Electrical Machine

Contents

1. Transformer

Theory at a Glance (For IES, GATE, PSU)

Introduction

The transformer is a static electromagnetic device, which transfers electrical energy from one electrical circuit to another electrical circuit through the medium of magnetic field (magnetic coupling) and without a change in the frequency. The two circuits are not connected electrically, but coupled magnetically and electromagnetic energy conversion takes place. Since a transformer has no moving part, it has maximum efficiency of all machines. Important applications of a transformer are:

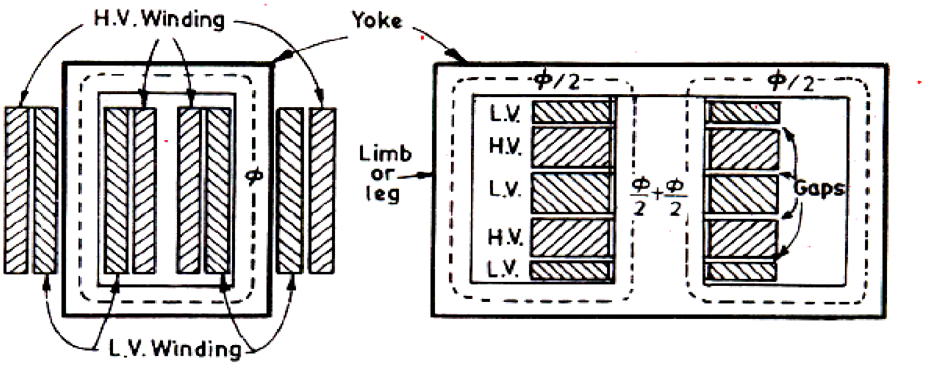
1. For changing voltage and current levels from one circuit to another.
2. For impedance matching of a source and its load for maximum power transfer in electronic and control circuits.
3. For isolating DC while permitting flow of AC between two circuits or for isolation.

Main Application

Voltage generation is limited to 11kV due to insulation limits, but transmission of electrical power is more economical at higher voltage. So the most important application of power transformer is to step-up & step-down the voltage of the transmission lines.

Transformer Construction

Based on the manner in which the windings are wound around the magnetic core, the transformers are of two types: (i) core type and (ii) shell type



(a) **(b)**

Constructional details of single-phase (a) core-type transformer (b) shell-type transformer

Core

The magnetic core is a stack of thin silicon-steel laminations about 0.35 mm thick for 50 Hz transformer. It provides magnetic coupling between two (or more) isolated electrical circuits. To minimize core losses, core should be made of a highly permeable material. Hence, core is made from cold-rolled grain-oriented sheet-steel (C.R.G.O.) magnetized in the rolling direction. **The core is laminated to reduce the eddy current losses**.

In the core-type, the windings surround a considerable part of the steel core. In the shell-type, the steel core surrounds a major part of the windings. For single-phase transformers, core-type has two legged core while shell-type has three legged core.

Both the high voltage winding and the low voltage winding are divided on both the limbs. When half of winding is placed on either limb, the leakage flux would correspond to only half magnetic vector. **Thus, the windings are divided to reduce leakage flux** (flux that links one winding and not the other)**.** The low voltage (L.V.) winding is placed near to the steel core in order to minimize the amount of insulation required.

In the shell type transformer, the L.V. and H.V. windings are wound over the central limb and are interleaved or sandwiched as shown in Figure. The bottom and top L.V. coils are of half the size of other L.V. coils. Shell-type transformers are preferred for low-voltage low-power levels, whereas core-type construction is used for high-voltage, high-power transformers.

In core-type transformer, the flux has a single path around the legs or yokes. In the shell-type transformer, the flux in the central limb divides equally and returns through the outer two legs.

There are two types of windings employed for transformers. **The concentric coils are used for core-type transformers and interleaved (or sandwiched) coils for shell-type transformers.**

During the assembly of the steel core, the butt joints are **staggered** to reduce the reluctance and it provides mechanical strength to the core. Low power transformers are air-cooled where as large power- transformers are immersed in oil for better cooling. In oil-cooled transformers, oil acts as coolant and as insulating medium.

Pulse transformers have cores made of **soft ferrites**. In communication circuits (high frequency circuits), cores are made of powdered **ferromagnetic alloys**. Air-core (core of non-magnetic material) transformers are used in radio devices.

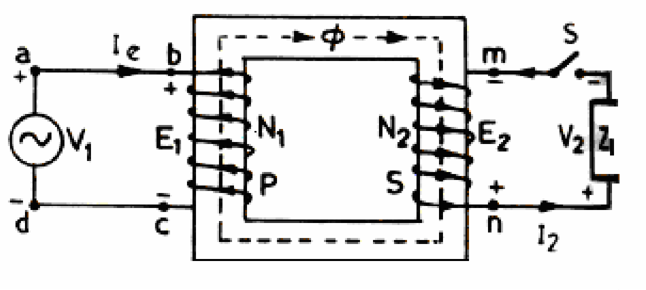
The cores are **stepped** in transformers to obtain optimum use of the copper material used for winding and ferroelectric material for core.

Principle of Transformer Action

A transformer works on the principle of electromagnetic induction according to which emf is induced in a coil if it links a changing flux. When the primary winding is supplied with an ac source, an **alternating mutual flux** linking both the windings is set up, which induces voltage in the primary and secondary windings.

Thus the transformer action requires the existence of alternating mutual flux linking the various windings on a common magnetic core.

Ideal Two-winding Transformer



Assumptions for an ideal transformer

1. No winding resistance – hence, copper losses are neglected.
2. No core losses – negligible Hysteresis and core losses.
3. The magnetization curve of the magnetic material is linear i.e. core has constant permeability.
4. No leakage flux i.e. all the flux is confined to magnetic core.

Transformer Action

1. The primary winding is excited by an alternating sinusoidal source V_1.
2. It establishes excitation current I_φ in the primary winding which produces excitation mmf = $N_1 I_\varphi$ (I_φ = excitation current).
3. Mmf will produce flux φ, which is in time phase with I_φ and varies sinusoidally, in the core which will induce emf in primary and secondary winding.

   Let the sinusoidal variation of flux φ be expressed as $\varphi = \varphi_{\max} \sin \omega t$

   The emf induced e_1 in primary N_1 turns $e_1 = -N_1 \frac{d\phi}{dt} = -N_1 \omega \phi_{\max} \cos \omega t$

   The maximum value of e_1, $E_{1\max} = N_1 \varphi_{\max} \omega$

$$\text{Rms value } = E_1 = \frac{E_{1\max}}{\sqrt{2}} = \frac{2\pi f N_1 \phi_{\max}}{\sqrt{2}} = 4.44 f \phi_{\max} N_1 \text{ volts}$$

   The current I_e in the primary is assumed to flow along the path abcda. The emf e_1 induced in N_1 turns must be in such a direction so as to oppose the cause, *i.e.* I_e, as per Lenz's law. Therefore, the direction of e_1 is as shown by the arrows in the primary N_1

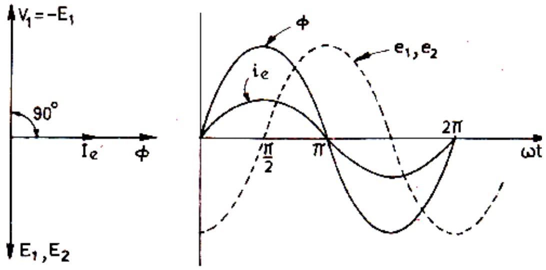
turns and it is seen to oppose V_1. Since primary winding resistance is negligible, e_1, at every instant must be equal and opposite to V_1. Hence, $V_1 = -E_1$.

The emf induced in the secondary $e_2 = -N_2 \frac{d\phi}{dt} = -N_2 \omega \phi_{\max} \cos \omega t$

Rms valve of emf E_2 is

$$E_2 = \frac{E_{2\max}}{\sqrt{2}} = \frac{2\pi f N_2 \phi_{\max}}{\sqrt{2}} = 4.44 f \phi_{\max} N_2 \text{ volts}$$

Hence, $\frac{E_1}{E_2} = \frac{N_1}{N_2} = 4.44 f \phi_m$ *i.e.* emf per turn in primary = emf per turn in the secondary.



The phasor diagram of an ideal transformer under no load conditions is as below:

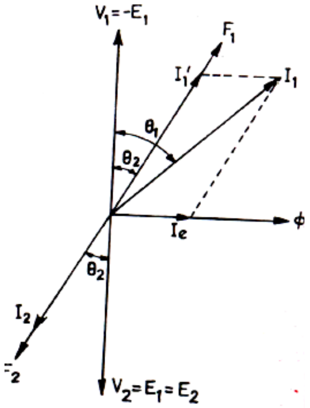
Emfs E_1 and E_2 lag the mutual flux that induces them by 90° The applied voltage V_1 leads the flux by 90°.

4. If secondary circuit is completed, it will produce a secondary current (load current). This load current produces a demagnetizing mmf (Lenz's Law). The direction of secondary current I_2 should be such that the secondary mmf F_2 (= $I_2 N_2$) is opposite to mutual flux in the core. For F_2 to be directed against , the current I_2 must leave the terminal *n,* pass through the load and enter the terminal *m*. The secondary winding behaves like a voltage source, therefore, terminal *n* must be treated as positive and terminal *m* as negative. If secondary winding is wound in a manner opposite to that shown in the Figure, terminal *m* would be positive with respect to terminal *n*. This shows that **polarity markings of the windings in transformers depend upon the manner in which the windings are wound around the legs with respect to each other**.

In order to maintain **constant mutual flux,** the primary current will increase and produce additional magnetizing mmf such that the net mmf and flux in the core is same as in the case of no-load. This increased primary current I_1' is called load component of primary current.

$$I_1' N_1 = I_2 N_2$$

The phasor diagram of an ideal transformer is shown figure.



Impedance Transformation

For secondary circuit, $\overline{Z}_L = \dfrac{\overline{E}_2}{\overline{I}_2}$

Effective input impedance at primary terminals, $\overline{Z}_i = \dfrac{\overline{E}_1}{\overline{I}_1}$

Using turns ratio, $\overline{Z}_i = \dfrac{\overline{E}_1}{\overline{I}_1} = (\dfrac{N_1}{N_2})^2 \dfrac{\overline{E}_2}{\overline{I}_2} = (\dfrac{N_1}{N_2})^2 . \overline{Z}_L$

An impedance of Z_L when viewed 'through' a transformer of turns ratio ($N_1 : N_2$) is seen as $(N_1 : N_2)^2 Z_L$. A transformer thus acts as an **impedance converter**. The transformer can be interposed in between a source and a load to 'match' the impedance for maximum power transfer to take place.

Similarly, impedance Z_1 in the primary circuit can be transferred (referred) to secondary side as $\left[\dfrac{N_2}{N_1}\right]^2 Z_1 = Z_1'$

For an ideal transformer, it may be summarized:

(i) Voltage is transformed into direct turn ratio.

(ii) Current is transformed into inverse turn ratio.

(iii) Impedance is transformed into direct turn ratio squared.

(iv) Power remains same.

(v) Frequency remains same.

Practical Transformer

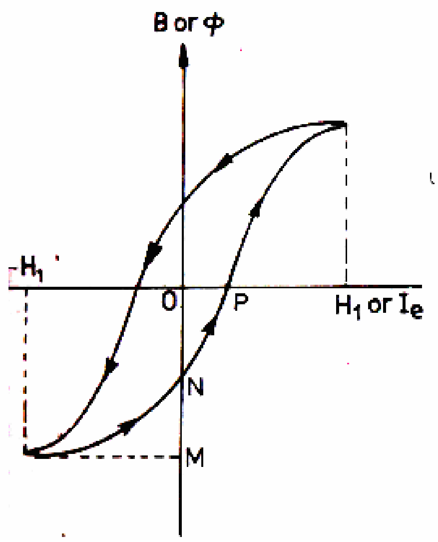
At no load

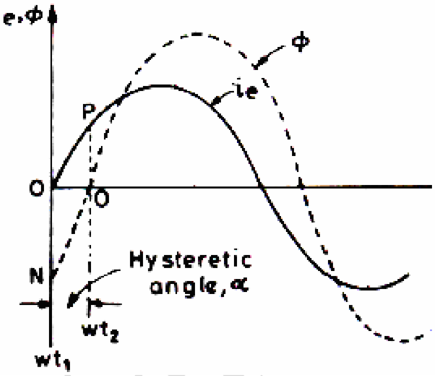
(a) Effect of transformer core loss: The core loss consists of hysteresis loss and eddy current loss and are always present in the ferromagnetic core of the transformer. Due to Hysteresis, the exciting current I_e leads the flux $_m$ by hysteretic angle α.

The exciting current consists of two components Iφ and I_c. Iφ is called reactive or magnetizing component and it provides the required magnetic flux $_m$. The second component I_c is called core-loss component. Total core loss is given as $P_c = V_1' I_c$.

$$V_1' I_c = P_c \quad \text{or} \quad I_c = \frac{P_c}{V_1'} \text{ Amp.}$$

$$I_e = \sqrt{I_m^2 + I_c^2}$$





(b) Effect of transformer winding resistance: the winding resistances are no longer considered zero and their effect is included.

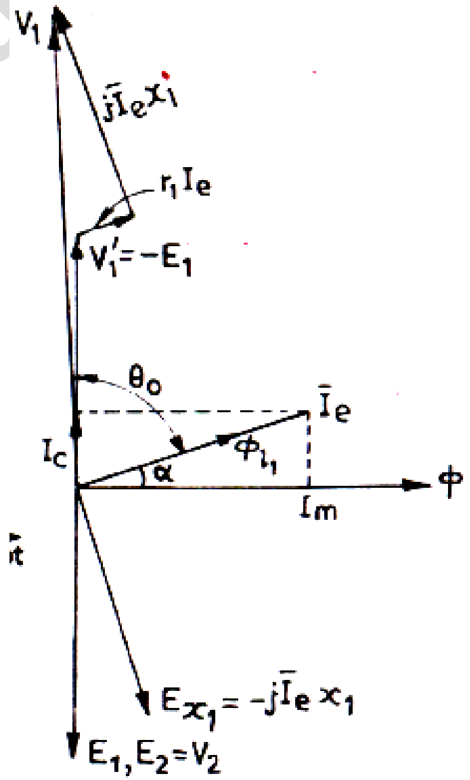
(c) Effect of leakage flux: Other than the mutual flux that links both the primary and secondary windings, there exists some leakage flux which exists only in the primary winding and is in phase with I_e. This leakage flux induces an emf in the primary winding given as $\overline{E}_{x1} = -j\overline{I}_e x_1$.

Hence total voltage drop in the primary winding and voltage in the primary at no load is

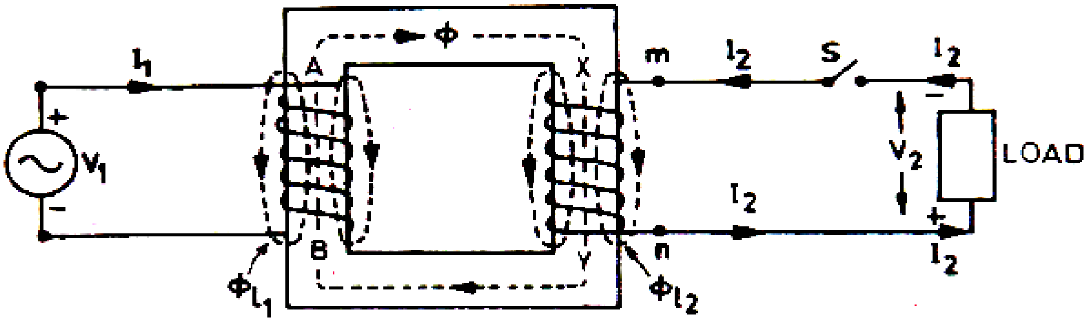
$$I_e(r_1 + jx_1) = I_e z_1$$
$$\overline{V}_1 = \overline{V}_1' + \overline{I}_e(r_1 + jx_1)$$

$\overline{E}_a$ and $\overline{E}_b$

Even at full load, primary leakage impedance drop is about 2 to 5 % of the applied voltage, so that the magnitude of V_1' or E_1 does not change appreciably from no load to full load.



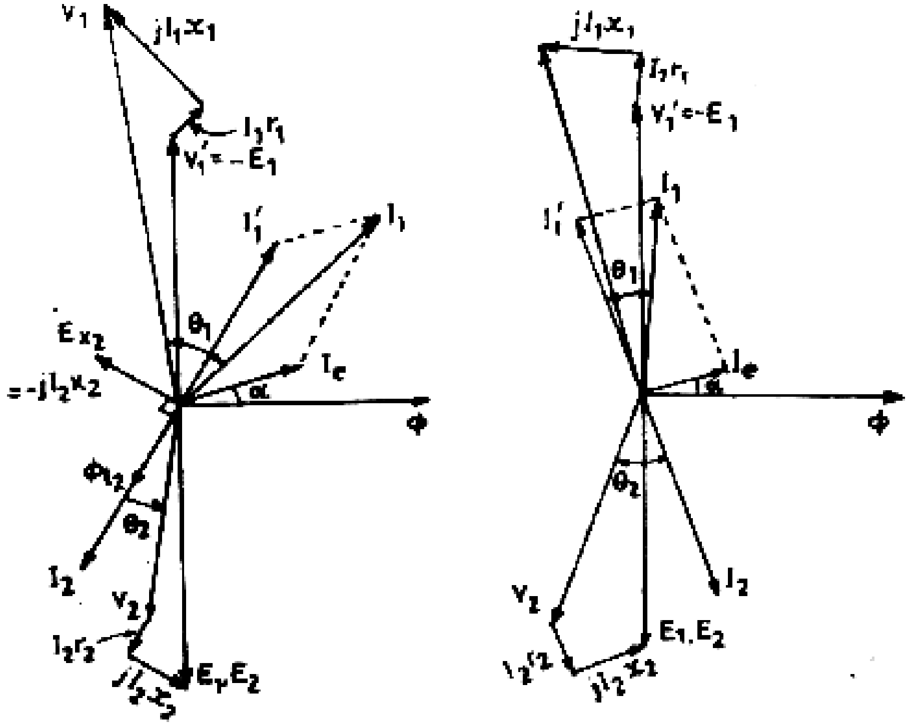
On Load



Assuming the load to have a lagging pf, I_2 lags V_2 by θ_2. Considering the resistive and leakage flux drop in the secondary winding, the voltage equation is $\overline{E}_2 = \overline{V}_2 + \overline{I}_2 \overline{z}_2$ where ($z_2 = r_2 + j x_2$).

