

Chapter 9a Transformers

- Review
- Lightbulb Preaching
- Ideal Transformer
- Non-ideal Transformer
- Ch 9 Homework
- Transmission

Recall $L_{coil} = \frac{N^2}{R_m [H]}$

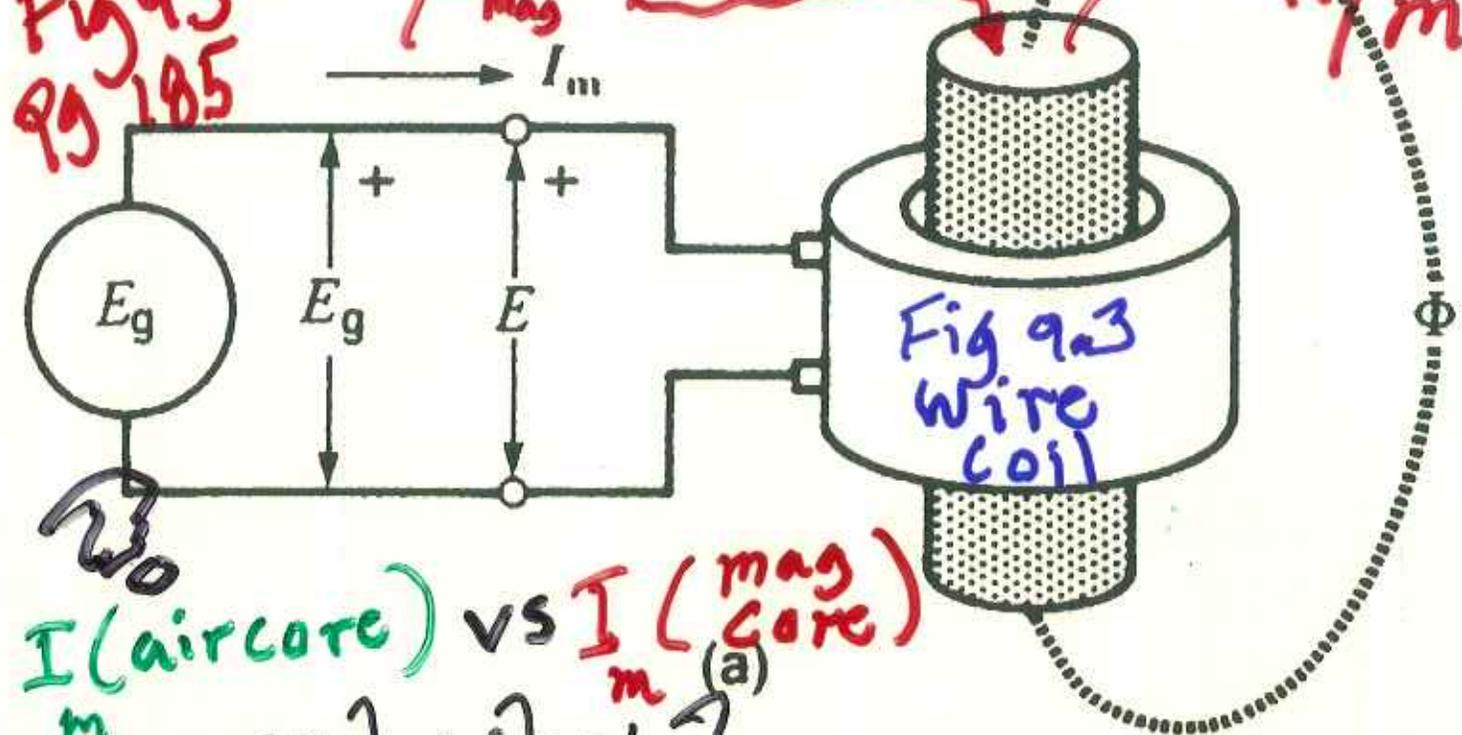
H
 H^{-1}

① $R_{mag} = \dots$ units?

$R_{mag} = \frac{l \text{ (flux path)}}{\mu_{mag} A \text{ (flux path)}}$

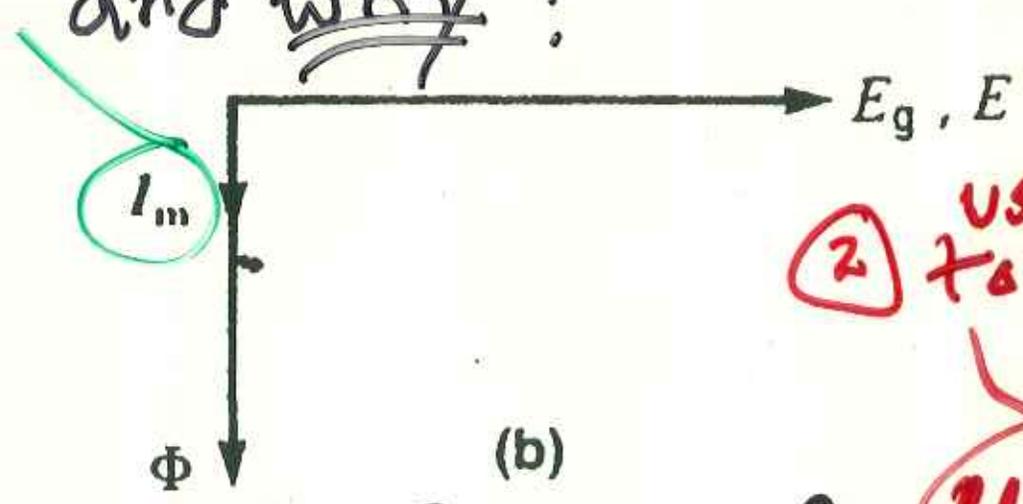
Magnetic Core
 μ_m in A/m

Fig 9.3
pg 185



I_m (air core) vs I_m (mag core) and why?

$\mu \uparrow$
 $L \uparrow$ size
 $\mu \downarrow$
At same core cost
size



② Use a core to achieve what?

$L_{coil} = \frac{N^2 A_{core}}{l_{core}} \mu_m$

? L_{coil} (air core) vs L_{coil} (magnetic core)

CFL vs LED Lighting

Talk #1

Incandescent

CFL

LED

$$\frac{\text{Lumens}}{\text{Watt}} \text{ metric}$$

① LED vs incandescent

Cost
LED = 5x Incan

Use only 15% P_e for same light
(W) (L)
last 30x longer

② LED vs CFL

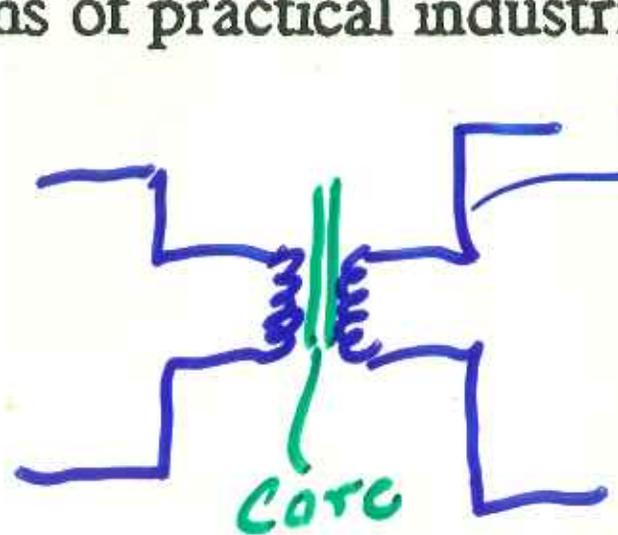
Use $\frac{1}{2}$ P_e (CFL) for same light
(L)
Lasts 5x longer than CFL

DOE by 2020 LED's will have 70%
market share
save \$300 billion

Fr Lines Not Cu but Al why

CHAPTER 9 The Ideal Transformer

This introductory chapter highlights the basic principles of transformers in general. In addition to the usual voltage and current transformations, the chapter goes on to show the meaning of polarity and how impedances can be shifted from primary to secondary and vice versa. The study of the ideal transformer also paves the way for developing the equivalent circuit and phasor diagrams of practical industrial transformers.



① Wire Choices?
- Diameter
- # Turns
Always Cu?

