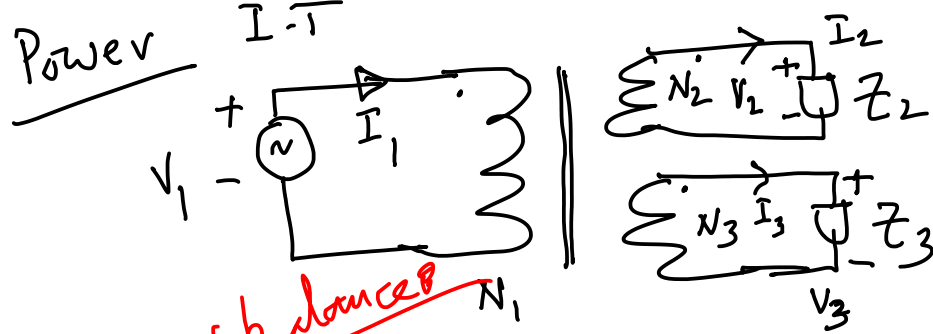


Complex Power delivered by
The source $= V I^* = S$

Power balance

$$\checkmark V_1 I_1^* = \checkmark V_2 I_2^* + \checkmark V_3 I_3^*$$

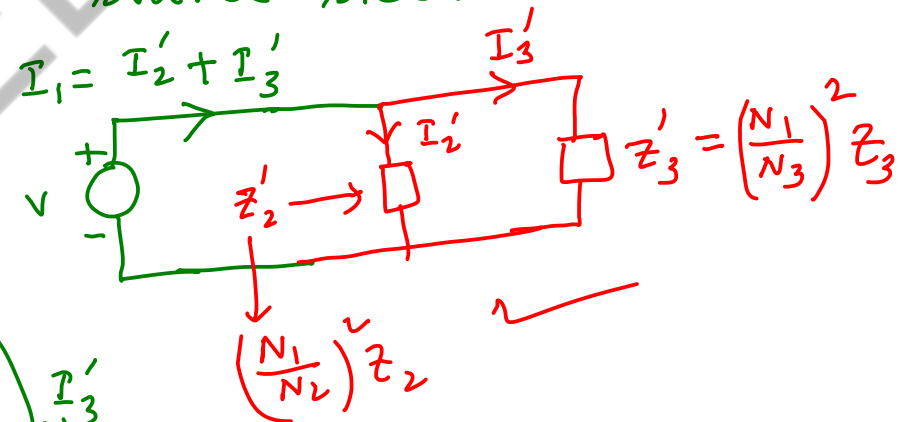
$$I_1^* = \frac{V_2}{V_1} I_2^* + \frac{V_3}{V_1} I_3^*$$

$$I_1^* = \frac{I_2^*}{(V_1/V_2)} + \frac{I_3^*}{(V_1/V_3)}$$

$$I_1 = (I_1^*)^* = \frac{I_2}{(V_1/V_2)} + \frac{I_3}{(V_1/V_3)} \quad \begin{matrix} I_2' \\ I_3' \end{matrix}$$

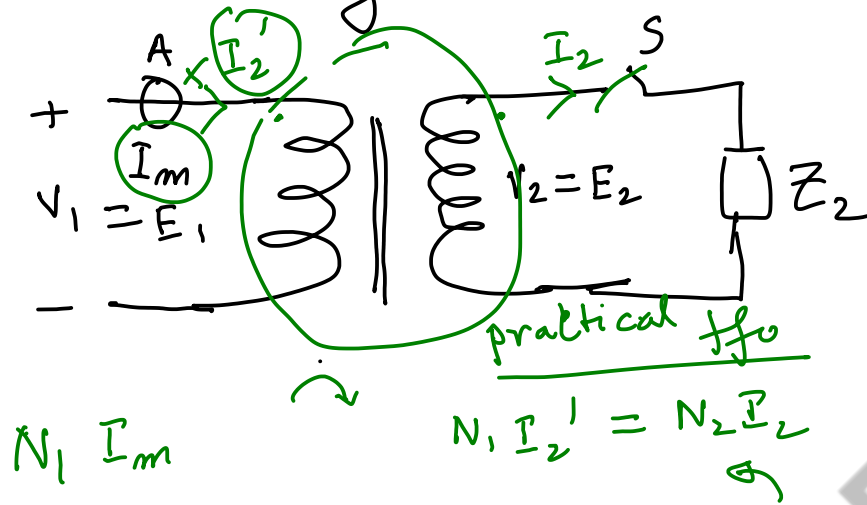
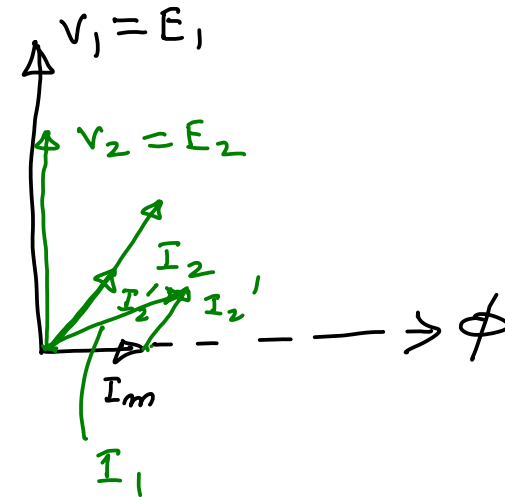
→ Power balance

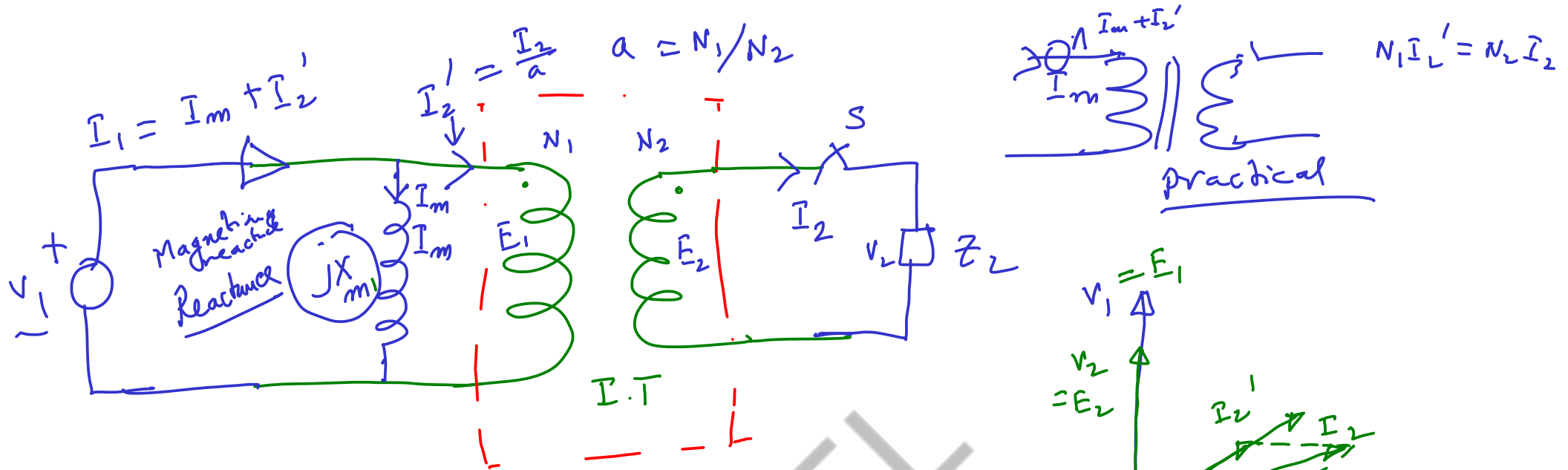
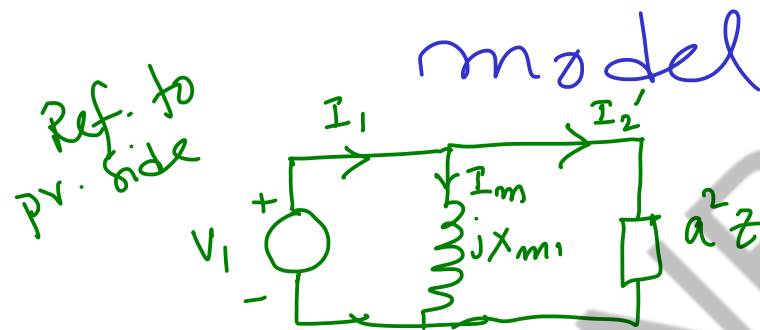
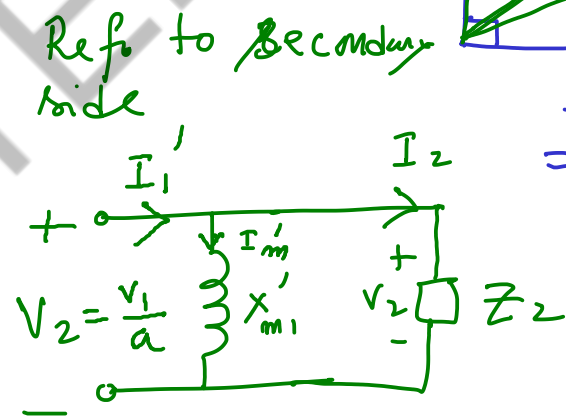
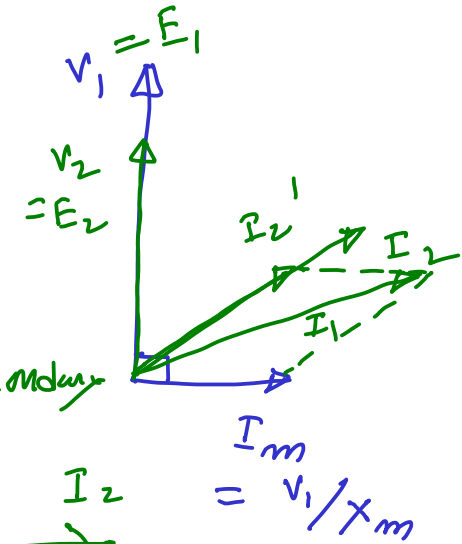
→ Equiv ckt. Ref. to source side :-



Practical Transformer: Add realities to an I.T

suppose magnetising current is finite and can not be neglected.