The load component of primary current I_1' is in phase opposition to the load current I_2. The total primary current is given by the sum of I_1' and I_e (exciting current). Thus, voltage equation for the primary circuit is $\overline{V}_1 = \overline{V}_1' + \overline{I}_1 (r_1 + j x_1)$

Angle θ_1 between V_1 and I_1 is the primary pf angle under load.



Transformer phasor diagram for *(a)* lagging p.f. load and *(b)* leading p.f. load.

Leakage flux in a transformer depends on the currents in the windings.

Equivalent Circuit of a Transformer

The primary current consists of two components, load component I_1' and exciting current I_e which is composed of I_c and I . I_c is in phase with V_1' and the product V_1' I_c gives core loss. The resistance r_c in parallel with V_1' represents core loss $P_c = I_2 R_c^2 = V_1' I_c$.

The current I lags V_1' by 90° and this is represented by a reactance X such that X = V_1' / I .

In transformer analysis, it is usual to refer the secondary quantities to primary side or primary quantities to secondary side.

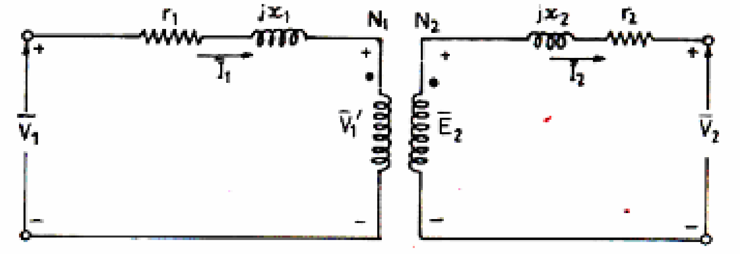
Total equivalent resistance referred to primary side

$$r_{e1} = r_1 + (N_1 / N_2)^2 r_2 = r_1 + r_2'$$

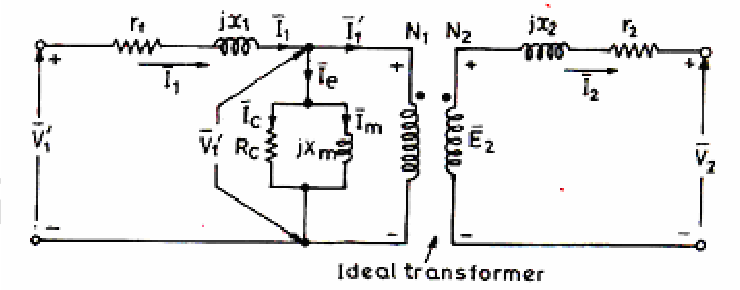
Similarly, total equivalent leakage reactance referred to primary side

$$x_{e1} = x_1 + (N_1 / N_2)^2 x_2 = x_1 + x_2'$$

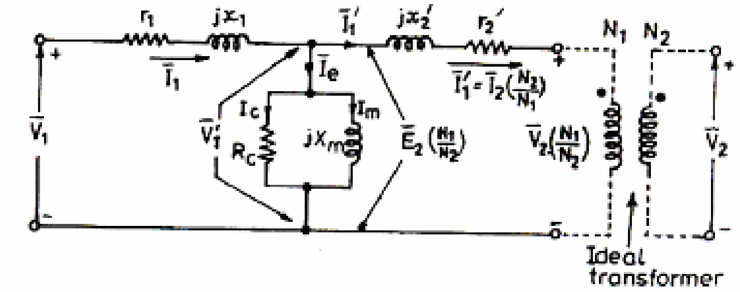
In a similar way, the resistance and leakage reactances can be referred to the secondary side.



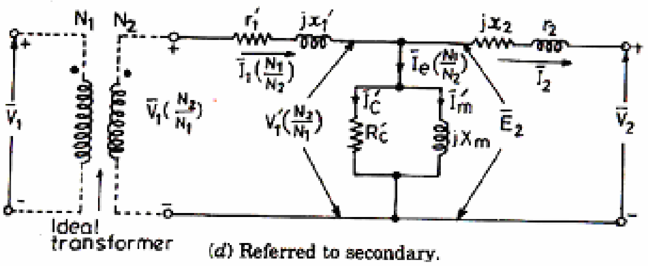
(a) Exciting current neglected.



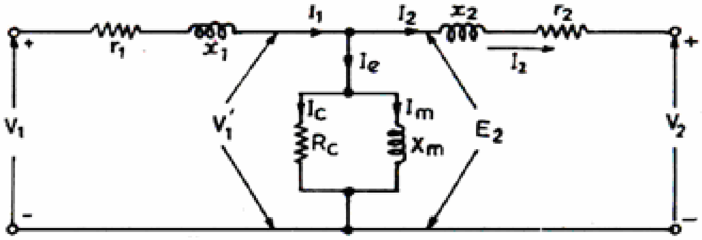
(b) Exact equivalent circuit.



(c) Referred to primary



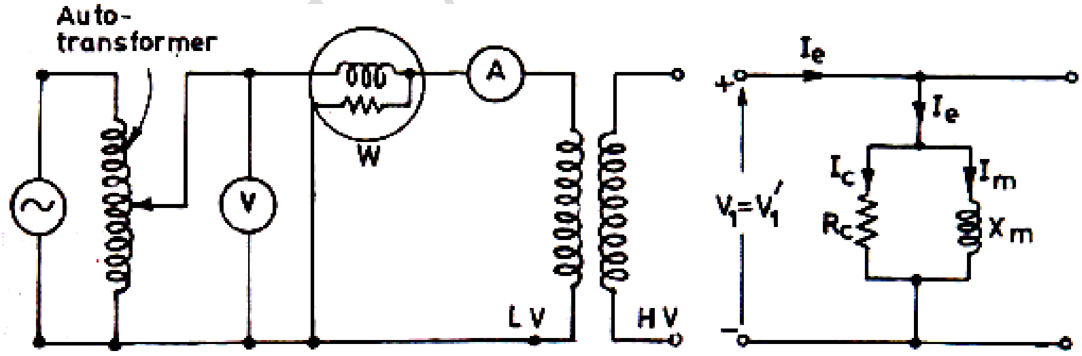
(d) Referred to secondary.



If the general equivalent circuit refers to the primary, the secondary quantities have been referred to the primary side. On the other hand, if the general equivalent circuit refers to the secondary, then the primary quantities must be referred to the secondary side.

Open-circuit and Short-circuit Tests

Open – circuit (or No Load Test): Rated voltage is applied on the low voltage side while the high voltage side is left open – circuited. All equipments are connected on the L.V. side. Only the exciting current I_e flows which is 2 – 6% of the rated full-load current. Thus, ohmic losses can be neglected. This test gives the core (constant) losses.



Let the readings be P_{OC}, I_{OC}, V_{OC}

V_{OC} = Voltmeter reading = rated LV = V_1

I_{OC} = Ammeter reading = exciting (no load) current = I_e

P_{OC} = Wattmeter reading = core losses

No load pf = $\cos\theta_0 = P_{OC} / V_1 I_e$

$I_c = I_e \cos \theta_0$ and I = $I_e \sin \theta_0$

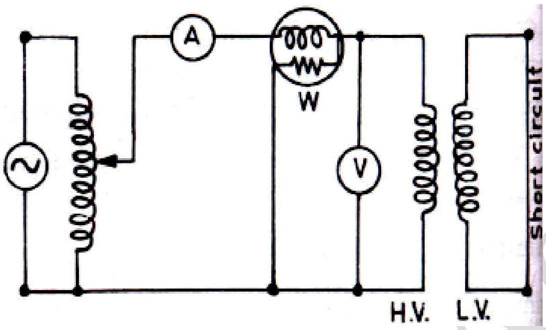
$$\mathbf{P_{OC} = V_1 I_e \cos \theta_0}$$
$$\mathbf{R_C = V_1^2 / P_{OC}}$$
$$\mathbf{I\phi = I_e \sin \theta_0}$$
$$\mathbf{X_M = V_{OC} / I_e \sin \theta_0}$$

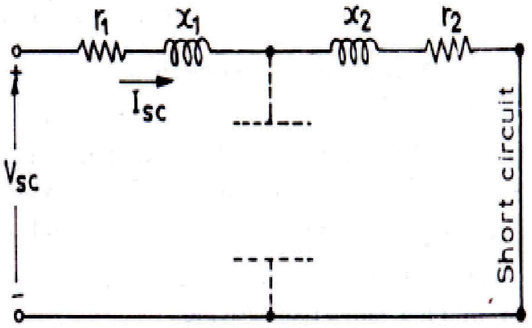
Thus, the open-circuit test gives

(i) Shunt branch parameters R_C and X_M.

(ii) Turns ratio (by connecting a voltmeter on the open circuit side).

Short – Circuit Test





Rated current is circulated in the HV side by means of an auto-transformer and LV side is short- circuited. All the instruments are placed on the HV side. Rated currents in the HV side causes rated current to flow on LV side. A primary voltage of 2 – 12% of its rated voltage is sufficient to circulate rated currents in both primary and secondary windings. Thus, core losses can be neglected.

Let the readings be P_{SC}, I_{SC}, V_{SC}

$$\mathbf{z_{eH} = V_{SC} / I_{SC}}$$
$$\mathbf{r_{eH} = P_{SC} / I^2_{SC}}$$
$$\mathbf{x_{eH} = \sqrt{z^2_{eH} - r^2_{eH}}}$$

x_{EH}, r_{EH} and z_{EH} are equivalent leakage reactance, equivalent resistance and equivalent leakage impedance referred to h.v. side.$r_1 = r_2 = r_{eH}/2$ and $x_1 = x_2 = x_{eH}/2$.

In OC test, the excitation current is 2-6% of rated full load current. Hence, voltage drop will be very small and also copper loss taking place in excited winding (LV) winding will be very small. It means OC test gives only shunt branch parameters and core loss. Thus, OC test gives shunt branch parameters.

In SC test, full load current can be flown at a very small voltage (2 – 12% of rated voltage). Hence, it only gives series parameters and full load copper losses.

OC test is performed on LV side and SC test on HV side because rating of measuring instruments lie in ordinary measurement zone.

Per-unit system

Choosing nominal voltage and nominal current on the primary side of a transformer as the base values V_{base} and I_{base}. Other base values like volt ampere S_{base}, short circuit impedance Z_{base} can be calculated from those values.

$$P_{base}, Q_{base}, S_{base} = V_{base} * I_{base}$$
$$R_{base}, X_{base}, Z_{base} = V_{base} / I_{base}$$

Then , p.u. values are given as

$$V_{p.u} = \frac{V(volt)}{V_{base}(volt)},$$
$$I_{p.u} = \frac{I(Amps)}{I_{base}(amps)} = \frac{I(amps)}{\frac{S_{base}}{V_{base}}}$$
$$Z_{p.u} = \frac{Z(ohm)}{Z_{base}(ohm)} = Z(ohm) * \frac{I_{base}}{V_{base}} = Z(ohm).\frac{S_{base}}{V_{base}^2}$$

An impedance $Z_{p.u.old}$ on the old base of $S_{baseold}$ and $V_{baseold}$ shall get modified on new base $S_{basenew}$,$V_{basenew}$ as

$$Z_{p.u.new} = (Z_{p.u.old} \cdot \frac{V_{base\quad old}^2}{S_{base\quad old}}) \frac{S_{base\quad new}}{V_{base\quad new}^2}$$

Major application of using pu system for transformers lies due to that fact that the **transformer equivalent parameters in p.u. system are equal on both hv and lv sides.**

Voltage Regulation

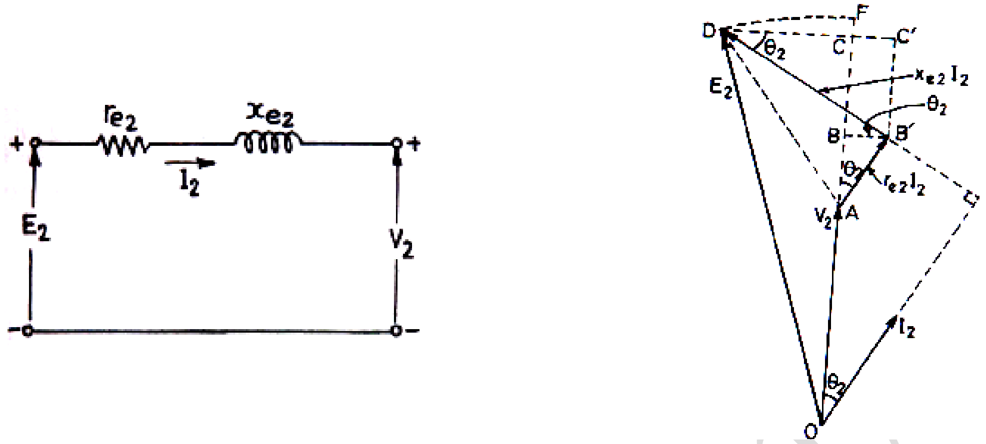
It is defined as the change in secondary terminal voltage (load terminal voltage) expressed as a percent of rated secondary voltage when a load at a specified p.f. is reduced to zero with the primary applied voltage held constant.

$$\text{Voltage regulation} = \frac{E_2 - V_2}{\text{secondary rated voltage}} \text{in p.u.}$$

The change in secondary terminal voltage with load current is due to the primary and secondary leakage impedances of the transformer. The magnitude of this change depends on the load pf, load current, total resistance and total leakage reactance of the transformer.

For a good power transformer, no load to full load voltage variation should be small, i.e. voltage regulation should be minimum.

The voltage regulation of a transformer can be obtained from its approximate equivalent circuit referred to primary or secondary.



Approximate equivalent circuit of a 2-winding transformer, referred to secondary and the phasor diagram of the circuit for a lagging power factor load.

$$\begin{aligned} E_2 &= OC = OA + AB + BC (or\, B'C') \\ &= OA + AB' \cos\theta_2 + DB' \sin\theta_2 \\ &= V_2 + I_2 r_{e2} \cos\theta_2 + I_2 x_{e2} \sin\theta_2 \end{aligned}$$

Thus the voltage drop in the secondary terminal voltage

$$= E_2 - V_2 = I_2 r_{e2} \cos\theta_2 + I_2 x_{e2} \sin\theta_2$$

Per unit voltage regulation for any load current I_2 is

$$\frac{E_2 - V_2}{E_2} = \frac{I_2 r_{e2}}{E_2} \cos\theta_2 + \frac{I_2 x_{e2}}{E_2} \sin\theta_2$$

$\frac{I_2 r_{e2}}{E_2} = \frac{\text{voltage drop across } r_{e2} \text{ at rated current}}{\text{Rated (=base) voltage } E_2}$ = p.u. equivalent resistance or p.u. resistance drop = ε_r

$$\varepsilon_r = \frac{I_2 r_{e2}}{E_2} = \frac{I_{2r}{}^2 r_{e2}}{E_2 I_{2r}} = \frac{\text{Ohmic loss at rated current}}{\text{Rated VA}}$$

Similarly, for rated current I_2, let $\frac{I_2\, x_{e2}}{E_2} = \varepsilon_x$

The per unit voltage regulation at rated current is given by $\varepsilon_r \cos\theta_2 + \varepsilon_x \sin\theta_2$

At lagging p.f., voltage regulation would be always positive.