② Three Materials Choices! Fe, Si, other

Start Ch 9 pg 183

Faradays Law

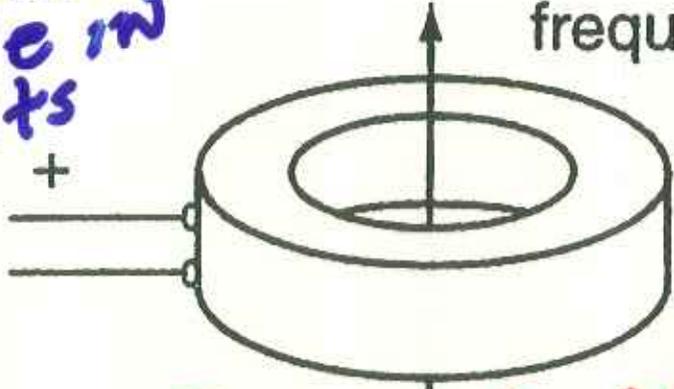
voltage at open wire in Volts

$$e = N \frac{d\Phi}{dt}$$

magnetic Flux in Webers

frequency f

of Turns of wire

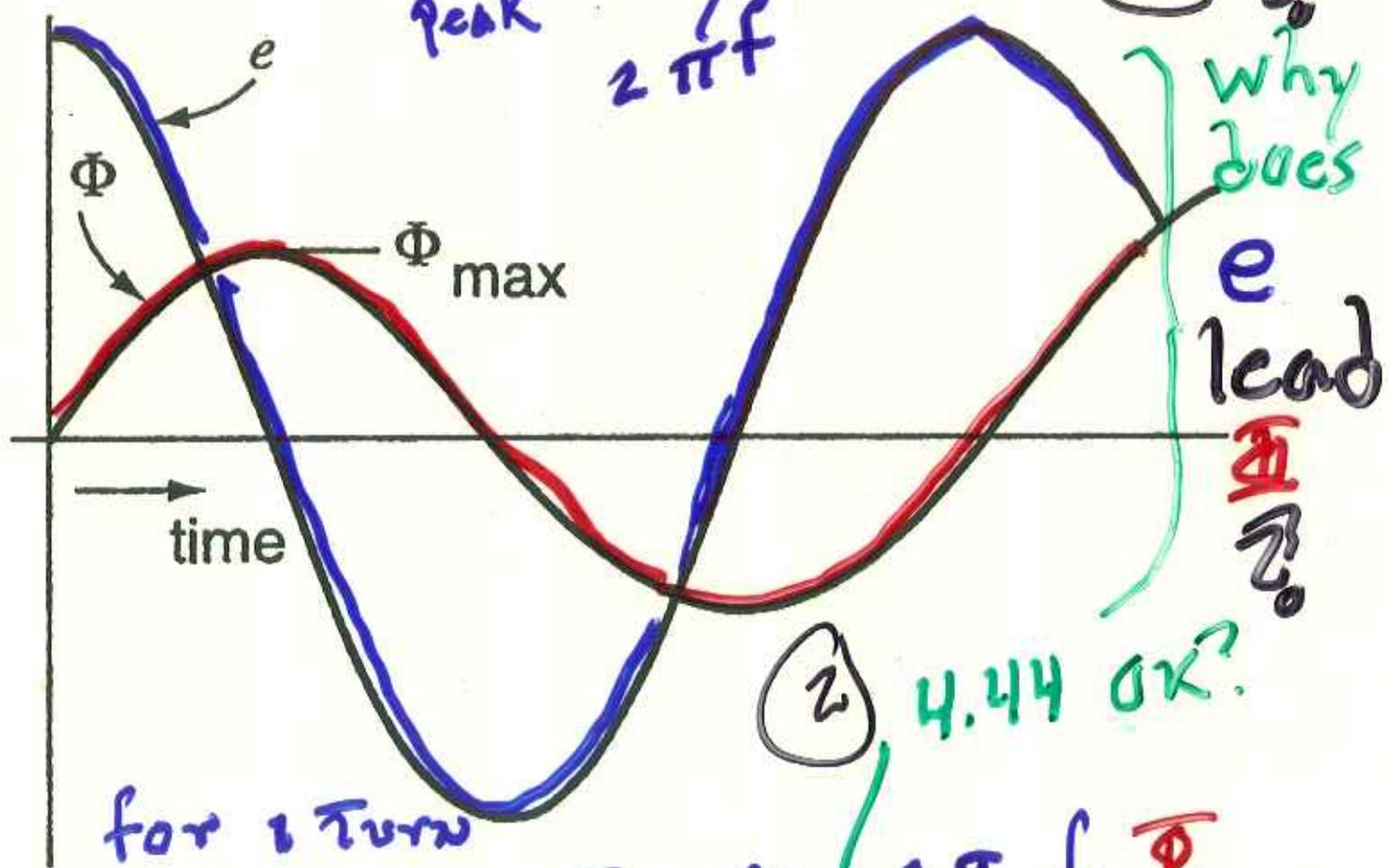


N turns

Fig 9.1

If $\Phi \sim \Phi_{max} \cos \omega t$ or $\Phi_{max} \sin \omega t$
 $e \sim N \omega \Phi_{max}$
 $\omega = 2\pi f$

$\frac{d}{dt} \sin = \cos$



2 4.44 OK?

for 1 turn

$$e_{rms} = \frac{e_{peak}}{\sqrt{2}} = \frac{2\pi f \Phi_{max}}{\sqrt{2}} = \sqrt{2} \pi f \Phi_{max}$$

Faradays Law:

$$e = N \frac{d\phi}{dt}$$



If $\phi(t)$ is a sinusoid @ ω

$$|e| = N \omega |\phi|$$

Copper

ω

$|\phi|$

$$\phi = BA$$

IRON CORES
AT $\phi \uparrow$

Si switches

Tradeoff

Cu

vs

Fe

Cu

Fe

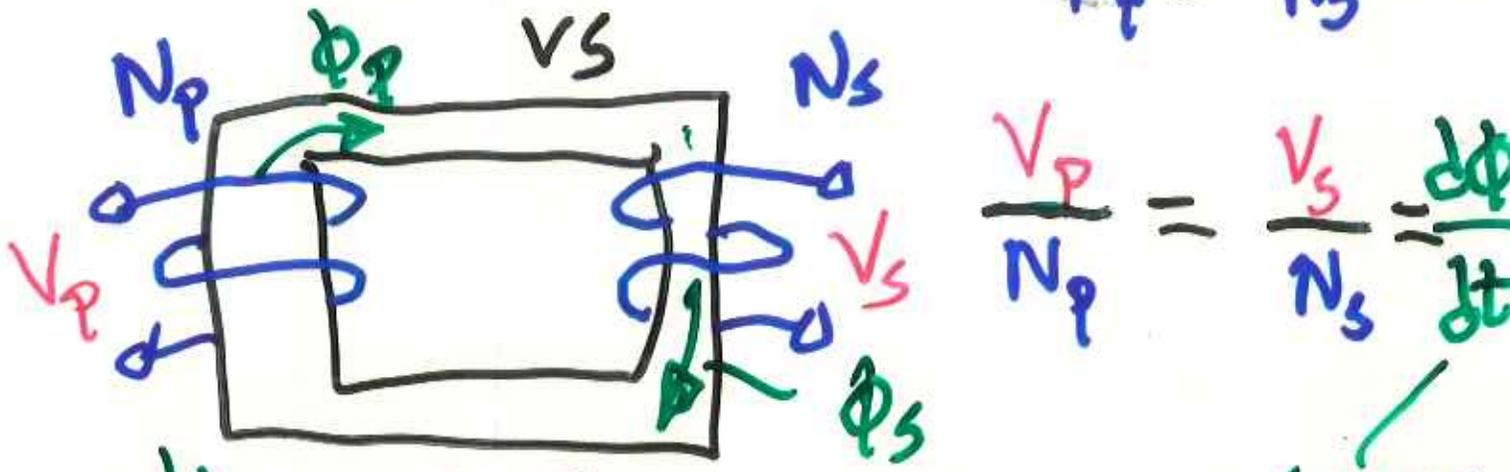
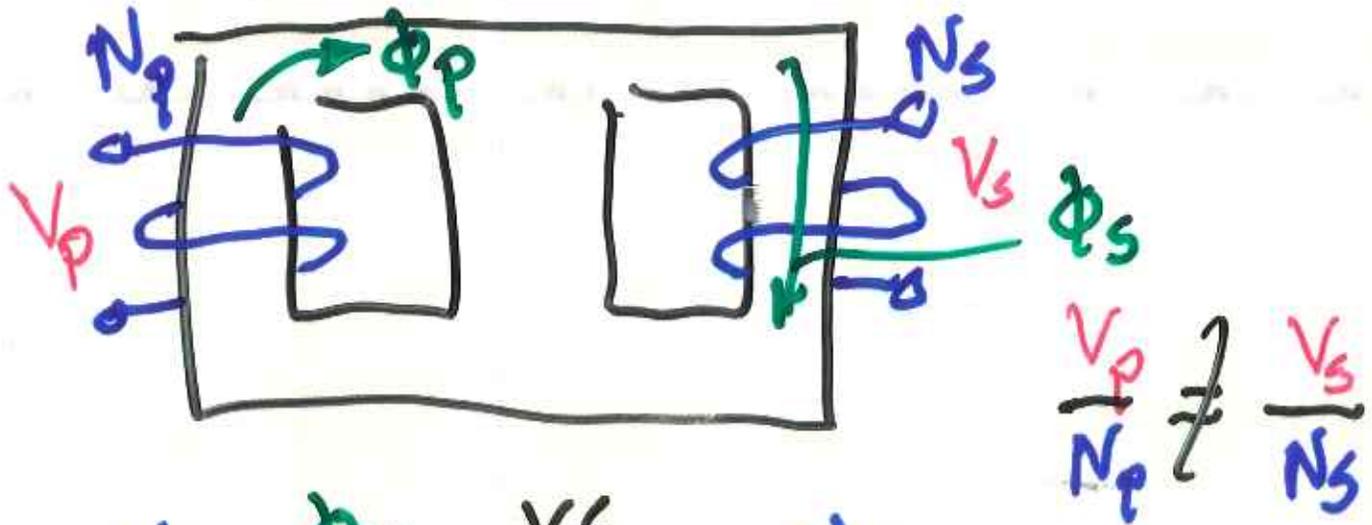


