

## Chapter 10 Practical Transformers

- Alt Energy/Global

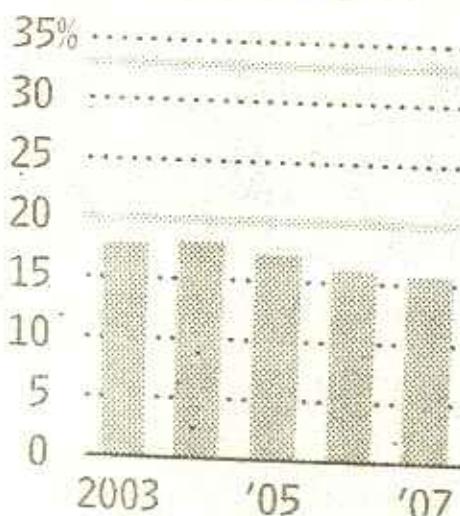
Warming/Infrastructure Preaching

- Ch 10 Introduction
- Non-ideal Transformers

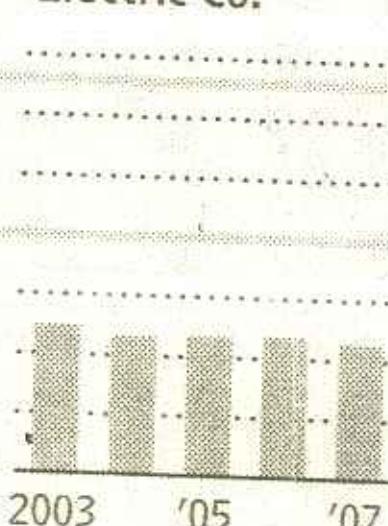
# Raising the Bar

Percentage of electricity generation from renewable resources for  
California's investor-owned utilities

Southern  
California Edison Co.



Pacific Gas &  
Electric Co.



San Diego  
Gas & Electric



2020 goal

33%

2010 goal

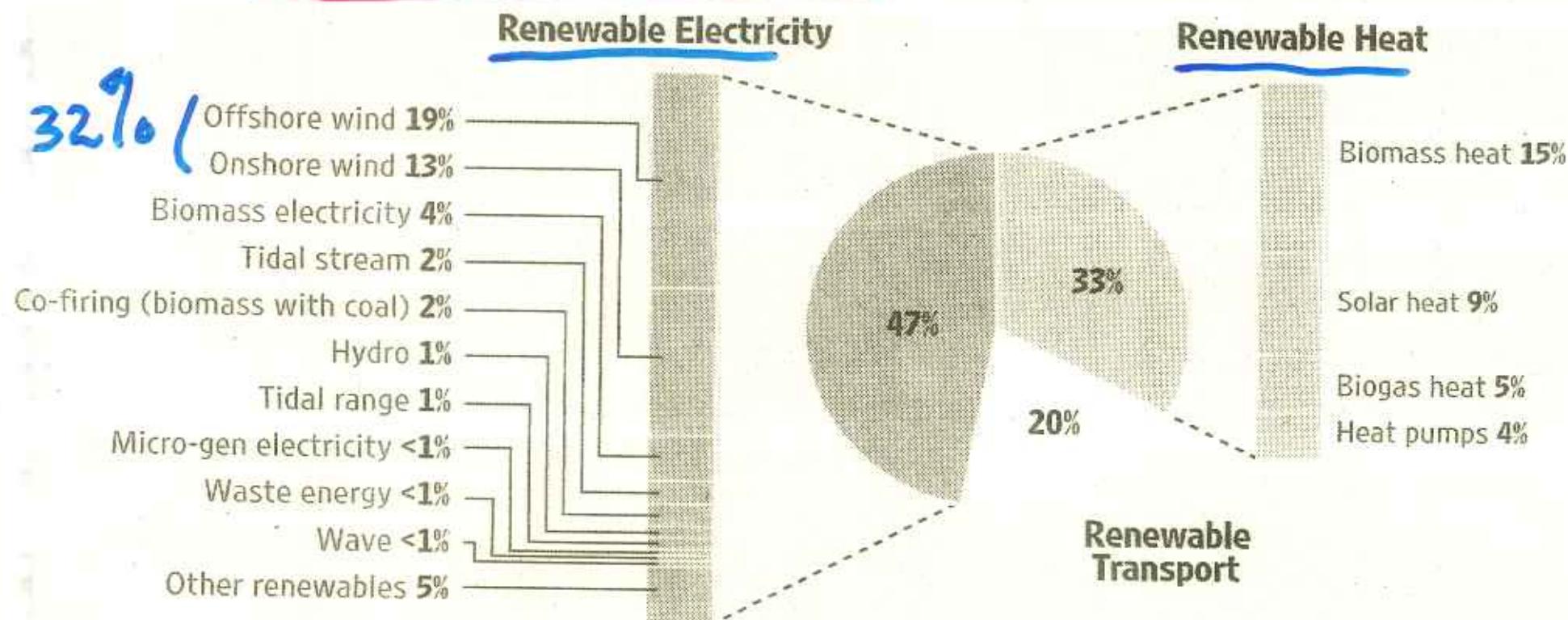
20%

Ca  
dreamers  
maybe  
"Quizas"

Source: California Public Utilities Commission

## Green Power

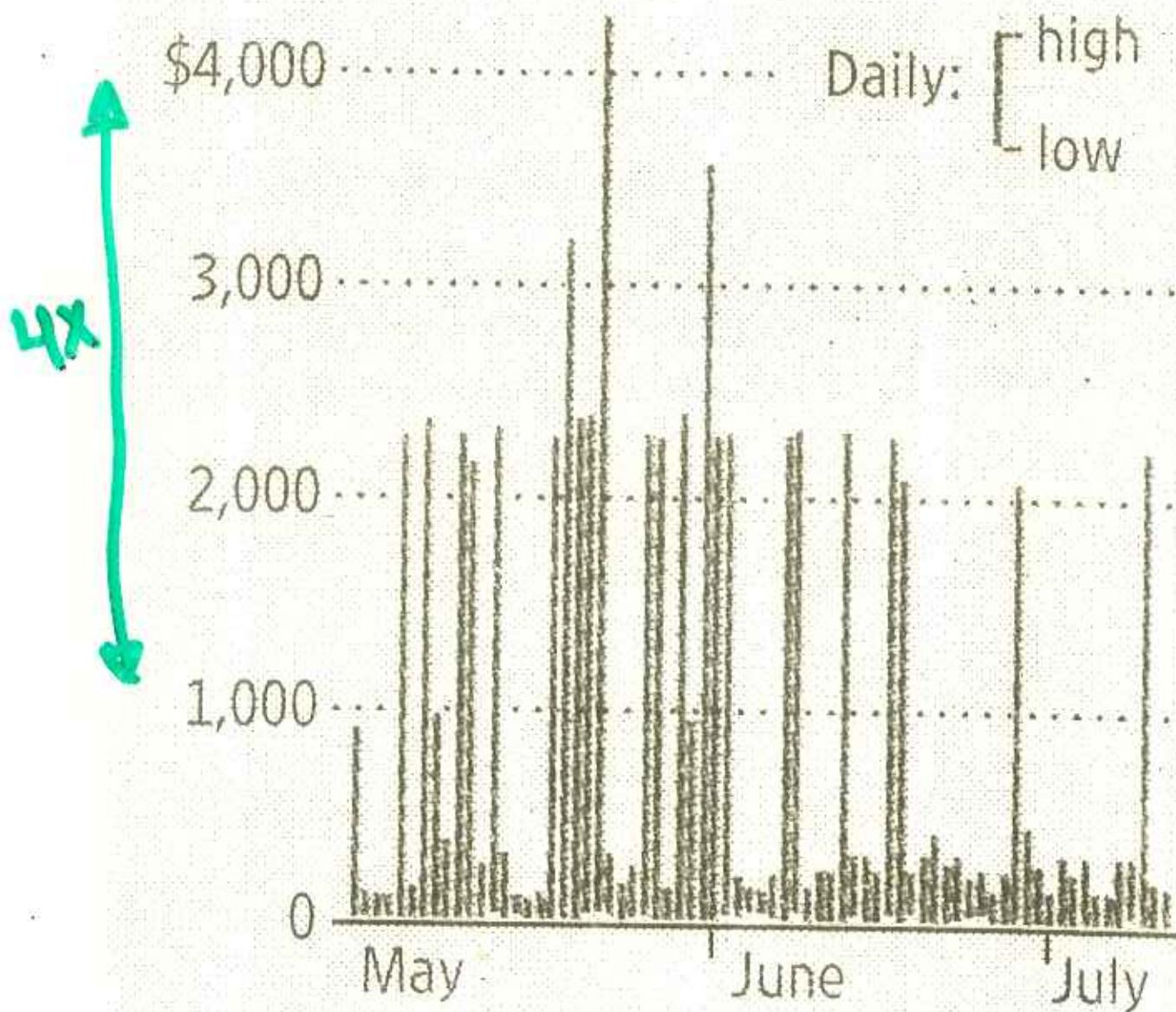
Britain wants renewables to account for 15% of its energy in 2020. Here's one scenario, where offshore wind would provide the single largest source of renewable electricity.