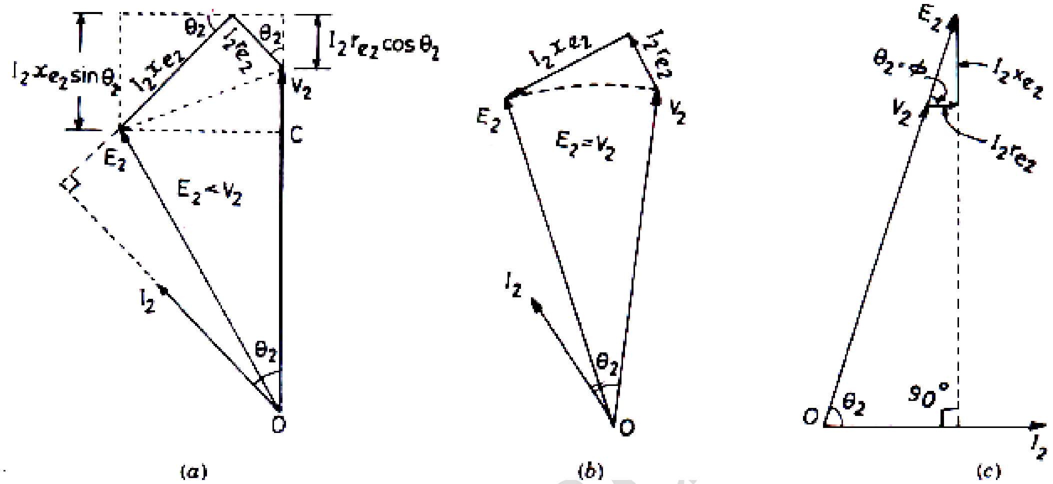
At leading p.f., $E_2 = OC = V_2 + I_2 r_{e2} \cos\theta_2 - I_2 x_{e2} \sin\theta_2$ $\quad E_2 - V_2 = I_2 r_{e2} \cos\theta_2 - I_2 x_{e2} \sin\theta_2$

$\therefore$ **p.u. voltage regulation at any load current I_2 is given by**

$$\frac{I_2 r_{e2}}{E_2}\cos\theta_2 - \frac{I_2 x_{e2}}{E_2}\sin\theta_2$$

In case I_2 is the rated (or full-load) current, then p.u. voltage regulation is given by $\varepsilon_r \cos\theta_2 - \varepsilon_x \sin\theta_2$

Hence, at leading p.f. voltage regulation may become negative.



Phasor diagrams for 1-phase transformer for (a) negative voltage regulation (V.R.) (b) zero V.R. and (c) maximum V.R.

Condition for Zero Voltage Regulation

Voltage regulation varies with load power factor. If load power factor is varied with constant values of load current and secondary emf, then zero voltage regulation will occur when

$$\varepsilon_r \cos\theta_2 + \varepsilon_x \sin\theta_2 = 0$$

$$\tan\theta_2 = -\frac{\varepsilon_r}{\varepsilon_x} = -\frac{I_2 r_{e2}}{E_2 \frac{I_2 x_{e2}}{E_2}} = -\frac{r_{e2}}{x_{e2}}$$

Magnitude of load pf, $\cos\theta_2 = x_{e2}/z_{e2}$

The negative value of tan θ_2 indicates that zero voltage regulation occurs when load pf is leading. For leading p.f.s. greater than x_{e2}/z_{e2}, the voltage regulation will be negative, i.e. the voltage will rise from its no load value, as the transformer load is increased.

Condition for Maximum Voltage Regulation

P.U. voltage regulation $= \varepsilon_r \cos\theta_2 + \varepsilon_x \sin\theta_2$

$$\frac{d}{d\theta_2}(\text{p.u. regulation}) = -\varepsilon_r \sin\theta_2 + \varepsilon_x \cos\theta_2 = 0$$

$\tan\theta_2 = \frac{\varepsilon_x}{\varepsilon_r} = \frac{x_{e2}}{r_{e2}}$ i.e. $\cos\theta_2 = \frac{r_{e2}}{z_{e2}}$

Maximum voltage regulation occurs at a lagging load p.f.

For max VR, lagging load p.f. angle should be equal to leakage impedance angle. The magnitude of maximum voltage regulation is equal to the p.u. value of the equivalent leakage impedance z_{e2} of the transformer.

Transformer Losses and Efficiency

There are mainly two kinds of losses (i) core losses (ii) ohmic losses

Core loss P_C: Core loss consists of hysteresis loss P_h and eddy current losses P_e.

i.e. $P_c = P_h + P_e$

$P_h = K_h f B_m^x$

$P_e = K_e f^2 B_m^2$

The Stein Meitz constant x varies 1.5 – 2.5. (x = 1.6, if unstated).

$V = \sqrt{2}\pi\ f\ N\ B_m\ A_i$

For a transformer number of turns N and net core area A_i are constant.

Hence, $P_h = K_h f \left[\frac{1}{\sqrt{2}\pi N A_i}\right]^x \left[\frac{V}{f}\right]^x$

$Ph = k_h V^x f^{1-x}$

$$P_e = K_e f^2 \left[\frac{1}{\sqrt{2}\pi N A_i}\right]^2 \left[\frac{V}{f}\right]^2 = k_e V^2$$

1. Hysteresis loss depends upon frequency and voltage where as eddy current loss depends only on voltage (squared).
2. K_h depends upon volume of core material & permeability of core material. Thus, permeability should be as high as possible for minimum hysteresis loss.
3. K_e depends on volume of material, resistivity and thickness of lamination

By plotting P_C/f against f, P_e and P_h can be calculated separately by extrapolating the graph.

Ohmic losses: Ohmic losses occur in both the primary and secondary winding resistances. They should be calculated at standard operating temperature of electrical machines 75°.

Apart from core loss and ohmic loss, stray load loss and dielectric loss also occur.

Efficiency: The efficiency of a transformer (or any other device) is defined as the ratio of output power to input power. Thus

Efficiency $\eta = \dfrac{\text{output power}}{\text{input power}}$

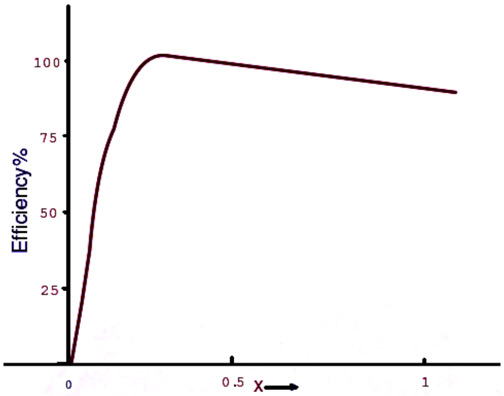
$$= \frac{V_2 I_2 \cos\theta_2}{V_2 I_2 \cos\theta_2 + P_c + I_2^2 r_{e2}}$$

Where P_c = total core loss,

$I_2^2 r_{e2}$ = total ohmic losses,

$V_2 I_2$ = output VA,

And $\cos\theta_2$ = load p.f.



The efficiency can also be expressed as

$$\eta = \frac{\text{output power}}{\text{input power}} = \frac{\text{input power} - \text{losses}}{\text{input power}} = 1 - \frac{\text{losses}}{\text{input power}}$$

Condition for maximum efficiency:

$$\eta \text{ at full load} = 1 - \frac{P_c + P_{sc}}{(\text{Rated VA})\cos\theta_2 + P_c + P_{sc}}$$

As before, maximum efficiency occurs when variable ohmic loss = Constant core loss,

$$\eta = 1 - \frac{P_c + n^2 P_{sc}}{n(\text{Rated VA})\cos\theta_2 + P_c + n^2 P_{sc}}$$

As before, maximum efficiency occurs when variable ohmic loss = Constant core loss,

$$n^2 P_{sc} = P_c \qquad \Rightarrow \qquad n = \sqrt{\frac{P_c}{P_{sc}}}$$

Above equation can now be re-written as

$$(kV\,A)_{max} \cdot \eta = (n)\,(kVA)_{rated}$$

$$\eta = \frac{\cos\theta_2}{\cos\theta_2 + \dfrac{P_c}{V_2 I_2} + \dfrac{I_2^2 r_{e2}}{V_2 I_2}}$$

$$\eta \text{ at full load} = 1 - \frac{P_c + P_{sc}}{(\text{Rated VA})\cos\theta_2 + P_c + P_{sc}}$$

At any other load current, say nI_{fl}, the efficiency is given by

$$\eta = 1 - \frac{P_c + n^2 P_{sc}}{n(\text{Rated VA})\cos\theta_2 + P_c + n^2 P_{sc}}$$

Maximum efficiency occurs when variable ohmic loss = constant core loss,

$$n^2 P_{sc} = P_C$$

$$n = \sqrt{\frac{P_c}{P_{sc}}}$$

Hence, $(kVA)_{\max\ \eta} = (n)(kVA)_{rated}$

The maximum efficiency, for a constant load current, occurs at unity power factor. The maximum efficiency in case of power transformers occurs when core loss is equal to full load copper loss.

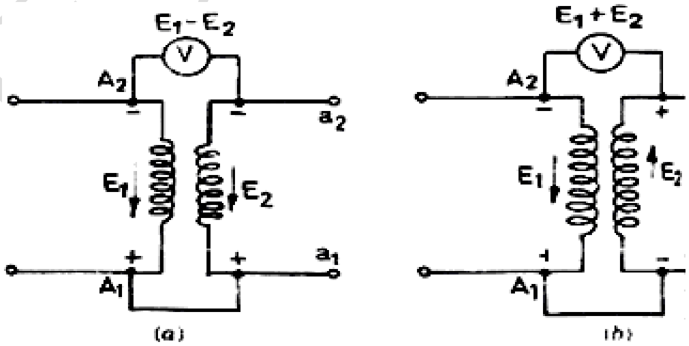
Power transformers are used at the sending and receiving ends of a high-voltage power transmission line for stepping up or stepping down the voltage. These transformers are manipulated to operate almost always at or near their rated capacity (kVA rating). In view of this, **a power transformer is designed to have maximum efficiency at or near its full load (rated) kVA**.

A distribution transformer has its secondary directly connected with the consumer's terminals. The load on a distribution transformer varies over a wide range during a 24 hour day. Since the primary of distribution transformers are always energised and, therefore, the core loss takes place continuously. In view of this, the distribution transformers are designed to have very low value of core loss. But for reduced core loss P_c, the maximum efficiency may occur at about one-half of its rated kVA. **Hence, the choice of a distribution transformer is based on energy efficiency**. Energy efficiency of a transformer is defined as the ratio of total energy output for certain period to the total energy input for the same period. When energy efficiency is computed for a day of 24 hours, it is called **all day efficiency**.

$$\text{All day } \eta = 1 - \frac{\text{daily Losses in kWh}}{\text{daily Input in kWh}}$$

Testing of Transformers

(A) Polarity Test



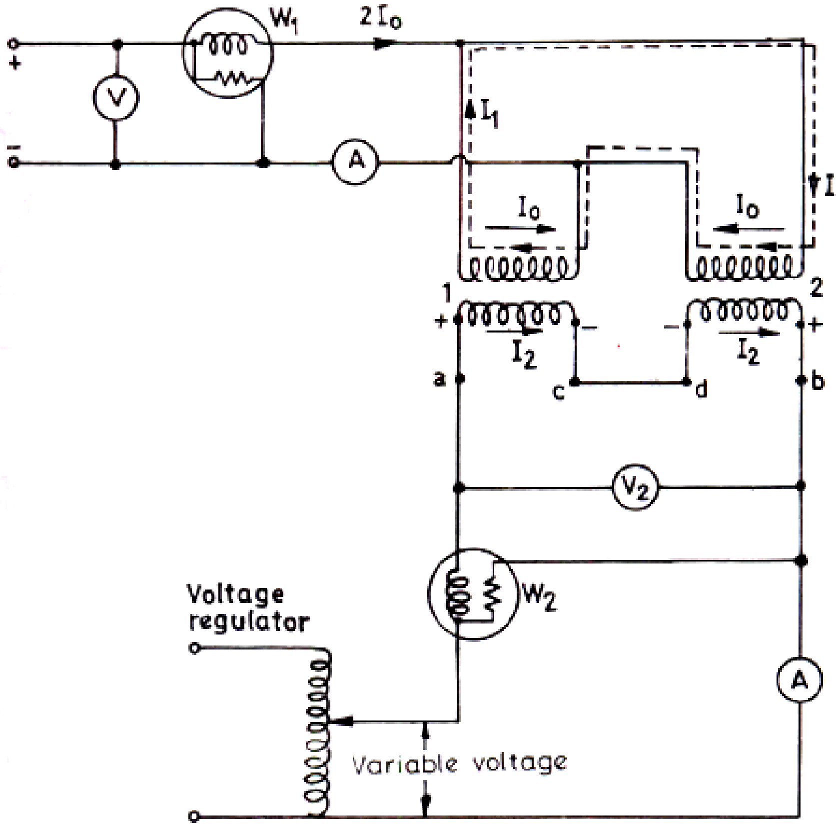
Polarity test on a two winding transformer to be operated in parallel (a) subtractive polarity and (b) additive polarity

On the primary and secondary sides of a two-winding transformer, one terminal is positive w.r.t. the other terminal at any one instant. These relative polarities of the primary and secondary terminals must be known if the transformers are to be operated in parallel or are to be used in poly-phase circuits. Terminals A_1 and A_2 are marked polarities arbitrarily. A_1 is connected to one of the secondary terminals and a voltmeter is connected between A_2 and other end of the secondary winding. Suitable voltage is applied on the HV side. Voltmeter reading is recorded between A_2 and other secondary terminal. If the reading is (E1 – E2), then secondary terminal connected to A_1 is marked a_1 and has same polarity as A_1. If the reading is (E1 + E2), then the secondary terminal connected to A_1 is marked a_2 and has opposite polarity as A1.

(B) Load Test (Back to back or Sumpner's test)

This test is used to determine maximum temperature rise in the transformer. This test on **single-phase transformers** requires two identical units with their primaries connected in parallel and are energized at rated voltage and frequency. With secondaries open, the wattmeter W_1 records the core losses of both the transformers. The two secondaries should connected in series with their polarities in phase opposition ($V_{ab} = 0$). Since $V_{ab} = 0$, current in ab = 0.

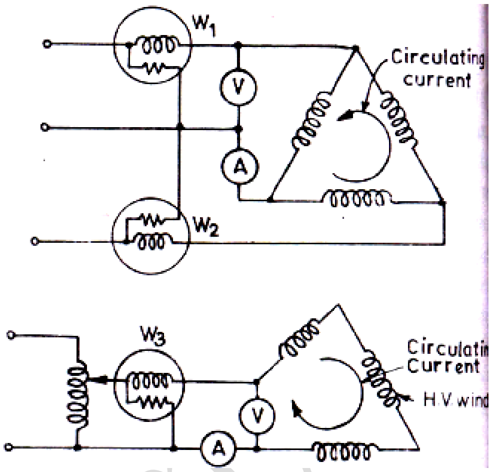
A voltage is injected in the secondary circuit by a voltage regulator till rated current flows in the two series-connected secondaries. Hence, primary winding also carry rated current. V_2 gives the sum of leakage impedance drops in both the windings. The low-injected voltage gives full load currents in primary and secondary windings and hence full load ohmic losses of both transformers are given by wattmeter W_2. Hence, $W_1 = 2P_c$ and $W_2 = 2P_{sc}$.



Sumpner's (or back to back) test on two identical single-phase transformers.

Load test on three-phase transformers

The primary and secondary windings are connected in delta. The lv winding is excited at normal voltage and frequency. W_1 and W_2 record the total core loss. The voltage injected in hv winding in open-delta is adjusted till full load current flows in it (hence, in lv winding also). W_3 records ohmic losses in all three phases. The magnitude of the low-injected voltage in the open delta is equal to (full load current) (3 z_{eH}).



Parallel Operation

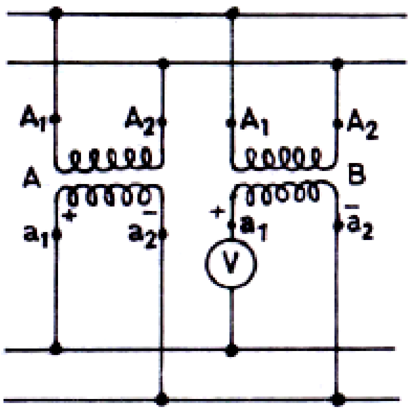
Parallel operation increases load sharing capacity by sharing more current.

Advantages of parallel operation:

1. Improved reliability.
2. Operation becomes more economic and efficient.

Conditions for Parallel Operation:

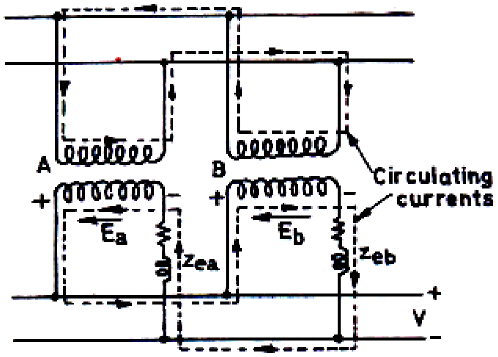
1. The transformers must have the same voltage ratios otherwise a circulating current will flow.
2. The per unit leakage impedances of the transformers based on their own kVA ratings must be equal otherwise transformer with smaller leakage impedance will share more load.
3. The ratio of equivalent leakage reactance to equivalent resistance, *i.e.* x_e/r_e should be same for all the transformers.
4. The transformers should be connected in correct polarity, otherwise large circulating currents will flow. (condition to be followed strictly).

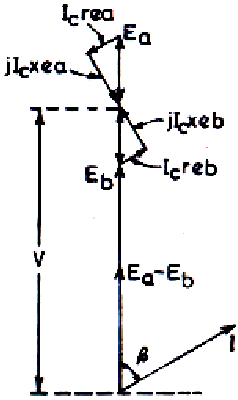


No – load operation

If no-load secondary voltages $\overline{E}_a$ and $\overline{E}_b$ are unequal or are out of phase, then the resultant voltage $\overline{E}_a$ - $\overline{E}_b$ will circulate a current I_c given by $\overline{I}_c = \dfrac{\overline{E}_a - \overline{E}_b}{\overline{z}_{ea} + \overline{z}_{eb}}$

z_{ea} and z_{eb} are equivalent leakage impedances referred to the secondaries of transformers A and B.





