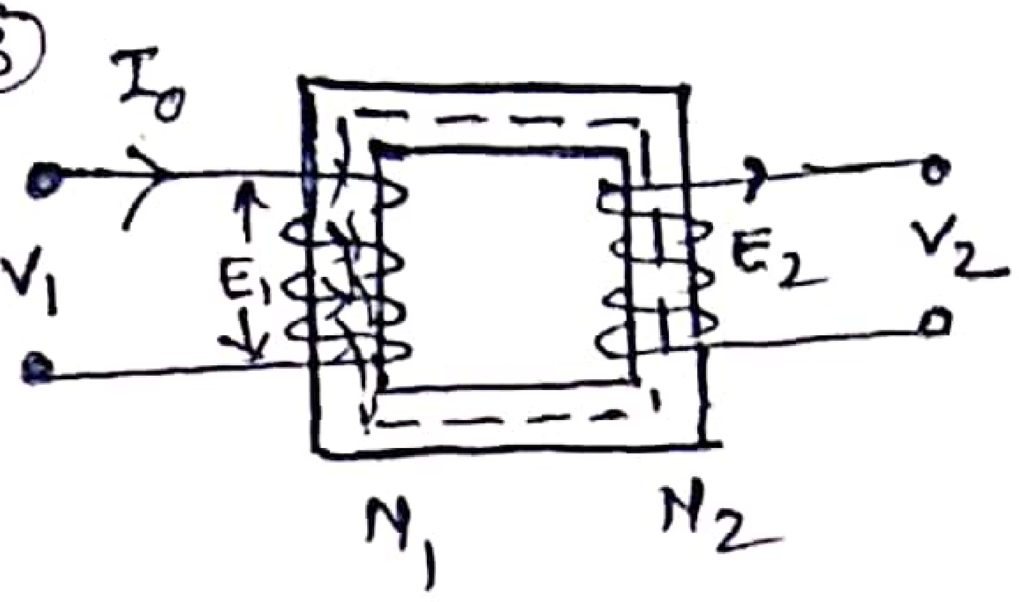
4.12 Phasor diagram of an ideal transformer at No load

$$\phi = \phi_m \sin \omega t \longrightarrow \text{Common to both Primary and secondary} \quad \text{---} (1)$$

$$E_1 = E_{1max} \sin\left(\omega t - \frac{\pi}{2}\right) \quad \text{---} (2)$$

$$E_2 = E_{2max} \sin\left(\omega t - \frac{\pi}{2}\right) \quad \text{---} (3)$$