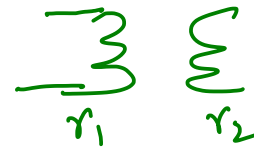




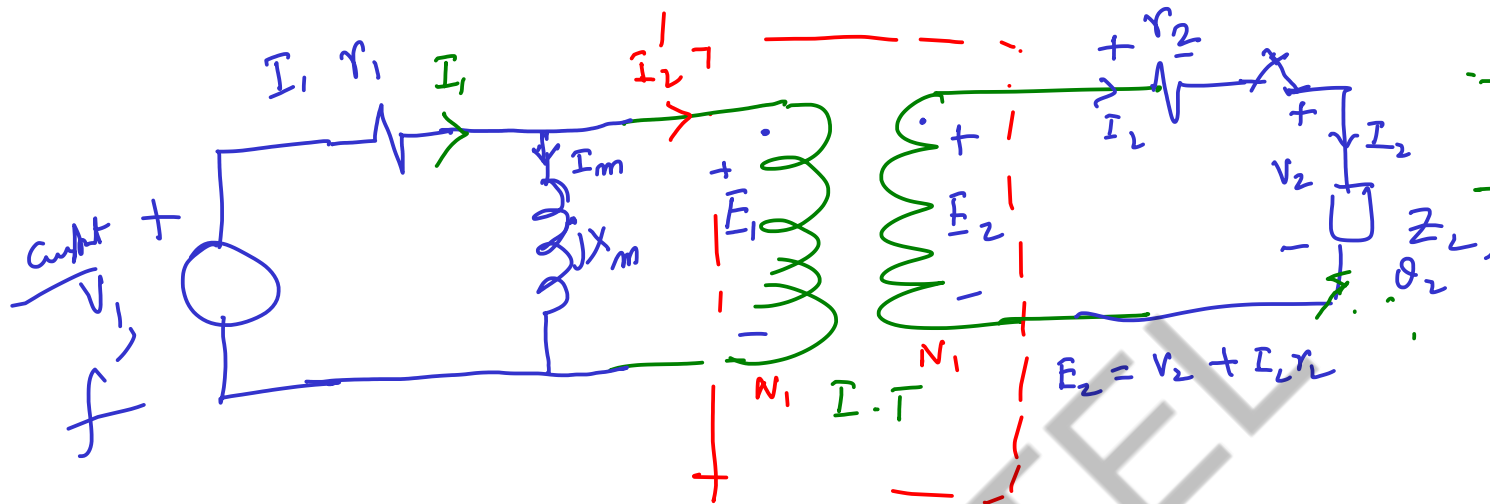
$$X_{m1}' = \frac{X_{m1}}{a^2}$$

winding resistances r_1, r_2

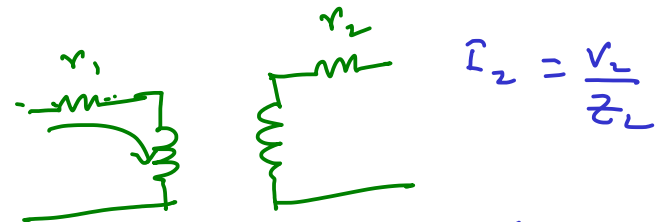
$$E_2 = V_2 + I_2 r_2$$



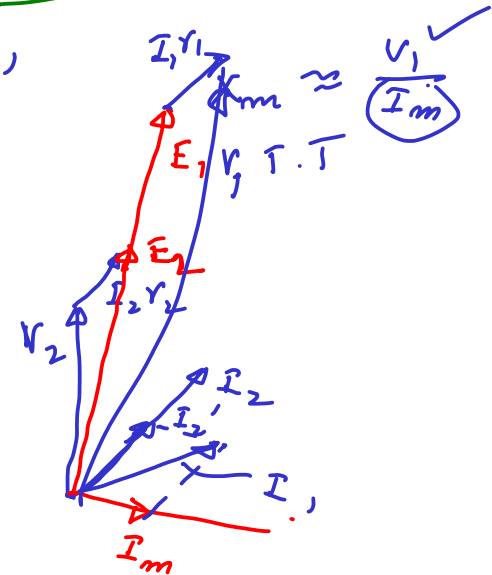
lec-9



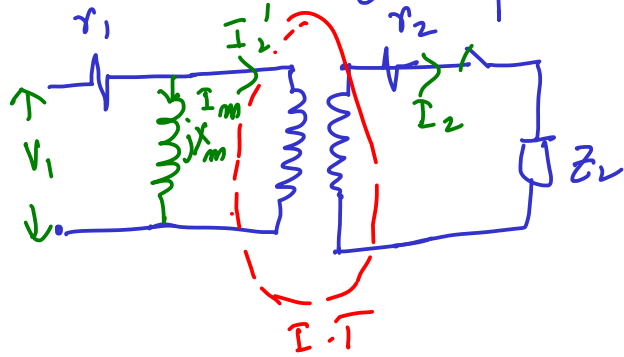
$$V_1 = E_1 + I_1 r_1$$



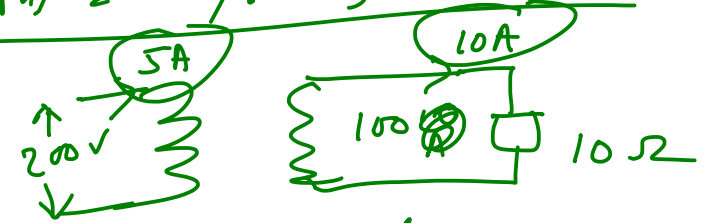
$$I_2 = \frac{V_2}{Z_L}$$



Model of a practical tfo $\equiv I.T + \text{some CKT elements.}$



X_m high
 r_1, r_2 are small. Practical:
 $I_{ph}, 200V/100V, 1kVA, 50Hz$

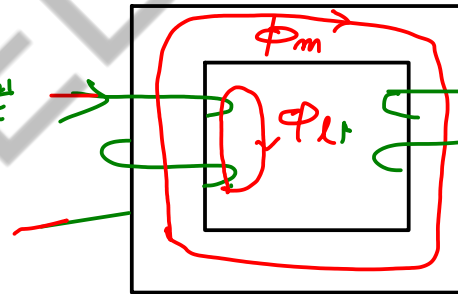


practical:

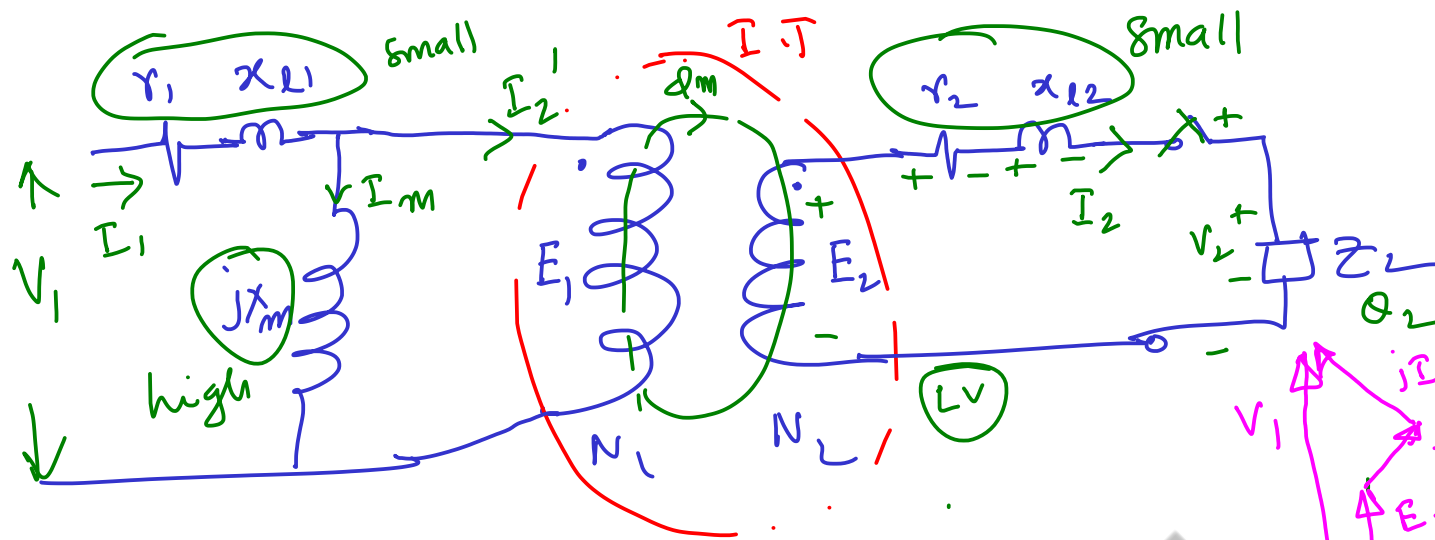
$$N_1 \frac{d}{dt} (\Phi_m + \Phi_{l1})$$

$$= N_1 \frac{d\Phi_m}{dt} + \underbrace{N_1 \frac{d\Phi_{l1}}{dt}}_{\eta}$$

Extra voltage drop
 voltage drop
 $L_{l1} \frac{di_{l1}}{dt}$



leakage flux causes an extra small voltage drop in the coil.