The circulating current flows in both primary and secondary windings due to transformer action and gives rise to additional ohmic losses and, therefore, reduce the efficiency of the parallel-operation.

The terminal voltage V on the secondary side of both the transformers must be same.

$$\overline{E}_a - \overline{I}_c \overline{z}_{ea} = \overline{E}_b + \overline{I}_c \overline{z}_{eb} = \overline{V}$$

The angle β by which I_c lags Ea – Eb is given by

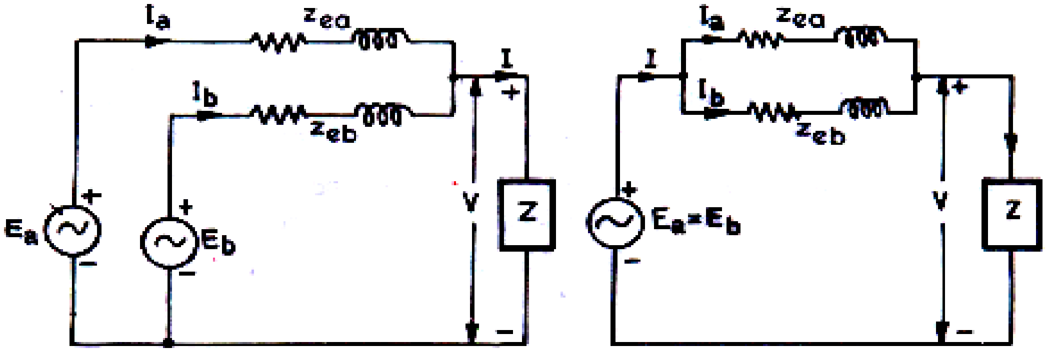
$$\beta = \tan^{-1} \frac{x_{ea} + x_{eb}}{r_{ea} + r_{eb}}$$

Thus, at no load, the effect of circulating current I_c is to boost lower voltage E_b to V and to reduce the higher voltage E_a to V.

On-load operation

Case I: Equal voltage ratio

In such case, secondary no-load voltages are equal



Circuit modelling of two transformers in parallel

The common secondary load voltage *V* and load current *I* is shared as *l*$_a$ and *I*$_b$ by the transformers *A* and *B* respectively. The voltage equation for *B* is:

$$\overline{E}_a - \overline{I}_a \overline{z}_{ea} = \overline{V} = \overline{I}\,\overline{Z}$$

Since $\overline{E}_a = \overline{E}_b ; \overline{E}_b - \overline{I}_a \overline{z}_{ea} = \overline{V} = \overline{I}\,\overline{Z}$

The voltage equationfor B is $\overline{E}_b - \overline{I}_b \overline{z}_{eb} = \overline{V} = \overline{I}\,\overline{Z}$

or $\overline{I}_a \overline{z}_{ea} = \overline{I}_b \overline{z}_{eb}$

$$\overline{I} = \overline{I}_a + \overline{I}_b = \overline{I}_a + \frac{\overline{I}_a \overline{z}_{ea}}{\overline{z}_{eb}}$$

$$\overline{I}_a = \overline{I} \frac{\overline{z}_{eb}}{\overline{z}_{ea} + \overline{z}_{eb}}$$

$$\overline{I}_b = \overline{I} \frac{\overline{z}_{ea}}{\overline{z}_{ea} + \overline{z}_{eb}}$$

$$\overline{S}_a = \overline{S} \frac{\overline{z}_{eb}}{\overline{z}_{ea} + \overline{z}_{eb}}$$

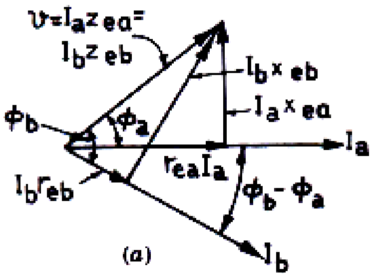
$$\overline{S}_b = \overline{S} \frac{\overline{z}_{ea}}{\overline{z}_{ea} + \overline{z}_{eb}}$$

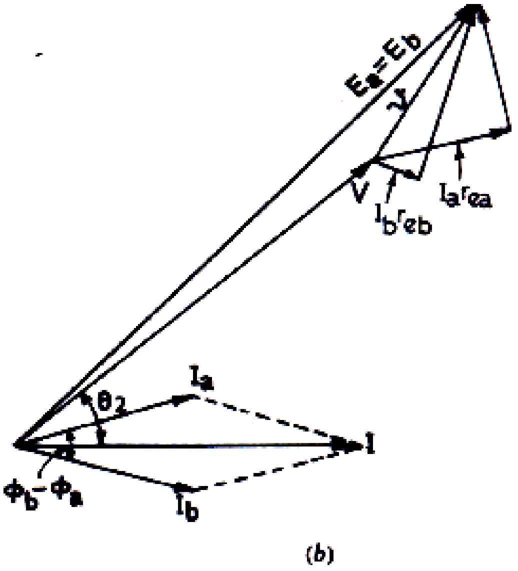
$$\overline{S}_a = \overline{V}\,\overline{I}_a ,\ \overline{S}_b = \overline{V}\,\overline{I}_b \quad \textbf{and} \quad \overline{S} = \overline{V}\,\overline{I}$$

A transformer with *lower* value of full-load current (or lower kVA rating) must have more leakage impedance in ohms. If transformers in parallel are to share the total load in proportion to their kVA ratings, then their equivalent leakage impedances *in ohms* must be *inversely proportional* to their kVA ratings.

(a) Let $Z_{ea} = Z_{eb}$, but $\frac{x_{ea}}{r_{ea}} \neq \frac{x_{eb}}{r_{eb}}$

assuming that $\phi_b > \phi_a$





$$I_a Z_{ea} = I_b z_{eb} = v.$$

$$I_a z_{ea} = I_b z_{eb} = v$$

Transformer A operates at a better *pf* and transformer *B* at a poor *pf* as compared to the load *pf*. Here z$_{ea}$ = z$_{eb}$ and *I*$_a$ =*I*$_b$*;* therefore, as per Eq., **the kVA shared by**

transformers A and B are equal. The total output kVA is reduced; because I is the phasor sum and not the arithmetic sum, of I_a and I_b.

$I_a < I/2$ and $I_b < I/2$ and **the total kVA of output is less than the sum of kVA ratings of the individual transformers**. In general when reactance to resistance ratios is not equal, their full load kVA output is less than the sum of their individual transformer kVA ratings. Also, **a transformer with greater leakage impedance angle operates at a poor *pf* as compared to the other with a lower leakage impedance angle.**

In case of equal voltage ratio and equal leakage impedances, no circulating current will flow.

(b) Let $z_{ea} > z_{eb}$, but $\frac{x_{ea}}{r_{ea}} = \frac{x_{eb}}{r_{eb}}$

When $\overline{E}_a = \overline{E}_b, I_a z_{ea} = I_b z_{eb}$ and since $z_{ea} > z_{eb}, I_a < I_b$

Both the transformers operate at the same power factor and total output kVA is increased. Since I is the arithmetic sum I_a and I_b, the total output kVA is equal to sum of kVA ratings of the individual transformers.

The kVA supplied by transformers A and B are E_aI_a and $E_bI_b \times 10^{-3}$ respectively. Here $z_{ea} > z_{eb}, I_a < I_b$, therefore $E_aI_a < E_bI_b$. It means that kVA shared by transformer A is less than that shared by transformer B.

***Note*: —** That transformer having greater equivalent leakage impedance shares less kVA (here $E_aI_a \times 10^{-3}$) and transformer having lower equivalent leakage impedance shares greater kVA.

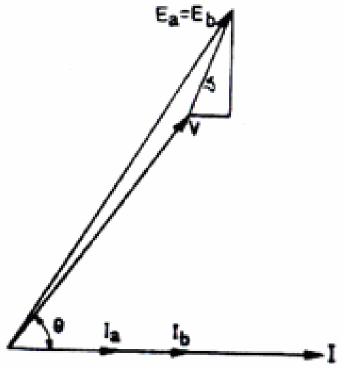
Transformers of different kVA ratings can be operated in parallel provided their equivalent leakage impedances in ohms are inversely proportional to their respective kVA ratings.

$$z_{ea} \alpha \frac{1}{S_{ar}} \text{ and } z_{eb} \alpha \frac{1}{S_{br}}$$

$$\frac{z_{ea}}{z_{eb}} = \frac{S_{br}}{S_{ar}}$$

$$I_a z_{ea} = I_b z_{eb}$$

$$\frac{I_a}{I_b} = \frac{S_{ar}}{S_{br}}$$



Parallel operation of transformers with $z_{ea} > z_{eb}$ but $\frac{x_{ea}}{r_{ea}} = \frac{x_{eb}}{r_{eb}}$

The transformer with smaller leakage impedance will get saturate first.

Case II: Unequal Voltage Ratios

1. In case of unequal voltage ratios, a circulating current will flow which will boost lower voltage magnitude and buck higher voltage magnitude so that the two transformers have same terminal voltage.

2. The currents in the two transformers will be unequal:

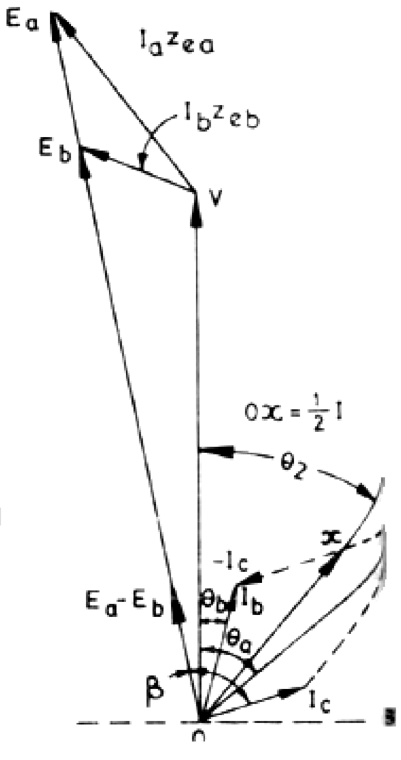
$$\bar{I}_a = \frac{\bar{1}}{2} + \bar{I}_c \text{ and } \bar{I}_b = \frac{\bar{1}}{2} - \bar{I}_c$$

3. The two transformers will operate at different power factors. The effect of circulating current is to reduce the power factor and increase the current shared by the transformer having greater no-load induced e.m.f. At the same time, the power factor of the second transformer with smaller no-load induced e.m.f. is increased and the current shared by it is decreased.

4. In case of unequal voltage ratios, a circulating current will flow which will boost lower voltage magnitude and buck higher voltage magnitude so that the two transformers have same terminal voltage.

5. The currents in the two transformers will be unequal:

$$\bar{I}_a = \frac{\bar{1}}{2} + \bar{I}_c \text{ and } \bar{I}_b = \frac{\bar{1}}{2} - \bar{I}_c$$



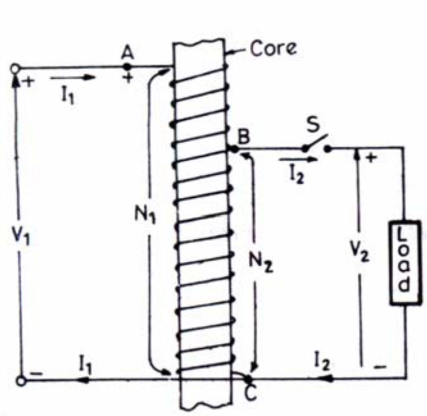
6. The two transformers will operate at different power factors. The effect of circulating current is to reduce the power factor and increase the current shared by the transformer having greater no-load induced e.m.f. At the same time, the power factor of the second transformer with smaller no-load induced e.m.f. is increased and the current shared by it is decreased.

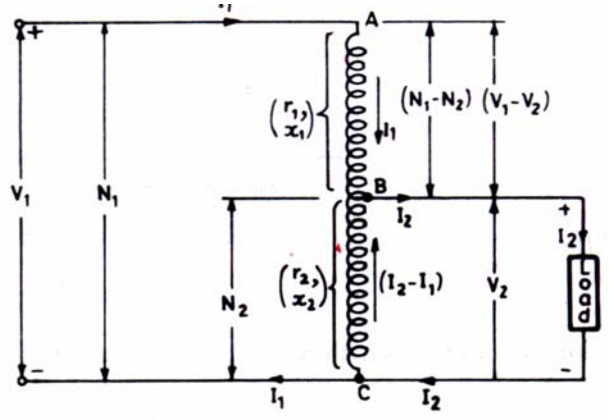
Auto - Transformers

When the primary and secondary windings are electrically connected so that a part of the winding is common to the two, the transformer is called an auto-transformer. Unlike a two winding transformer, in an auto- transformer the two windings are not electrically isolated. They are used particularly economical where the voltage-ratio required is small (less than 2) and electrical isolation of the two windings is not essential. The major applications are induction motor starters, interconnection of HV systems at voltage levels with ratio less than 2 and in obtaining variable voltage power supplies.

Advantages of auto- transformer over two-winding transformer

They require less copper in winding, hence are more economical. Further, they have lower reactance, lower losses, smaller exciting current, better voltage regulation and higher operating efficiency because in an auto-transformer a part of energy transfer is through conduction process.





The given auto-transformer has N_1 turns primary with N_2 turns tapped for a lower secondary voltage. The winding section BC is common to both primary and secondary circuits.

For a two-winding transformer, turn-ratio $a = (V_1 - V_2)/V_2$

$= (N_1 - N_2)/N_2$ where, $(N_1 > N_2)$

$= N_1/N_2 - 1$

Auto- transformer turn ratio, $a' = V_1/V_2 = N_1/N_2\ (>1)$

Therefore, $a' = 1 + a$

VA Ratings

For two-winding transformer: $(VA)_{TW} = (V_1 - V_2)I_2 = (I_2 - I_1)\,V_2$

For auto- transformer: $(VA)_{auto} = V_1 I_1 = V_2 I_2$

From above, $(VA)_{auto} = 1/[1-(1/a')]\ (VA)_{TW}$; $a' > 1$

Therefore, $(VA)_{auto} > (VA)_{TW}$; (since part of VA is transferred conductively in auto-transformer).

$$\frac{\text{Transformed VA}}{\text{Input VA}} = \frac{(V_1 - V_2)I_1}{V_1 I_1} = 1 - \frac{V_2}{V_1} = (1 - k)$$

$$\frac{\text{Conducted VA}}{\text{Input VA}} = \frac{V_2 - V_1}{V_1 I_1} = k$$

As $a' = N_1/N_2$ approaches unity, (VA)' >> (VA)

Hence, auto- transformer is used for required turn-ratio is 2 or less.

Copper requirement

For a two-winding transformer and auto-transformer having same voltage-ratio and VA rating, the weight of copper required by both of them is as below:

$$\frac{G_{auto}}{G_{TW}} = \frac{I_1(N_1 - N_2) + (I_2 - I_1)N_2}{I_1 N_1 + I_2 N_2} = 1 - \frac{N_2}{N_1} = 1 - \frac{V_2}{V_1}$$

Copper saving = $G_{TW} - G_{auto} = 1/a' \, G_{TW}$

$R_2' = \left(\frac{N_1}{N_2} - 1\right)^2 R_2$ and $X_2' = \left(\frac{N_1}{N_2} - 1\right)^2 X_2$

Three Phase Transformers

There exist two arrangements:

(i) A bank of three single – phase transformers

(ii) A three – phase transformer (single unit)

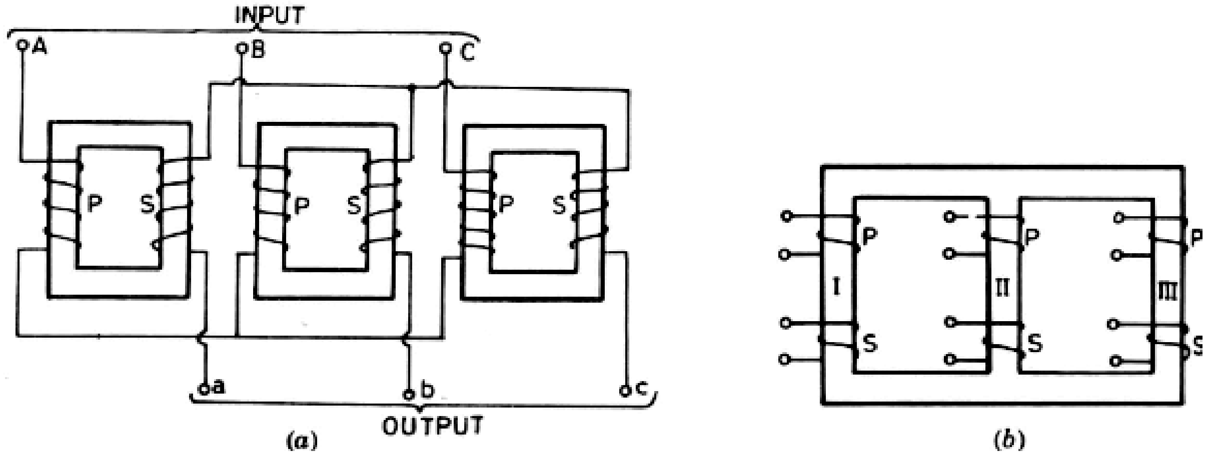


Fig. (a) Three-phase transformer bank, both windings in star (b) three-phase core-type transformer

Three-phase transformer is cheaper (about 15% less cost) than a bank of three single-phase transformers, occupies much less space and are more efficient. But single-phase units are easier to transport. Moreover, in case of fault they can be used as open-delta with 58% rating.