Reduce both Cu Fe via ω

Revolution for \$/50

Si switch

$\left(\begin{matrix} kA \sim MW \\ \mu s \end{matrix} \right)$



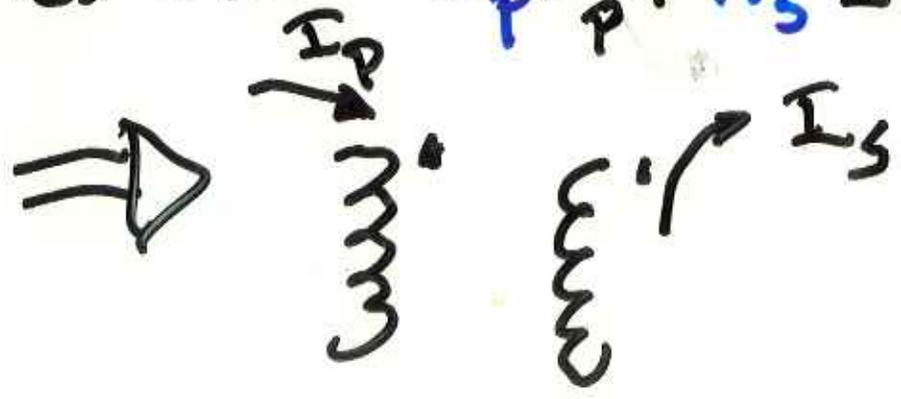
$\frac{d\Phi}{dt} = \omega \Phi$ for sinusoids

same flux

Faraday's Law

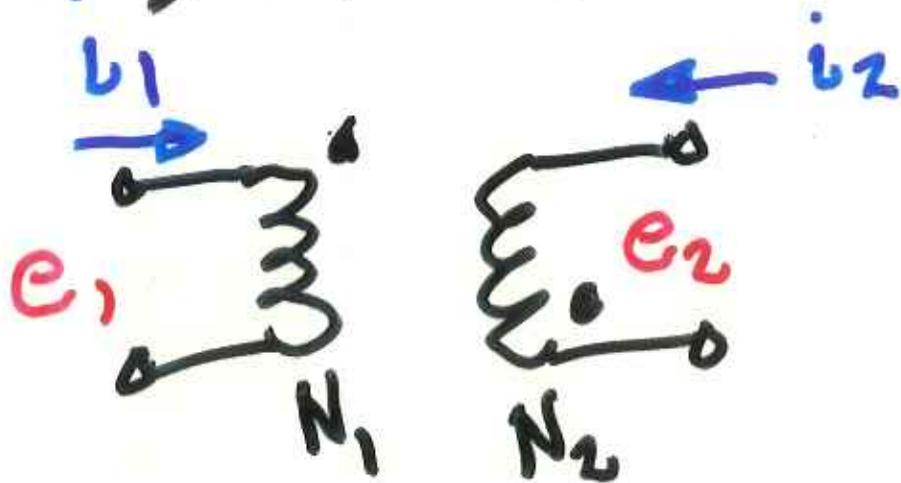
I levels:

Ampere's Law $N_p I_p + N_s I_s = 0$



Dot convention

Dot Convention



Ampere's Law

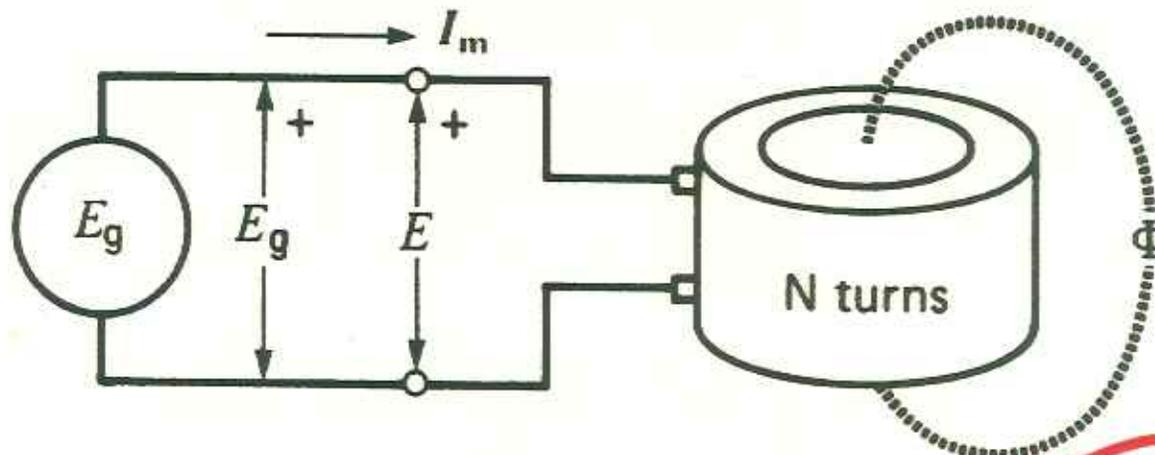
$$N_1 i_1 + N_2 i_2 = 0$$

⇒ if i_1 into dot on N_1
 i_2 out dot on N_2

For e_1 and e_2 phase match

dots tell

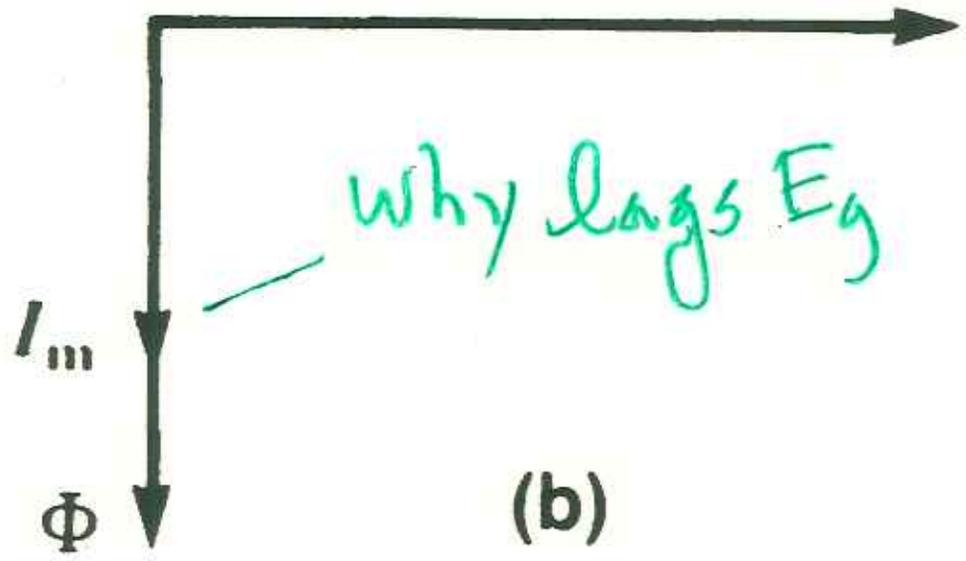
e_1 ⊕ @ dot
 e_2 ⊕ @ dot



(a)

$\phi \sim \sin \omega t$
 $\phi = \omega \cos \omega t$

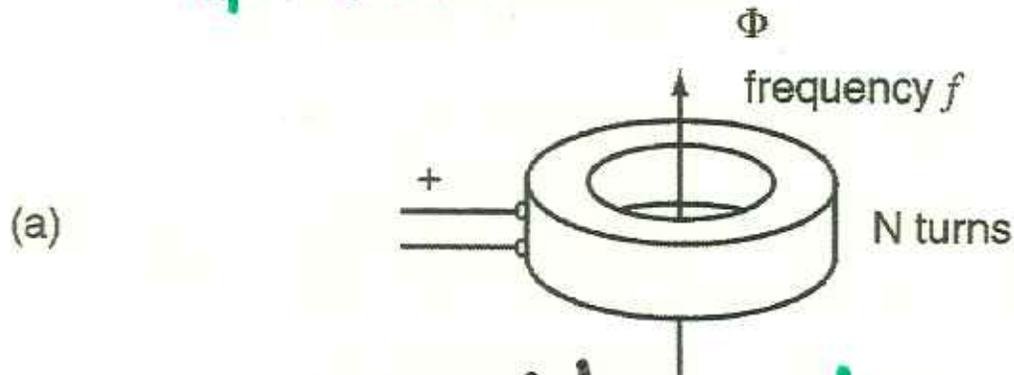
~~If~~ Non-air core E_g, E_{core} has a maximum flux or it will saturate!



(b)

ϕ_{max}

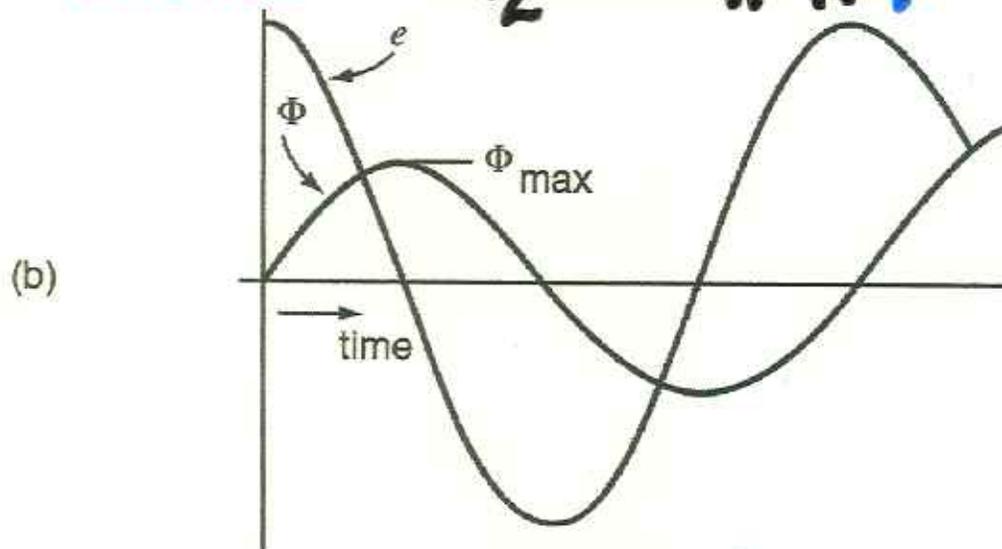
Φ in a core



$$e = N \frac{\omega}{2\pi f} \Phi, \quad \Phi = \frac{e}{2\pi N f}$$

$$\Phi_{\max} = \frac{\sqrt{2} e}{2} \frac{1}{\pi N f} = \frac{e}{\sqrt{2} \pi N f}$$

4.44



Why hyperventilate on Φ_{\max} ?