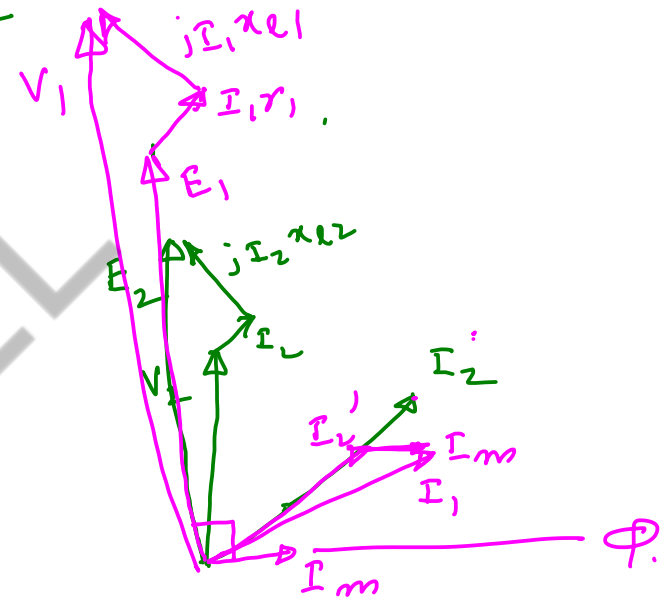


effect -
Core loss to be
~~not~~ yet
taken into account.

$$V_1 = E_1 + I_1(r_1 + jx_{L1})$$

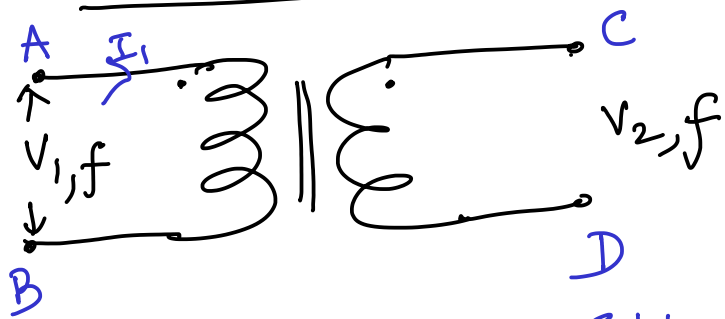
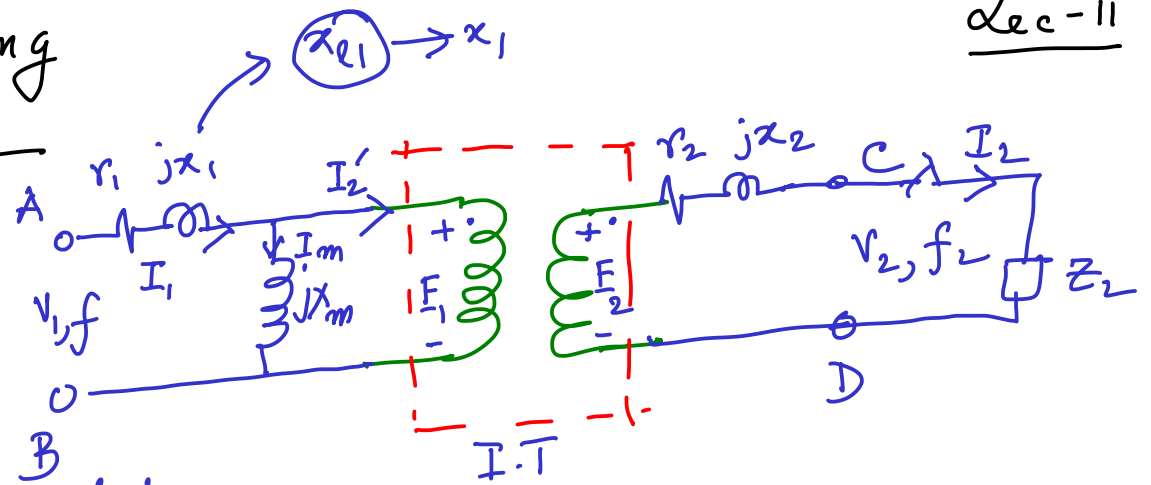
$$|V_1| \approx |E_1|$$

$$|E_2| \approx |V_2|$$



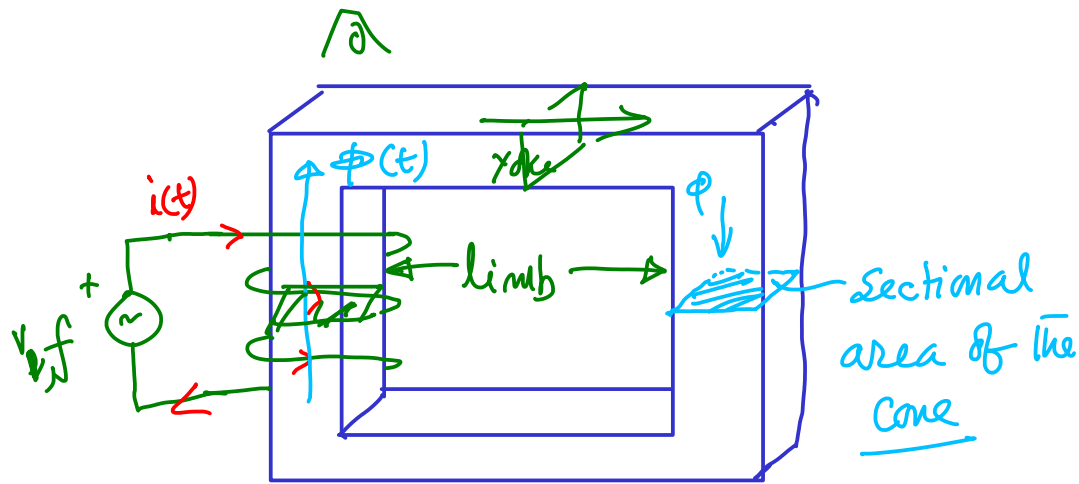
Practical transformer modelling & Equivalent circuit.

Lec-11

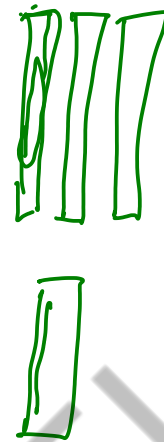
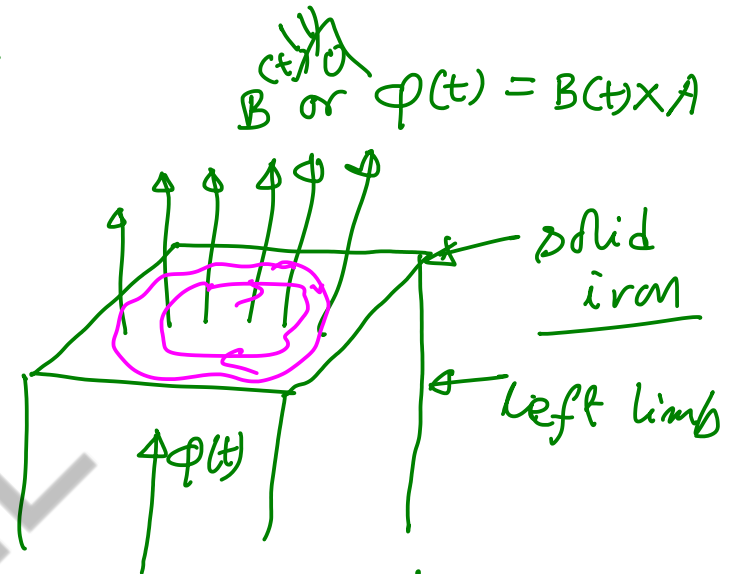
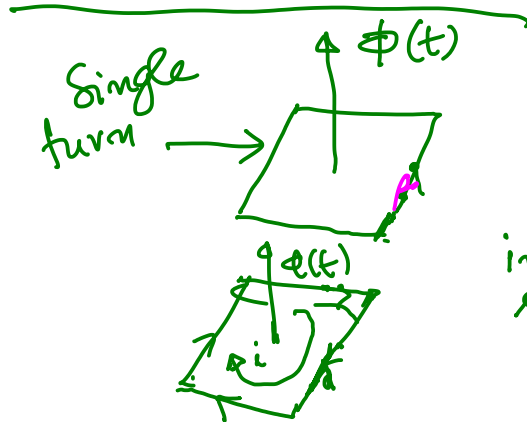


Core loss $\left\{ \begin{array}{l} \text{Eddy current loss} \\ \text{Hysteresis loss.} \end{array} \right.$

NPTTEL



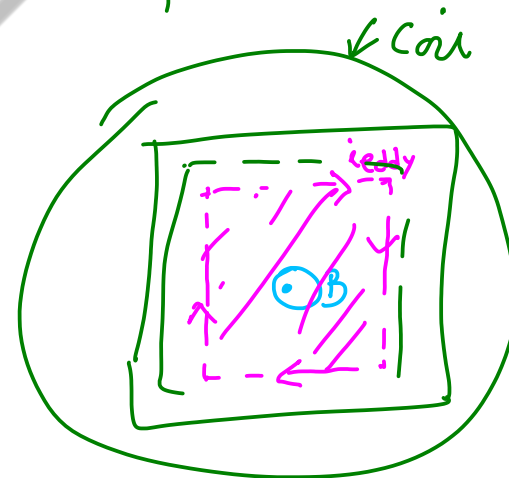
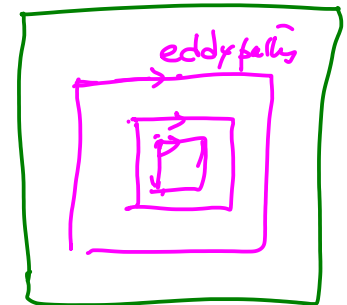
Core material can conduct current. (say iron)

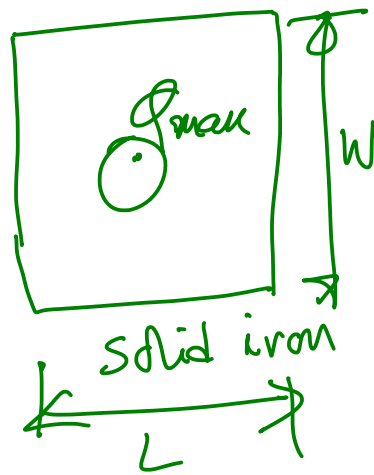
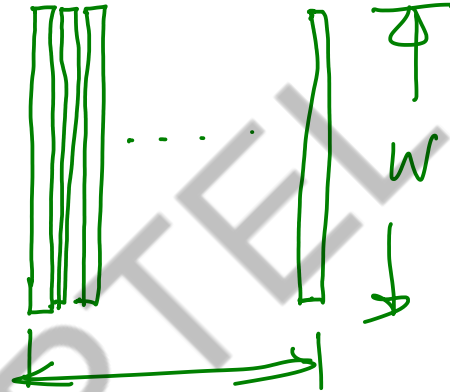
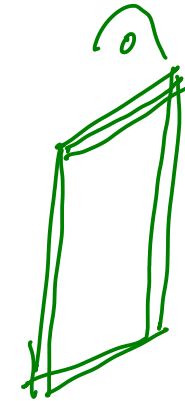


