Experiment No: 2

Open circuit and short circuit tests on single phase transformer

1 Aim

- To understand the basic working principle of a transformer.
- To obtain the equivalent circuit parameters from OC and SC tests, and to estimate efficiency & regulation at various loads.

2 Theory

The physical basis of the transformer is mutual induction between two circuits linked by a common magnetic field. Transformer is required to pass electrical energy from one circuit to another, via the medium of the pulsating magnetic field, *as efficiently and economically* as possible. This could be achieved using either iron or steel which serves as a good permeable path for the mutual magnetic flux. An elementary linked circuit is shown in Fig.1. The principle of operation of this circuit can be explained as follows:
Let an alternating voltage v_1 be applied to a primary coil of N_1 turns linking a suitable iron core. A current flows in the coil, establishing a flux ϕ_p in the core. This flux induces an emf e_1 in the coil to counterbalance the applied voltage v_1. This e.m.f. is

$$e_1 = N_1 \frac{d\phi_p}{dt}.$$

Assuming sinusoidal time variation of the flux, let $\phi_p = \Phi_m \sin \omega t$. Then,

$$e_1 = N_1 \omega \Phi_m \cos \omega t, \quad \text{where} \quad \omega = 2\pi F$$

The r.m.s. value of this voltage is given by:

$$E_1 = 4.44 F N_1 \Phi_m$$

Now if there is a secondary coil of N_2 turns, wound on the same core, then by mutual induction an emf e_2 is developed therein. The r.m.s. value of this voltage is given by:

$$E_2 = 4.44 F N_2 \Phi'_m$$

where Φ'_m is the maximum value of the (sinusoidal) flux linking the secondary coil (ϕ_s).
If it is assumed that $\phi_p = \phi_s$ then the primary and secondary e.m.f.'s bear the following ratio:

$$\frac{e_1}{e_2} = \frac{\overline{E}_2}{\overline{E}_1} = \frac{N_2}{N_1}$$

Note that in actual practice, $\phi_p \neq \phi_s$ since some of the flux paths linking the primary coil do not link the secondary coil and similarly some of the flux paths linking the secondary coil do not link the primary coil. The fluxes which do not link both the coils are called the "leakage fluxes" of the primary and secondary coil.

In a practical transformer a very large proportion of the primary and secondary flux paths are common and leakage fluxes are comparatively small. Therefore $\phi_p \approx \phi_s = \phi_{mutual}$ and therefore $\Phi_m \approx \Phi'_m$.
If in addition, winding resistances are neglected – being usually small in a practical transformer, then

$$\overline{V}_1 \approx \overline{E}_1$$

Similarly,

$$\overline{V}_2 \approx \overline{E}_2$$

Although the iron core is highly permeable, it is not possible to generate a magnetic field in it without the application of a small m.m.f.(magneto-motive force), denoted by M_m. Thus even when the secondary winding is open circuited, a small magnetizing current (i_m) is needed to maintain the magnetic flux. The current of the primary circuit on no-load is of the order of 5% of full load current.
Also, the pulsation of flux in the core is productive of core loss, due to hysteresis and eddy currents. These losses are given by:

$$P_h = K_h B_{max}^{1.6} F, \qquad P_e = K_e B_{max}^2 F^2 \qquad \text{and } P_c = P_h + P_e$$

where P_h, P_e and P_c are hysteresis, eddy current and core losses respectively, K_h and K_e are constants which depend on the magnetic material, and B_{max} is the maximum flux density in the core. These losses will remain almost constant if the supply voltage and frequency are held constant. The continuous loss of energy in the core requires a continuous supply from the electrical source to which the primary is connected. Therefore, there must be a current component i_c which accounts for these losses. It should be noted that magnetizing current (i_m) and core loss component of current(i_c) are in phase quadrature. The resultant of these two currents is the no-load current i_o. Generally the magnitude of this current is very small compared to that of the rated current of the transformer (may be of the order of 5% of the rated). This current makes a phase angle ζ_o of the order of ($\cos^{-1}(0.2)$) with the applied voltage.