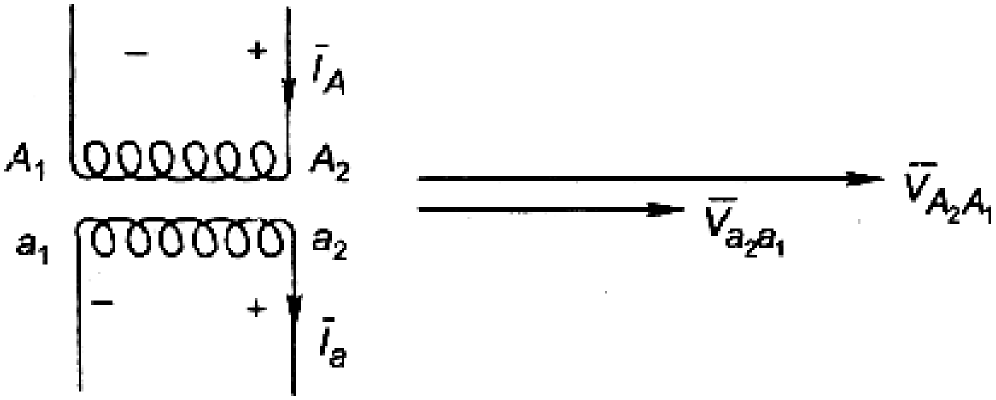
Types: (i) Core type; and (ii) Shell type

Transformer Labeling and Connections

Terminals on HV side in each phase – A, B, C (in capital letters)

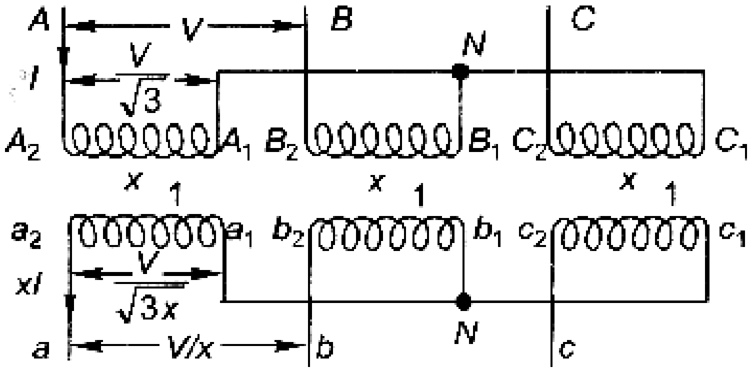
Terminals on LV side in each phase – a, b, c (in small letters)

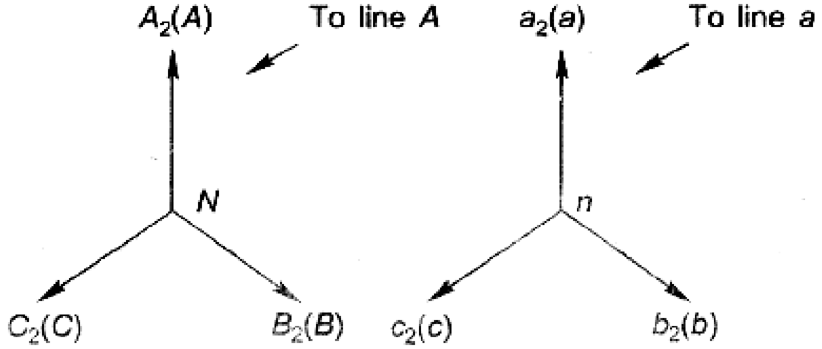
Similar polarities are indicated by similar suffices 1 or 2 on both sides.



Labelling for transformer terminals

Star/Star (*Yy*) Connection – (0° and 180° connections are obtained)

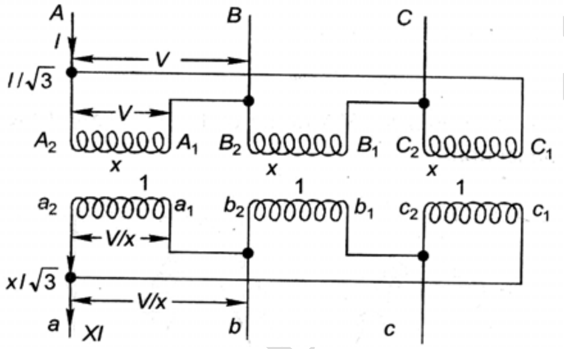




The phasor diagram is shown from which it is easily seen that the voltage of the corresponding phases (and therefore of the corresponding lines) are in phase. This is known as the 0°-connection. The letters within brackets on the phasor diagram indicate the lines, to which the terminals are connected. If the winding terminals on secondary side are reversed, the 180°-connection is obtained.

Phase transformation ratio → x : 1
Line transformation ratio → x : 1

Delta/Delta (*Dd*) Connection – (0° and 180° connections are obtained)



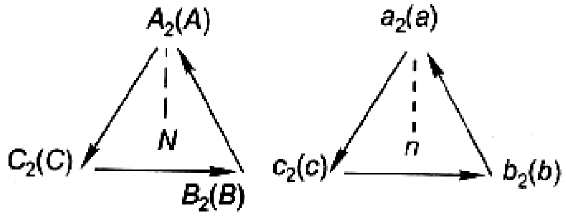
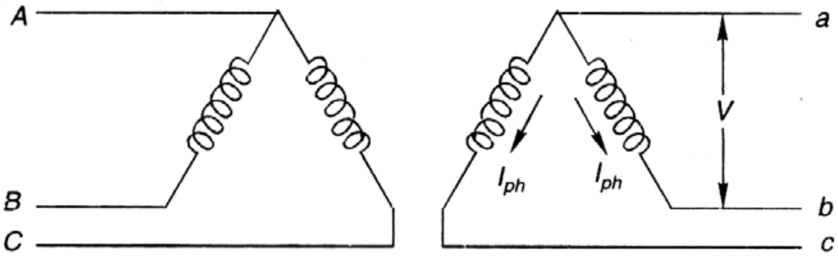


Figure shows the delta/delta connection and the corresponding phasor diagram. The sum of voltages around the secondary delta must be zero; otherwise delta, being a closed circuit, means a short circuit. With polarities indicated on the primary and secondary sides, voltages $V_{a_2a_1}$, $V_{b_2b_1}$ and $V_{c_2c_1}$ add to zero as per the phasor diagram if the delta is formed by connecting a_1b_2, b_1c_2 and c_1a_2. It is easily seen from the phasor diagram that the primary and secondary line voltages are in phase so I t is the 0°-connection. However, if the secondary leads *a, b, c* are taken out from the delta nodes a_1b_2, b_1c_2, c_1,c_2, the secondary voltages are *n* phase opposition to the primary voltage. This is the 180°-connection.

Phase transformation ratio → x : 1
Line transformation ratio → x : 1

If one of the transformers is disconnected, it results in open-delta connection. It can supply a balanced load.



In the delta/delta connection if one of the transformers is disconnected, the resulting connection is known as *open-delta.* Supposing the *b*-phase transformer is removed, and the open-delta is excited from balanced 3-phase supply, then the voltage $V_{b_1b_2} = V_{bc}$ does not change as it equals – ($V_{ca} + V_{ab}$); thus the voltage on the secondary side still remain balanced 3-phase. If the maximum allowable secondary phase current is I_{ph}, the transformer can handle VA of

$$S_{\text{open-delta}} = \sqrt{3}\, VI_{ph}$$

Which for normal delta/delta connection is

$$S_{\text{delta}} = 3VI_{ph}$$

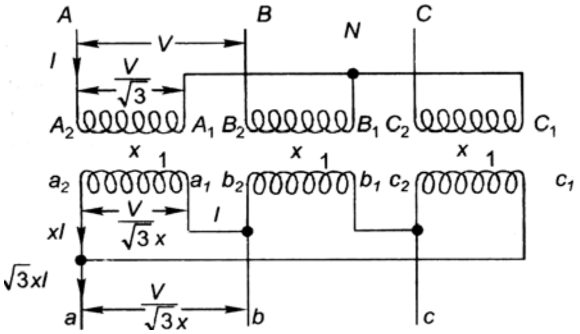
Thus the open-delta connection has a VA rating of $1/\sqrt{3} = 0.58$ of the rating of the normal delta/delta connection.

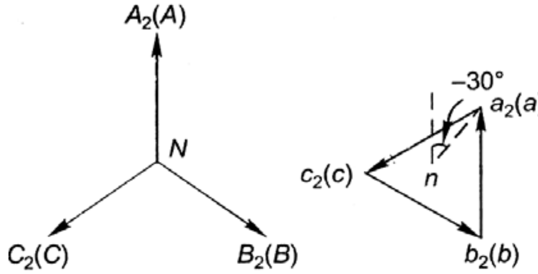
The maximum allowable secondary phase current is I_{ph}, the transformer can handle $VA_{\text{open-delta}} = \sqrt{3}\, VI_{ph} = S'$

For normal (Δ/Δ) Connection, VA delta = $3VI_{ph} = S$

$$\frac{S'}{S} = \frac{1}{\sqrt{3}} = 0.58$$

Star/Delta (*Yd*) Connection – (+30° and –30° connections are obtained)





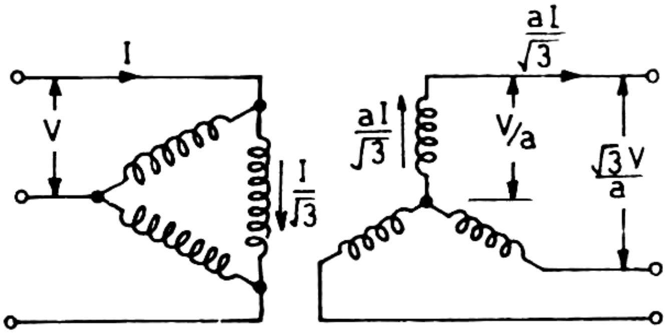
Star connection is formed on primary side by connecting together 1 suffixed terminals; 2 suffixed terminals being connected to appropriate lines; the delta is formed by connecting c_1a_2, a_1b_2 and b_1c_2 with the lines connected to these junctions being labelled as a, b and c respectively. The phasor diagram on the delta side shows that the sum of voltage around delta is zero. This is a must, as otherwise, closed delta would mean a short circuit. It is also observed from the phasor diagram that phase a to neutral voltage on the star side; this is also the phase relationship between the respective line-to-line voltage. This connection, therefore, is known as –30° - connection.

Similarly ± 90°-connections are also possible in the star/delta connection by relabelling the delta side lines. For example for + 90° connection relabel $c \rightarrow a$, $b \rightarrow c$ and $a \rightarrow b$.

Phase transformation ratio → x : 1

Line transformation ratio → √3 : x

Delta/Star (Δ/Y) Connection – (+30° and –30° connection are obtained)



This connection is simply the interchange of primary and secondary roles in the star/delta connection. One just interchanges capital and small letter suffixings. Of course what was the –30°-connection will now be the + 30°-connection and vice versa. If the phase transformation ratio is $x : 1$ (delta/star), the transformation ratio for line quantities will be $(x/\sqrt{3}):1$.

Phase transformation ratio → x : 1
Line transformation ratio → x/√3:1

Delta/Zig-Zag Star (Δ/Y) Connection – (0° and 180° connection are obtained)

Phase transformation ratio → x : 1
Line transformation ratio → x : 3/2 or 2/3x:1

Transformer Noise

The hum, leading to noise, originates in the ferromagnetic core of a transformer. The major cause of noise in transformers is the magnetostriction. When ferromagnetic transformer core is magnetized, the core length along the alternating flux decreases and increases alternatively, with a corresponding increase and decrease of its cross-section. This phenomenon involving very small changes in dimensions of the magnetized core is called *magnetostriction.*

As the steel laminations change their dimensions alternately, the ferromagnetic core vibrates and humming is produced. This humming traverses from the core to the transformer oil, to tank and then to the surroundings in the form of noise. The degree of humming level depends on the flux density in the core. Greater the core flux density, greater is the tendency for humming in transformers.

In brief, the factors producing the noise in transformers are the following:
(i) The first cause of hum, and therefore the noise, is the magnetostriction.
(ii) The details of core construction, size and gauge of laminations and the degree of tightness of clamping the core by nuts and bolts do influence the frequency of mechanical vibrations and therefore the noise in transformers.
(iii) Joints in the core are also responsible for noise production though to a lesser degree.

Most of the noise emission from a transformer may be reduced:
(a) By using low value of flux density in the core.
(b) By proper tightening of the core by clamps, bolts etc.
(c) By sound-insulating the transformer core from the tank wall in case of large transformers or by sound-insulating the transformer core from where it is installed in case of small transformers.

OBJECTIVE QUESTIONS (GATE, IES)

Previous Years GATE Questions

Transformer Losses and Efficiency

GATE-1. A single phase transformer has a maximum efficiency of 90% at 111 load and unity power factor. Efficiency at half load at the same power factor is: [GATE-2003]

(a) 86.7% (b) 88.26%
(c) 88.9% (d) 87.8%

GATE-2. A 500 kVA, 3-phase transformer has iron losses of 300 W and full load copper losses of 600 W. The percentage load at which the transformer is expected to have maximum efficiency is: [GATE-2003]

(a) 50.0% (b) 70.7% (c) 141.4% (d) 200.0%

Data for Q.3 and Q.4 are given below. Solve the problems and choose the correct answers.

A 300 kVA transformer has 95% efficiency at full load 0.8 pf lagging and 96% efficiency at half load, unity pf.

GATE-3. The iron loss (P_i) and copper loss (P_c) *in* kW, under full load operation are: [GATE-2006]

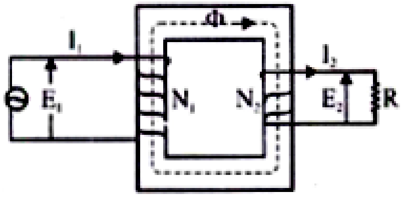
(a) P_c= 4.12, P_i, = 8.51
(b) P_C = 6.59, P_i = 9.21
(c) P_c= 8.51, P_i = 4.12
(d) P_C = 12.72, P_i = 3.07

GATE-4. What is the maximum efficiency (in %) at unity pf load? [GATE-2006]

(a) 95.1 (b) 96.2 **(c)** 96.4 (d) 98.1

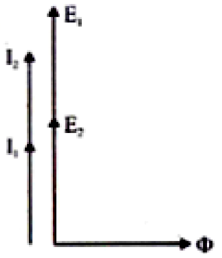
Principle of Transformer Action

GATE-5. Figure shows an ideal single-phase transformer. The primary and secondary coils are wound on the core as shown. Turns ratio (N_1/N_2) = 2. The correct phasors of voltages E_l, E_2, currents I_1, I_2 and core flux Φ are as shown in figure.

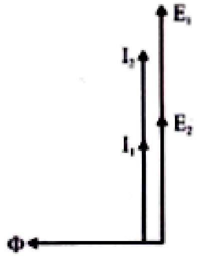


[GATE-2003]

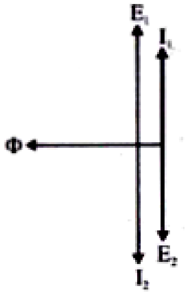
(a)



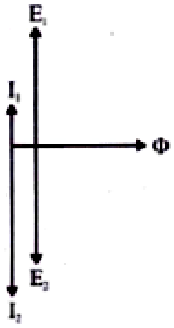
(b)



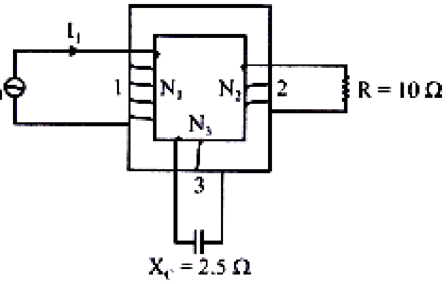
(c)



(d)



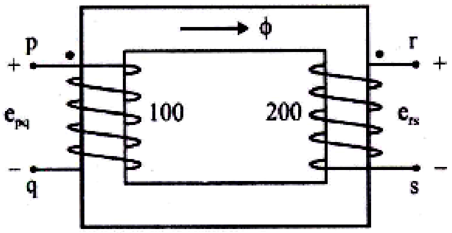
GATE-6. **Figure shows an ideal three winding transformer are wound on the same case as shown. The turns ratio $N_1 : N_2 : N_3$ is 4 : 2 : 1. A resistor of 10 Ω is connected across winding-2. A capacitor of reactance 2.5 Ω is connected across winding-3. Winding-1 is connected across a 400 V, as supply. If the supply voltage phasor V1= 400∠0°, the supply current phasor I_1 is given by:**

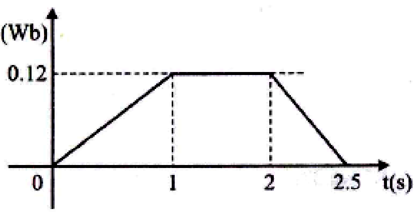


[GATE-2003]

(a) (–10 + jlO) A (b) (–10 – jl0) A (c) (10 + jlO) A (d) (10 – jl0) A

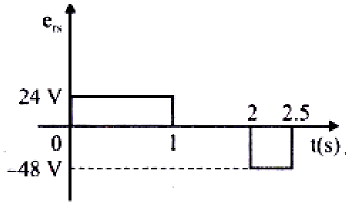
GATE-7. **The core of a two-winding transformer is subjected to a magnetic Flux variation as indicated in the figure. [GATE-2008]**



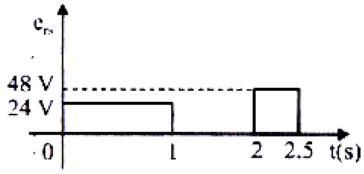


The induced emf $\frac{400}{1000}V, (e_{rs})$ in the secondary winding as a function of time will be the form

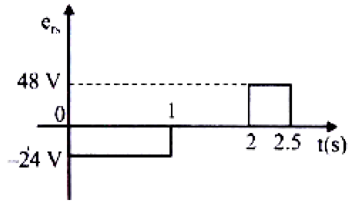
(a)



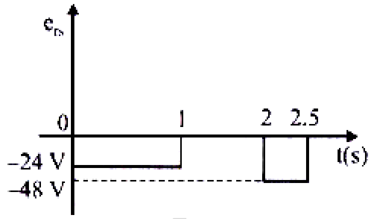
(c)



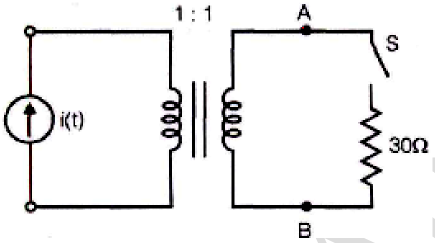
(b)

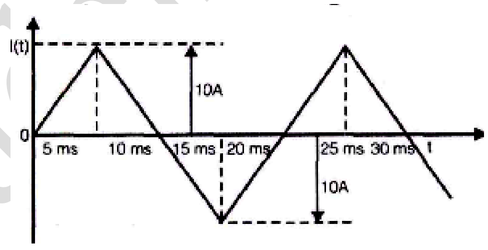


(d)



Common Data for Questions Q8 and Q9:
The circuit diagram shows a two-winding, lossless transformer with no leakage flux, excited from a current source, i(t), whose waveform is also shown. The transformer has a magnetizing inductance of 400/π mH.