Source: U.K. Department for Business, Enterprise & Regulatory Reform, "U.K. Renewable Energy Strategy," Consultative document, June 2008

# Price Shock

Daily electricity price ranges in southern Texas; dollars per megawatt hour



Source: Electric Reliability Council of Texas

# *Less Power TO THE People*



## Refineries

- ① No new refineries in 30 years
- ② 60 billion invested in refinery environment
- ③ No offshore drilling  
No LNG terminals

## Choices / Consequences

NASA Goddard corrections  
to global warming: Not so hot

- ① Hottest year 1934 not 1998
- ② 6/10 warmest years 30's  
BEFORE big CO<sub>2</sub> emissions 40's
- ③ Warming 1920 → now  
 $0.2^{\circ}\text{C} \pm 0.15$  Whoa!

$\frac{2}{3}$  of  $T$  rise  
within  
measurement  
error



HW 34 135  
Ch 10 and ?

## CHAPTER 10 Practical Transformers

The factors that cause a practical transformer to diverge from the ideal are explained. A particularly easy way of understanding leakage reactance is developed and incorporated into the equivalent circuit diagram. It is well known that the notion of leakage reactance is fundamental to an understanding of transformers and all rotating ac machines. Also, an interesting table makes use of per unit values to describe the properties of transformers over a tremendous power range (Section 10.13).

$$\text{P.U. } \frac{V}{V_{\text{base}}}, \frac{I}{I_{\text{base}}}, \frac{S}{S_{\text{base}}}$$

$Z_{\text{pu}}$   
 $Z_{\text{rated}}$   
<sup>exam</sup>

VS

$Z_{\text{pu}}$   
<sup>operating</sup>

# Transformers

Essential  
to AC

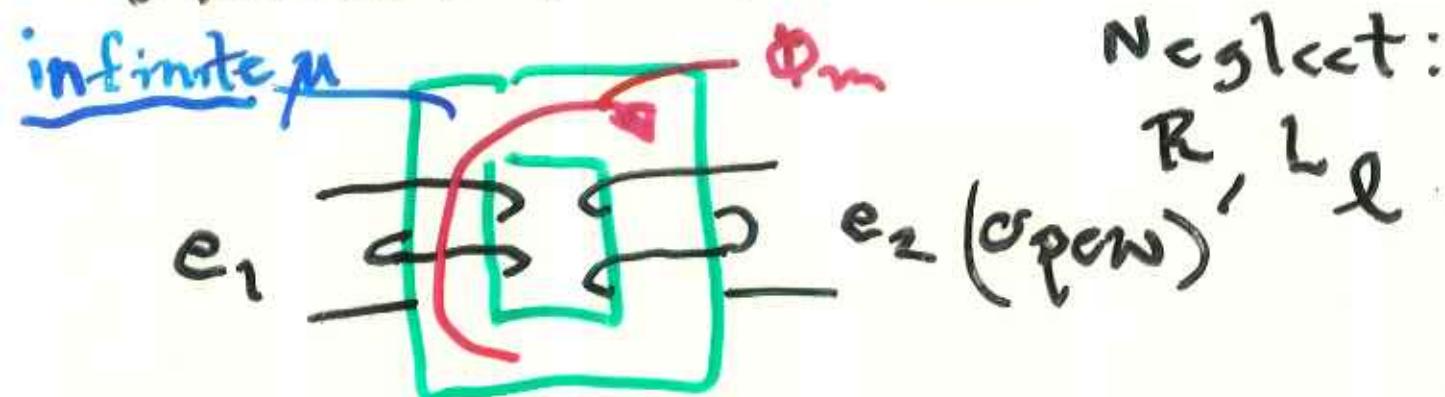
Westinghouse      AC  
Edison              DC

Power

Gen: 15 - 30 kV

Trans: 100 - 765 kV

Distribution: 115 - 12 kV



Faraday's Law:  $e_1 = N_1 \frac{d\Phi_m}{dt}$

$$\frac{e_1}{N_1} = \frac{e_2}{N_2} \quad \frac{\text{Volts}}{\text{turn}} \quad e_2 = N_2 \frac{d\Phi_m}{dt}$$

in  $\rightarrow$  Finite  $\mu$



$L_m$  arises from  
finite  $\mu$

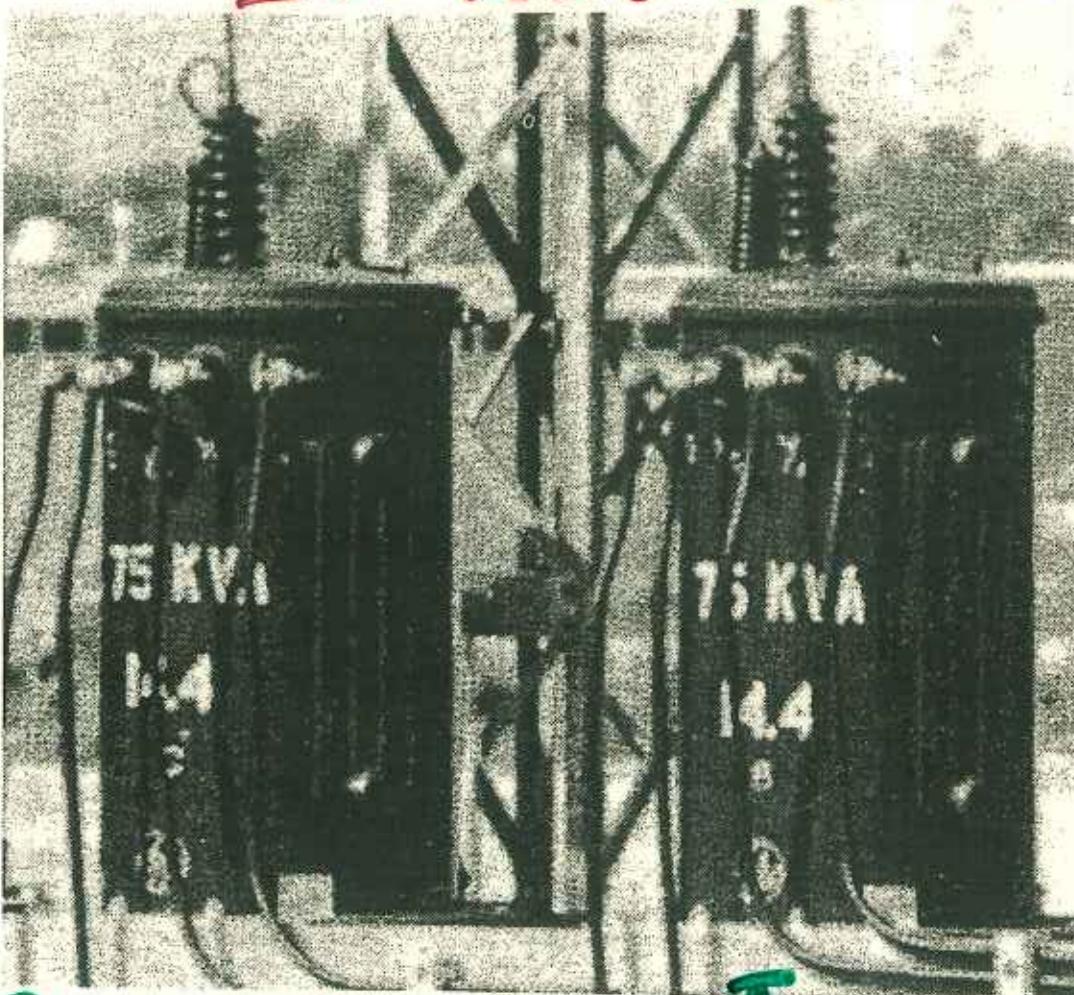
$L_m \rightarrow ? \mu \rightarrow \infty$

$$i_{Lm} \approx 290 i_m$$

11) 75KVA Trf 1 Industrial  
14.4KV / 240 } Plant  
Trf.