If a load of finite impedance is connected across the second coil, a current i_2 will flow through it. This tends to alter the mmf and thereby the flux in the core. But this is prevented by an immediate and automatic adjustment of the primary current i_1, thereby maintaining the flux ϕ at the original value. This value of flux is required to produce the emf of self induction e_1. Any reduction of the flux would cause a reduction of e_1, leaving a voltage difference between v_1 and e_1 which would be sufficient to increase the primary current and thereby re-establish the flux. Thus any current which flows in the secondary causes its counterpart to flow in the primary so that the flux ϕ (and therefore the mmf - M_m) shall always be maintained at a value such that the voltage applied v_1 to the primary terminals shall be balanced by the induced emf e_1 (neglecting voltage drops due to resistance and leakage flux effects). Thus if current flows in the secondary (i_2), then $i_1 = i_o + \frac{N_2}{N_1} i_2$ so that effective mmf in the core remains at M_m. In phasor notation:

$$\overline{I}_1 = \overline{I}_o + \tfrac{N_2}{N_1}\overline{I}_2$$

$\overline{I}_o$ is quite small compared to the rated current and is usually neglected if transformer is loaded. Thus:

$$\overline{I}_1 \approx \tfrac{N_2}{N_1}\overline{I}_2$$

It is therefore, evident that energy is conveyed from the primary to secondary by the flux: the primary stores the energy in the magnetic field, and an extraction of some of this for the secondary load is made up by the addition of energy from the primary, which consequently takes an increased current.

Thus by making the assumptions :

- Winding resistances are small
- Magnetising current is small
- Core losses are small
- Leakage fluxes are small

we can infer that (for an “ideal transformer”):

$$\frac{\overline{I}_1}{\overline{I}_2} = \frac{N_2}{N_1} = \frac{\overline{E}_2}{\overline{E}_1} = \frac{\overline{V}_2}{\overline{V}_1} \tag{1}$$

2.1 Equivalent Circuit of a practical Transformer

The practical transformer has coils of finite resistance. Though this resistance is actually distributed uniformly, it can be conceived as concentrated. Also, all the flux produced by the primary current cannot be confined into a desired path completely as an electric current. Though a greater proportion links both the coils(known as mutual flux), a small proportion called the leakage flux links one or other winding, but not both. It does not contribute to the transfer of energy from primary to secondary. On account of the leakage flux, both the windings have a voltage drop which is due to ‘leakage reactance’. The transformer shown in Fig.1 can be resolved into an equivalent circuit as shown in Fig.2 (a) in which the resistance and leakage reactance of primary and secondary respectively are represented by lumped R_1, X_1, R_2 and X_2. This equivalent circuit can be further simplified by referring all quantities in the secondary side of the transformer to primary side and is shown in Fig.2(b). These referred quantities are given by:

$$R_2' = R_2(\tfrac{N_1}{N_2})^2 \qquad X_2' = X_2(\tfrac{N_1}{N_2})^2 \qquad I_2' = I_2(\tfrac{N_2}{N_1}) \qquad V_2' = V_2(\tfrac{N_1}{N_2})$$

Generally the voltage drops I_1R_1 and I_1X_1 are small and magnitude of $\overline{E}_1$ is approximately equal to that of $\overline{V}_1$. Under this condition, the shunt branch (comprising X_m and R_o) can be connected across the supply terminals. This approximate equivalent circuit (shown in Fig.3) simplifies the computation of currents and other performance characteristics of a practical transformer.

2.2 Determination of Equivalent Circuit Parameters

The equivalent circuit shown in fig.2(b) or 3 can be used to predict the performance of the transformer. All the circuit parameters must be known so that the equivalent circuit can be used for the above purpose. These parameters can be easily determined by performing tests that involve little power consumption. Two tests, a no-load test(or open circuit test) and short circuit test will provide information for determining the parameters of the equivalent circuit.

2.2.1 Open circuit (OC) test

The shunt branch parameters can be determined by performing this test. Since, the core loss and the magnetizing current depend on applied voltage, this test is performed by applying the rated voltage to one of the windings keeping the other winding open (generally HV winding is kept open and rated voltage is applied to LV winding). The circuit diagram to conduct this test is shown in Fig.4. Since, the secondary terminals are open (no load is connected across the secondary), current drawn from the source is called as *no load current*. On no-load, the approximate equivalent circuit shown in Fig.3 can be further reduced and is shown in Fig.5 (a). Under no-load condition the power input to the transformer is equal to the sum of losses in the primary winding resistance R_1, (refer fig.2b) and core loss. Since, no load current is very small, the loss in winding resistance is neglected. Hence, on no load the power drawn from the source is dissipated as heat in the core. If I_o and P_i are the current and input power drawn by the transformer at rated voltage V_1 respectively, then