Here $N_1 = N_2$

$$V_1 = -E_1 \quad \text{---} (4)$$

exciting / No load Current $\bar{I_0} = \bar{I_c} + \bar{I_m}$ ---(5)
Current

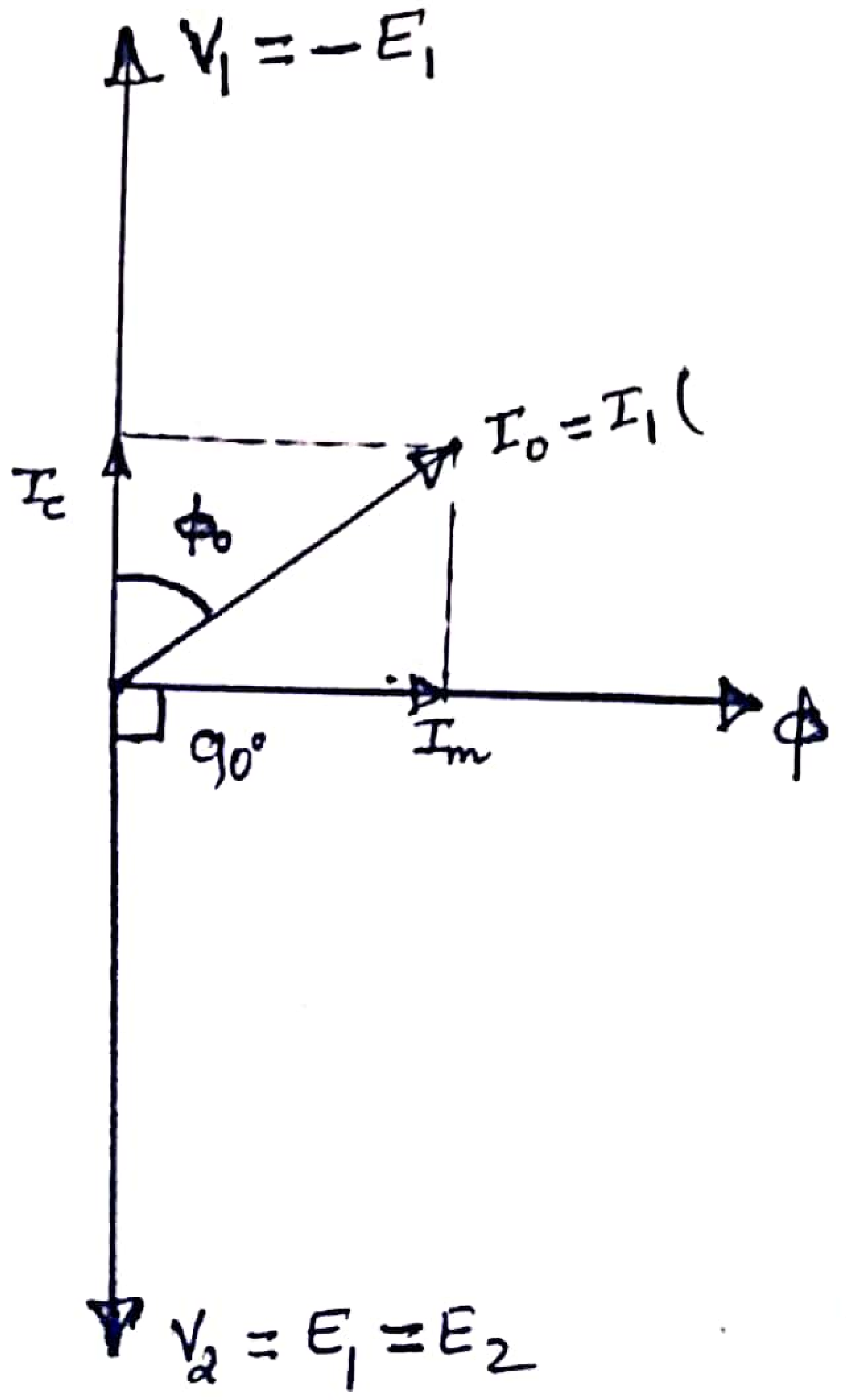
For No load $I_2 = 0$

$$I_1 = I_0 .$$

$$V_2 = E_2 \quad \text{---} (6)$$

$I_m \rightarrow$ is the reactive or magnetizing current since its function is to provide the required magnetic flux ϕ

$I_c \rightarrow$ core loss current component



ϕ_0 = No load phase angle

$$I_c = I_0 \cos\phi_0$$

$$I_m = I_0 \sin\phi_0$$

$$I_0 = \sqrt{I_c^2 + I_m^2}$$

for ideal transformer

$$r_1 = 0$$

$$r_2 = 0$$

$$\left.\begin{aligned} I_1 r_1 &= 0 \\ I_2 r_2 &= 0 \end{aligned}\right] \text{drop zero}$$

No load means secondary terminal is open circuited.

4.13 Phasor diagram of an ideal transformer at load conditio

$\phi = \phi_m \sin\omega t$ ——— (I)

$E_1 = E_{1max} \sin(\omega t - \frac{\pi}{2})$ ——— (II)

