_1 - E_2}{Z_1 + Z_2}$$

$$I_2 = \frac{E_2 Z_1}{Z_L (Z_1 + Z_2)} - \frac{E_1 - E_2}{Z_1 + Z_2}$$

Where the second term **$(E_1 - E_2) / (Z_1 + Z_2)$** is the circulating current **I_c** which adds to the load shared by transformer-1 whose output voltage **E_1** is higher and subtracts from the load shared by transformer-2 whose output **E_1** is lower. *Hence transformer-1 gets overloaded and the transformers will not share the load according to their ratings.*