### Losses

1. Wire  $I^2 R_{\text{wire}}$   
 $I - \text{load is drawn}$

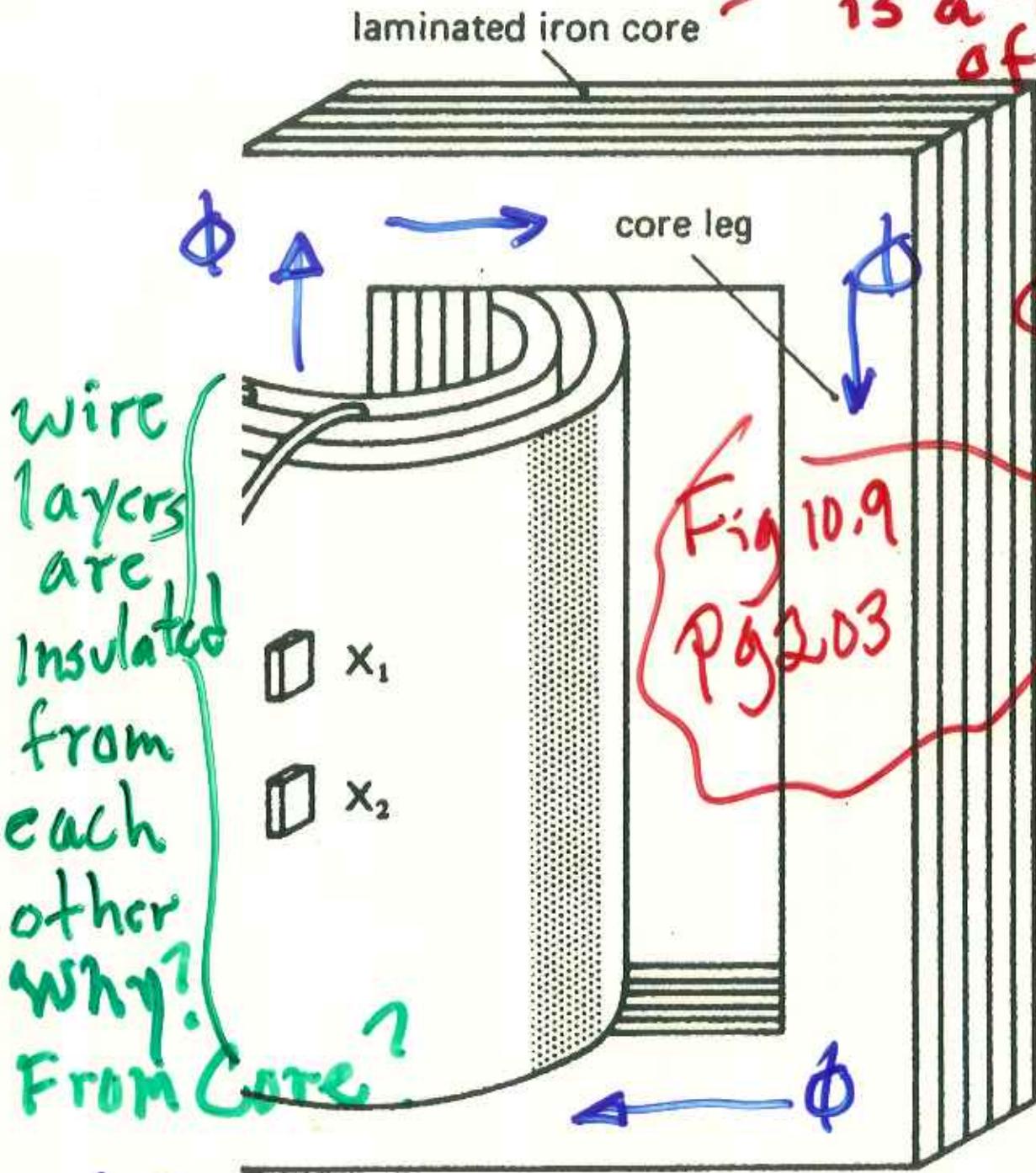


2. Core loss -  $\Phi_{\text{max}}$

$V_{\text{IN}}(\text{max}) \leftrightarrow \Phi_{\text{max}}$

- eddy current loss  $f^2$
- hysteresis loss -  $f$

# Details of Trf Construction



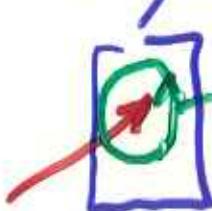
Q Why core is a laminate of Fe:Si and insulator

Q Why not laminate etc

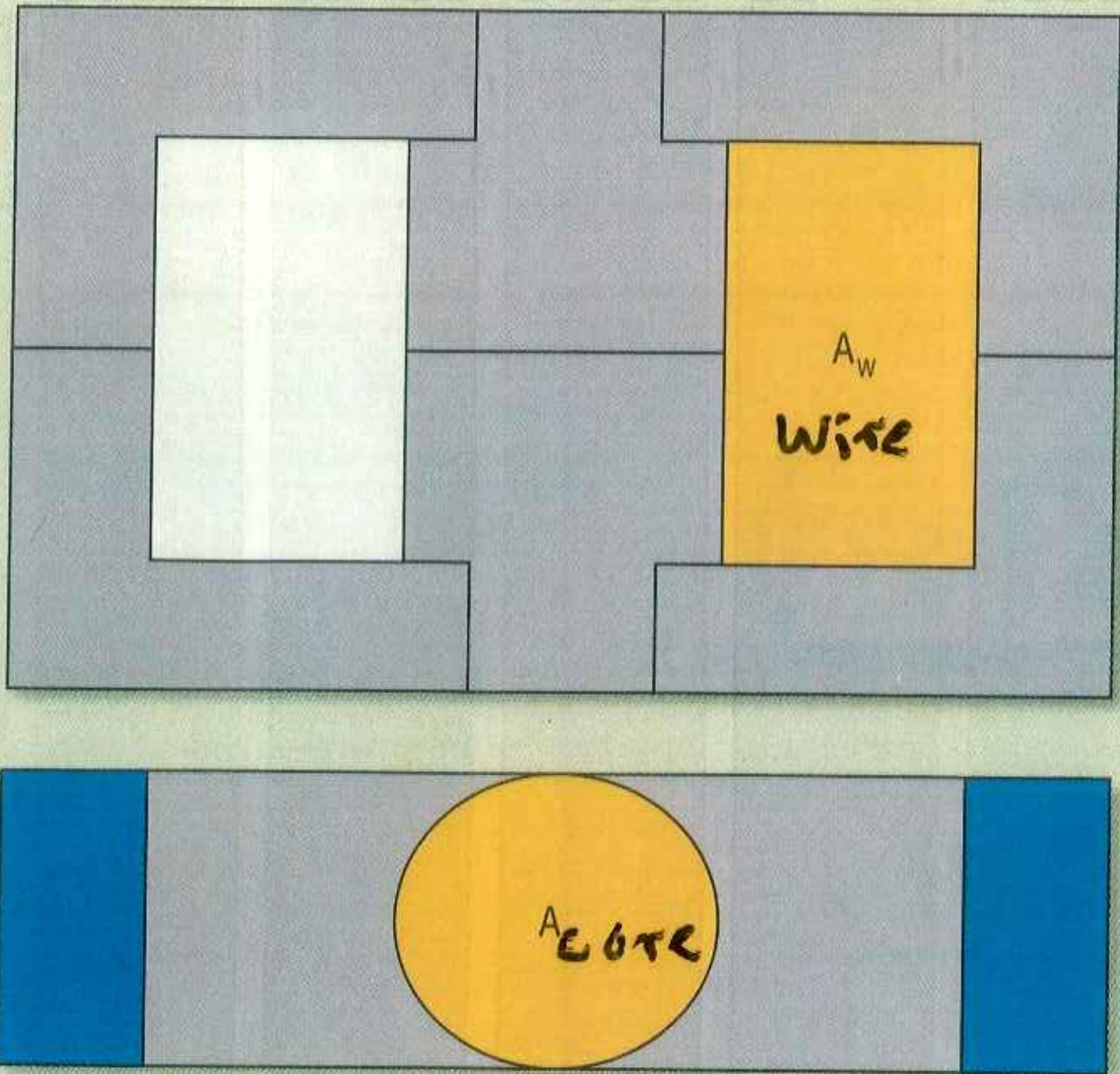


$$B \times A = \Phi \text{, If } A \uparrow \text{ then } \Phi \uparrow$$

fixed



eddy current opposes flux



**Fig. 4.** The area product of a transformer is the product of the window-winding area,  $A_w$  and the cross-sectional area of the core,  $A_{\text{core}}^{[3]}$ .

$$N_{\text{RESET}} = 1 - D_{\text{MAX}} = 1 - .55$$

$$P(\text{rating}) \approx A_w * A_{\text{core}}$$

Want in well designed transformer

①  $\underline{I}^2 R_{\text{wire}} \approx \text{Core Losses}$

e.g. fewer absolute # turns  
 $\Rightarrow R_w \downarrow$  but  $l_m \downarrow \Rightarrow$   
 $i_m \uparrow$  Core losses  $\uparrow$