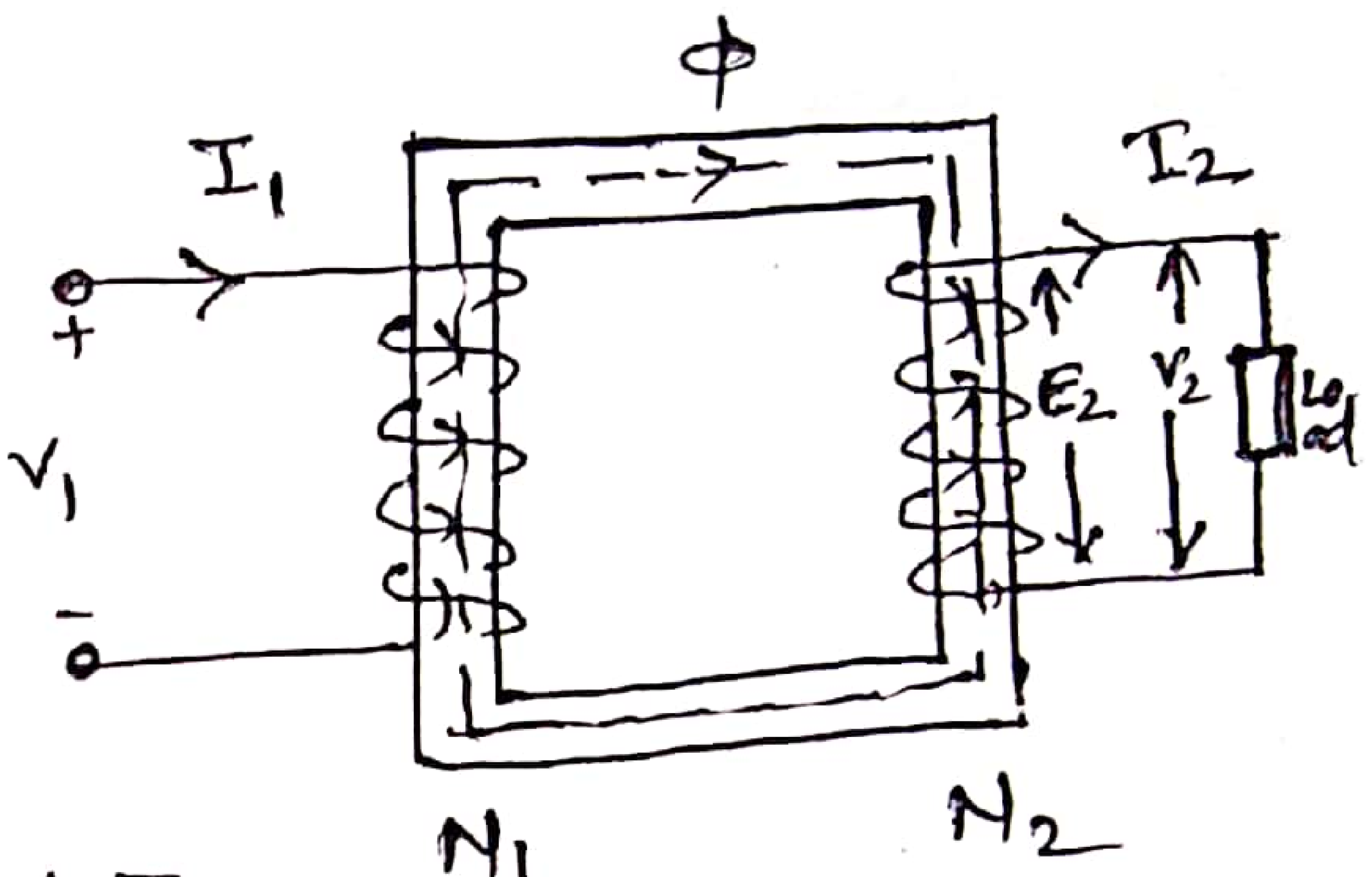
$E_2 = E_{2max} \sin(\omega t - \frac{\pi}{2})$ ——— (III)

$V_1 = -E_1$ ——— (IV)

$$\boxed{\begin{array}{c} I_1' N_1 = I_2 N_2 \\ F_1 = F_2 \end{array}}$$

Total Primary Current $I_1 = I_1' + I_e$ ——— (V)