$$\cos\zeta_o = \frac{P_i}{V_1.I_0}$$

From fig.5(b),

$$I_c{=}I_0\cos\zeta_o, \qquad I_m{=}I_0\sin\zeta_o,$$

Therefore,

$$R_0 = V_1/I_c, \qquad X_m = V_1/I_m$$

2.2.2 Short circuit (SC) test

Consider the circuit shown in Fig.3. Suppose the input voltage is reduced to a small fraction of rated value and secondary terminals are short-circuited. A current will circulate in the secondary winding. Since a small fraction of rated voltage is applied to the primary winding, the flux in the core and hence the core loss is very small. Hence, the power input on short circuit is dissipated as heat in the winding. The circuit diagram to conduct this test is shown in Fig.6 (a). In this test, the LV terminals of the transformer are short circuited. The primary voltage is gradually applied till the rated current flows in the winding. Since, the applied voltage is very small (may be of the order of $5-8\%$), the magnetizing branch can now be eliminated from the equivalent circuit. The modified equivalent circuit is shown in Fig.6(b). If V_{sc} is the applied voltage to circulate the rated current (I_2') on short circuit, and P_c is the power input to the transformer then,

$$Z_{sc} = \frac{V_{sc}}{I_2'} \qquad \cos\theta = \frac{P_c}{V_{sc}.I_2'}$$

Therefore,

$$(R_1 + R_2') = Z_{sc}\cos\theta, \qquad (X_1 + X_2') = Z_{sc}\sin\theta$$

2.3 Efficiency

Efficiency of the transformer is defined as:

$$\eta = \frac{\text{output power}}{\text{input power}}$$

Interms of losses,

$$\eta = \frac{\text{output power}}{\text{output power+ iron losses+copper losses}}$$

Let 'S' be the rated VA of the transformer, 'x' is the fraction of full load the transformer is supplying, and ζ is the load power factor angle. Under this condition the output power of the transformer is $= x.S.\cos\zeta$. If P_c is the copper loss (loss in winding resistance) at rated current, the corresponding loss while supplying the fraction of load is $= x^2.P_c$. With transformers of normal design, the flux in the core varies only a few percent between no-load to full load. Consequently it is permissible to regard the core loss (iron loss) as constant, regardless of load. Let this loss be P_i. Therefore equation becomes :

$$\eta = \frac{x.S.\cos\zeta}{x.S.\cos\zeta+P_i+P_c.x^2}$$

2.4 Regulation

From Fig.3 it can be seen that if the input voltage is held constant, the voltage at the secondary terminals varies with load. Regulation is defined as the change in magnitude of secondary (terminal) voltage, when the load is thrown off with primary voltage held constant. Since, the change in secondary voltage depends only on the load current, the equivalent circuit is further simplified and is shown in Fig.7. The vector diagrams for lagging, unity and leading powerfactor loads are shown in Fig.8. It can be proved that angle σ is very small and can be neglected. In that case, the expression for regulation is given by

$$\%regulation = \frac{I_2'.R_{eq}.\cos\zeta \pm I_2'.X_{eq}.\sin\zeta}{V_2'} \times 100 \tag{2}$$

where
I_2'=load current, $R_{eq} = R_1 + R_2'$, $X_{eq} = X_1 + X_2'$, '+' sign for lagging pf & '-' for leading pf.

Note to TAs/RAs: Open the cover of the transformer and show the students HV and LV terminals, conductors used for LV and HV winding. Also show them E & I laminations, and ferrite core.

3 Procedure

Note down the name plate readings and determine the rated currents for both the windings.

3.1 No-Load Test:

- Connect the circuit as shown in fig.4.
- Apply voltage to the LV side in steps upto the rated voltage and for each case record primary current and power drawn from the source. Also, observe the current waveform on the power analyzer.
- Increase the applied voltage by 10% and repeat the above step.
- Reduce the output voltage of the variac to zero and switch-off the supply.

3.2 Short-Circuit Test:

- Connect the circuit as shown in Fig.6(a). Set the autotransformer output to zero. **It is extremely important to note that a low voltage is to be applied to the primary winding.**
- Adjust the output of the autotransformer such that rated current flows through the windings. Record the applied voltage, current and input power.
- Reduce the output voltage of the autotransformer to zero and put off the supply.