②  $\underline{I_p}^2 R_{wp} = \underline{I_s}^2 R_{ws}$

Different diameter wire  
Primary  $\textcircled{vs}$  Secondary

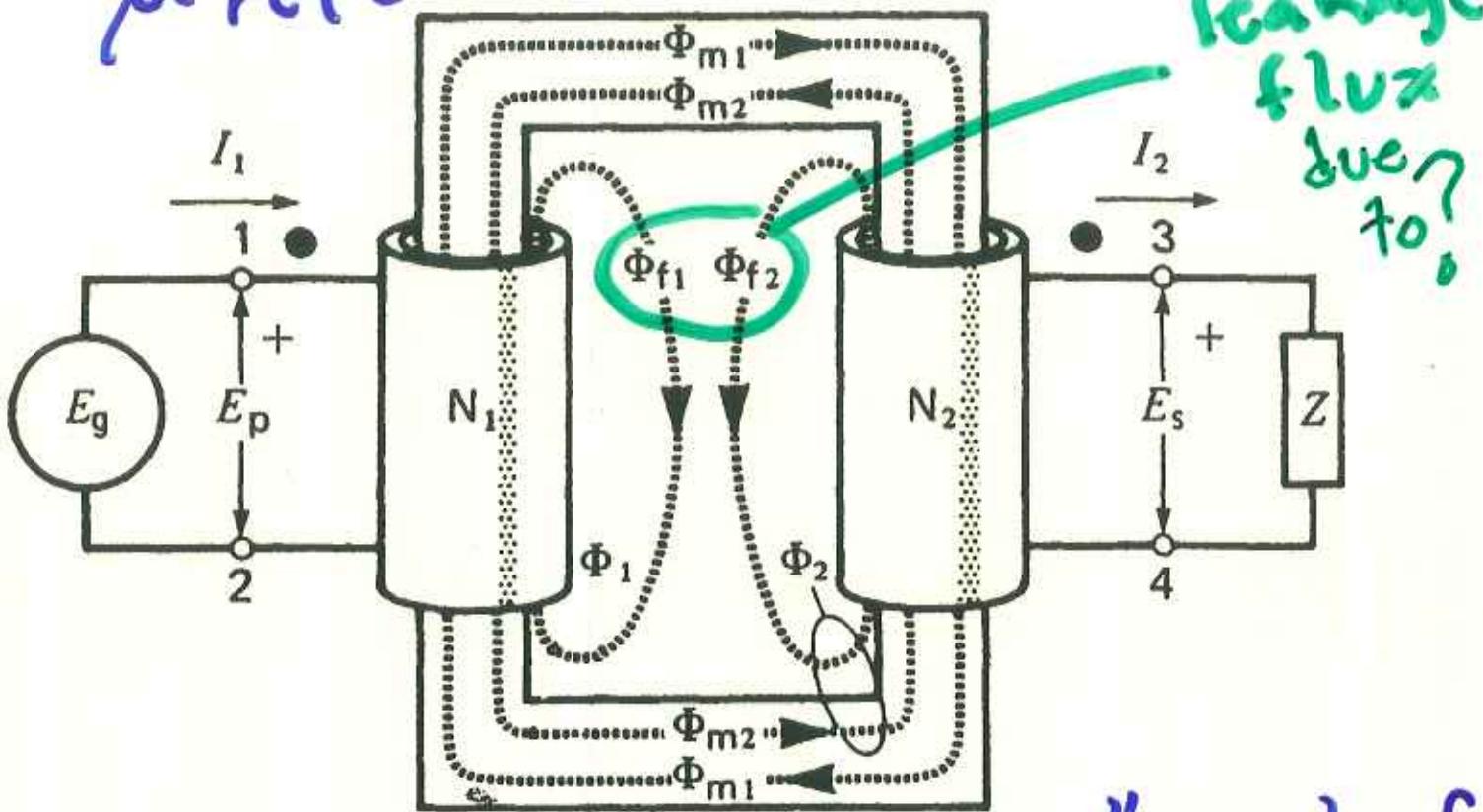
Pbm 10-34

$$\mu(\text{air}) = \mu_0$$

5  $\mu(\text{core}) = \mu_{\text{rel}} \mu_0$

$$\mu_{\text{rel}} (\text{Fe-Si Steel}) = 10^5$$

$$\mu_{\text{rel}} (\text{ferrite}) = 10^3$$



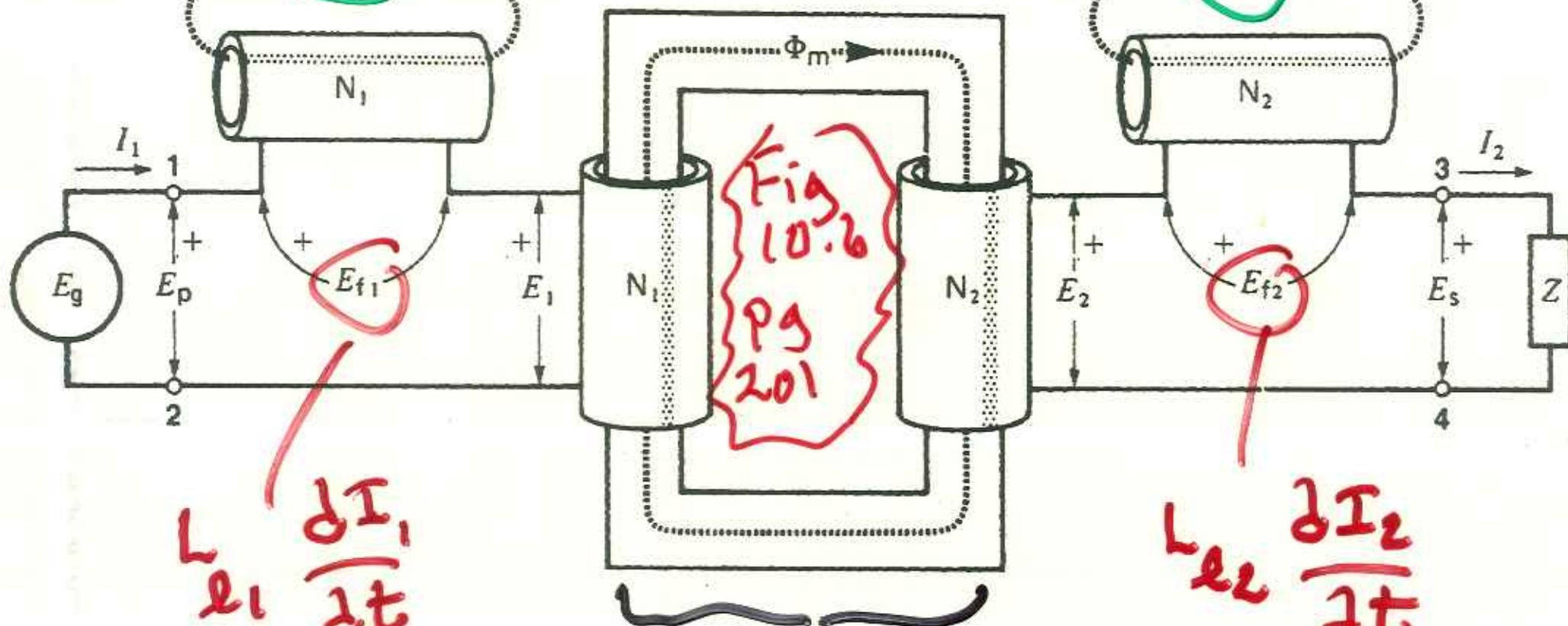
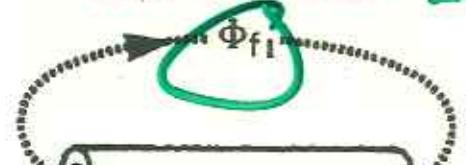
Lots of flux "leaks" out of practical cores into the air

$\Phi(\text{leakage})$



Contrast to  $e^-$  leakage out of a wire  
 $\sigma_{\text{metal}} = 10^{18}$        $\sigma_{\text{air}} = 10^{-8}$