$$1 \times \frac{d\phi}{dt}$$

RMS:
in two single turns

$$= \sqrt{2} \pi f \phi_{max} \times 1$$



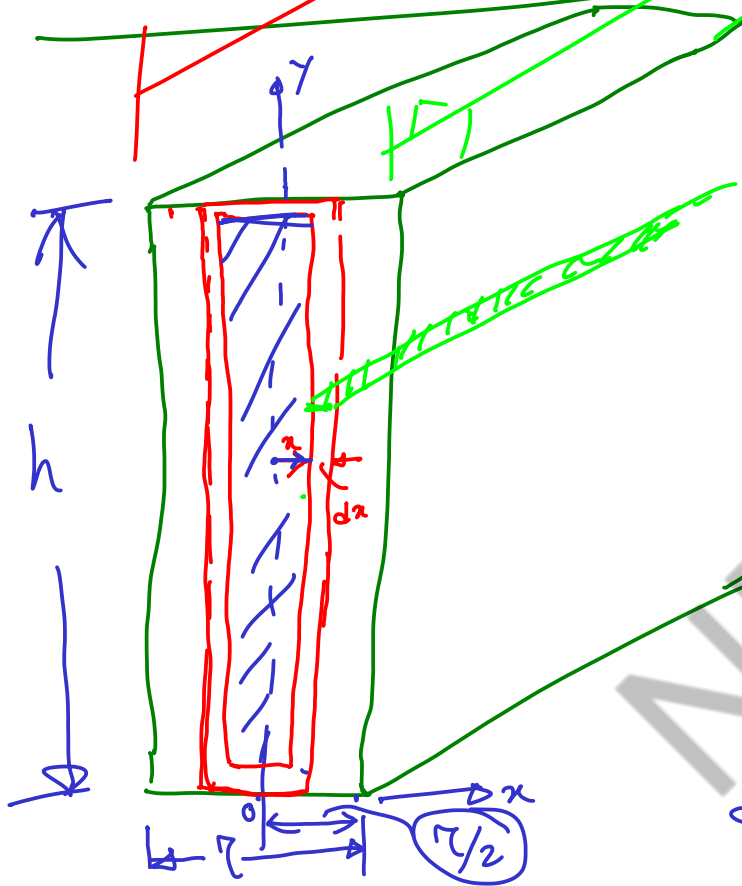


$$I_{\max} \approx \frac{V_1}{\sqrt{2\pi f N}},$$

Thin insulated
plates
instead of solid iron

$\frac{P}{A}$

Eddy current loss $\propto \tau$



To find out an approximate expression for Eddy loss in a thin plate $\because \tau \ll h$

RMS induced voltage in the loop

$$E_{\text{ddy}} = \sqrt{2} \pi f B_{\text{max}} (2xh) \times 1$$

Eddy power loss in this loop

$$= \frac{E_{\text{ddy}}^2}{R_{\text{eddy path}}} = \frac{2\pi^2 f^2 B_{\text{max}}^2 4x^2 h^2}{\rho (2x + 2h) L dx}$$

$$= \frac{8\pi^2 f^2 B_{\text{max}}^2 h^2 x^2 L dx}{\rho \int_0^{\tau/2} (2x + 2h) L dx}$$

$$dP_{\text{eddy}} = \frac{4\pi^2 f^2 B_{\text{max}}^2 h^2 L x^2 dx}{\rho}$$

$$dP_{\text{eddy}} = \frac{4\pi^2 f^2 B_{\text{max}}^2 h L}{\rho} x^2 dx$$

$$P_{\text{eddy total}} = \frac{4\pi^2 f^2 B_{\text{max}}^2 h L}{\rho} \int_0^{\tau/2} x^2 dx$$

Silicon steel

$$= \frac{4\pi^2 f^2 B_{\text{max}}^2 h L}{\rho} \frac{\tau^3}{8} \times \frac{1}{3}$$

$$\tau \approx 0.25 \text{ to } 0.50 \text{ mm}$$

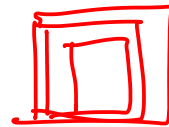
$$= \frac{1}{6\rho} \pi^2 f^2 B_{\text{max}}^2 (h L \tau) \tau^2$$

$$P_{\text{eddy total}} = \frac{1}{6\rho} \pi^2 B_{\text{max}}^2 f^2 \tau^2 \times \text{volume of iron.}$$

→ higher resistivity

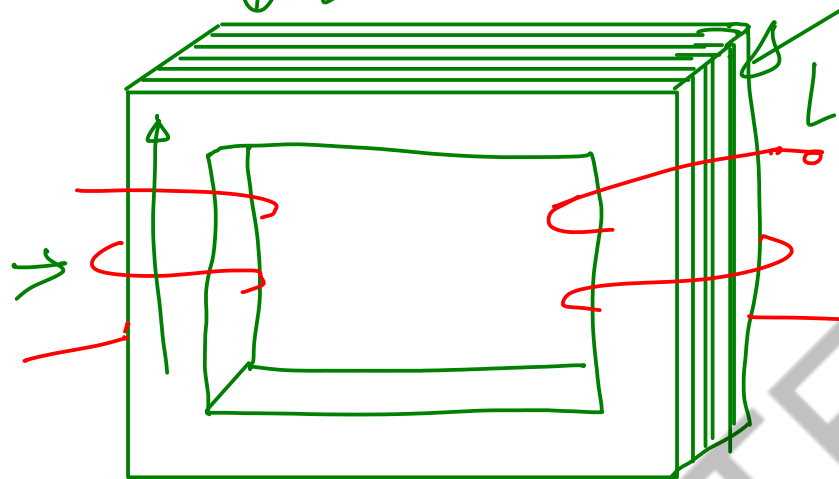
$$P_{\text{eddy}} / \text{vol}$$

$$= \frac{1}{6\rho} \pi^2 B_{\text{max}}^2 f^2 \tau^2 \quad \text{w/ per unit vol.}$$



Approx
✓ Expression

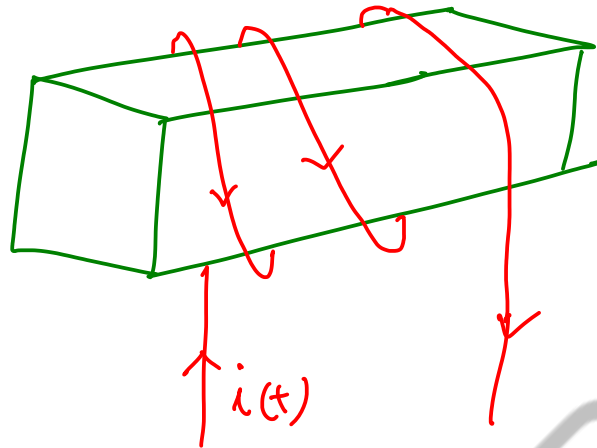
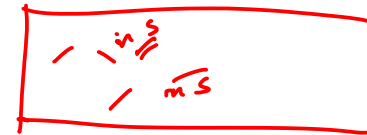
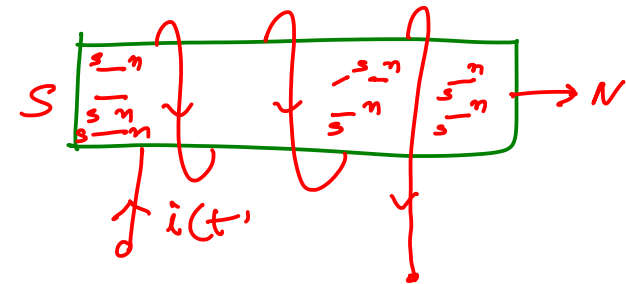
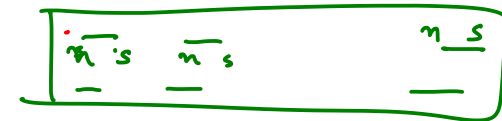
① Lamination



Laminated plate

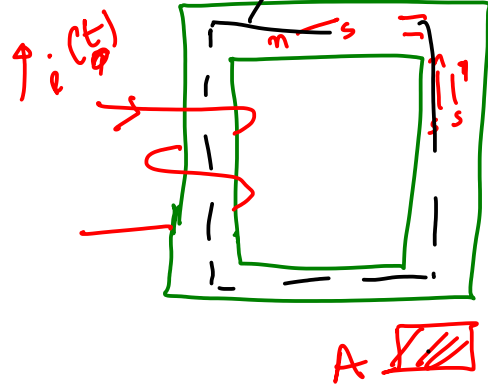
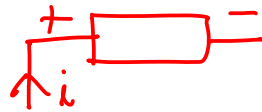
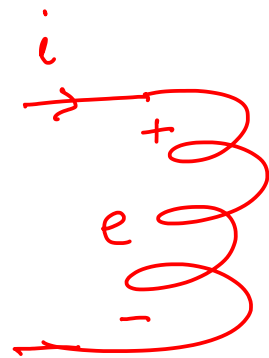


Hysteresis loss takes place in the core.



Reverse.

Hysteresis loss :-



$$t \rightarrow i \rightarrow H \rightarrow B$$

$$t + dt \rightarrow i + di \rightarrow H + dH \rightarrow B + dB$$

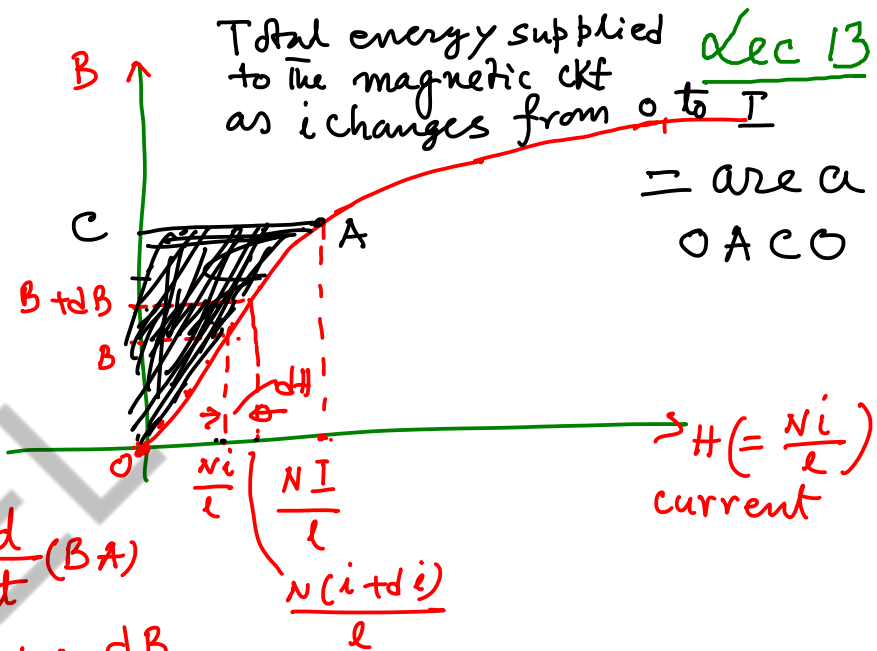
Energy absorbed by the coil in time dt

$$p dt = i N A \frac{dB}{dt} dt = \frac{N i}{l} dB (A l) \rightarrow \text{vol. of the core mat.}$$