4 Report

- Determine the equivalent circuit parameters from the test results.
- Using equivalent circuit parameters compute the following:

- regulation at 25%, 75% and full load for powerfactor = 1, 0.6 lag and 0.6 lead.
- efficiency at 25%, 50%, 75% and full load for powerfactor = 1, 0.8 lag, and 0.6 lead.

- Plot the variation of
  - Efficiency with load VA for each power factor
  - Regulation with powerfactor.

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5 Questions to be answered

- Which winding (LV or HV) should be kept open while conducting OC test? Justify your answer.
- Assume that the transformer has the following name plate ratings:
  40 kVA, 440 V/ 11 kV, 50 Hz
  what do these numbers imply?
- Comment on the nature of the current waveform drawn from the source during OC test for (i) 50%, (ii) 100% and (iii) 110% of the rated voltage.
- Can the regulation be negative? What does it signify?
- Assume that you have been given a transformer manufactured in the US (The supply voltage and frequency are 110 V and 60 Hz respectively). What voltage will you apply if this transformer is to be used in this country? Justify your answer.
- Assume that you have been given two transformers of identical VA, and voltage ratings. But one of them is a 10 kHz transformer and another is a 100 Hz transformer. Just by inspection, how would you identify which one is the high frequency transformer? Justify your answer.

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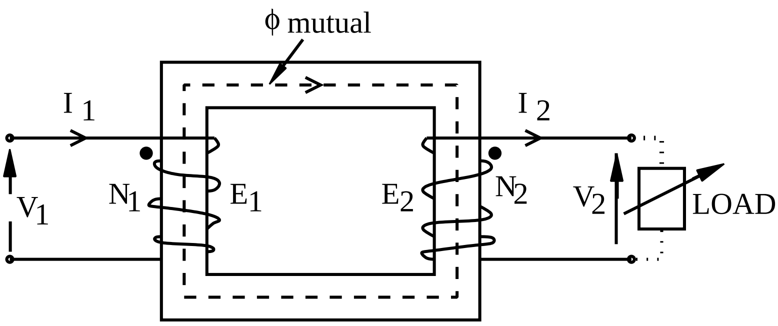
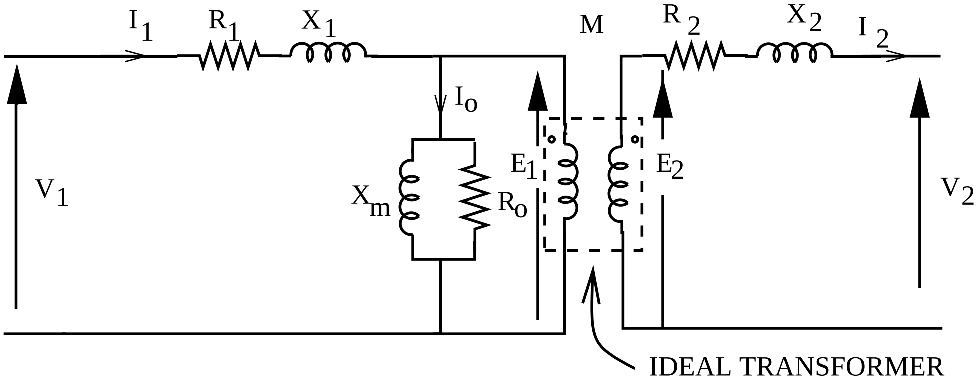
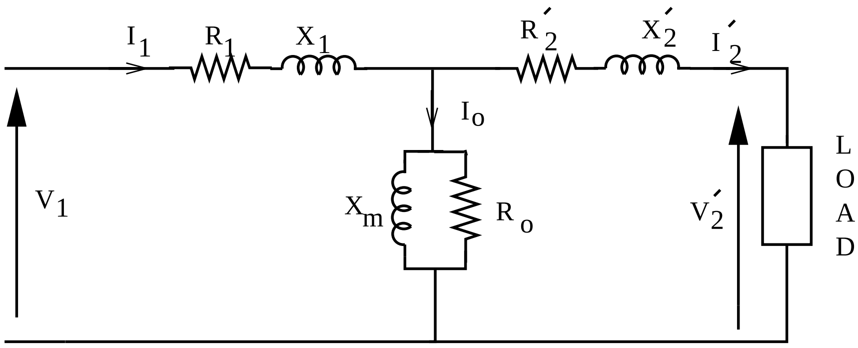