creates  $L_{e1}$



$$L_{e1} \frac{\delta I_1}{\delta t}$$

extra V

depends on loading

creates  $L_{e2}$

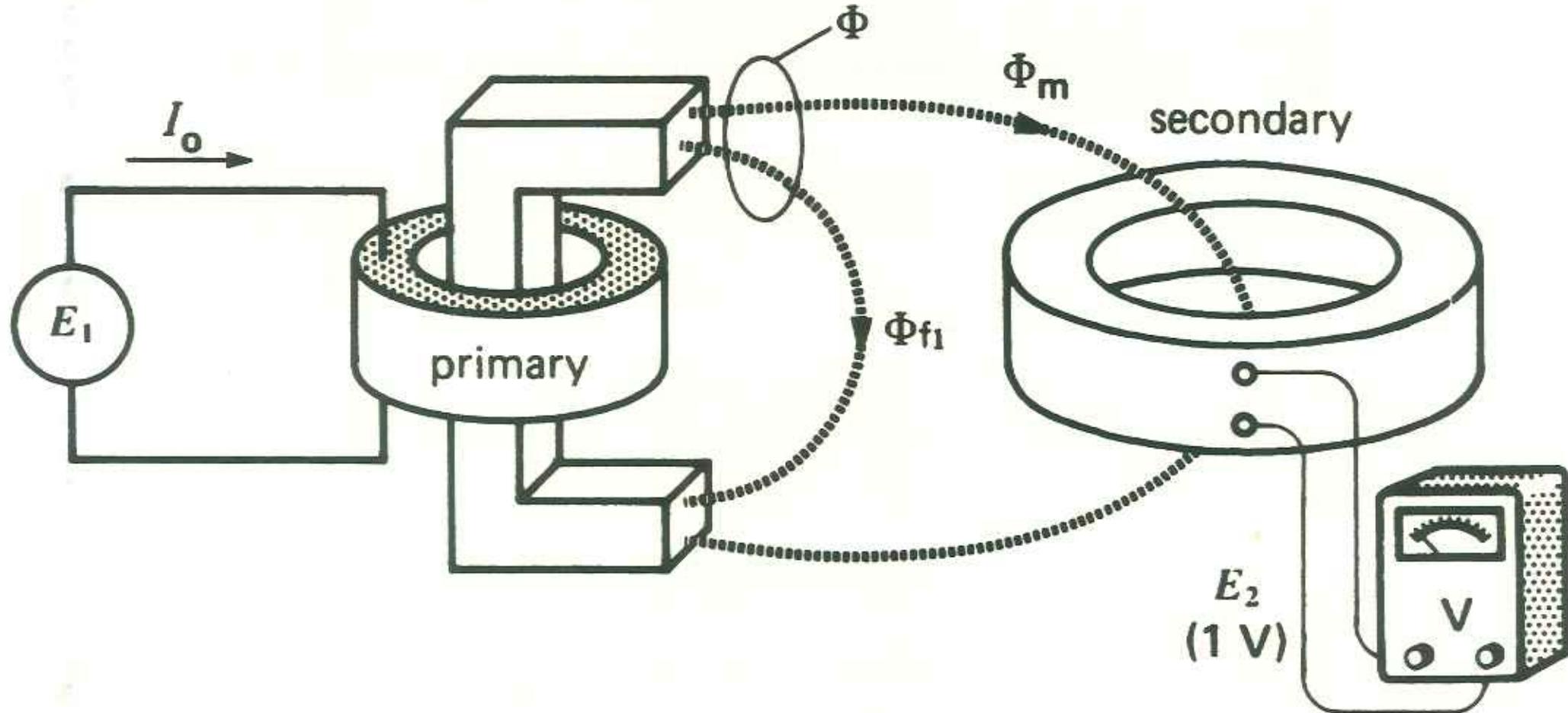


$$L_{e2} \frac{\delta I_2}{\delta t}$$

extra V

drop

ideal  
Trf

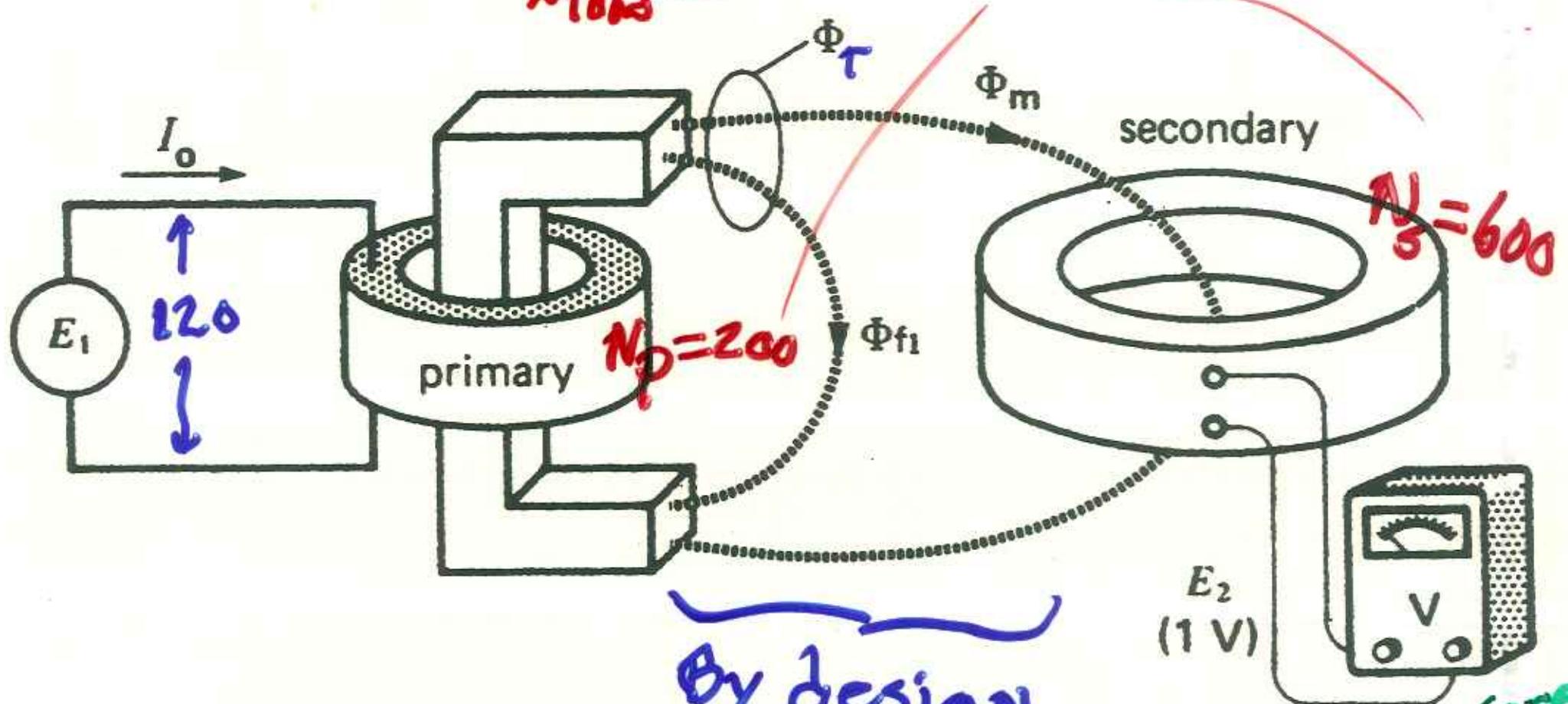


Pbm 10.18

$$I_0^{\text{in}}(\text{no load}) = 3 \text{ A} \quad (\text{flows where? why?})$$

$I_{1002}$  is  $\infty$

Given



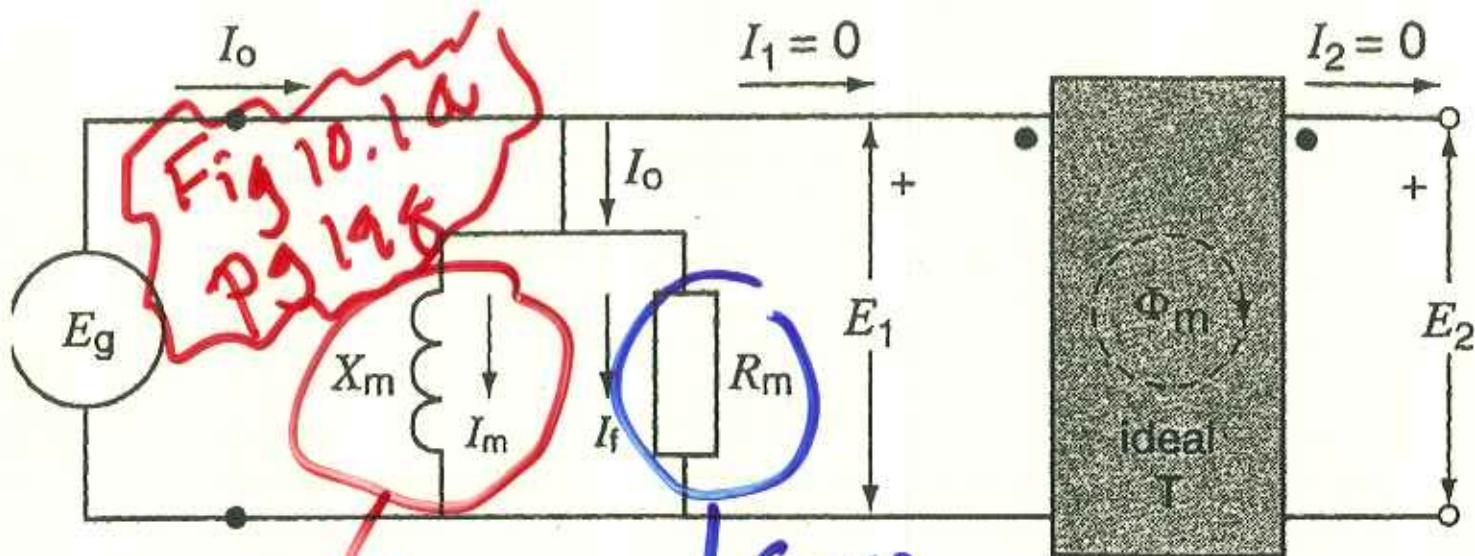
By design

$$\Phi_T = \underbrace{\Phi_m + \Phi_{f1}}_{\cdot 4 \Phi_T} \cdot \underbrace{6 \Phi_T}_{\cdot 6 \Phi_T}$$

Design core  
for lots of  
leakage.

# Real Transformers

1.  $\mu$  is finite  $L_m \approx \frac{N^2 \mu A_{act}}{l_{core}}$   
 not  $\infty$   $\mu \uparrow N \downarrow A_{act}$   
 $L_m$  appears finite and draws  
 $I_m$  at open load  $Z_{load} = \infty$
2. Magnetic Core Losses:  $R_m$



extra current flows even when  $I_2 = 0$

$I_{Core}$  Losses represented by  $R$

Core losses are?