$$p dt = H dB \times \text{volume.}$$

$$\phi = i N A \frac{dB}{dt}$$

$$e = N \frac{d}{dt} (B A)$$



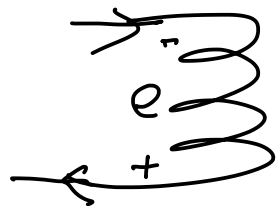
$i \sim$ = Sinusoidal time varying current

$$\int H dB \text{ x vol.}$$

$0 < \omega t < \frac{\pi}{2}$ i +ve & increasing

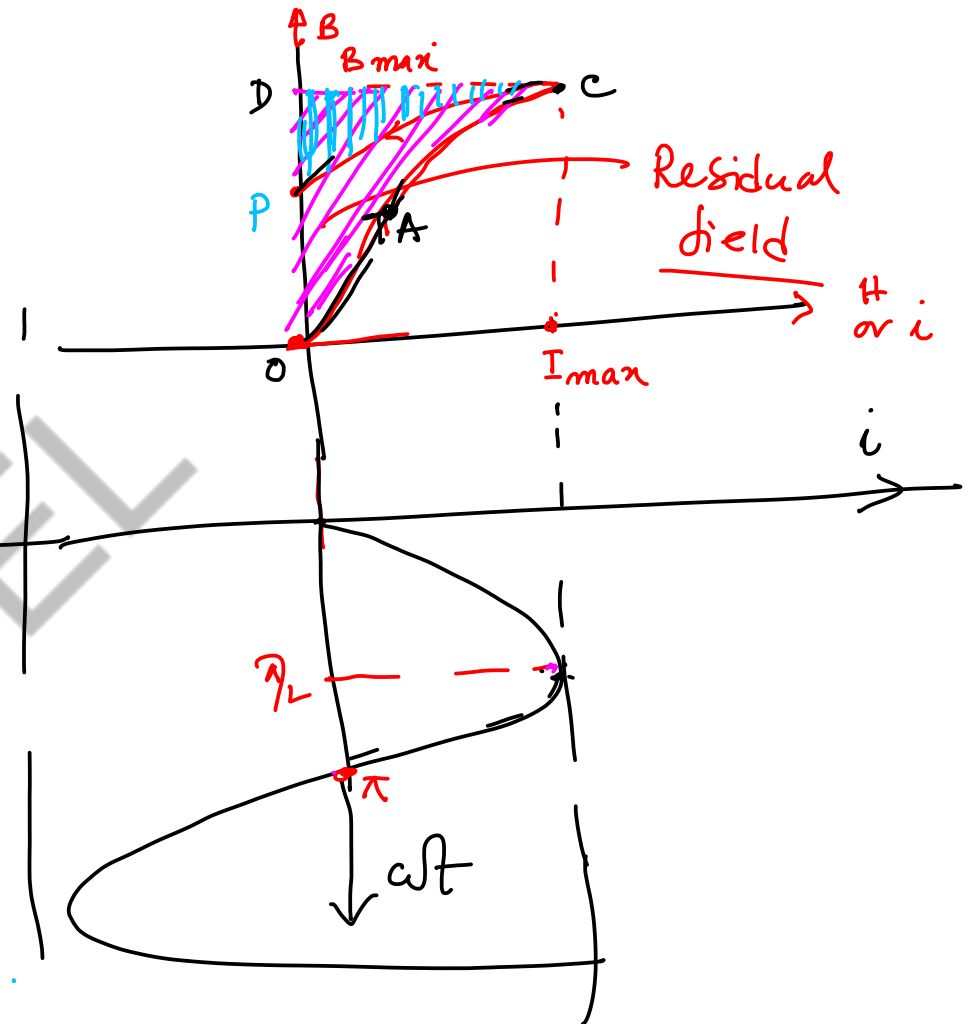
energy absorbed = area OACDO

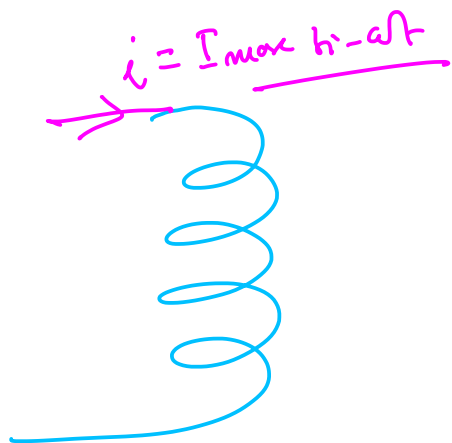
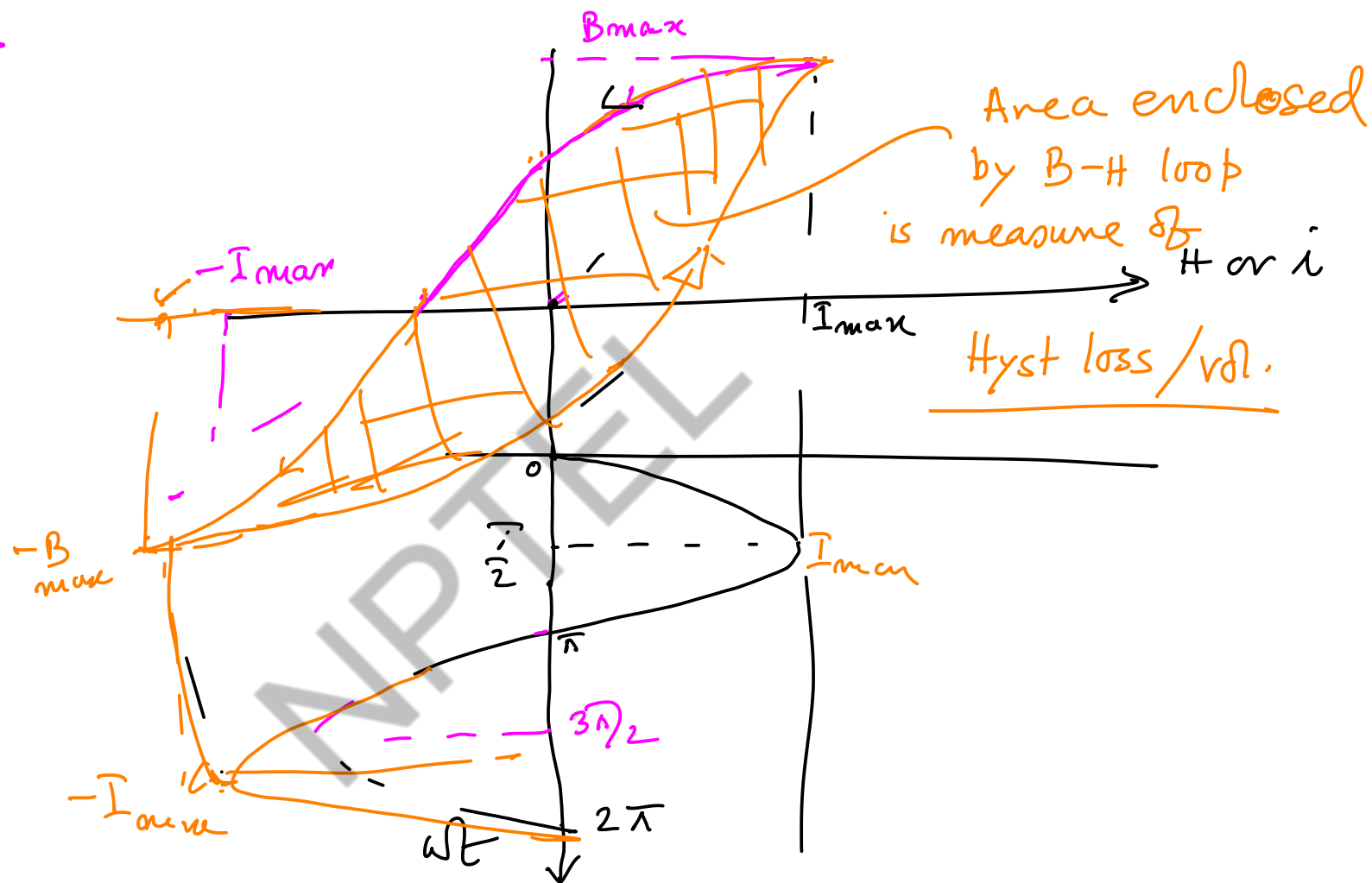
during $\frac{\pi}{2} < \omega t < \pi$



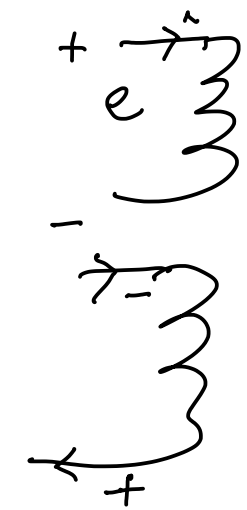
Energy is returned to the source

= area PCDP per unit vol.