Fig.1 Elementary Transformer



(a)



(b)

Fig.2 Development of Transformer Equivalent Circuit

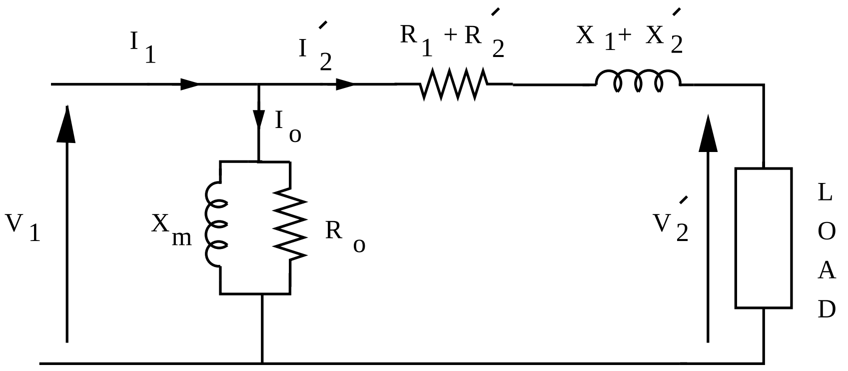


Fig.3 Approximate equivalent circuit of transformer

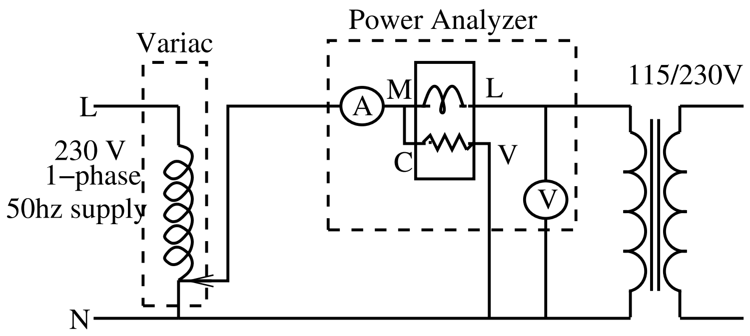


Fig.4 Circuit Diagram for No−Load Test

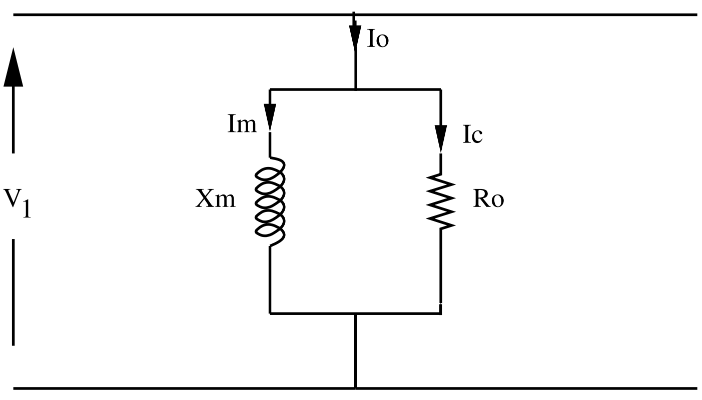


Fig.5(a) Equivalent Circuit on No−Load

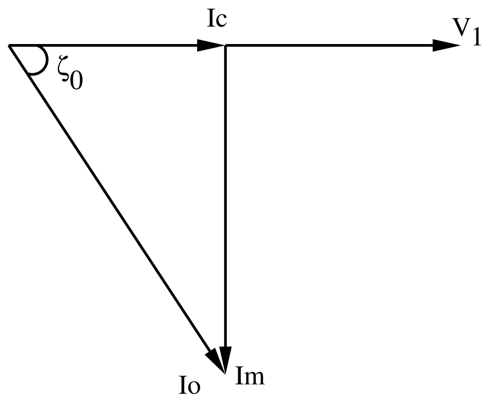


Fig.5(b) Phasor Diagram on No−Load

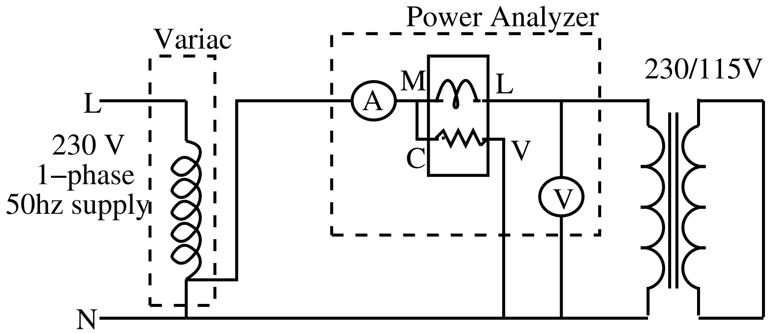