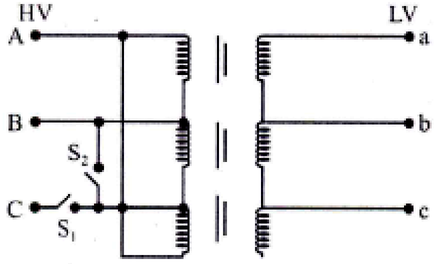


GATE-8. **The peak voltage across A and B, with S open is:** **[GATE-2009]**
(a) $\frac{400}{\pi V}$ (b) 800V (c) $\frac{4000}{\pi V}$ (d) $\frac{800}{\pi V}$

GATE-9. **If the waveform of i(t) is changed to i(t) = 10sin $(100\pi t)$ A, the peak voltage across A and B with S closed is:** **[GATE-2009]**
(a) 400 V (b) 240 V (c) 320 V (d) 160 B

Three Phase Transformers

GATE-10. **Figure shows a Δ-Y connected 3-phase distribution transformer used to step down the voltage from 11 000 V to 4 15 V line-to-line. It has two switches S_1 & S_2. Under normal conditions S_1 is closed and S_2 is open. Under certain superior conditions S_1 is open and S_2 is closed. In such a case the magnitude of the voltage across the LV terminals a and c is:**

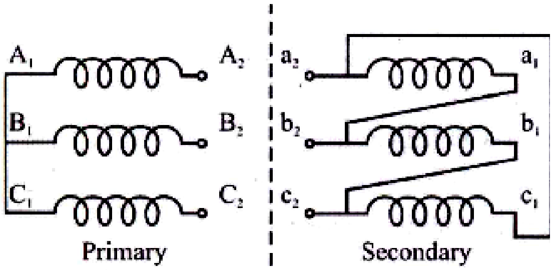


[GATE– 2003]

(a) 240 V (b) 480 V (c) 4'15 V (d) 0 V

GATE-11. Which three-phase connection can be used in a transformer to introduce a phase difference of 30° between its output and corresponding input line voltages [GATE-2005]
(a) Star-Star (b) Star-Delta (c) Delta-Delta (d) Delta-Zigzag

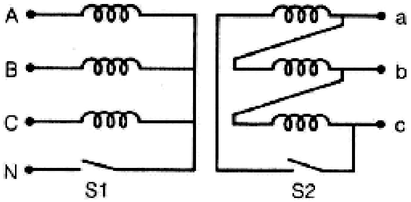
GATE-12. Three single-phase transformers are connected to form a 3-phase transformer bank. The transformers are connected in the following manner:



The transformer connection will be represented by: [GATE-2008]
(a) Yd0 (b) Yd 1 (c) Yd6 (d) Yd l1

Common Data for Questions Q13 and Q14:

The star-delta transformer shown above is excited on the star side with balanced, 4-wire, 3-phase, sinusoidal voltage supply of rated magnitude. The transformer is under no load condition.

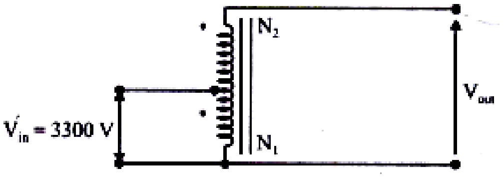


GATE-13. With both S1 and S2 open, the core flux waveform will be: [GATE-2009]
(a) A sinusoid at fundamental frequency (b) Flat –topped with harmonic
(c) Peaky with third-harmonic (d) None of these

GATE-14. With S2 closed and S1 open, the current waveform in the delta winding will be: [GATE-2009]
(a) A sinusoid at fundamental frequency
(b) Flat-topped with third harmonic
(c) Only third-harmonic
(d) None of these

Auto - Transformers

GATE-15. A 50 kVA, 33001230 V single-phase transformer is connected as an autotransformer shown in figure. The nominal rating of the autotransformer will be:
(a) 50.0 kVA (b) 53.3 kVA
(c) 717.4 kVA (d) 767,4 kVA

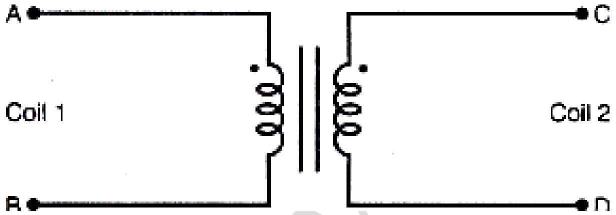


[GATE-2004]

GATE-16. **A single-phase 50 kVA, 250 V/500V two winding transformer has an efficiency of 95% at full load, unity power factor. If it is reconfigured as a 500V/750V autotransformer, its efficiency at its new rated load at unity power factor will be:** **[GATE-2007]**
(a) 95.752% (b) 97.851% (c) 98.276 % (d) 99.241%

Statement for Linked Answer Questions Q17 and Q18:

The figure above shows coils 1 and 2, with dot markings as shown, having 4000 and 6000 turns respectively. Both the coils have a rated current of 25 A. Coil 1 is excited with single phase, 400 V, 50 Hz supply.



GATE-17. **The coils are to be connected to obtain a single-phase, $\frac{400}{1000}V$, auto-transformer to drive a load of 10 kVA.Which of the options given should be exercised to realize the required auto-transformer?** **[GATE-2009]**
(a) Connect A and D; Common B
(b) Connect B and D; Common C
(c) Connect A and C; Common B
(d) Connect A and C; Common D

GATE-18. **In the autotransformer obtained in Question 97, the current in each coil is:** **[GATE-2009]**
(a) Coil-1 is 25 A and Coil-2 is 10 A
(b) Coil-1 is 10 A and Coil-2 is 25 A
(c) Coil-1 is 10 A and Coil-2 is 15 A
(d) Coil-1 is 15 A and Coil-2 is 10 A.

Per-unit System

GATE-19. **The resistance and reactance of a 100 kVA 110001400V, $\Delta - Y$ distribution transformer are 0.02 and 0.07 pu respectively. The phase impedance of the transformer referred to the primary is:** **[GATE-2004]**
(a) $(0.02 + j0.07)\Omega$ (b) $(0.55 + j\,1.925)\Omega$
(c) $(15.125 + j52.94)\Omega$ (d) $(72.6 + j254.1)\Omega$

Transformer Construction

GATE-20. **The equivalent circuit of a transformer has leakage reactances X_1, X'_2, and magnetizing reactance X_M. Their magnitudes satisfy** **[GATE-2005]**
(a) $X_1 \gg X'_2 \gg X_M$
(b) $X_1 \ll X'_2 \ll X_M$
(c) $X_1 \approx X'_2 \gg X_M$
(d) $X_1 \approx X'_2 \ll X_M$

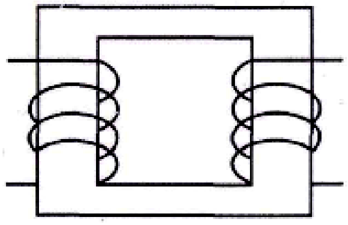
GATE-21. The single phase, 50 Hz iron core transformer in the circuit has both the vertical arms of cross sectional area 20 cm^2 and both the horizontal arms of cross sectional area 10 cm^2. If the two windings shown were wound instead on opposite horizontal arms, the mutual inductance will: **[GATE-2009]**

(a) Double

(b) Remain same

(c) Be halved

(d) Become one quarter



Open-circuit and Short-circuit Tests

GATE-22. In transformers, which of the following statements is valid? [GATE-2006]
(a) In an open circuit test, copper losses are obtained while in short circuit test, core losses are obtained
(b) In an open circuit test, current is drawn at high power factor
(c) In a short circuit test, current is drawn at zero power factor
(d) In an open circuit test, current is drawn at low power factor

GATE-23. It is desired to measure parameters of 230 V /115 V, 2 kVA, single-phase transformer. The following wattmeters are available in a laboratory
W_1 : 250V, 10A, Low Power Factor **[GATE-2008]**
W_2 : 250V, 5A, Low Power Factor
W_3 : 150V, 10A, High Power Factor
W_4 : 150V, 5A, High Power Factor.

The wattmeters used in open circuit test and short circuit test of the transformer will respectively be: **[GATE-2008]**
(a) W_1 and W_2 (b) W_2 and W_4 (c) W_1 and W_4 (d) W_2 and W_3

Parallel Operation

GATE-24. Two transformers are to be operated in parallel such that they share load in proportion to their kVA ratings. The rating of the first transformer is 500 kVAand its pu leakage impedance is 0.05 pu. If the rating of second transformer is 250 kVA, its pu leakage impedance is: **[GATE-2006]**
(a) 0.20 (b) 0.10 (c) 0.05 (d) 0.025

Voltage Regulation

GATE-25. In a transformer, zero voltage regulation at full load is: **[GATE-2007]**
(a) Not possible
(b) Possible at unity power factor load
(c) Possible at leading power factor load
(d) Possible at lagging power factor load

Previous Years IES Questions

Transformer Losses and Efficiency

IES-1. A single-phase transformer when supplied from 220V, 50Hz has eddy current loss of 50W. If the transformer is connected to a voltage of 330V, 50Hz, the eddy current loss will be: [IES-2001]

(a) 168.75W (b) 112.5W (c) 75W (d) 50W

IES-2. If P_c and P_{sc} represent core and full-load ohmic losses respectively, the maximum kVA delivered to load corresponding to maximum efficiency is equal to rated kVA multiplied by: [IES-2001]

(a) $P_c\ /P_{sc}$ (b) $\sqrt{P_c/P_{sc}}$

(c) $(P_c/P_{sc})^2$ (d) $(P_c/P_{sc})^2\ (P_{sc}/P_c)^2$

IES-3. The full-load copper-loss and iron-loss of a transformer are 6400W and 5000W respectively. The copper-loss and iron-loss at half load will be, respectively [IES-2002]

(a) 3200 W and 2500 W (b) 3200 W and 5200 W

(c) 1600 W and 1250 W (d) 1600 W and 5000 W

IES-4. Assertion (A): The distribution transformers are designed for minimum core losses. **[IES-2002]**

Reason (R): Primary windings of distribution transformers are energized throughout the day.

IES-5. If P_1 and P_2 be the iron and copper losses of a transformer at full load, and the maximum efficiency of the transformer is at 75% of the full load, then what is the ratio of P_1 and P_2? [IES-2006]

(a) 9/16 (b) 10/16 (c) 3/4 (d) 3/16

IES-6. If the iron core of a transformer is replaced by an air core, then the hysteresis losses in the transformer will: [IES-2006]

(a) Increase (b) Decrease

(c) Remain unchanged (d) Become zero

IES-7. The equivalent circuit of a transformer has the leakage reactances X_1, X_2' and the magnetising reactance X_m. What is the relationship between their magnitudes? [IES-2006]

(a) $X_1 >> X_2' >> X_m$ (b) $X_1 << X_2' << X_m$

(c) $X_1 \approx X_2' >> X_m$ (d) $X_1 \approx X_2' << X_m$

IES-8. If the voltage applied to a transformer primary is increased by keeping the V/f ratio fixed, then the magnetizing current and the core loss will, respectively, [IES-2006]

(a) Decrease and remain the same
(b) Increase and decrease
(c) Remain the same and remain the same
(d) Remain the same and increase

ES-9. A 500 kVA transformer has constant losses of 500 Wand copper losses at full load are 2000 W. Then at what load, is the efficiency maximum? [IES-2007]

(a) 250 kVA (b) 500 kVA (c) 1000 kVA (d) 125 kVA

IES-10. On which of the following factors does hysteresis loss depend? [IES-2007]

1. Flux density 2. Frequency
3. Thickness of lamination 4. Time

Select the correct answer using the code given below:

(a) 2 and 3 (b) 1 and 2 (c) 3 and 4 (d) 1 and 4

IES-11. A single-phase transformer rated for 220/440 V, 50 Hz operates at no load at 220 V, 40 Hz. This frequency operation at rated voltage results in which one of the following? [IES-2008]

(a) Increase of both eddy-current and hysteresis losses
(b) Reduction of both eddy-current and hysteresis losses
(c) Reduction of hysteresis loss and increase in eddy-current loss
(d) Increase of hysteresis loss and no change in the eddy-current loss

IES-12. What is the load at which maximum efficiency occurs in case of a 100 kVA transformer with iron loss of 1kW and full-load copper loss of 2 kW? [IES-2008]

(a) 100 kVA (b) 70.7 kVA (c) 50.5 kVA (d) 25.2 kVA

IES-13. The full-load copper loss and iron loss of a transformer are 6400 Wand 5000 W, respectively. What are the above copper loss and iron loss, respectively at half-load? [IES-2008]

(a) 3200 W, 2500 W (b) 3200 W, 5000 W

(c) 1600 W, 1250 W (d) 1600 W, 5000 W

IIES-14. **When are eddy-current losses in a transformer reduced? [IES-2008]**
(a) If laminations are thick
(b) If the number of turns in primary winding is reduced
(c) If the number of turns in secondary winding is reduced
(d) If laminations are thin

Auto - Transformer

IES-15. **In case of auto-transformers, which of the following statements are correct? [IES-2001]**

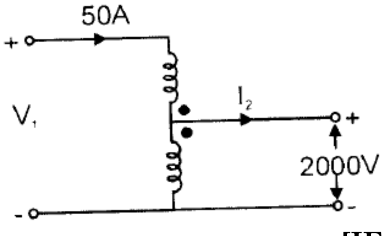
1. **An auto-transformer requires less copper as compared to a conventional, 2-winding transformer of the same capacity.**
2. **An auto-transformer provides isolation between the primary and secondary windings**
3. **An auto-transformer has less leakage reactance as compared to the conventional, 2-winding transformer of the same capacity.**

Select the correct answer using the codes given below:
(a) 1, 2 and 3 (b) 1 and 2 (c) 1 and 3 (d) 2 and 3

IES-16. **A two-winding transformer is used as an autotransformer. The kVA rating of the autotransformer compared to the two-winding transformer will be: [IES-2002]**
(a) 3 times (b) 2 times (c) 1.5 times (d) Same

IES-17. **A two-winding transformer is converted into an auto-transformer. If we apply additive polarity and subtractive polarity for the connections, then the secondary voltage is 2640 V and 2160 V, respectively. What is the ratio of primary to secondary voltage of the original transformer? [IES-2006]**
(a) 66 : 54 (b) 54 : 66 (c) 10 : 1 (d) 1 : 10

IES-18. **A single-phase, 10kVA, 2000/200V, 50Hz transformer is connected to form an auto transformer as shown in the figure given below. What are the values of V_1 and I_2, respectively?**



[IES-2005]
(a) 2200V, 55A (b) 2200V, 45A (c) 2000V, 45A (d) 1800V, 45A

IES-19. **If the wave form of the voltage impressed on the primary of a $Y-\Delta$ bank contains 5^{th} harmonics, what are the wave forms of the resultant voltages of the primary and the secondary? [IES-2005]**

	Primary	**Secondary**
(a)	Peaked	Peaked
(b)	Peaked	Flat-topped

(c) Flat-topped	Peaked
(d) Flat-topped	Flat-topped

IES-20. What is the efficiency of an auto-transformer in comparison to that of a two-winding transformer of the same rating? [IES-2006]
(a) Slightly less than that of a two-winding transformer
(b) Same as that of a two-winding transformer
(c) More than that of a two-winding transformer
(d) As low as 1/5th of the efficiency of a two-winding transformer

IES-21. What is the power transmitted inductively in an auto-transformer which supplies a load at 161 volts with an applied primary voltage of 230 volts?
(a) 35% of the input (b) 70% of the input **[IES-2009]**
(c) 15% of the input (d) 30% of the input

IES-22. What is the power transferred conductively from primary to secondary of an auto-transformer having transformation ratio of 0.8 supplying a load of 3 kW? [IES-2009]
(a) 0.6 kW (b) 2.4 kW (c) 1.5 kW (d) 0.27 kW

Per Unit Values

IES-23. A 20kVA, 2000/200V, 1-phase transformer has name-plate leakage impedance of 8%. Voltage required to be applied on the high-voltage side to circulate full-load current with the low-voltage winding short-circuited will be: [IES-2002]
(a) 16 V (b) 56.56 V (d) 160 V (d) 568.68 V

IES-24. A 4 kVA, 400/200 V single-phase transformer has resistance of 0.02 p.u. and reactance of 0.06 p.u. Its actual resistance and reactance referred to h.v. side are, respectively [IES-2002]
(a) 0.2 ohm and 0.6 ohm (b) 0.8 ohm and 2.4 ohm
(c) 0.08 ohm and 0.24 ohm (d) 2 ohm and 6 ohm

Open-circuit and Short-circuit Tests

IES-25. In a 100 kVA, 1100/220V, 50Hz single-phase transformer with 2000 turns on the high-voltage side, the open-circuit test result gives 200V, 91 A, 5kW on low-voltage side. The core-loss component of current is, approximately [IES-2002]
(a) 9.1A (b) 22.7 A (c) 45.0 A (d) 91 A

IES-26. What is the core loss in a high frequency ferrite core transformer used in SMPS power supply? [IES-2009]
(a) 10% of rated power (b) 5% of rated power
(c) 2% of rated power (d) 1% of rated power

IES-27. **A1 kVA, 200/100V, 50Hz, single-phase transformer gave the following test results on 50Hz:** **[IES-2003]**

OC (LV side) : 100 V, 20 watts
SC (HV side) : 5A, 25 watts

It is assumed that no-load loss components are equally divided. The above tests were then conducted on the same transformer at 40 Hz.