AC Inductor



$X_L = 60, R = 8$

500 turns for X_L

CHAPTER 9

9-1 a. $I_m = \frac{E_g}{X_L} = \frac{120}{60} = 2A$ AC rms

b. $I_{m(peak)} = \sqrt{2} I_m = \sqrt{2} \times 2 = 2.83A$

mmf

c. $U_{(peak)} = NI_{m(peak)} = 500 \times 2.83 = 1415 A\text{-turn}$

d. $\phi_{max} = \frac{E_g}{4.44 f N} = \frac{120}{4.44 \times 60 \times 500} = 0.9 \text{ mWb}$?

reduce 120V to 40V

9-2

$U = 1415 \times 40/120 = 472A$

$\phi_{max} = 0.9 \times 40/120 = 0.3 \text{ mWb}$

} lowers mag values

Core losses ~ Φ_{max}^2
Not Δ_{rms}

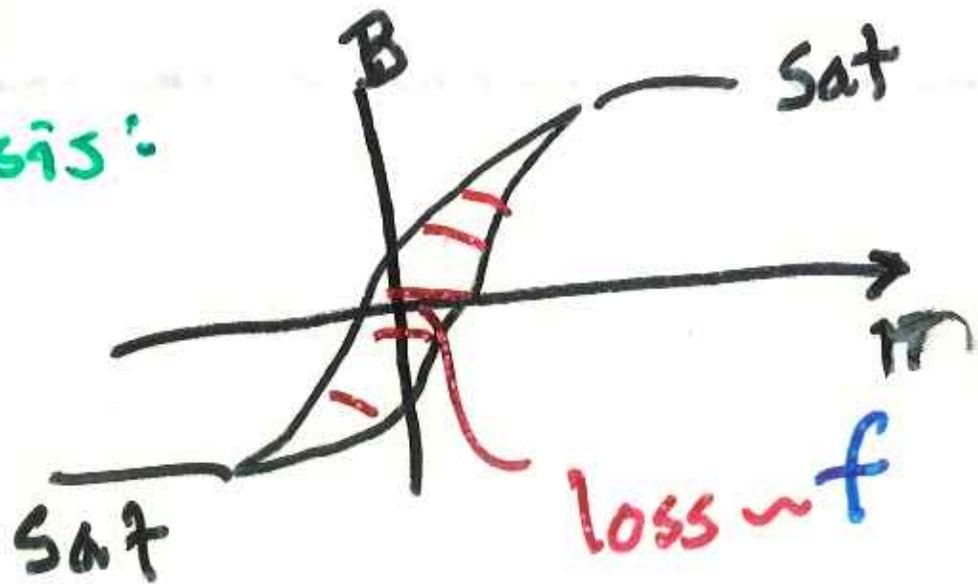
Why?

Core loss have two parts

1. hysteresis ~ f why
2. eddy current ~ f² why?

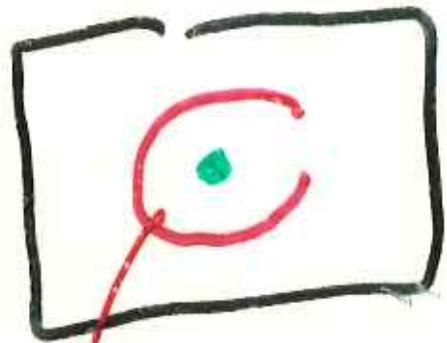
Hf
N
E

Hysteresis:



Eddy Current:

Voltage induced within core

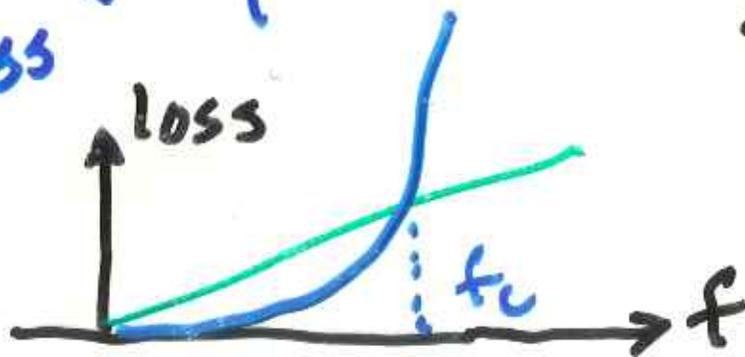


$$V_{\phi} \sim \dot{\phi} \sim f\phi$$

$$P_{\text{eddy loss}} \sim \frac{(V_{\phi})^2}{R_{\text{core}}}$$

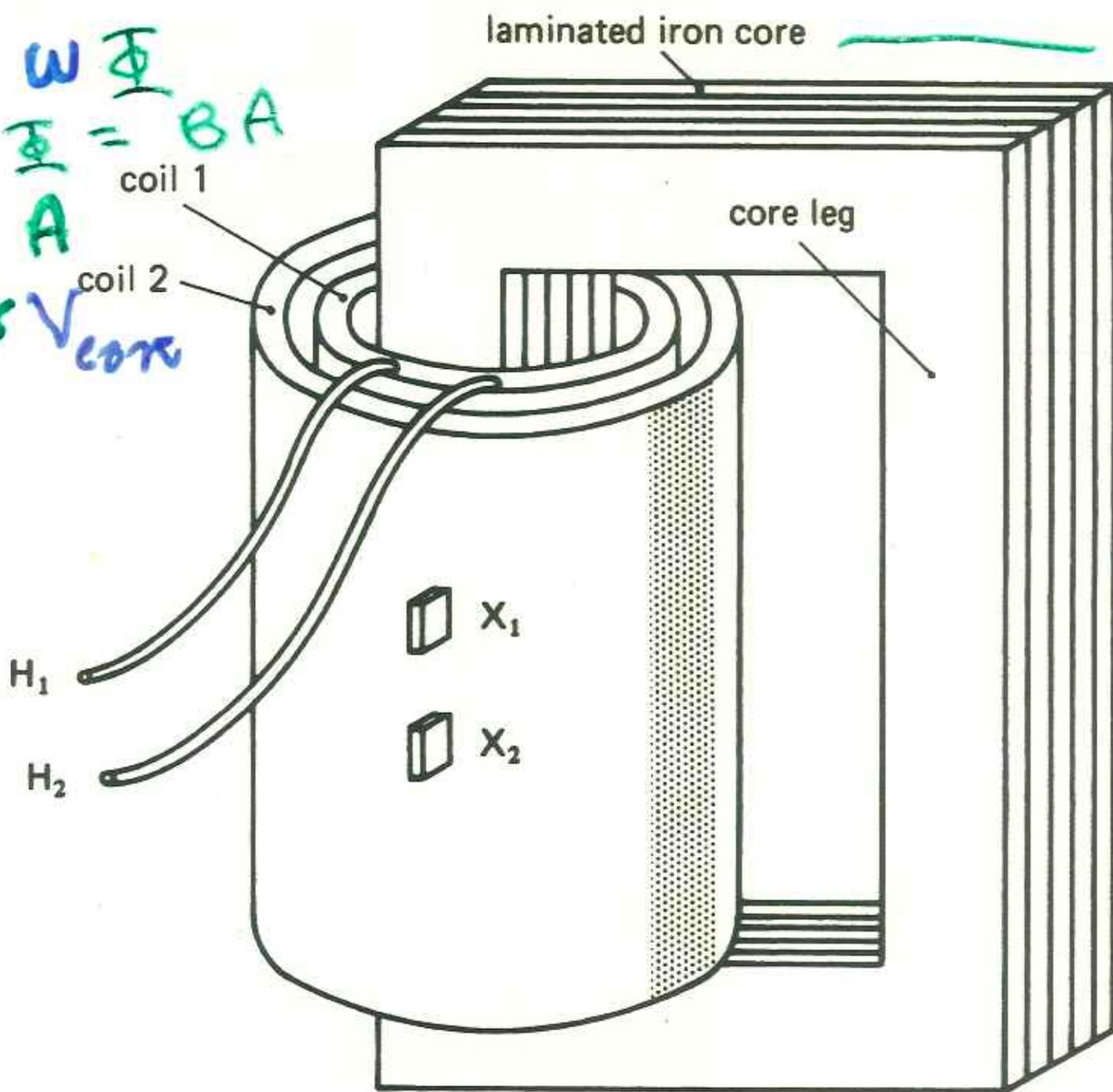
$$P_{\text{eddy loss}} \sim f^2$$

low for Fe:Si
high for ferrites



$$f_c = ?$$

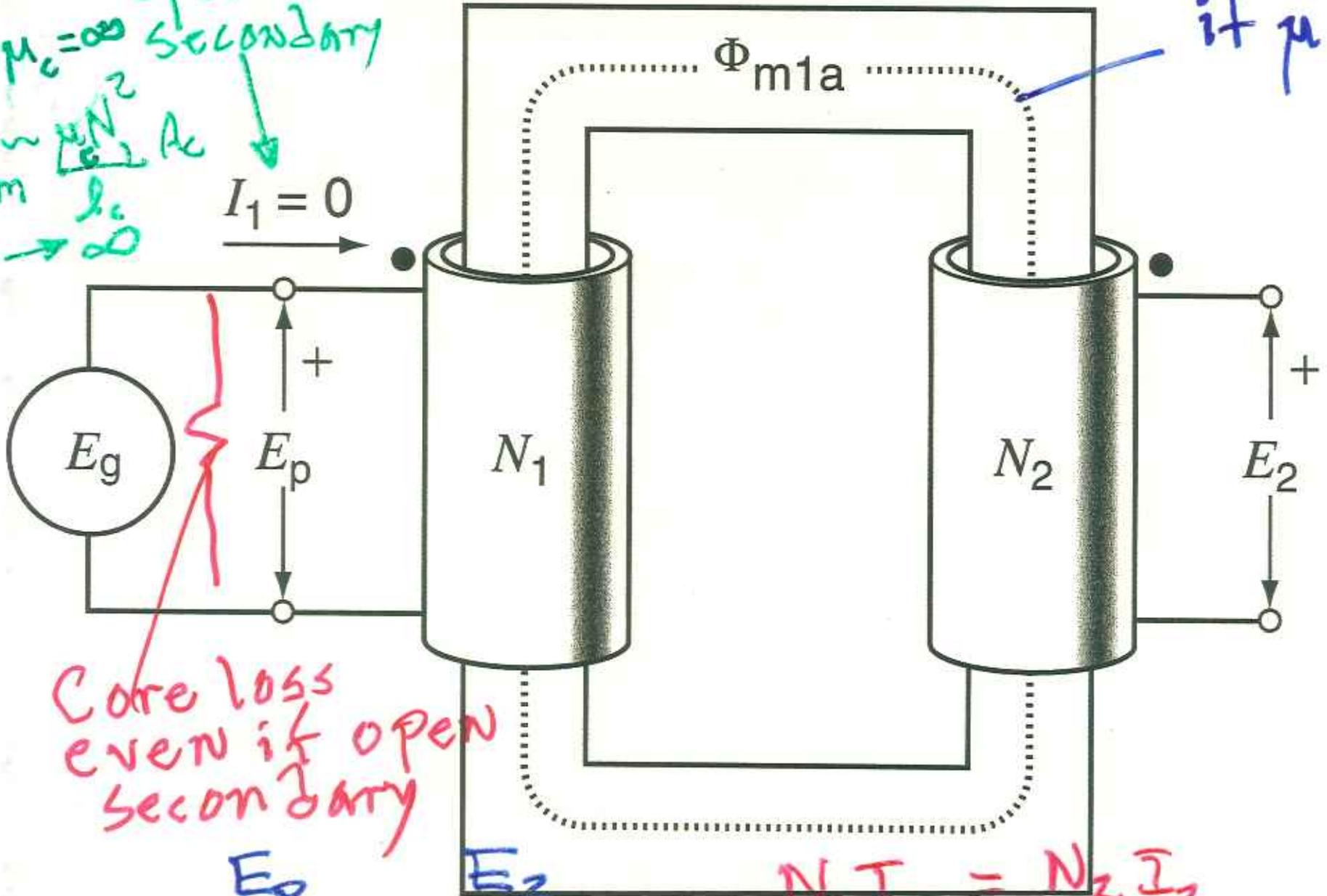
$V_{\text{core}} \sim W \Phi$
 $\Phi = BA$
lower A
lowers V_{core}



makes smaller core area
 $V_{\text{core}} \downarrow$
peddy
 $\sim V_c^2 \downarrow$

if $\mu_c = \infty$ open secondary
 $L_m \sim \frac{\mu N^2}{l_c} A_c$
 $\rightarrow \infty$

if $\mu \rightarrow \infty$



Core loss even if open secondary

$$\frac{E_p}{N_1} = \frac{E_2}{N_2}$$

$$N_1 I_1 = N_2 I_2$$

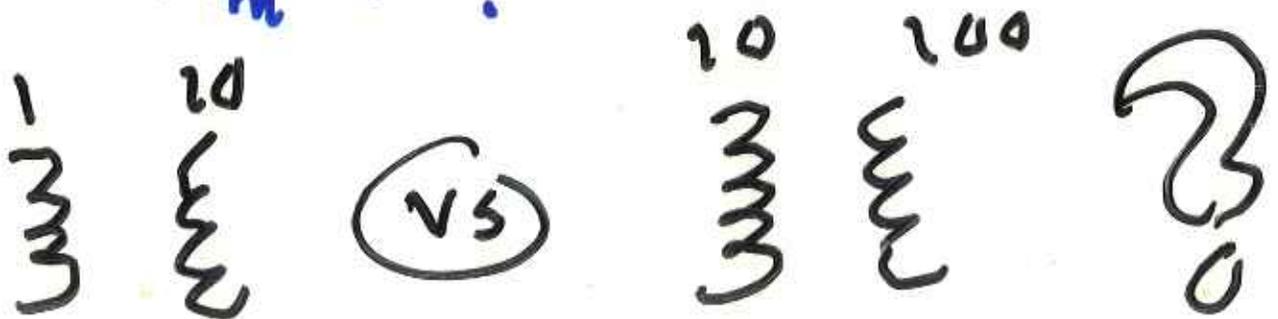
Z_{in} (open circuit transformer)