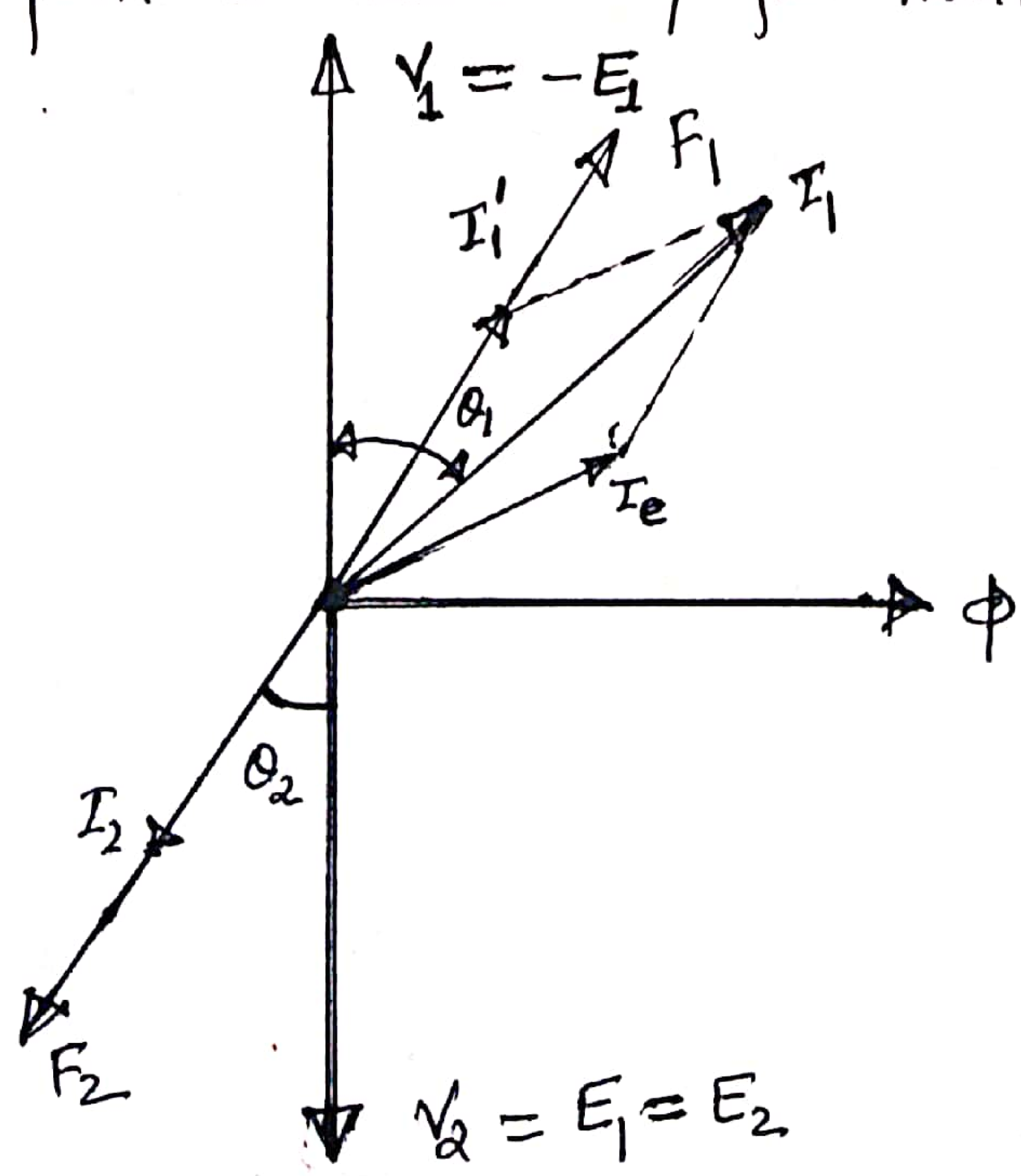
I_1' = compensating current required for maintaining the flux ϕ constant



→ When a load connected across the secondary terminals then according to Lenz's law, the direction of secondary current I_2 should be such that the secondary mmf $F_2 = N_2 I_2$ is opposite to mutual flux ϕ. This will result reduction in flux ϕ.

To neutralize the demagnetizing effect of secondary mmf, the primary current (I_1) draws extra current I_1' from the supply and make the mutual flux constant.