Fig.6(a) Circuit Diagram for Short−Circuit Test

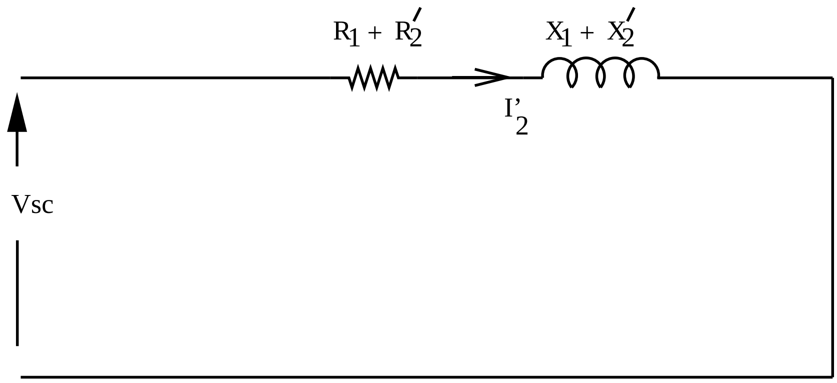


Fig.6(b) Equivalent Circuit on Short Circuit

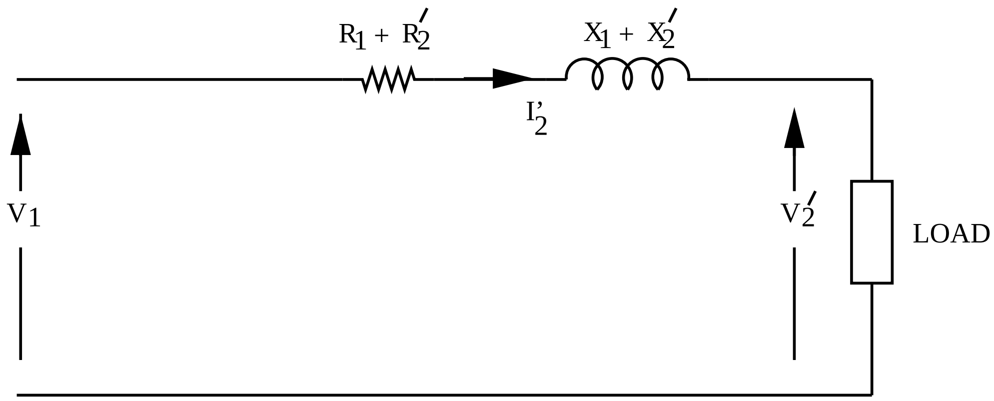
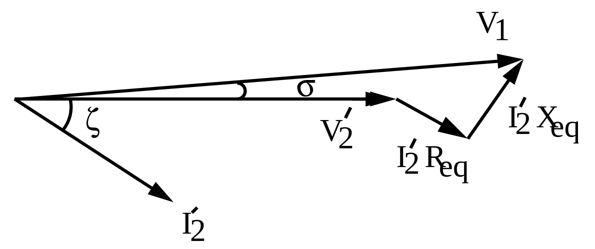
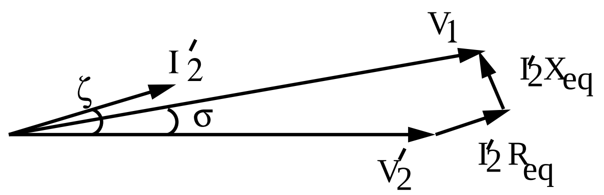


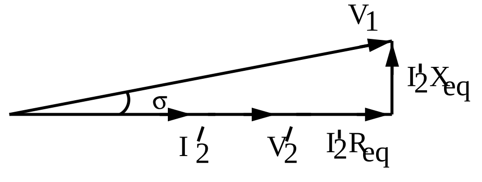
Fig.7 Equivalent Circuit to determine Regulation



(a) Lagging Power Factor



(b) Leading Power Factor



(c) Unity Power Factor

Fig.8 Vector diagram for various load conditions