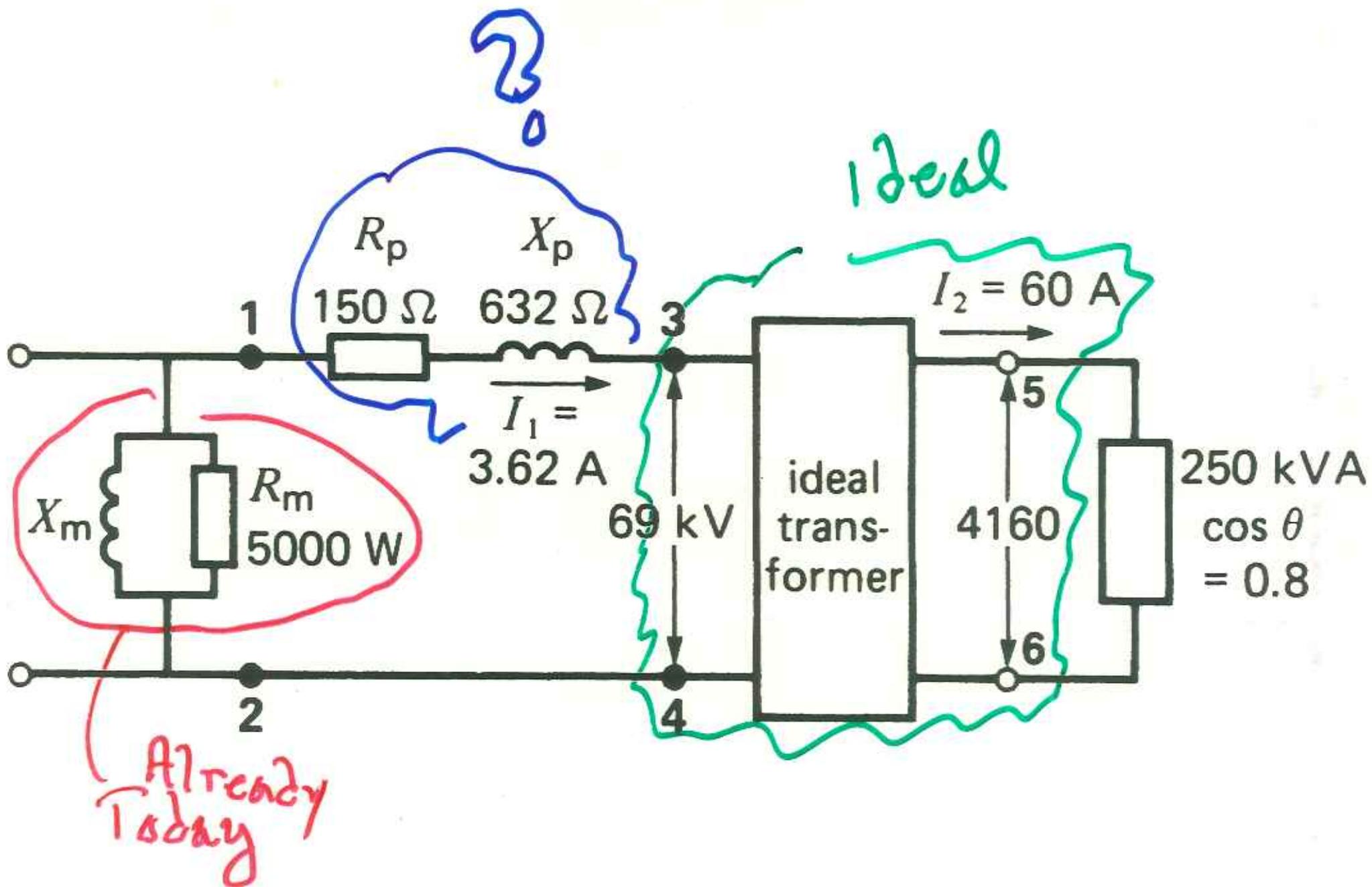


Core loss
Goal
 $R \rightarrow ?$

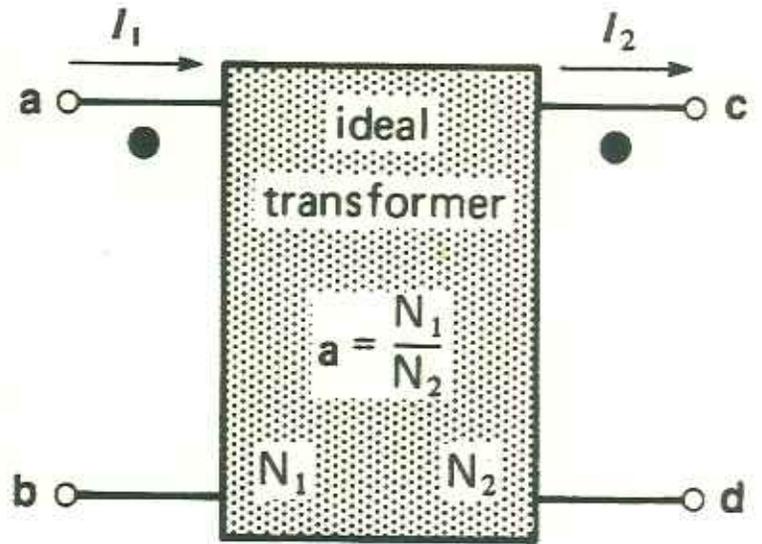
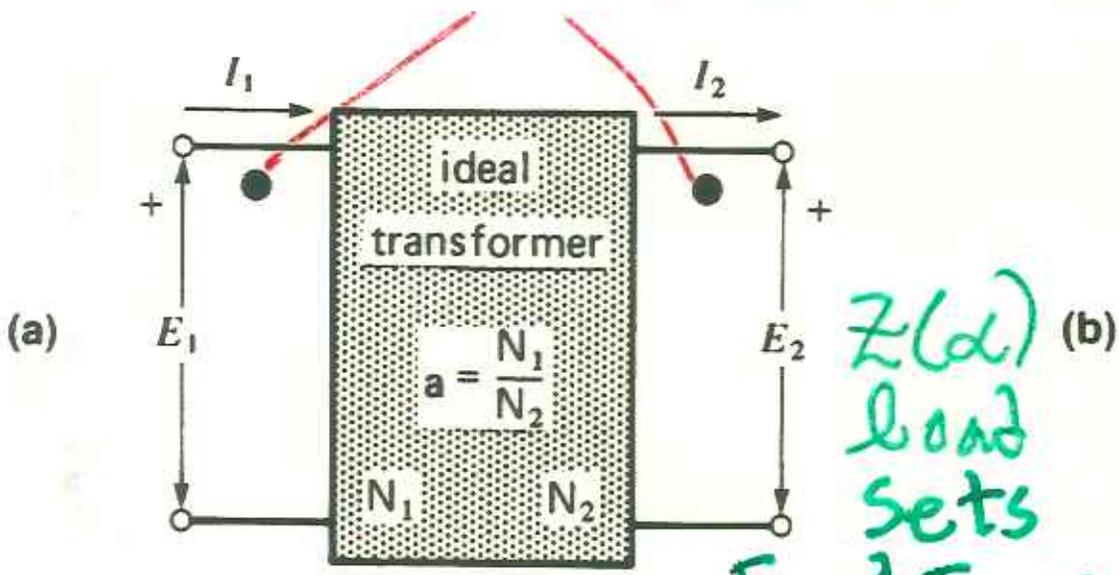
$$L_m = \frac{N_p^2}{\frac{R_{core} l_c}{\mu_c A_c}} = \frac{N_p^2 \mu_c A_c}{l_c}$$

Power Transformer goal
 $L_m \rightarrow ?$



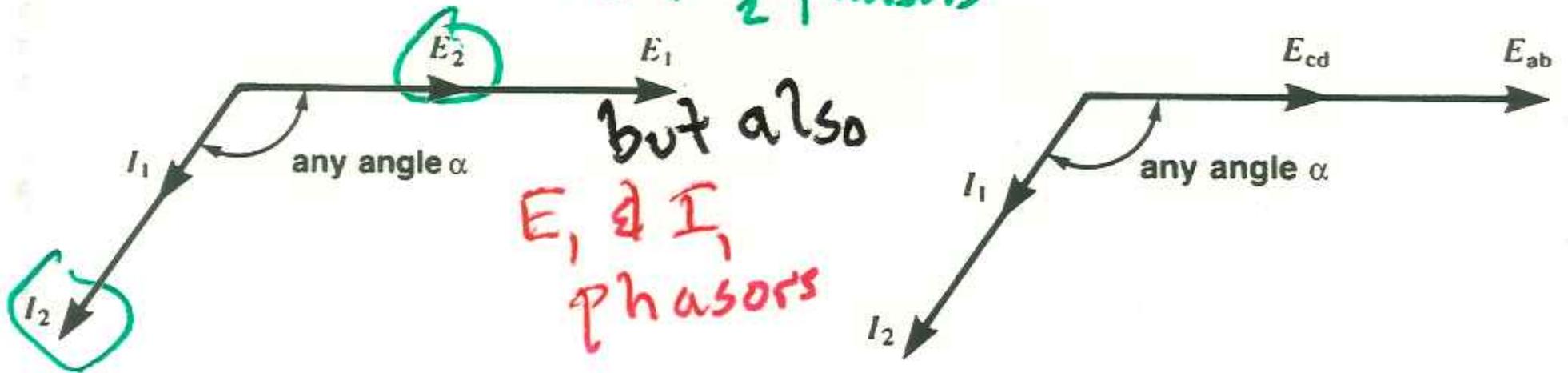


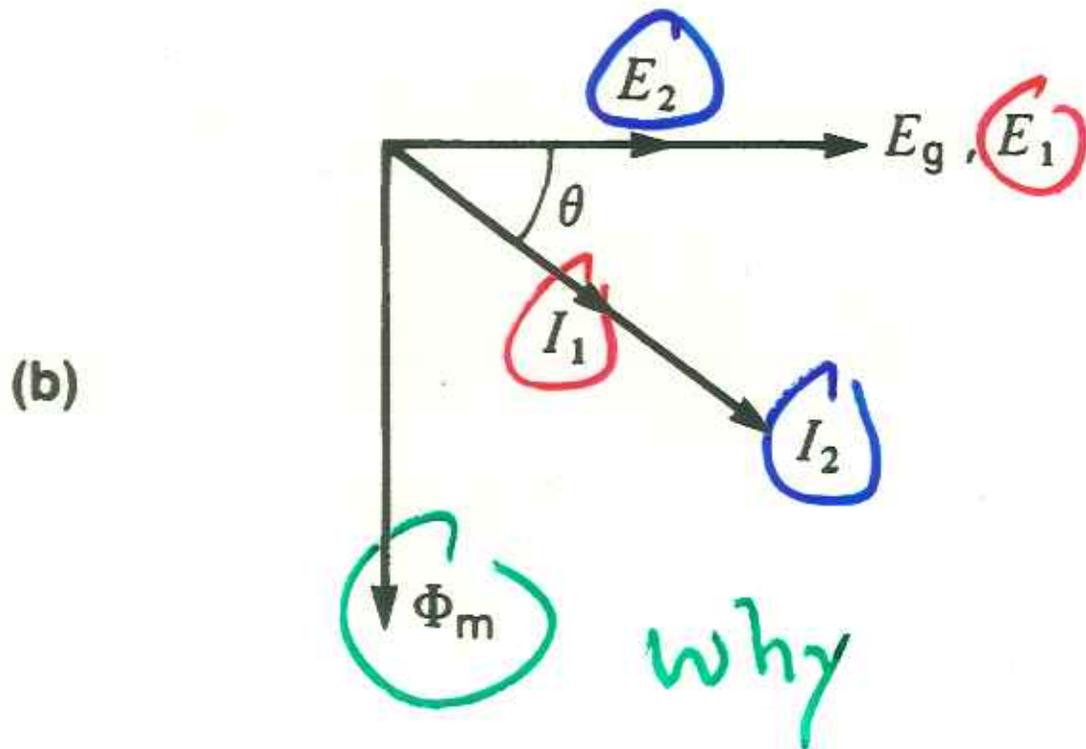
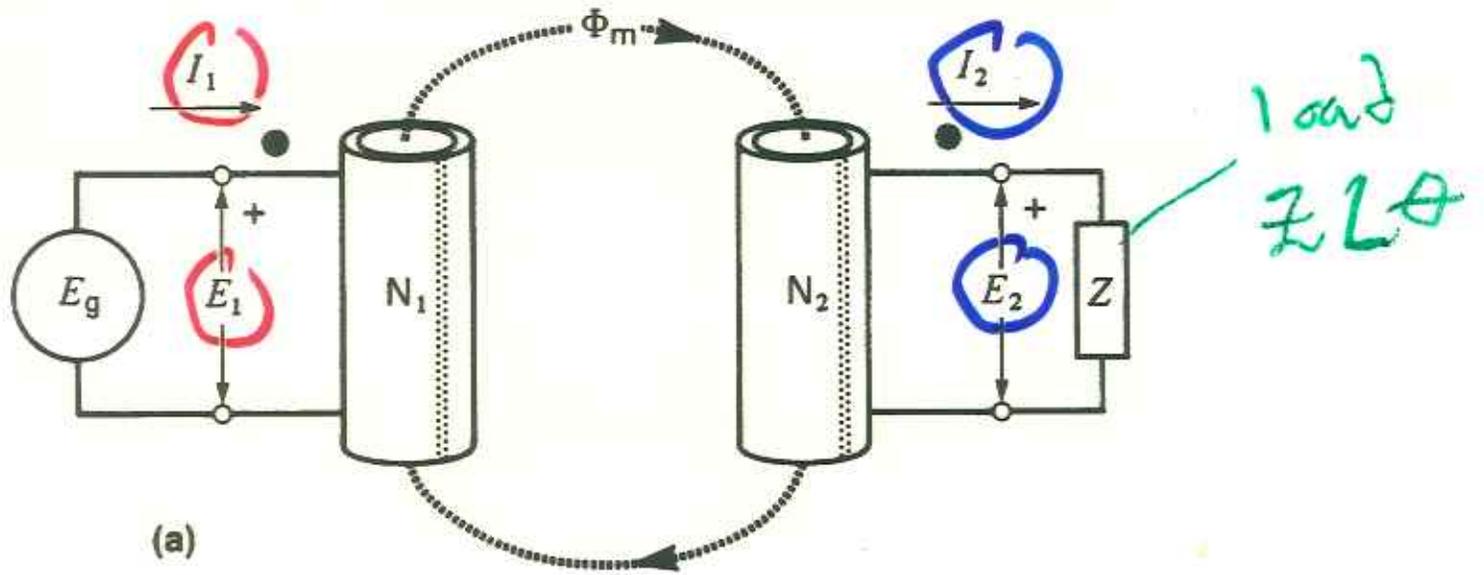
$$\sum N_x i_x = 0$$