Constant flux is necessary for maintaining the value of E_1 & E_2



Load is inductive (RL)

Hence I_2 lag V_2 by θ_2.

4.14 Losses in Transformer:-

(a) Copper loss /- Ohamic Loss (P_{cu}):-

Copper loss (I^2R) takes place due to flow of current in primary and secondary winding. We know that winding has some resistance and when current flows through them, heat is produced. Therefore, some energy is lost as heat energy.

$$P_{cu} = I_1^2 r_1 + I_2^2 r_2$$
$$= I_1^2 r_{e_1}$$
$$= I_2^2 r_{e_2}$$

r_{e_1} → total equivalent resistance referred to primary

r_{e_2} → total equivalent resistance referred to secondary.

Copper loss is called variable loss because it depends upon load current.

(b) Core loss or Iron loss:- (P_c or P_i)!-

Core losses are due to magnetic properties of the material used for construction of core. Core loss is further classified into two types —

(I) Hysteresis loss (P_h)

(II) Eddy Current loss (P_e)

$$\boxed{P_c = P_h + P_e}$$

Core loss is called as constant loss.

(I) Hysteresis Loss :- It is due to reversal of magnetization in the transformer core.

$$\boxed{P_h = K_h f B_m^x}$$

x = Steinmetz's constant varies from 1.5 to 2.5. It also depends on magnetic material.

(II) Eddy Current loss :-

In transformer, primary winding setup an alternating magnetizing flux and it links with the body of transformer and this circulates current in the body which is known as eddy current. This current produces a loss in the core which is known as eddy current loss.

$$\boxed{P_e = K_e f^2 B_m^2}$$

(c) **dielectric loss :-** Dielectric loss occurs in the insulating material of the transformer that is in the oil of the transformer, or in solid insulations.

(d) **Stray loss :-** The occurence of these stray losses is due to the presence of leakage field. The percentage of these losses are very small as compared to the iron and copper losses so they can be neglected.

4.15 Efficiency of Transformer :-

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

Efficiency at full load

$$\% \eta_{fl} = \frac{KVA \cos\phi}{KVA \cos\phi + P_c + P_{cufl}} \times 100$$

$$= \frac{V_2 I_2 \cos\theta_2}{V_2 I_2 \cos\theta_2 + P_c + P_{cufl}} \times 100$$

P_i or P_c = core loss

P_{cufl} = full load copper loss

$\cos\phi$ or $\cos\theta_2$ = load Power factor

Efficiency at fraction of full load –

$$\% \eta = \frac{n \times (KVA) \cos\phi}{n (KVA) \cos\phi + P_c + n^2 P_{cufl}} \times 100$$

$$= \frac{n \times (V_2 I_2 \cos\theta_2)}{n \times (V_2 I_2 \cos\theta_2) + P_c + n^2 P_{cufl}} \times 100$$

$n \rightarrow$ fraction of full load

if $n = 1$, it means full load

$n = \frac{1}{2}$ it " half load

$n = \frac{1}{4}$ " " quarter load

4.16 - Condition for maximum efficiency :-

$$\eta = \frac{n\,(KVA)\cos\phi}{n\,(KVA)\cos\phi + P_c + n^2 P_{cufl}}$$

$$\eta = \frac{KVA\cos\phi}{(KVA\cos\phi) + \left(\frac{P_c}{n} + n\,P_{cufl}\right)}$$

for maximum efficiency of transformer -

factor $\left(\frac{P_c}{n} + n\,P_{cufl}\right)$ should be minimum

$$\therefore \frac{d}{dn}\left[\frac{P_c}{n} + n\,P_{cufl}\right] = 0$$

$$-\frac{P_c}{n^2} + P_{cufl} = 0$$

$$\boxed{P_c = n^2 P_{cufl}}$$ at any load

core loss = copper loss

for full load, $n = 1$

then $\boxed{P_c = P_{cufl}}$

Hence for maximum efficiency, iron loss and copper loss must be equal.