Dec-14

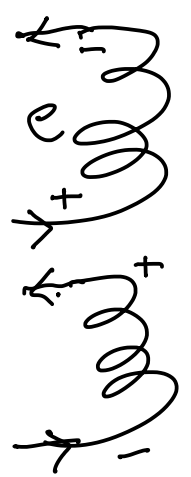


$$0 < \omega t < \frac{\pi}{2}$$

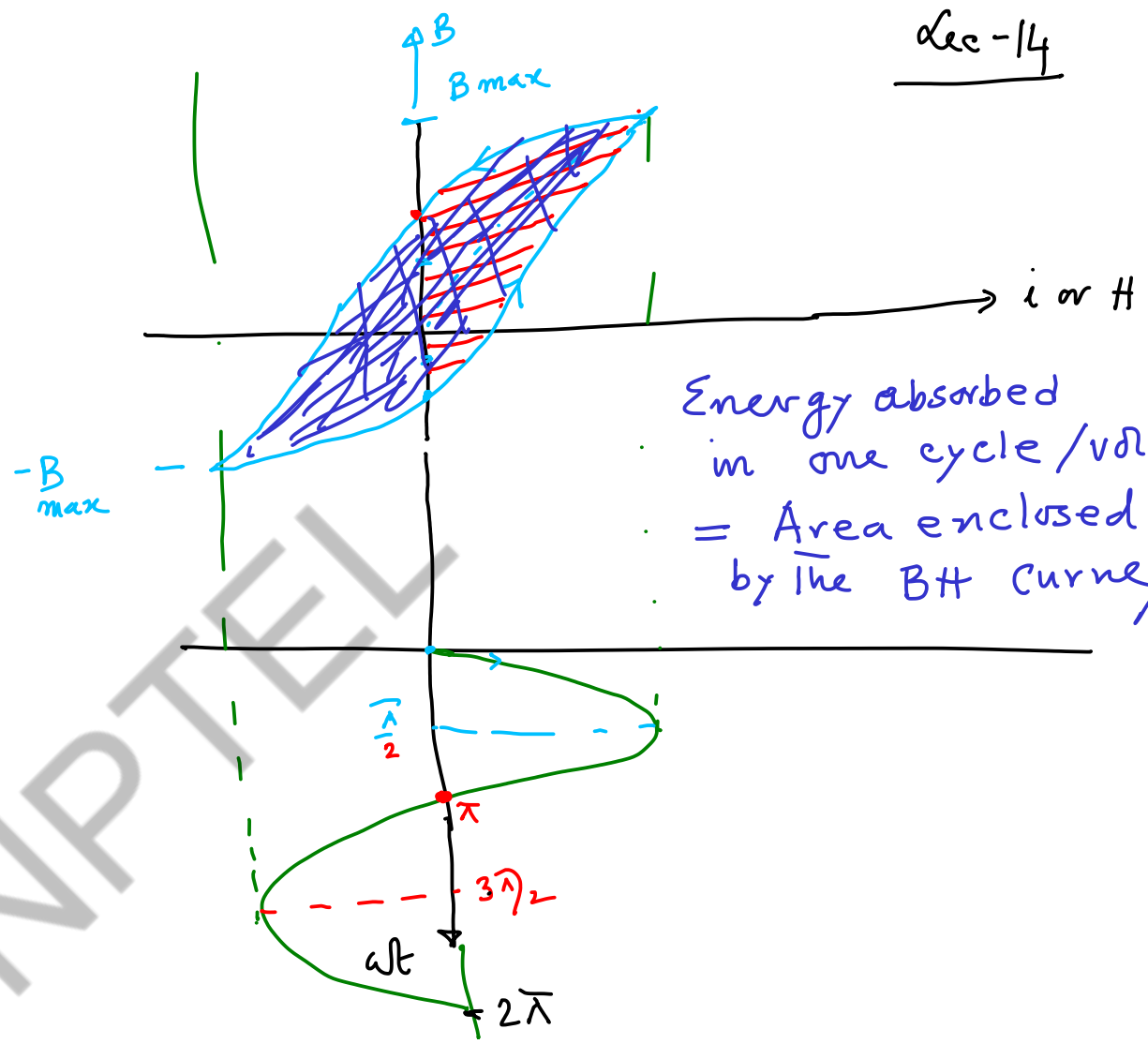
$\frac{\pi}{2} < \omega t < \pi$
energy returns back to supply.



$\pi < \omega t < 3\pi/2$
absorbs



returns back energy



Energy absorbed in one cycle/vol.
= Area enclosed by the BH curve/vol

NPTTEL

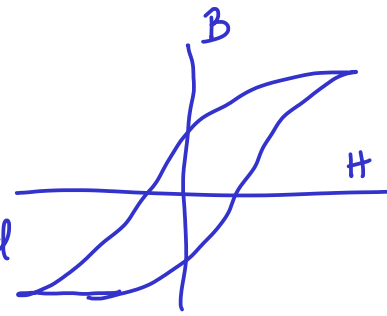
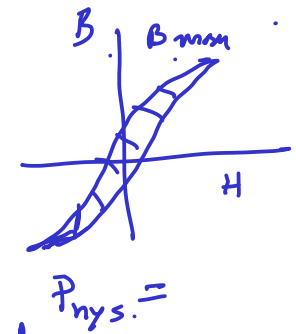
CRGO : Cold rolled
grain oriented
silicon steel

factors on which Hys loss depend

(i) Area enclosed by it

(ii) B_{max}

(iii) $f \rightarrow$ frequency



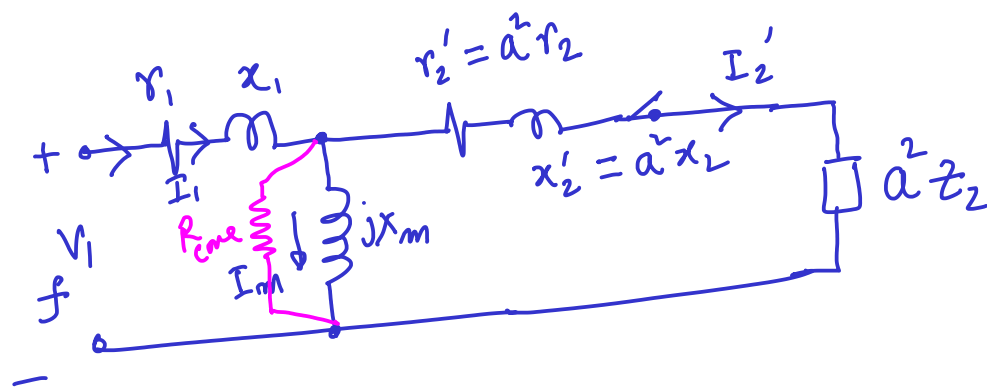
empirical formula

$$\left\{ \begin{array}{l} P_h \propto B_{max}^{1.6} f / vol \\ P_e \propto B_{max}^2 f^2 / vol \end{array} \right.$$

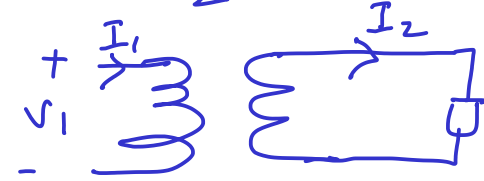
Coming back :

to Equivalent CKT.

of a practical tfo



$$a = \frac{N_1}{N_2}$$



$$P_{\text{core loss}} = P_{\text{eddy}} + P_{\text{hys}}$$

$$= k_e B_{\text{max}}^2 f^2 + k_h B_{\text{max}}^{1.6} \times f$$

Value of B_{max} practically remains same from no load to loaded condition

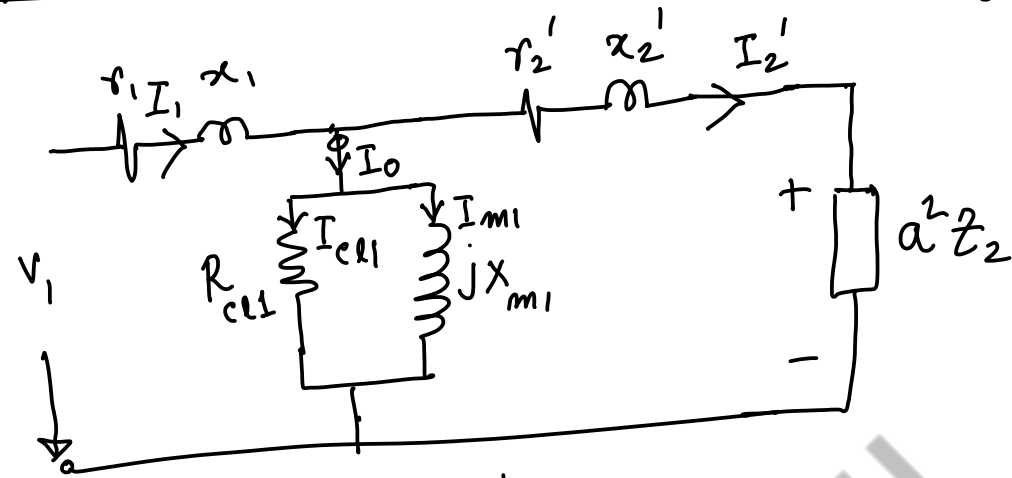
$$B_{\text{max}} = \frac{\Phi_{\text{max}}}{A}$$

$$P_{\text{max}} = \frac{E_1}{4.44 f N_1} \approx \frac{V_1}{4.44 f N_1}$$

— o —

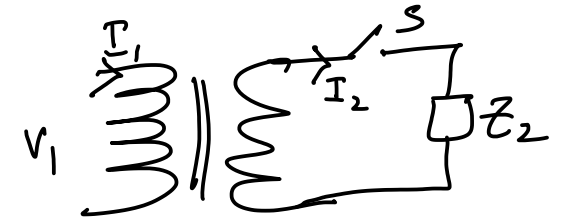
Exact Equivalent ckt. Ref. to primary side