? What are phasors like for  $E_2, E_1, I_m, I_f, I_0$

26  
a

## Short Circuit Test

$$S = 5 \text{ MVA}$$

$$69 \text{ KV}$$

$$4.16 \text{ KV}$$

T<sub>ref</sub> rating

16.6 turns ratio

$$P_{sc} = 2.4 \text{ KW}$$

Measured

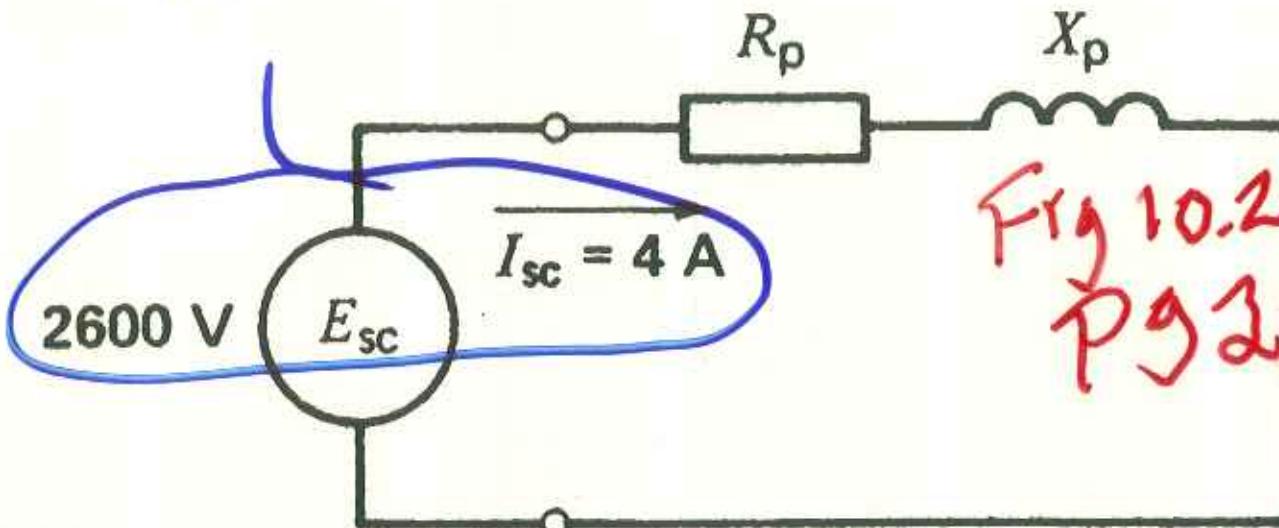


Fig 10.29  
Pg 213

$$Z_p = \sqrt{R_p^2 + X_p^2} = \frac{E_{sc}}{I_{sc}} = \frac{2600}{4} = 650 \Omega$$

$$\text{measured}$$

$$R_p = \frac{P_{sc}}{I_{sc}^2} = \frac{2400}{16} = 150 \Omega$$

$$X_p = ?$$

2  
650  
150

632

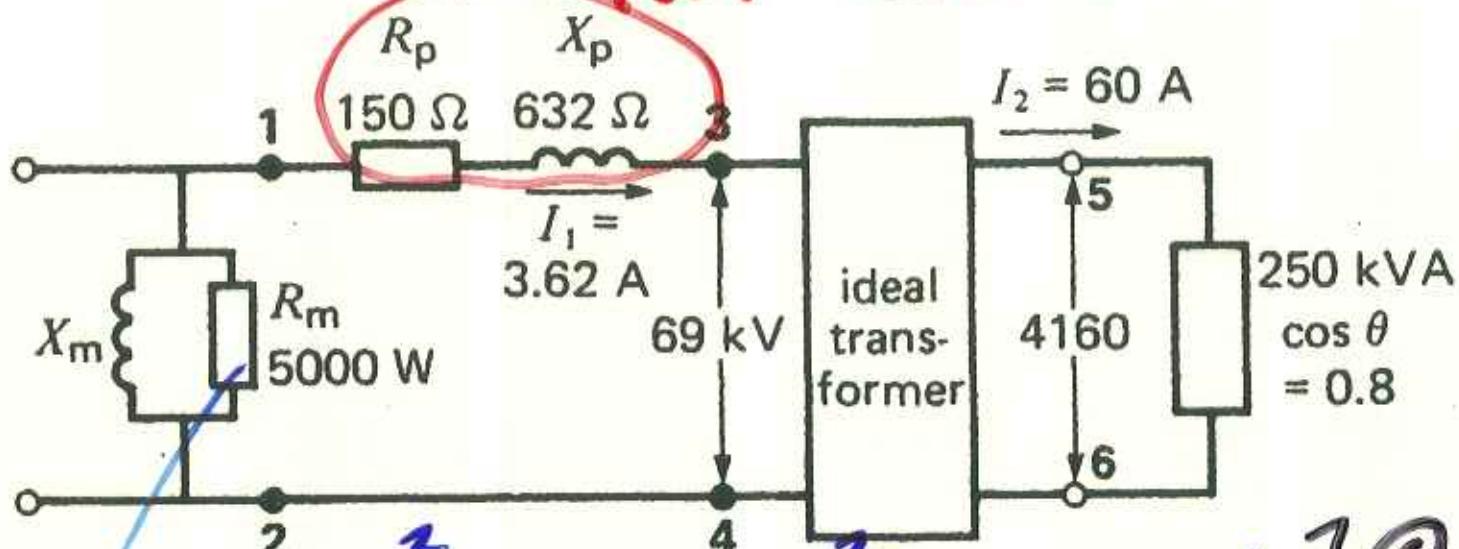
# Open Circuit Test

Excite LV winding

$$\left. \begin{array}{l} E_{IN} = 4160 \\ I_{mag} = 2 \text{ A} \end{array} \right\} \quad \left. \begin{array}{l} P_m = 5 \text{ kW} \\ S = (2)(4160) \\ = 8320 \end{array} \right.$$

From  
shortckt  
test

Q = ?



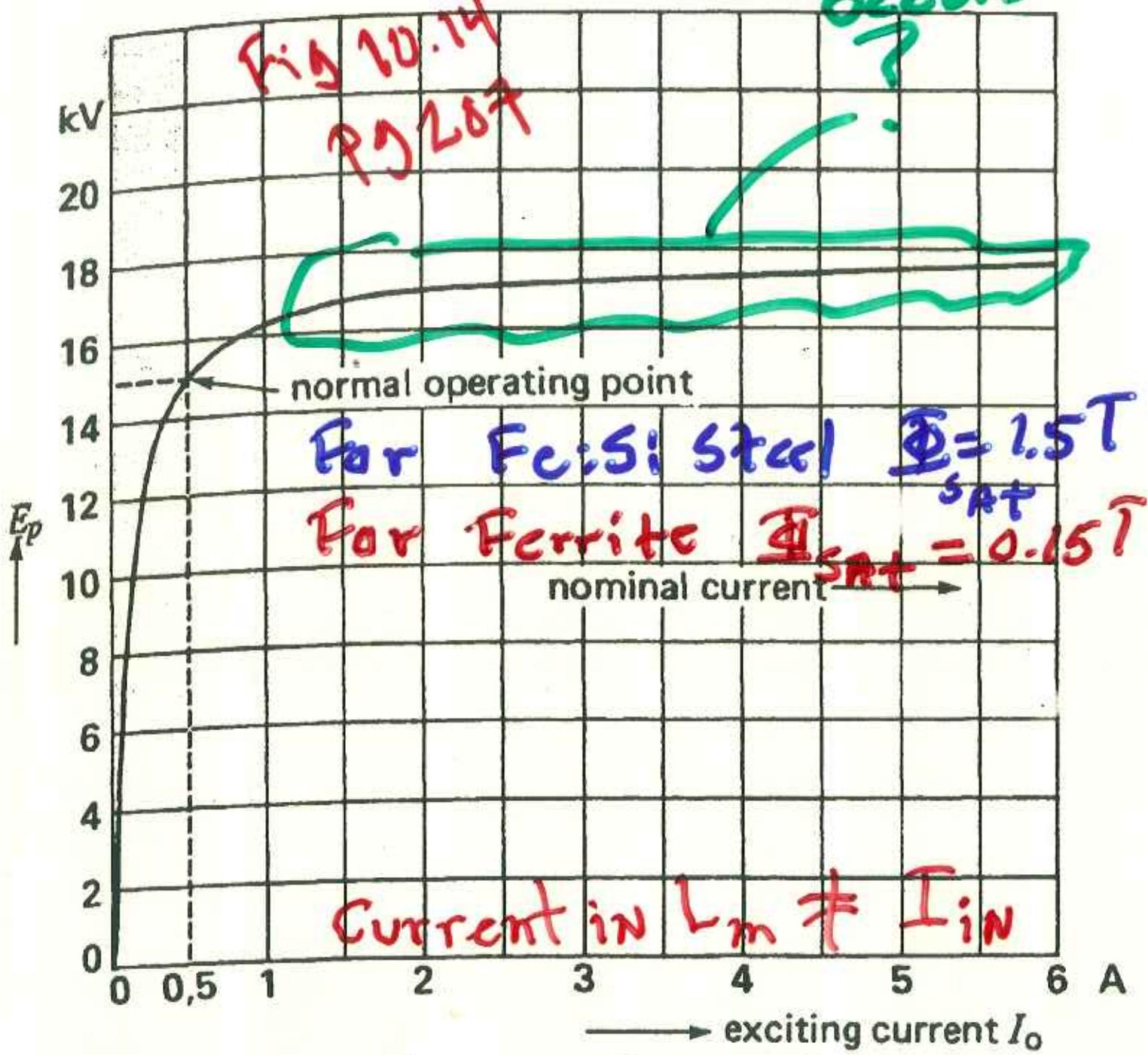
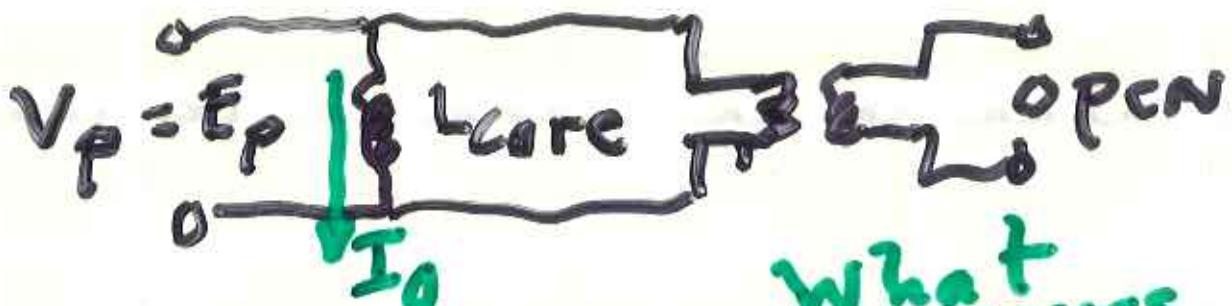
$$R_m = \frac{E_s^2}{P_m} = \frac{(4160)^2}{5000} = 3.46 \text{ k}\Omega \quad \text{@ } \left. \begin{array}{l} S \\ \text{sec} \end{array} \right\}$$