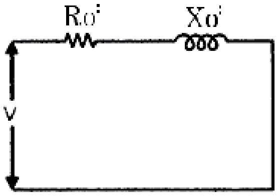
Tests results were:

OC (HV): 160V, W_1 watts
SC (LV): 10A, W_2 watts

Neglecting skin effect, W_1 and W_2 will be:

(a) W_1 = 16 watts, W_2 = 25 watts
(b) W_1 = 25 watts, W_2 = 31.25 watts
(c) W_1 = 20 watts, W_2 = 20 watts
(d) W_1 = 14.4 watts, W_2 = 25 watts

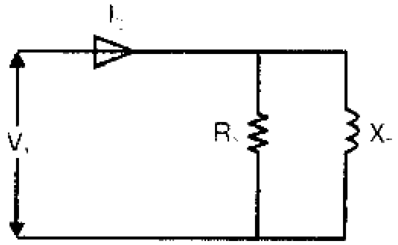
IES-28. **At which condition of the transformer the equivalent circuit will be as shown in the below figure?**



(a) Under short circuit
(b) Under open circuit **[IES-2009]**
(c) Under no load
(d) Under rated load

IES-29. **At which condition of the transformer the equivalent circuit will be as shown figure?**

(a) Under short circuit
(b) Under rated load
(c) Under open circuit
(d) Under load and no load



[IES-2009]

Three Phase Transformer

IES-30. **Possible three-to-three phase transformer connection for parallel operation is:** **[IES-2002]**

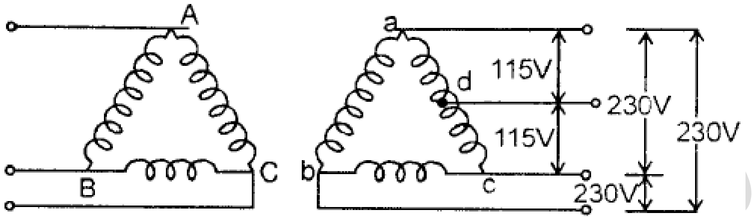
(a) Δ – Y to Δ – Y (b) Δ – Δ to Δ – Y
(c) Y – Y to Δ – Y (d) Δ – Y to Y – Δ

IES-31. **A delta/star transformer has a phase-to-phase voltage transformation ratio of $K\left(K=\frac{\text{delta phase voltage}}{\text{star phase voltage}}\right)$.** **[IES-2002]**

The line-to-line voltage ratio of star/delta

(a) $K/\sqrt{3}$ (b) K (c) $K\sqrt{3}$ (d) $\sqrt{3}/K$

IES-32. **The diagram given below shows the connection of a four-wire delta bank for obtaining a 3-phase 4-wire distribution system. The secondary voltages between the terminals are as indicated.** **[IES-2004]**



What is the voltage between the terminals b and d in the above system when the primary side is energized from an appropriate symmetrical 3-phase system?

(a) $230/\sqrt{2}$ V (b) $230/\sqrt{3}$ V (c) $115\times\sqrt{3}$ V (d) $115\times\sqrt{2}$ V

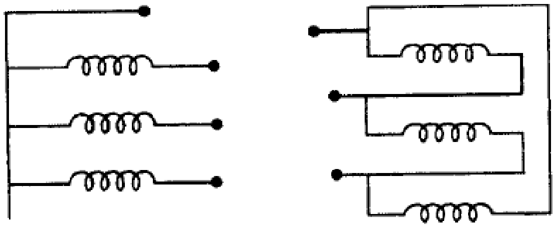
IES-33. **Assertion (A):** Δ-connected tertiary windings tend to act as an automatic feedback control system. **[IES-2004]**

Reason (R): In the event of unbalanced secondary load currents, both secondary and primary load voltages are restored to their normal phase magnitude and angle.

IES-34. **Three single phase 1000/220V transformers arc connected to form 3-phase transformer bank. High voltage side is connected in star, and low voltage side is in delta. What are the voltage ratings and turn ratio of 3-phase transformer?** **[IES-2005]**

(a) 19052 / 220V, 50
(b) 19052 / 220V, $50\sqrt{3}$
(c) 11000/381V, $50\sqrt{3}$
(d) 11000 / 220V, 50

IES-35. **What is the phase displacement between primary and secondary voltages for a star-delta, 3-phase transformer connection shown figure?**



[IES-2005]

(a) 30° lagging (b) 30° leading (c) 0° (d) 180°

IES-36. Which three-phase connection can be used in a transformer to introduce a phase difference of 30° between its output and corresponding input line voltages? [IES-2006]

(a) Star-delta (b) Star-star (c) Delta-delta (d) Delta-zigzag

Parallel Operation

IES-37. Two 10kV /440V, 1-phase transformers of ratings 600 kVA and 350 kVA are connected in parallel to share a load of 800 kVA. The reactances of the transformers, referred to the secondary side are $0.0198\,\Omega$ and $0.0304\,\Omega$ respectively (resistances negligible). The load shared by the two transformers will be, respectively [IES-2002]

(a) 484.5 kVA and 315.5 kVA (b) 315.5 kVA and 484.5 kVA
(c) 533 kVA and 267 kVA (d) 267 kVA and 533 kVA

IES-38. Two transformers, with equal voltage ratio and negligible excitation current, connected in parallel, share load in the ratio of their kVA rating only, if their p.u. impedances (based on their own kVA) are: [IES-2002]

(a) Equal (b) In the inverse ratio of their ratings
(c) In the direct ratio of their ratings (d) Purely reactive

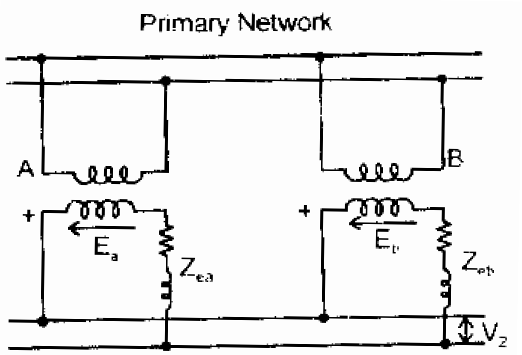
IES-39. Two transformers operating in parallel will share the load depending upon their [IES-2003]

(a) Ratings
(b) Leakage reactance
(c) Efficiency
(d) Per unit impedance

IES-40. If per unit impedances of two transformers connected in parallel are not equal, then which one of the following statements is correct? [IES-2004]

(a) The power factor of the two transformers will be different from that of the connected load
(b) Transformers will get overloaded
(c) Dead short circuit occurs
(d) The transformer with higher per unit impedance will share more load

IES-41. Two single phase transformers A and Bare connected in parallel, observing all requirements of a parallel operation, except that the induced voltage E_a is slightly greater than E_b; Z_{ea} and Z_{eb} being the equivalent impedances of A and B, both referred to the secondary side.



Under this operating condition with the primary bus-bars being energised, a circulating current will flow: [IES-2005]
(a) Only in the secondary windings of A and B
(b) In both the primary and the secondary windings of A and B
(c) In both the primary and the secondary windings of A and B, as well as in the primary side network
(d) In the primary and the secondary windings of A and B and boost the voltages on the secondary side of both A and B

DIRECTION:
The following three items consist of two statements, one labelled as 'Assertion A' and the other labelled as 'Reason R'. You are to examine these two statements carefully and decide if the Assertion A and the Reason R are individually true and if so, whether the Reason is a correct explanation of the Assertion. Select your answers to these items using the codes given below:

Codes:
(a) Both A and R are true and R is the correct explanation of A
(b) Both A and R are true but R is not the correct explanation of A
(c) A is true but R is false
(d) A is false but R is true

IES-42. Two Transformers when operating in parallel will share the load depending upon which of the following? [IES-2007]
(a) Magnetizing current (b) Leakage reactance
(c) Per unit impedance (d) Efficiency

Transformer Construction

IES-43. The use of higher flux density in the transformer design [IES-2003]
(a) Reduces the weight per kVA
(b) Increases the weight per kVA
(c) Has no relation with the weight of transformer
(d) Increases the weight per kW

IES-44. The function of oil in a transformer is to provide [IES-2003]

(a) Insulation and cooling (b) Protection against lightning
(c) Protection against short circuit (d) Lubrication

IES-45. Which among the following magnetic materials has the highest energy-product to make it a permanent magnet? [IES-2006]
(a) Alnico (b) Ferrite
(c) Samariurm Cobalt (d) Cobalt-Iron alloy

IES-46. Assertion (A): For obtaining improved magnetic properties, the transformer magnetic core is assembled using cold-rolled silicon-steel sheets. **[IES-2005]**
Reason (R): The laminations for the core could be cut out of the cold-rolled silicon steel sheets, cutting either in the direction of rolling or transverse thereof, without affecting the magnetic properties in any way.

IES-47. Cores of large power transformers are made from which one of the following? [IES-2008]
(a) Hot-rolled steel (b) Cold-rolled non-grain oriented steel
(c) Cold-rolled grain oriented steel (d) Ferrite

Principle of Transformer Action

IES-48. Assertion (A): Transformer is not used in a D.C. line. [IES-2004]
Reason (R): Losses in the D.C. circuit are not negligible.

IES-49. Match List-I (Type of coil) with List-II (Use of coil) and select the correct answer using the codes given below the lists: [IES-2005]

List-I	List-II
A. Sandwitch coils	**1. Lw voltage coils for currents above 100A**
B. Disc coils	**2. High voltage windings of small transformers**
C. Cross-over coils	**3. Cooling oil is in contact with each turn of the winding**
D. Spiral type	**4. Shell-type transformer core**

Codes:	**A**	**B**	**C**	**D**		**A**	**B**	**C**	**D**
(a)	2	3	4	1	(b)	4	1	2	3
(c)	2	1	4	3	(d)	4	3	2	1

Voltage Regulation

IES-50. Percentage resistance and percentage reactance of a transformer are 1% and 4%, respectively. What is voltage regulation at power factor 0.8 lagging and 0.8 leading? [IES-2006]
(a) 2.4% and –0.8%, respectively (b) 3.2% and –1.6%, respectively

(c) 3.2% and –3.2%, respectively (d) 4.8% and 1.6%, respectively

IES-51. A transformer has a percentage resistance of 2% and percentage reactance of 4%. What are its regulations at power factor 0.8 lagging and 0.8 leading, respectively? [IES-2008]

(a) 4% and –0.8% (b) 3.2% and –1.6%
(c) 1.6% and –3.2% (d) 4.8% and –0.6%

IES-52. Consider the following tests: [IES-2009]

1. Load test 2. Short circuit test
3. OC test 4. Retardation test

Which of the above tests are to be conducted for the determination of voltage regulation of a transformer?

(a) 1 only (b) 2 only
(c) 2 and 3 (d) 3 and 4

IES-53. Assertion (A): Both the efficiency and regulation of a 3-winding ideal transformer are: 100%. **[IES-2008]**

Reason (R): The flux leakage and the magnetic reluctance of the magnetic core in an ideal transformer are zero. Moreover, losses are absent in ideal transformers.

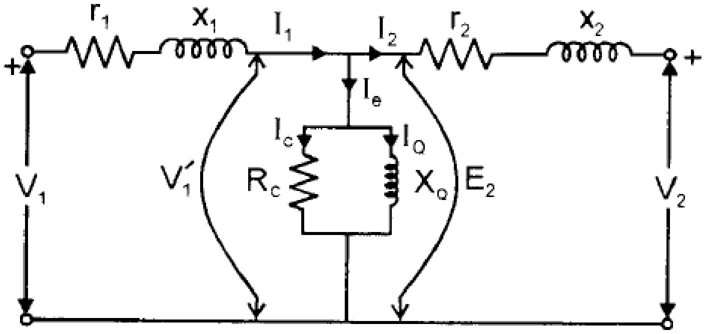
(a) Both A and R are true and R is the correct explanation of A
(b) Both A and R are true but R is not the correct explanation of A
(c) A is true but R is false
(d) A is false but R is true

IES-54. Match List-I (Test) with List-II (Quantities) and select the correct answer using the code given below the lists: [IES-2005]

List-I	List-II
A. OC Test	**1. Copper loss and iron loss**
B. SC Test	**2. Total losses**
C. Sumpner's Test	**3. Iron loss**
D. Load Test	**4. Copper loss**

Codes:	**A**	**B**	**C**	**D**		**A**	**B**	**C**	**D**
(a)	3	4	1	2	(b)	2	1	4	3
(c)	3	1	4	2	(d)	2	4	1	3

IES-55. The exact equivalent circuit of a two-winding transformer is given in the figure given below. For affecting simplification, the parallel magnetising branch, consisting of R_C and X_Q is shifted to the left of the primary leakage impedance $(r_1 + jx_1)'$. This simplification introduces the inaccuracy, in the neglect of: [IES-2005]



(a) Voltage-drop in the primary impedance due to the secondary current
(b) Voltage-drop in the primary impedance due to the exciting current
(c) Voltage-drop in the secondary impedance due to the exciting current
(d) Reduction in values of R_C and X_Q of the exciting circuit

Other Questions

IES-56. Consider the following statements regarding transformers: [IES-2007]

1. **The function of the magnetizing component of no load current is to sustain the alternating flux in the core.**
2. **Short circuit test is performed to find core losses only.**
3. **The function of the breather in transformer is to arrest flow of moisture when outside air enters the transformer.**

Which of the statements given above are correct′?

(a) 1 and 2 (b) 1 and 3 (c) 2 and 3 (d) 1, 2 and 3

IES-57. Sludge formation in transformer oil is due to which one of the following?