$$a = N_1/N_2$$



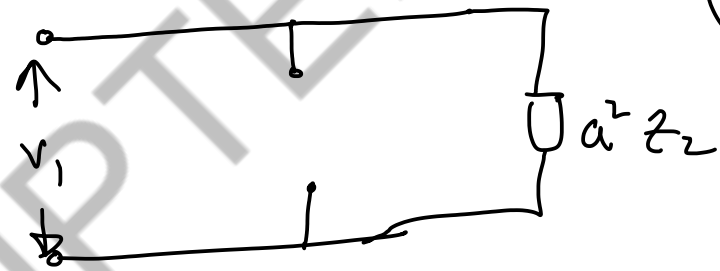
no load current

$$I_o = I_{cl} + I_m$$



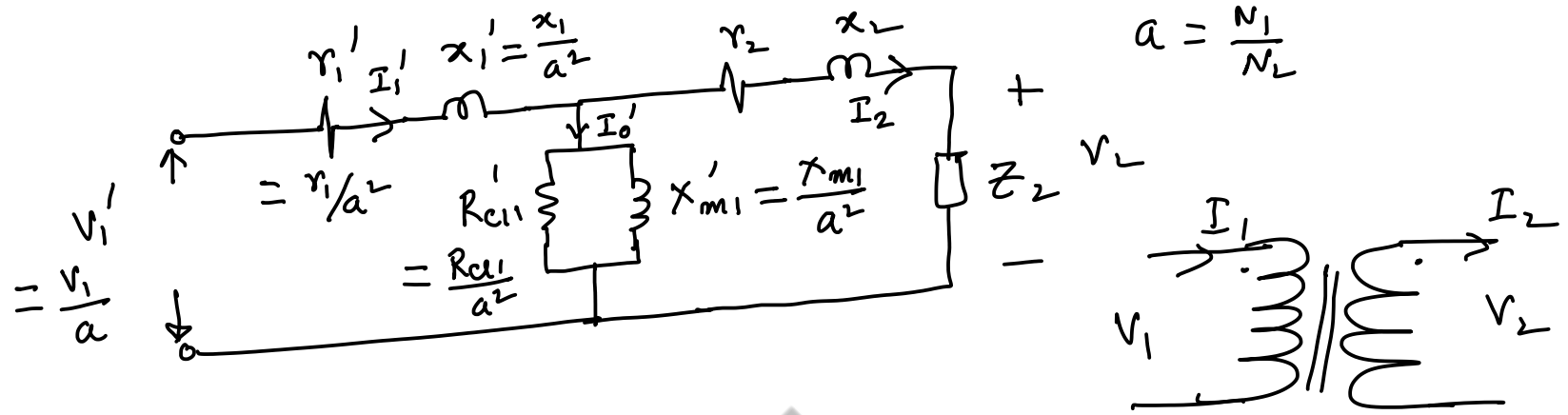
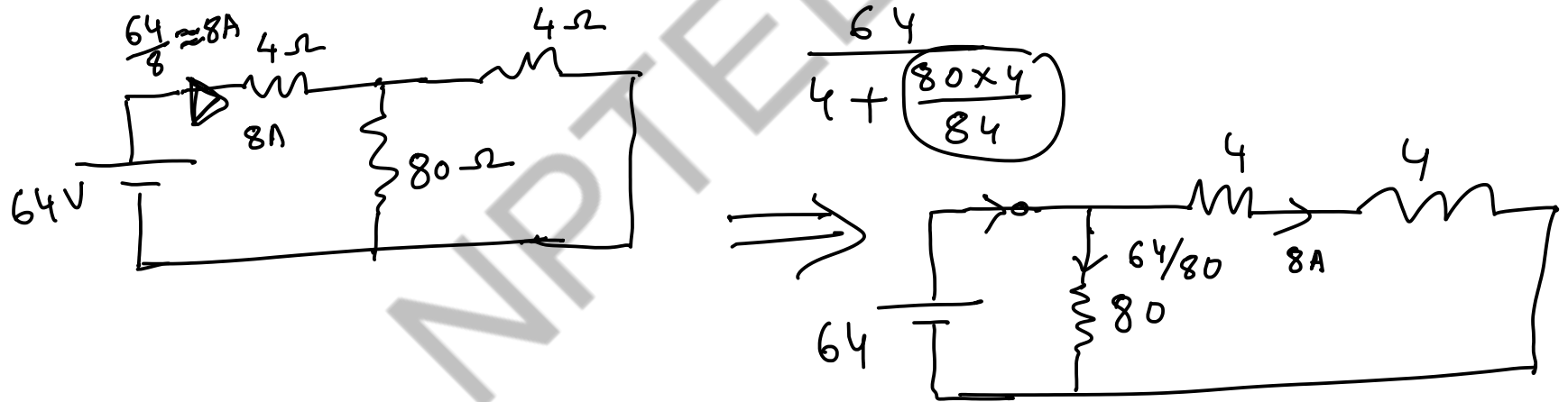
$$\begin{aligned} r_1 = 0 & \quad r_2 = 0 \Rightarrow r_2' = 0 \\ x_1 = 0 & \quad x_2 = 0 \Rightarrow x_2' = 0 \end{aligned} \quad \Downarrow$$

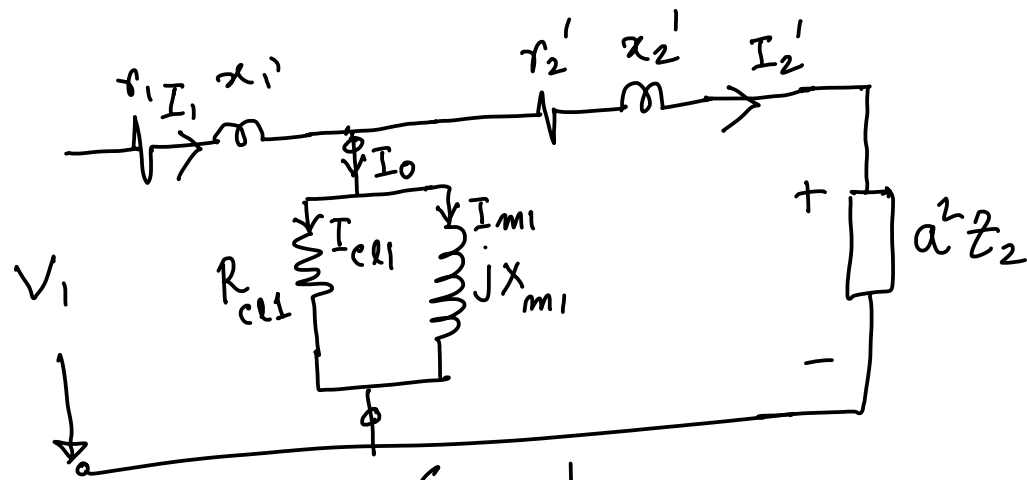
$$\begin{aligned} R_{cl} &\rightarrow \infty \\ X_m &\rightarrow \infty \end{aligned}$$



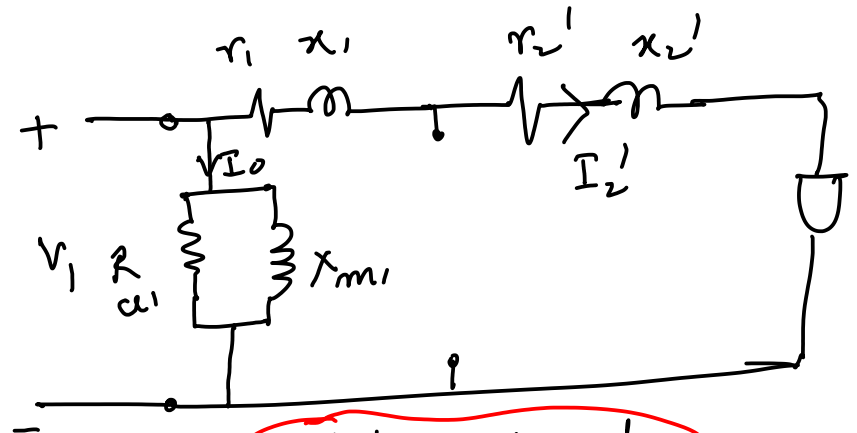
$r_1, x_1 \text{ \& } r_2', x_2' \ll R_{cl} \text{ \& } X_m$

Equivalent ckt. ref. to secondary side (or load side)

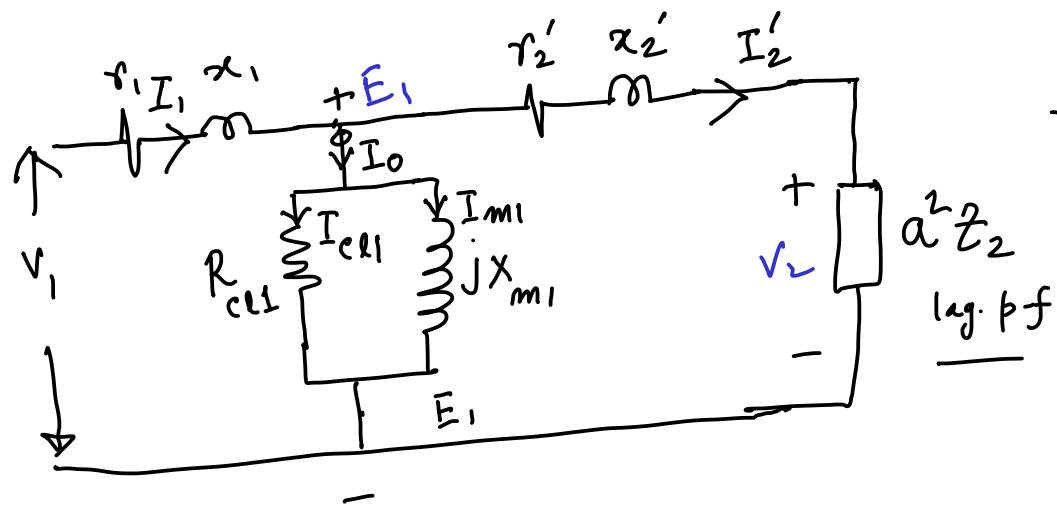




Exact.
 $r_1, x_1, r_2', x_2' \ll R_{cl}, X_{m1}$



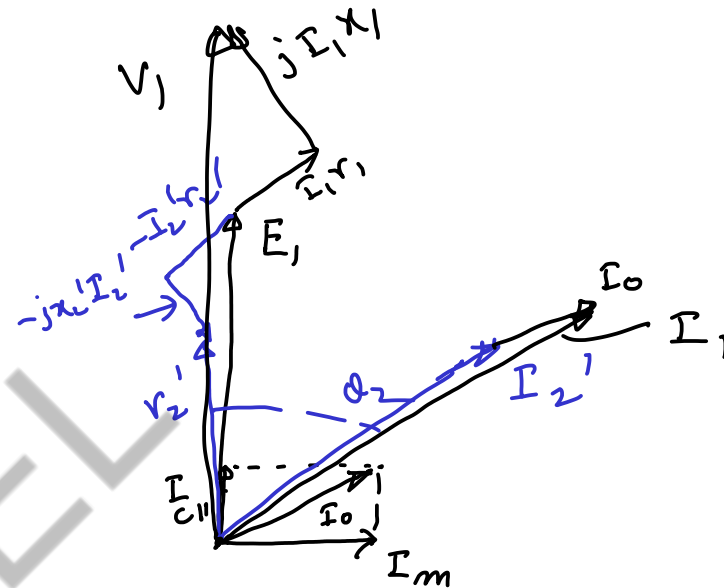
Approximate
 equivalent
 circuit



Exact Equiv ckt.