$$X_m = \frac{E_s^2}{Q_m} = \frac{(4160)^2}{6650} = 2.6 \text{ k}\Omega$$

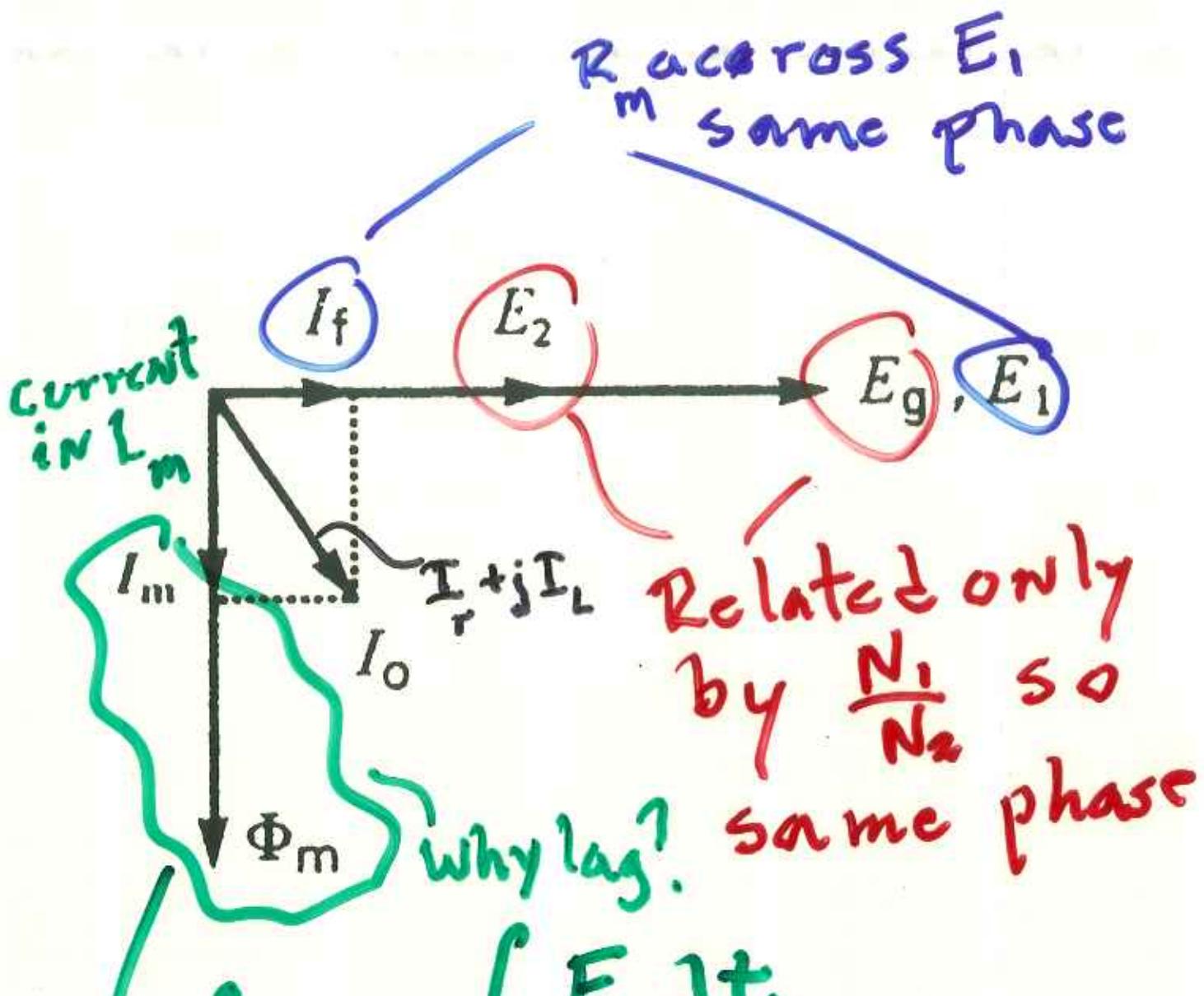
$$R_m(\text{primary}) = (16.6)3.46 = 715 \text{ k}\Omega$$