$Z(\alpha)$
load
sets

E_2 & I_2 phasors



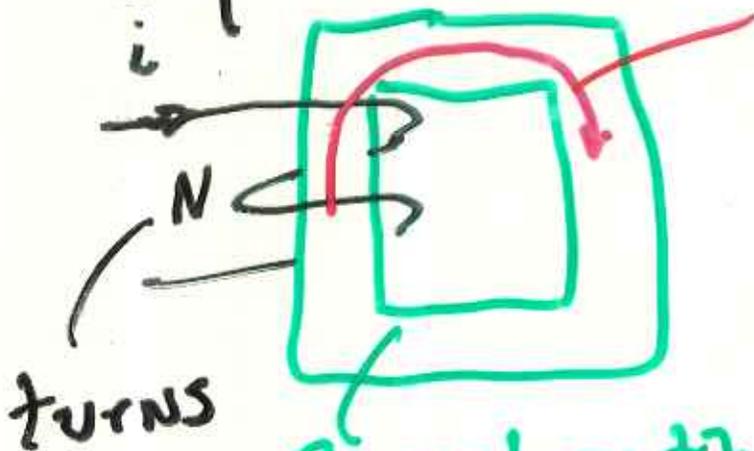


Magnetic Circuits (RHR)



core: μ_c
 $\mu_0 \rightarrow$
 air: $4\pi \times 10^{-7} \frac{H}{m}$

Ampere's Law



H
 CW

$$H = \frac{Ni}{l}$$

$$\vec{B} = \mu \vec{H}$$

$$\mu = \mu_0 \mu_r$$

2000

$$\Phi = AB$$

Magnet core guides flux

But

$$\frac{\mu_c}{\mu_0} \approx 10^3 \text{ vs } 1$$

susceptibility

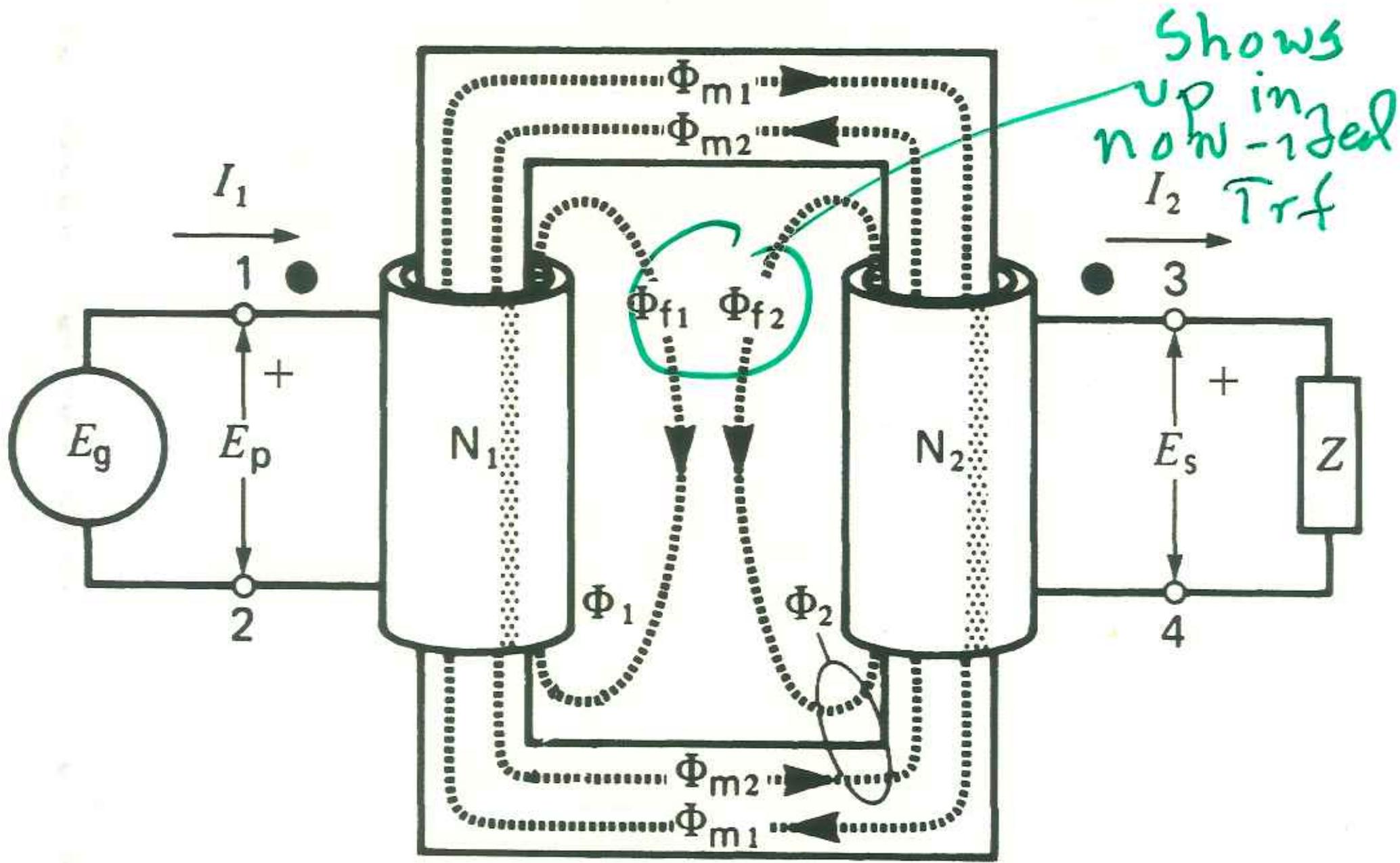
Conductivity

$$\sigma(\text{wire})$$

$$\sigma(\text{air})$$

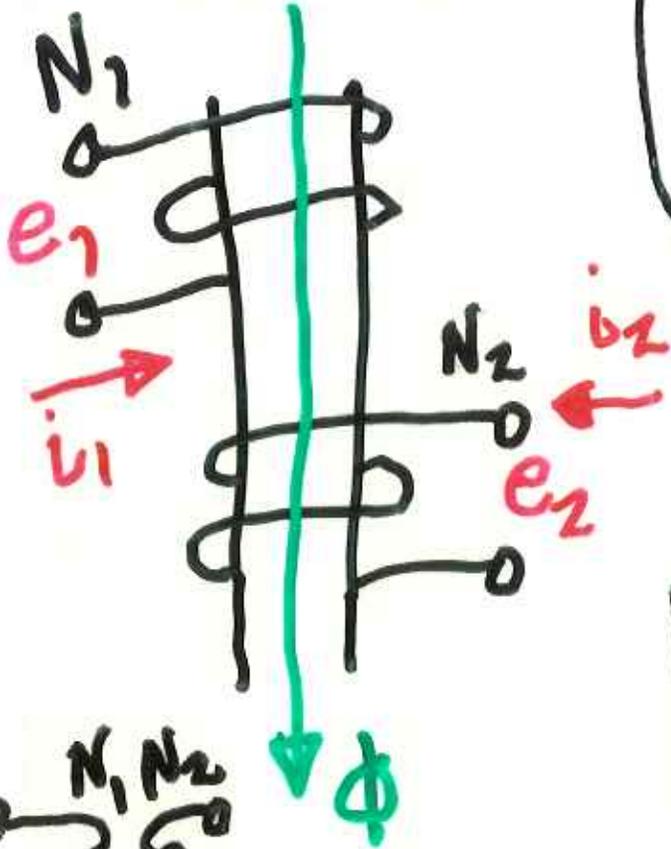
\Rightarrow LEAKAGE FLUX!