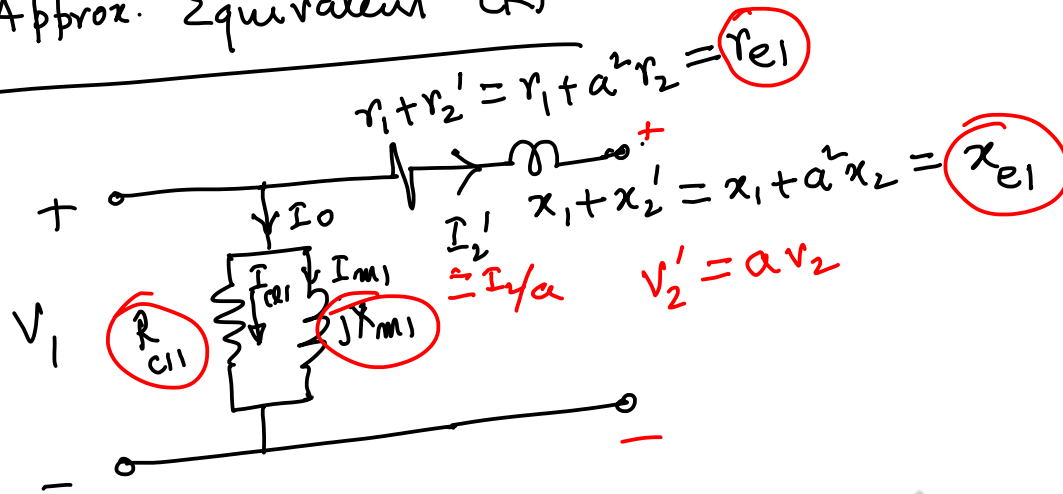
$$E_1 = (r_2' + jx_2') I_2'$$

$$V_1 = E_1 + I_1 (r_1 + jx_1)$$

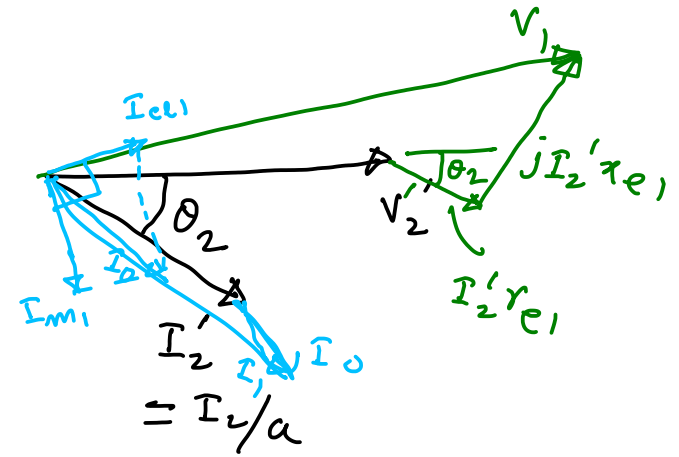


Approx. Equivalent CKT.

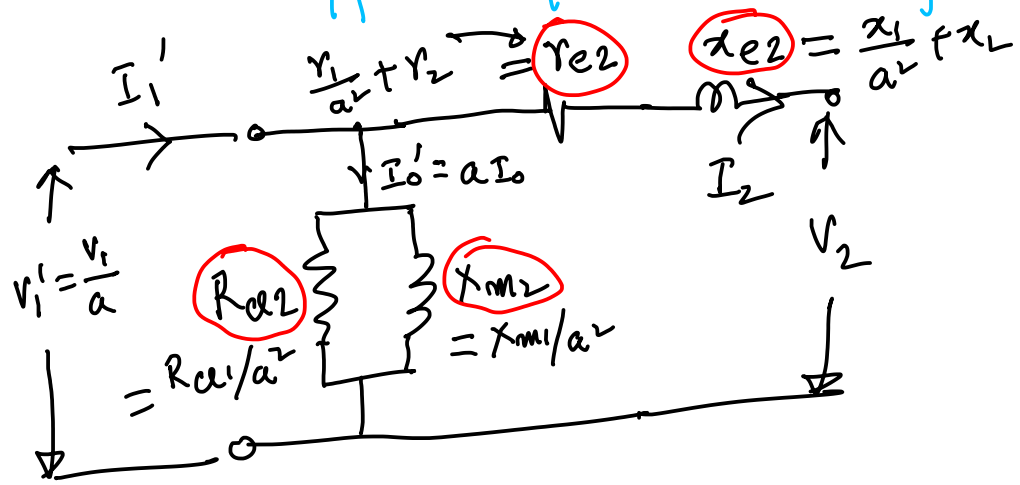
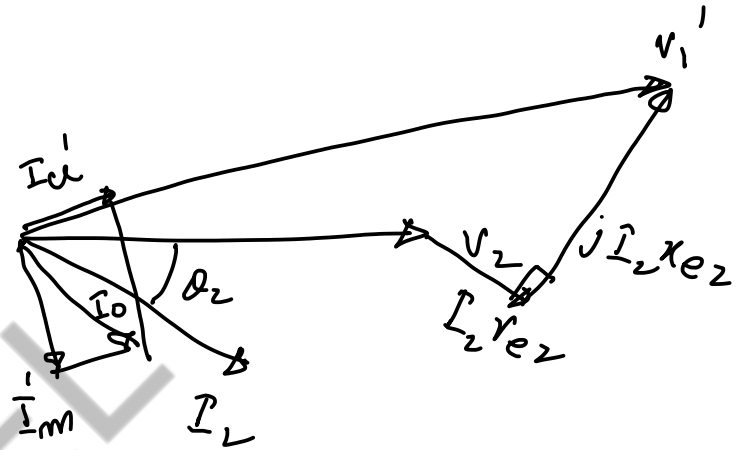
Dec-16



$$V_1 = V_2' + I_2' (r_{e1} + jx_{e1})$$



Approx. Equiv ckt. ref. to secondary side



1 Ph, 1 kVA, 200V/100V, 50Hz tfo

$$a = 200/100V = 2$$

$$\frac{I_{Hv \text{ rated}}}{I_{rated}} = \frac{I_1}{I_{rated}} = \frac{1000}{200} A = 5 A$$

$$\frac{I_{Lv \text{ rated}}}{I_{rated}} = \frac{I_2}{I_{rated}} = \frac{1000}{100} A = 10 A$$

no load current

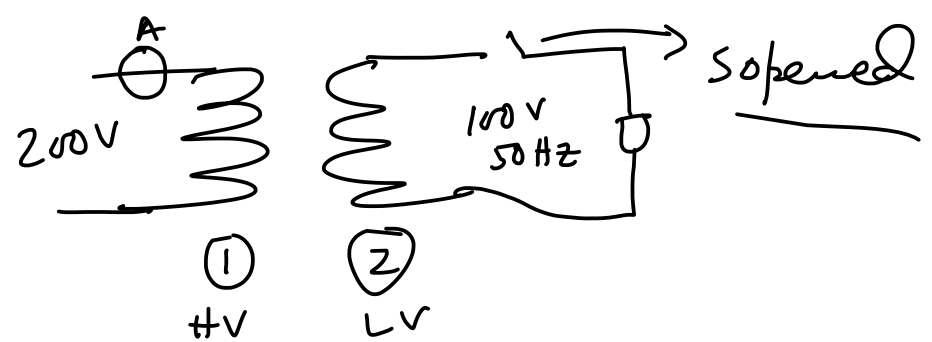
$$I_o (= I_{cl} + I_m)$$

2 to 5% of the rated
for well designed tfo

$$\bullet I_{o1} = 5\% \text{ of } 5 = 5 \times 0.05 = 0.25 A$$

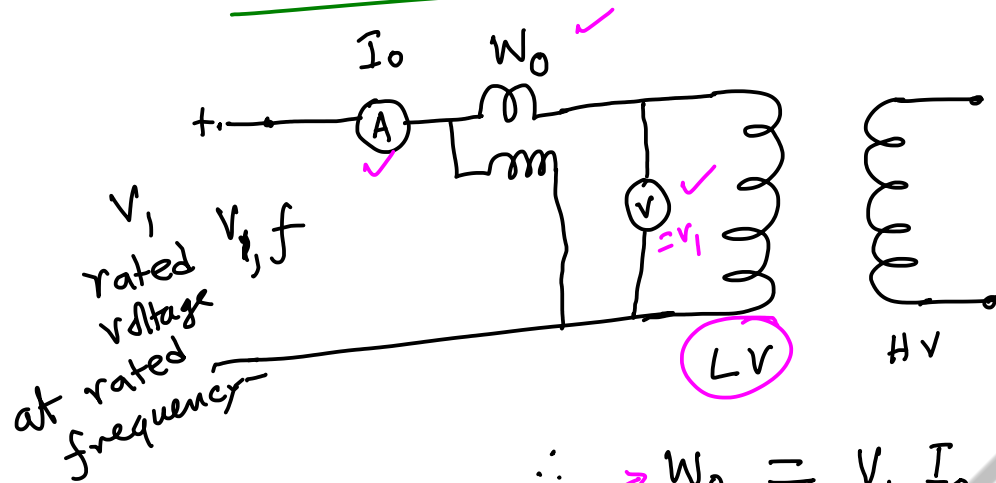
if energised
from LV side

$$I_{o2} = 5\% \text{ of } 10 A = 0.5 A$$



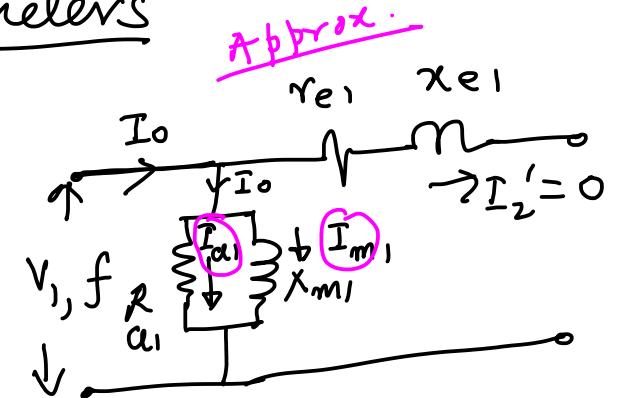
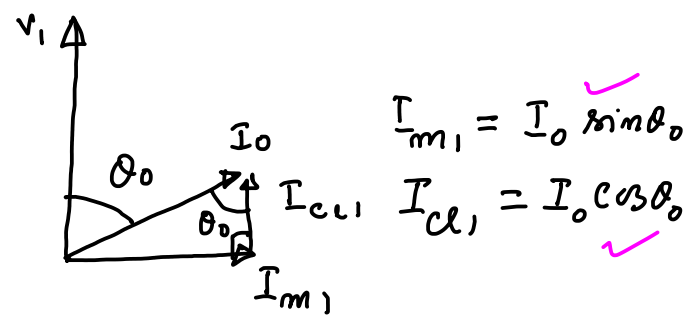
Determination of Equivalent Ckt. parameters

Open Circuit Test & S.C Test or no load



$$R_{01} = \frac{V_1}{I_{01}} \quad \checkmark$$

$$X_{01} = \frac{V_1}{I_{m1}} \quad \checkmark$$



R_{02}
 X_{02}

practically records the core loss
The loss $I_0^2 R_{01} \ll$ core loss
as flux is rated & I_0 is only about 2 to 5% rated current.

$$\therefore W_0 = V_1 I_0 \cos \theta_0$$

$$I_0 \cos \theta_0 = \frac{W_0}{V_1} = I_{01}$$

$$\cos \theta_0 = \frac{W_0}{V_1 I_0} \quad \text{from this } \theta_0 \text{ is known}$$