$$X_m(\text{primary}) = (16.6)2.6 = 952 \text{ k}\Omega$$

2D



$L_{core}$  in saturation decreases by  $\frac{\mu_r}{\mu_0} = 10^4$

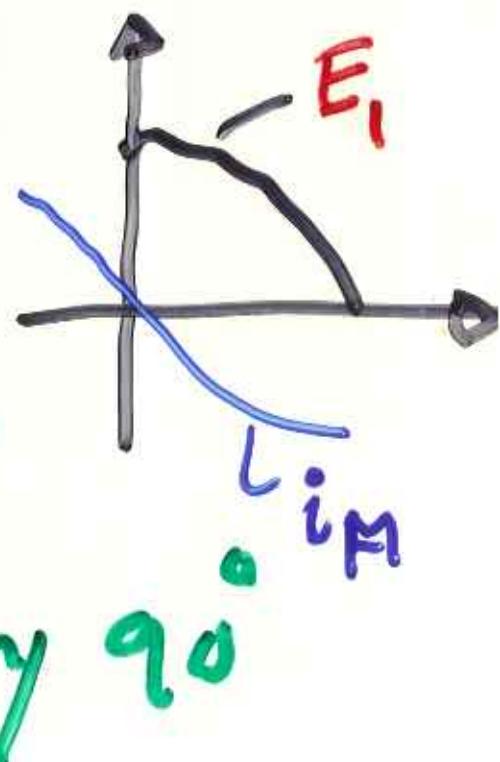


$$i_m = \frac{\int E_1 dt}{L}$$

$$E_1 \sim \cos \omega t$$

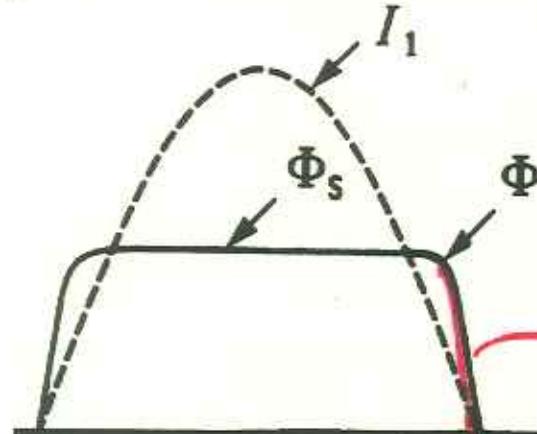
$$i_m \sim -\sin \omega t$$

$i_m, \Phi_m$  lags by  $90^\circ$

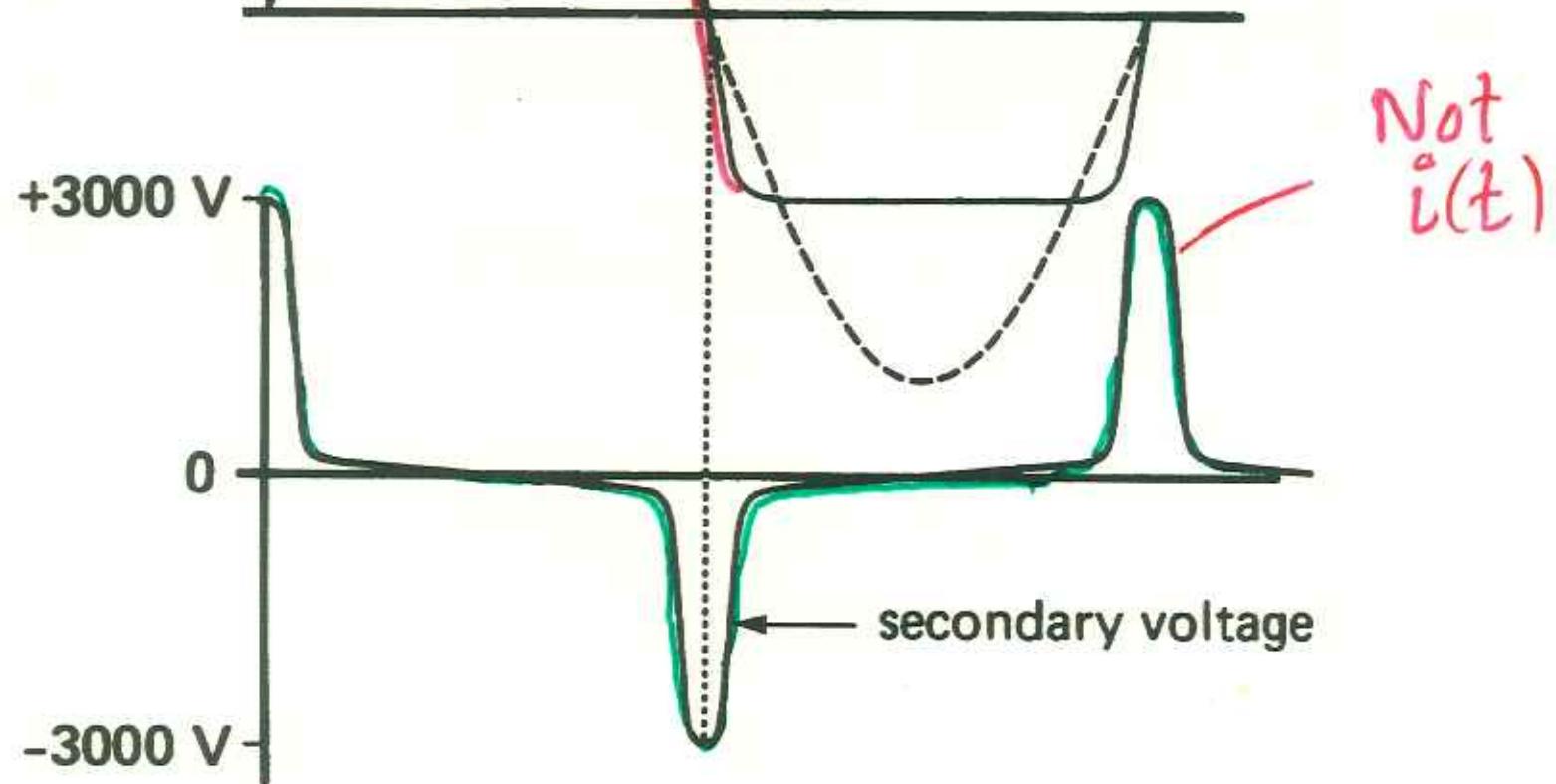


Open secondary C.T.

$$\vec{I} \propto \epsilon V(t)$$



$d\Phi/dt$  exists only here



$$4160 \left\{ \begin{array}{l} \\ \end{array} \right. \left\{ \begin{array}{l} \\ \end{array} \right. 480$$

$$R_{pu} = .59 \quad \left\{ \begin{array}{l} X_e \\ R_w \\ \text{wire} \end{array} \right.$$

$X_m^{pu} = 30 \quad S = 2.5 \text{ MVA} \quad R_m^{pu} = 50 \quad \text{FOR CORE}$

What are actual values

$$Z_{base}^{pu}(4160) = \frac{(4160)^2}{2.5 \text{ MVA}} = 69 \Omega$$

$$Z_{base}^{sec}(480) = \frac{(480)^2}{2.5 \text{ MVA}} = .92 \Omega$$

$$X_f(\text{primary}) = \frac{4160}{69} \cdot 0.025 = 17 \Omega$$

$$X_f(\text{secondary}) = \frac{0.92}{Z_B} \cdot 0.025 = \frac{23}{69} \Omega = 0.33 \Omega$$

$$\text{Core } X_m(\text{actual}) = 30 \quad 69 = 2 \text{ K}\Omega$$

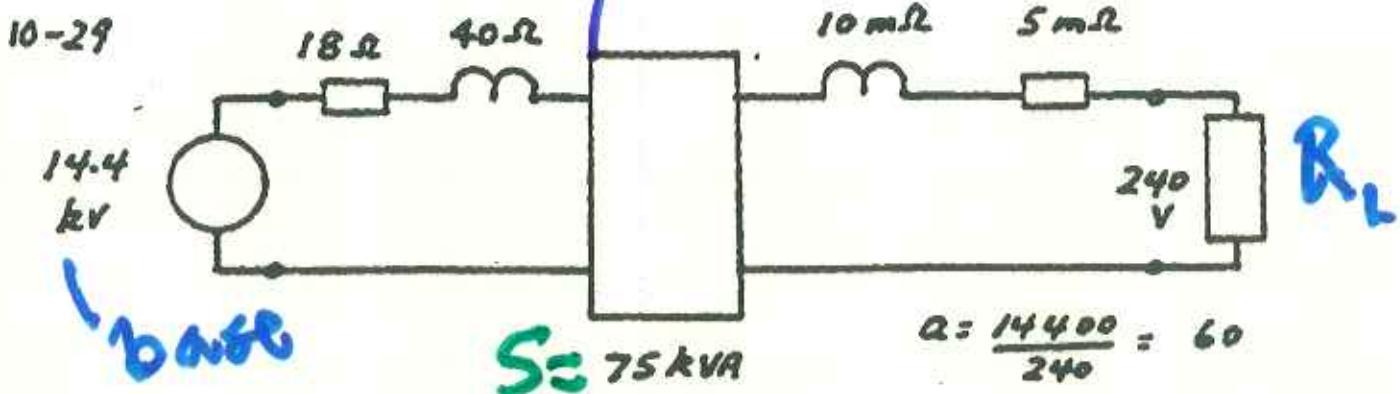
$$R_m(\text{actual}) = \frac{50}{69} = 0.73 \text{ K}\Omega$$

Can you do  $R(\text{actual})$ ?

2t

$$\frac{N_1}{N_2} = \frac{14.4 \text{ kV}}{0.240 \text{ kV}} = 60 = a$$

$R_s$



a.  $R$  referred to primary =  $18 + a^2 R_s = 18 + 60^2 \times 0.005$   
 $= 36 \Omega$

$X$  referred to primary =  $40 + a^2 X_s = 40 + 60^2 \times 0.01$   
 $= 76 \Omega$

$Z_p = \sqrt{36^2 + 76^2} = 84.1 \Omega$

b.  $Z_{\text{nominal}} = E_p^2 / S_{\text{nominal}} = \frac{14400}{75000} = 276.5 \Omega$

Per unit value of  $Z$  } primary  
 base quantity } base }  $\Omega$

.. Percent impedance =  $\frac{84.1}{276.5} \times 100 = 3.04 \%$

c.  $Z$  referred to secondary =  $Z_p / a^2 = \frac{84.1}{60^2} = 23.36 \text{ m}\Omega$

d. 3.04% (Note that the nominal impedance is

$$\frac{240^2}{75000} = 0.768 \Omega \quad \therefore \frac{23.36 \times 10^{-3}}{0.768} \times 100 = 3.04\%$$

$Z_{\text{sec}}$   
 $\underline{\text{per}}$   
 $\underline{\text{base}}$

Message for per unit approach

is  
 $Z(\text{pu}) = Z(\Omega)$   
 primary

Cannot use pu for  
Cu loss in watts

10-29 e.  $I_N$  on primary side =  $\frac{75000}{14400} = 5.208A$  R only

Total  $I^2R$  loss =  $5.208^2 \times 36 = 976W.$

Note that we could have found the copper losses by adding the primary and secondary losses, found independently; the same result is obtained.

f. percent  $R = (36 / 2765) \times 100 = 1.3\%$

percent  $X = (76 / 2765) \times 100 = 2.75\%.$