(a) Ingress of duct particles and moisture in the oil **[IES-2008]**
(b) Appearance of small fragments of paper, varnish, cotton and other organic materials in the oil
(c) Chemical reaction of transformer oil with the insulating materials
(d) Oxidation of transformer oil

IES-58. Match List I (Transformer) with List II (Voltage ratio) and select the correct answer: [IES-2002]

List-I	**List–II**
A. Power transformer	**1.** 230V/230 V
B. Auto transformer	**2.** 220V/240 V
C. Welding transformer	**3.** 400V/100V
D. Isolation transformer	**4.** 132kV/11kV

Codes:	**A**	**B**	**C**	**D**		**A**	**B**	**C**	**D**
(a)	4	2	3	1	(b)	4	2	1	3
(c)	2	4	1	3	(d)	2	4	3	1

Answers with Explanation (Objective)

Previous Year GATE Answer

GATE-1. Ans. (d) Efficiency $= \eta = \dfrac{x \times MVA \times p.f.}{x \times MVA \times p.f. + W_{Cu} \times x^2 + W_i}$

Where x = % of loading of the transformer
W_{Cu} = Cu losses at fL condition
W_i = iron loss of transformer

where $(\eta_{\max}) \to$ then $x = \sqrt{\dfrac{W_{Cu}}{W_i}} = 1$

$\therefore \quad W_{Cu} = W_i$

$\therefore \quad 90\% = \dfrac{MVA \times 1 \times 1}{MVA + 2W_i}$

$\therefore \quad W_i = 0.0555 \text{ MVA}$

At half load

$$\eta = \frac{MVA \times 0.5}{MVA \times 0.5 + 0.01389\ MVA + 0.055\ MVA} = \frac{0.5}{0.5 + 0.0694} = 87.8\%$$

GATE-2. Ans. (b) $x = \sqrt{\dfrac{W_i}{W_{Cu}}}$

W_i = Iron loss of transformer
W_{Cu} = Cu loss of transformer

GATE-3. Ans. (c) Efficiency, $\eta = 95\% = \dfrac{(KVA)0.8}{(KVA)0.8 + w_{cu} + w_i}$ ....(i)

$96\% = \dfrac{0.5(KVA)}{0.5(KVA) + 0.25w_{cu} + w_i}$ ....(ii)

From, equation (i)

$w_{cu} + w_i = 12.63$

From equation (ii)

$0.25\, w_{cu} + 0.96 w_i = 6.25$

From above two equations

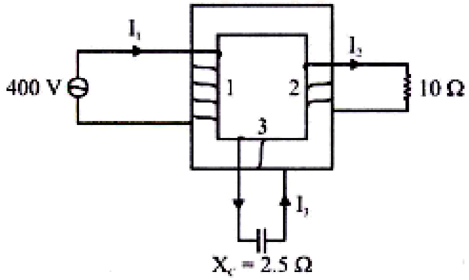
$w_{cu} = 8.51, w_i = 4.12$

GATE-4. Ans. (b) $x = \sqrt{\dfrac{4.12}{8.51}} = 0.696$

$$\eta_{\max} = \frac{0.696 \times 300}{0.696 \times 300 + 4.12 + 4.12} = 96.2\%$$

GATE-5. Ans. (d)

GATE-6. Ans. (d) $\frac{E_1}{E_2} = \frac{N_1}{N_2} = \frac{4}{2}$



$$E_2 = \frac{E_1}{2} = 200\text{ V} \quad \text{and} \quad \frac{E_1}{E_3} = \frac{N_1}{N_3} = \frac{4}{1}$$

$$\Rightarrow E_3 = 100\text{ V}$$

$$I_2 = \frac{E_2}{R} = \frac{200}{10} = 20\text{A}$$

$$I_3 = \frac{100}{-jx_c} = \frac{-100}{j2.5} = j\,40 \quad \left[\because j^2 = -1\right]$$

Now, I_2 refered to primary side i.e. I_1"

$$\frac{I_1'}{I_2} = \frac{N_2}{N_1} = \frac{2}{4} \quad \Rightarrow \quad I_1' = \frac{20}{2} = 10\text{A}$$

$$\therefore \quad I_1' = 10\text{A}$$

Now, I_3 refered to primary side i.e. I_1"

$$\frac{I_1''}{(-I_3)} = \frac{N_3}{N_1} = \frac{1}{4} \quad \Rightarrow \quad I_1'' = -j10\text{A}$$

- ve sign is taken to consider coil current direction I_3.

Hence, $I_1 = I_1' + I_1'' = 10 - j\,10$ A

GATE-7. Ans. (a) Induced emf in secondary $= -N_2 dj\phi dt$

During $-0 < t < 1$

$$E_1 = -\frac{d\phi}{dt} = -0.12\text{ V}$$

E_1 and E_2 are in oppsition

$$E_2 = 2E_1 = 0.24\text{ V}$$

During $1 < t < 2$

$$d\phi/dt = 0, \text{ then } E_1 = E_2 = 0$$

During $2 < t < 2.5$

$$E_1 = -\frac{d\phi}{dt} = 0.24\text{ V}$$

Then $E_2 = -0.48\text{ V}$

GATE-8. Ans. (d) $V = M\frac{dl}{dt} = M \times(\text{slope of I vs t ch}) = \frac{400}{\pi} \times 10 - 3 \times \left[\frac{10}{5 \times 10 - 3}\right] = \frac{800}{\pi}$ volts

GATE-9. Ans. (d) $V = L\frac{dl}{dt} = \left(\frac{400}{\pi}\right)\frac{dl}{dt}$

$\frac{dl}{dt}$ is Ma $\propto^{m} \rightarrow$ 5 m sec

$$V = \frac{4\omega}{\pi}\times\frac{10}{5}\left[\frac{800}{\pi}\right]V$$

if $\quad i(t) = 10\sin(100\pi t)$

$$V = \frac{400}{\pi}\times\frac{d}{dt}i(t)$$

$$V = \frac{400}{\pi}\times\pi\times10\cos(100\ \pi t)$$

$$V = 400\cos(100\pi t)$$

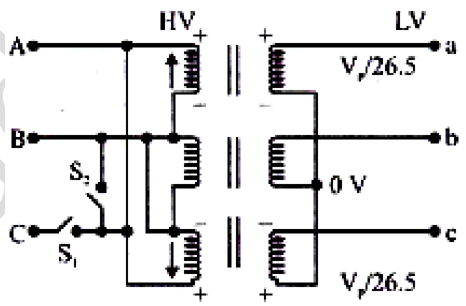
$$V_m = 400V$$

GATE-10. Ans. (d) When the switch S_1 is open and S_2 is closed then

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{11000}{415} = 26.50$$

The voltage inducing in phase 'a' of Y- winding is opposite to that in phase 'c', therefore

$$V_{ac} = \frac{V_p}{26.5} - \frac{V_p}{26.5} = 0\,\text{volt}$$



GATE-11. Ans. (b)

GATE-12. Ans. (b)

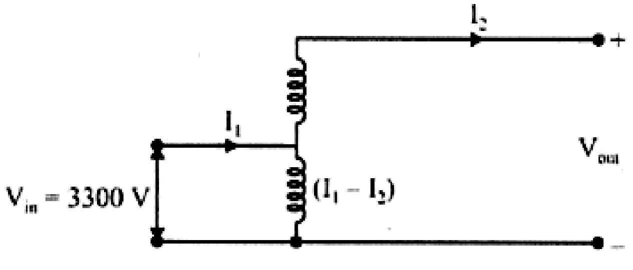
GATE-13. Ans. (b) Y connection consist 3rd harmonics in line current due to hysteresis A saturation.

GATE-14. Ans. (a) It will be open delta connection and O/P will be sinusoidal at fundamental frequency.

GATE-15. Ans. (d) $I_2 = \frac{50\times10^3}{230} = 217.4\,A$

These KVA rating of auto transformer = V_0

$I_2 = (3530)(217.4) = 767.42\,KVA$

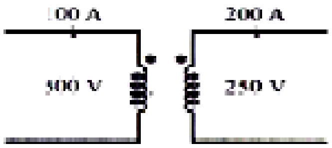


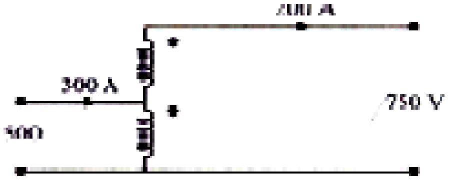
V_{in} = 3300 volts

V_o = 3300 + 230 = 3530 V

GATE-16. Ans. (c) $\eta_{2wdg} = \dfrac{0.95 = 50 \times 1 \times 1}{50 + w_{Cu} + w_i}$

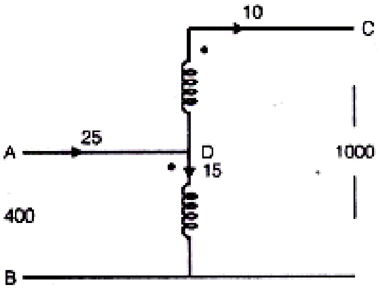
$\therefore \quad w_{Cu} + w_i = 2.631$





$$\text{For auto transformer, } \eta = \frac{150}{150 + 2.631} = 98.276\%$$

GATE-17. Ans. (a)



GATE-18. Ans. (d) KVA Rating = 25 × 400 = 1000 × 10 = 10000 KVA

GATE-19. Ans. (d) p.u impedance = 0.02 + 0.07 j

Base impedance referred to primary

$$Z = Z_{(p.u)} \times Z_{Base} = (0.02 + 0.07j)\ (3630\ \Omega) = (72.6 + j254.1)\Omega$$

GATE-20. Ans. (d)

GATE-21. Ans. (c) Inductance $= \dfrac{NBA}{1}$ (proportional to A… cross section) when cross section becomes half, inductance becomes half.

GATE-22. Ans. (d)

GATE-23. Ans. (d)

GATE-24. Ans. (b) p.u leakage impedance $\alpha\ \dfrac{1}{KVA}$

$\therefore \quad 500KVA \times 0.05 = 250KVA \times X$

GATE-25. Ans. (c)

Previous Year IES Answer

IES-1. Ans. (b) $P_e \infty V^2 \quad \Rightarrow \quad P_e(\text{at } 330V) = \left(\dfrac{330}{220}\right)^2 \times 50 = 112.5W$

IES-2. Ans. (b)

IES-3. Ans. (d) Copper loss = $(1/2)^2$ × 6400 = 1600 W

Iron loss does not depend upon the load but upon the applied voltage.

IES-4. Ans. (a)

IES-5. Ans. (a) $\eta = \sqrt{\frac{p_1}{p_2}}$ where, $\eta = \frac{75}{100} = \frac{3}{4}$

$\therefore \; \frac{p_1}{p_2} = \frac{9}{16}$

IES-6. Ans. (d) Air-core means non-iron core so there will be no hysteresis losses.

IES-7. Ans. (d)

IES-8. Ans. (d) Magnetizing flux $\phi \alpha \frac{V}{f}$ but core loss depends upon the frequency.

IES-9. Ans. (a) Load for $\eta_{\max}$ = full load $\sqrt{\frac{\text{Iron loss}}{\text{copper loss}}}$

IES-10. Ans. (b) Hysterisis loss not depend on thickness of lamination and time.

IES-11. Ans. (d) Eddy current loss $P_e = k_e B^2{}_{\max} f^2 t^2$

$B_{\max} \alpha \frac{V}{f}$. So, $P_e = k_e V^2 f^2$

where, t = thickness; f = frequency; and $B_{\max}$ = flux density

So, P_e will be same or no change in eddy current loss.

IES-12. Ans. (b) Load for $\eta_{\max}$ = full load $\sqrt{\frac{\text{iron loss}}{\text{copper loss}}} = 100\sqrt{\frac{1}{2}} = 70.7$ kVA

ES-13. Ans. (d) Iron losses not change due to load variations copper losses $\propto$ (loading in Pu)^2.

IES-14. Ans. (d) $P_e = K_e B^2 f^2 t^2$ where t is thickness.

IES-15. Ans. (c) A part of the winding being common, leakage flux and therefore leakage reactance is less.

IES-16. Ans. (b) Answer would depend upon the voltage ratio a = $\frac{V_1}{V_2}$ and type of auto-transformer i.e., step-up or step-down.

For step-up transformer

$$(\text{KVA})_{\text{Auto}} = \left(\frac{1}{1-a}\right)(\text{KVA})_{\text{two-wdg}} \qquad [\text{where } a < 1]$$

For step-down transformer

$$(\text{KVA})_{\text{Auto}} = \left(\frac{a}{a-1}\right)(\text{KVA})_{\text{two-wdg}} \qquad [\text{where } a > 1]$$

Let, N1 = N2 (Ideal two winding transformer) for step-up transformer $a = \frac{1}{2}$

then $(\text{KVA})_{\text{auto}} = 2 \times (\text{KVA})_{\text{two-wdg}}$

For step-down transformer = 2, then $(\text{KVA})_{\text{auto}} = 2 \times (\text{KVA})_{\text{two-wdg}}$

IES-17. Ans. (c) Let V_1 (primary) $> V_2$ (secondary)

So, $V_1 + V_2 = 2640$ ----- (i)

$V_1 - V_2 = 2160$ ----- (ii)

From (i) & (ii) $V_1 = 2400V$ & $V_2 = 240V$

$\therefore\ V_1 : V_2 = 10 : 1$

IES-18. Ans. (d) $V_1 = 2000 - 200 = 1800$ V due to opposite polarity connection

$$(kVA)_{auto} = 1800 \times 50 \qquad \Rightarrow I_2 = \frac{1800 \times 50}{2000} = 45A$$

IES-19. Ans. (b)

IES-20. Ans. (c)

IES-21. Ans. (d) $S_{trans} = S_{in}\left(1 - \frac{V_L}{V_H}\right)\times 100\% = S_{in}\left(1 - \frac{161}{230}\right)\times 100\% = 30\%$ of S_{in}

IES-22. Ans. (b) Power transferred conductively = 3 × 0.8 = 2.4 kW.

IES-23. Ans. (c) V = 0.08 X 1 pu

$\therefore\ V_{actual} = 0.08 \times 2000 = 160$ V

IES-24. Ans. (b) $R_{actual} = 0.02 \times \frac{(400)^2}{4000} = 0.8\Omega$

IES-25. Ans. (b) Core-loss component $= \frac{5000}{220} = 22.73A$

IES-26. Ans. (d) Core losses will be lesser in case of using high frequency ferrite core.

IES-27. Ans. (d) $P_c = 10W$ and $P_m = 10$ W as no-load components of power are equally divided.

$V_{OC(HV)} = 160$ V $\Rightarrow V_{OC(LV)} = \frac{160}{2} = 80V$

As $P_c = \frac{V^2}{R_C}$ and $P_m = \frac{V^2}{\omega L_m}$

$\therefore\ P_c\,(\text{at } 40\,\text{Hz}) = \left(\frac{80}{100}\right)^2 \times 10 = 6.4$ W

and $P_m\ (\text{at } 40\,\text{Hz}) = \left(\frac{80}{100}\right)^2 \times 10 \times \frac{50}{40} = 8W$

$\therefore\ W_1 = P_c + P_m = 6.4 + 8 = 14.4$ W

Similarly $I_{SC(LV)} = 10A \Rightarrow I_{SC(HV)} = \frac{10}{2} = 5A$

as $P_{cu} = I^2R$

$\therefore\ P_{cu}\ (\text{at } 40\text{ Hz}) = \left(\frac{5}{5}\right)^2 \times 25 = 25W$

$\therefore\ W_2 = 25$ W

IES. 28. Ans. (a)

IES-29. Ans. (c)

IES-30. Ans. (a) To ensure co-phasor primary and secondary windings.

IES-31. Ans. (d)

IES-32. Ans. (c) $V_{bd} = V_{bc} + V_{cd} = 230\angle 0° + 115\angle -120° = 115\sqrt{3}$ V

IES-33. Ans. (a) A delta-connected tertiary reduces the impedance offered to the zero sequence currents thereby allowing a larger earth-fault current to flow for proper operation of protective equipment. Further it limits voltage imbalance when the load is unbalanced. It also permits the third harmonic current to flow thereby reducing third-harmonic voltages. When used for this purpose, the tertiary winding is called a stabilizing winding.

IES-34. Ans. (b) $V_1 = 11000 \times 13\text{V}$ (star-connection)

$V_2 = 220$ V (delta-connection)

$\therefore \quad V_1 : V_2 = 19052 : 220$ V and $\dfrac{N_1}{N_2} = \dfrac{V_1}{V_2} = 50\sqrt{3}$

IES-35. Ans. (a)

IES-36. Ans. (a)

IES-37. Ans. (a) $S_1 = \dfrac{800}{0.0198 \times \left(\dfrac{1}{0.0198} + \dfrac{1}{0.0304}\right)} = 484.5\,\text{kVA}$

$$S_2 = \frac{800}{0.0304 \times \left(\dfrac{1}{0.0198} + \dfrac{1}{0.0304}\right)} = 800 - S_1 = 315.5\ \text{kVA}$$

IES-38. Ans. (a) 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.

IES-39. Ans. (d)

IES-40. Ans. (a) 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.

IES-41. Ans. (b) Due to transformer action, the circulating current will flow both in the primaries and secondaries. It is usual in practice to keep the circulating current less than 10% of the rated current, consequently the transformer turns ratios must be as nearly equal as is possible.

IES-42. Ans. (c) Load sharing not depend on η and magnetizing current. Equivalent impedance also have resistance so option B. Leakage reactance is also not correct.

IES-43. Ans. (a) $\phi = \text{B.A.}$ i.e. A (area of the core) $\propto \dfrac{1}{\text{B}}$ for constant ϕ.

IES-44. Ans. (a)
IES-45. Ans. (a)
IES-46. Ans. (c)
IES-47. Ans. (c) Grains are oriented to increase μ_r.
IES-48. Ans. (b)
IES-49. Ans. (b)
IES-50. Ans. (b) Percentage voltage regulation for lagging p.f. $=(\in_r \text{COS}\theta + \in_x \sin\theta)\times 100$

as $\in_r = 0.01$ & $\in_x = 0.04$

$\therefore$ % VR = (0.01 × 0.8 + 0.04 × 0.6) × 100 = 3.2%

$\therefore$ % VR for leading p. f. = (0.01 × 0.8 – 0.04 × 0.6) × 100 = –1.6%

IES-51. Ans. (a) For lagging load '% R' = 1 (2 × 0.8 + 4 × 0.6) = 4%
For leading load '% R' = 1(2 × 0.8 – 4 × 0.6) = – 0.8%.

IES-52. Ans. (c)
IES-53. Ans. (d) Regulation of ideal transfer is 0% hence assertion is not correct.

IES-54. Ans. (a)
IES-55. Ans. (b) In approximate equivalent circuit, the parallel magnetising branch is shifted to the left of the primary leakage impedance with the assumption that voltage drop in the primary impedance due to the exciting current can be neglected.
IES-56. Ans. (b) Short circuit test is performed to find copper losses not core losses.
IES-57. Ans. (d) Dust & Moisture is already taken care by Silica Jel. Due to heating oxidation of transformer oil is there.
IES-58. Ans. (a)