Hence for maximum efficiency of transformer

$$\boxed{\text{Core loss} = \text{Copper loss}}$$

Value of load current I_2 for which maximum efficiency will occur -

$$\boxed{I_2 = I_2(\text{rated}) \sqrt{\frac{P_c}{P_{cufl}}}}$$

Value of load KVA for which maximum efficiency will occurs.

$$\boxed{KVA\Big|_{\text{for max } \eta} = KVA(\text{rated}) \times \sqrt{\frac{P_c}{P_{cufl}}}}$$

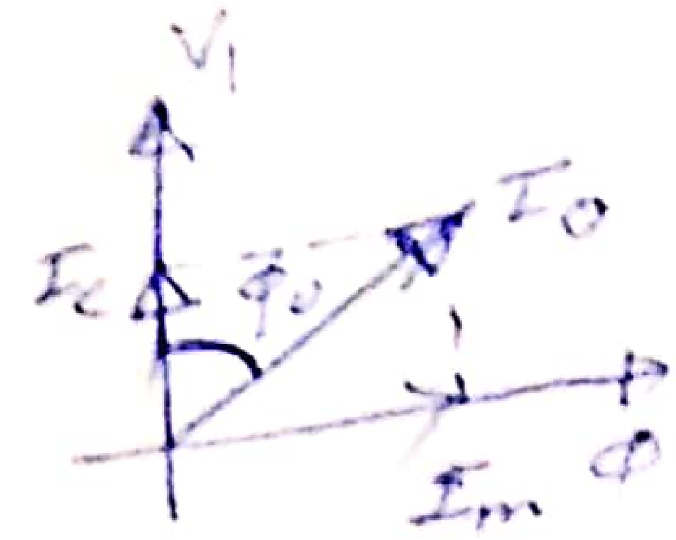
Problems on Transformer Efficiency & Circuit

Q.1 A transformer on no load has a core loss of 50W, draws a current of 2A and has an induced emf of 230V(rms).
Determine - (I) No load Power factor
(II) core loss current (I_c)
(III) Magnetizing current (I_m)

Hint :- $P_c = V I_0 \cos\phi_0 \Rightarrow \cos\phi_0 = 0.108$

$I_c = I_0 \cos\phi_0 \Rightarrow 0.216\,A$

$I_m = I_0 \sin\phi_0 \Rightarrow 1.98\,A$



Q.2 A single phase transformer has a maximum efficiency of 90% at full load and unity power factor, calculate efficiency at half load and at same power factor.

$$\eta_{fl} = \frac{KVA \times \cos\phi}{KVA \times \cos\phi + P_c + P_{cu}} \times 100$$

for max efficiency $P_{cu} = P_c$

$$0.9 = \frac{KVA \times \cos\phi}{KVA \times \cos\phi + 2P_c} \qquad \cos\phi = 1$$

$$P_c = 0.055KVA = P_{cu}$$

At half load:- $$\eta = \frac{\frac{1}{2} \times KVA \times 1}{\frac{1}{2} \times KVA \times 1 + P_c + \frac{1}{4} P_{cu}} \times 100$$

$$= 87.8\,\%$$

Q.3 In a 25 KVA, 2000V/200V, transformer the iron loss & copper losses are 300W & 400W respectively. Calculate

(a) the efficiency on unity power factor at (I) full load → 97.27%
(II) half load = 96.8%

(b) Determine the load for maximum efficiency and calculate max. efficiency :-
Ans - $n = 0.866$, $\eta_m = 97.3\%$

Hint :-

$$\%\eta = \frac{n \times KVA \times \cos\phi}{n \times KVA \times \cos\phi + P_c + n^2 P_{cu}}$$

Here P_c & P_{cu} should be in KW.

Q.4 The efficiency of 100 KVA, 110V/220V, 50Hz 1 ϕ transformer is 98.5% at half load at 0.8 p.f and 98.8% at full load unity power factor.

Calculate -

1. iron loss $P_c = 4.07$ KW
2. full load copper loss $P_{cufl} = 8.06$ KW
3. maximum efficiency at u.p.f.

$$n^2 P_{cufl} = P_c$$

$$n = 0.71$$

$$\eta_m = 98.86\%$$