$\approx 10^{12}$



Shows up in non-ideal Trf

ideal trf



$$\frac{e_1}{N_1} \equiv \frac{e_2}{N_2} \equiv \dot{\phi}$$

lossless case

$$e_1 i_1 \equiv e_2 i_2$$

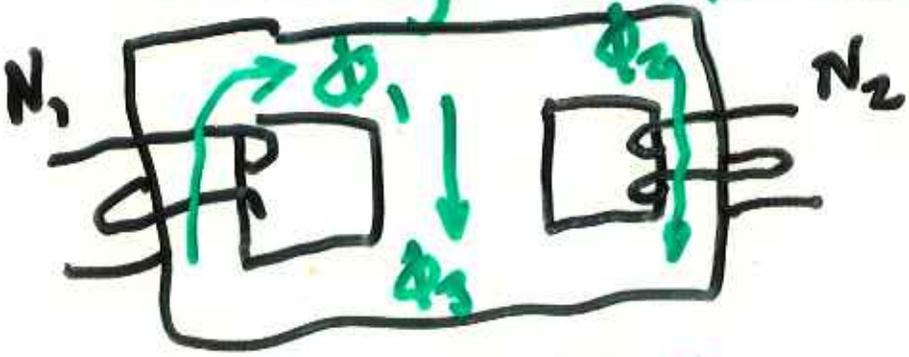
$$i_1 N_1 \equiv N_2 i_2$$



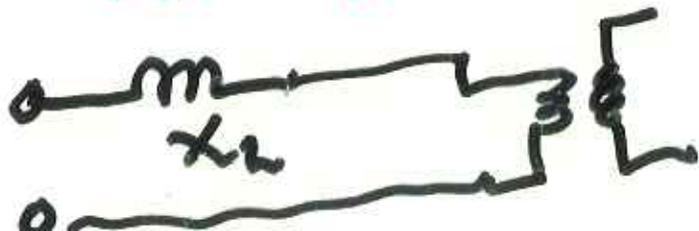
Real Trf

Leakage flux exists \Rightarrow

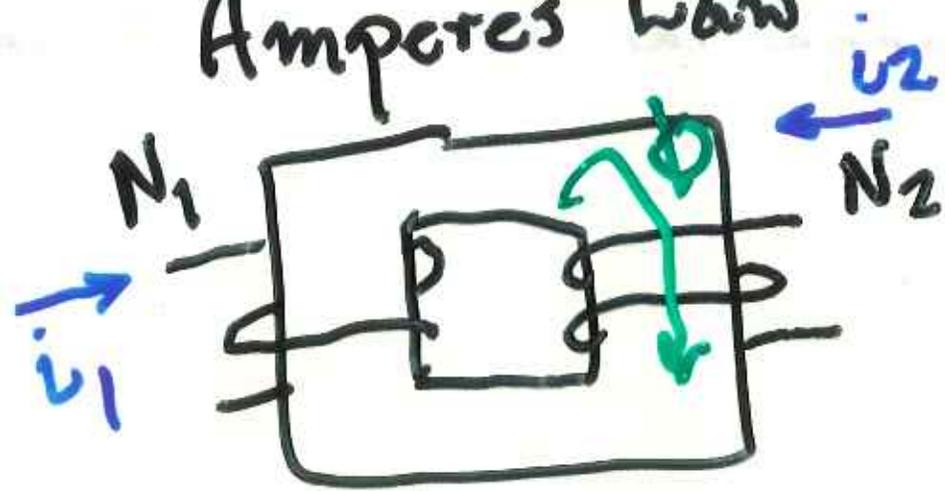
ϕ_1 in N_1
not
 ϕ_2 in N_2



$$\phi_1 = \phi_2 + \phi_3$$



Ampere's Law



$$R_m \sim \frac{l_{\text{core}}}{\mu A_{\text{core}}}$$

$$\underbrace{N_1 i_1 \pm N_2 i_2}_{\text{sum of mmf}} = \phi R_m$$

$\mu \rightarrow \infty$ then $\phi R_m \equiv 0$

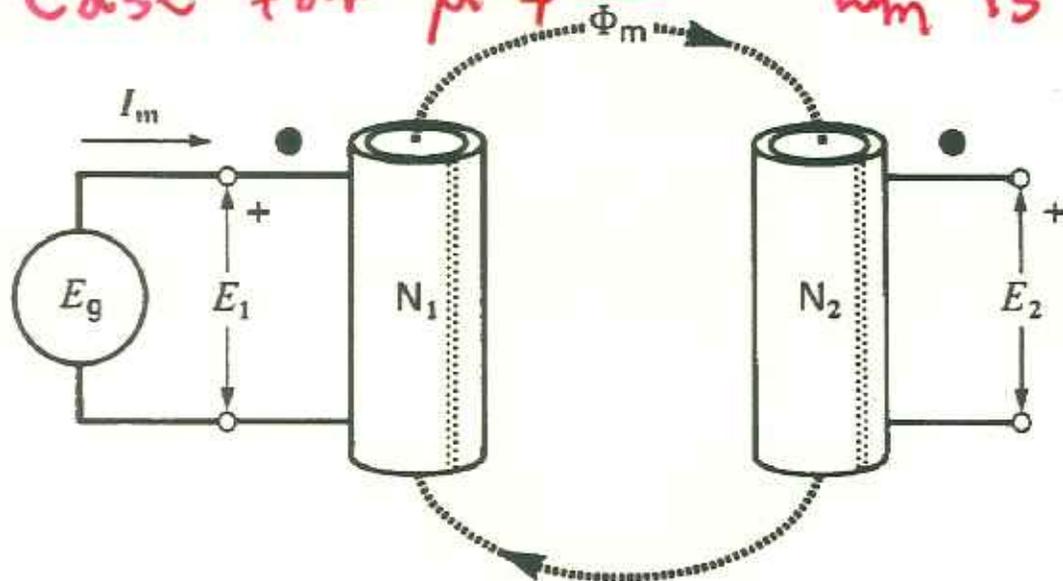
$$N_1 i_1 \approx N_2 i_2 \quad \left. \vphantom{N_1 i_1} \right\} \text{approx.}$$

Opposing ϕ net $\phi_{\text{total}} \rightarrow 0$

Current levels do not saturate a trf.

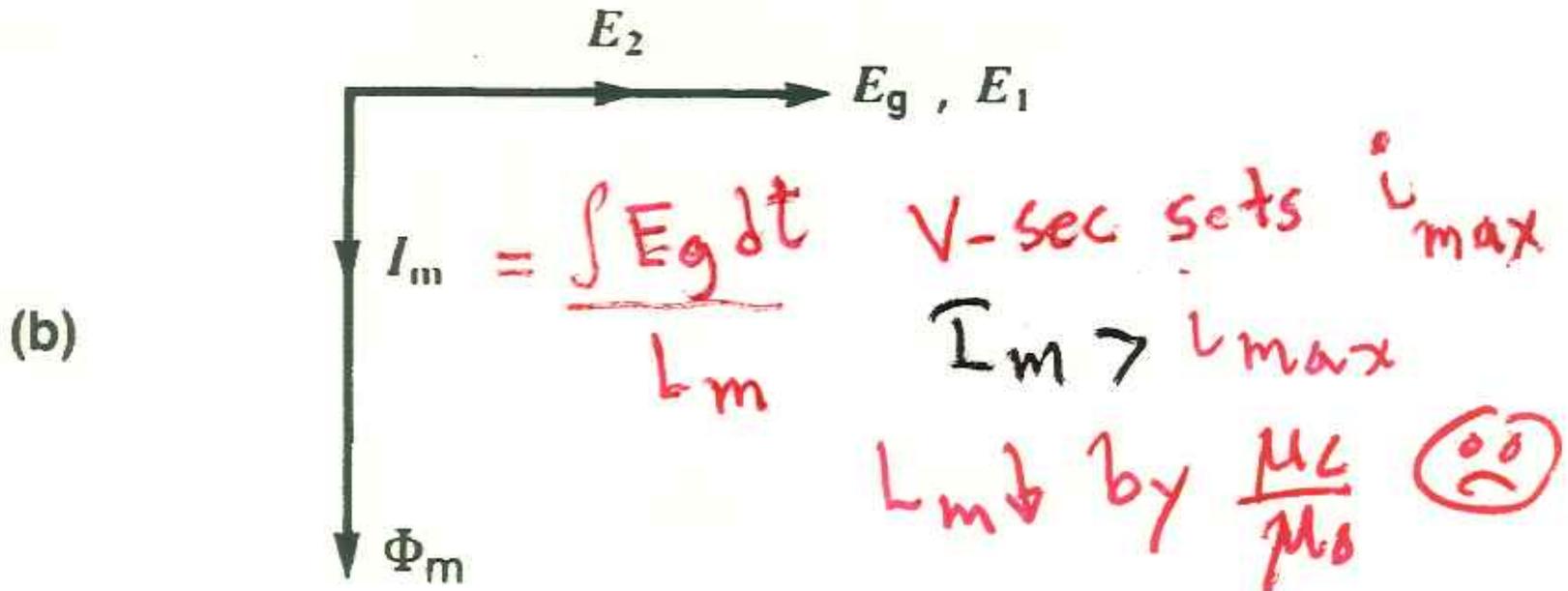
! V-sec saturates!
! a transformer !

Case for $\mu \neq \infty$ l_m is finite



open secondary

(a)

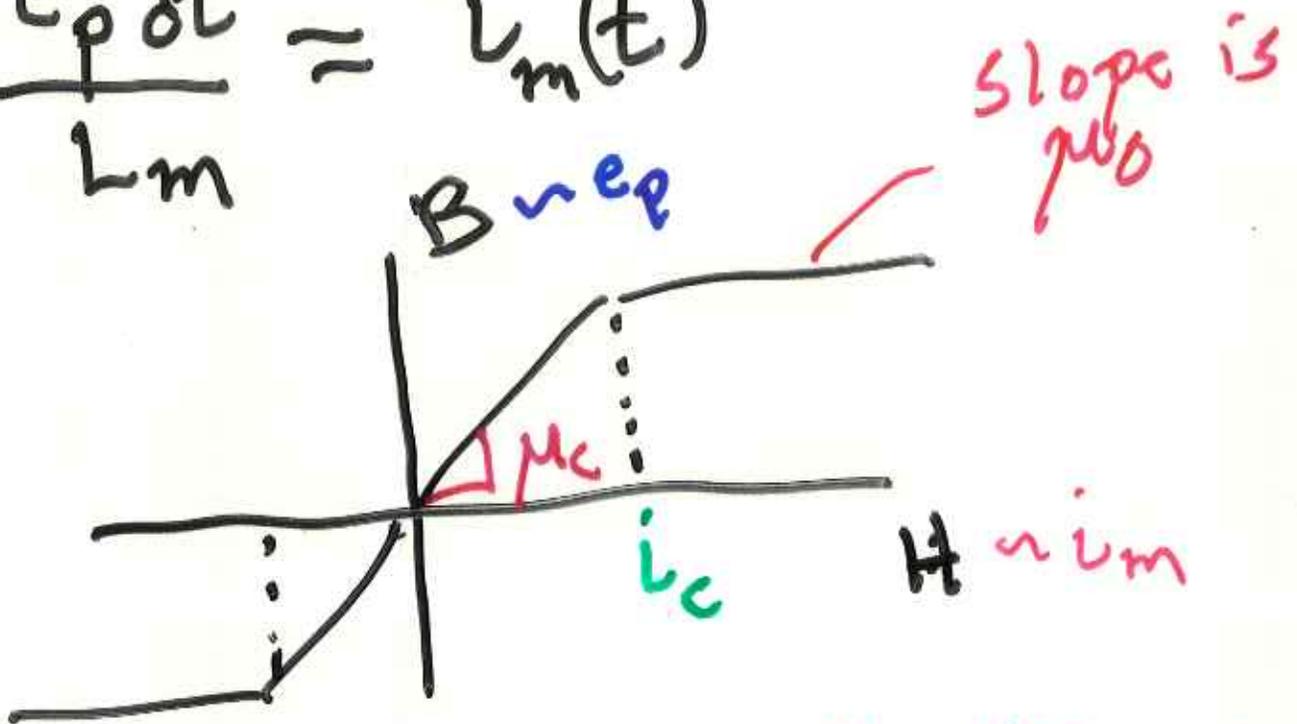


(b)

$$e = L \frac{di}{dt}$$

$$e_p = L_m \frac{di_m}{dt}$$

$$\int \frac{e_p dt}{L_m} = i_m(t)$$



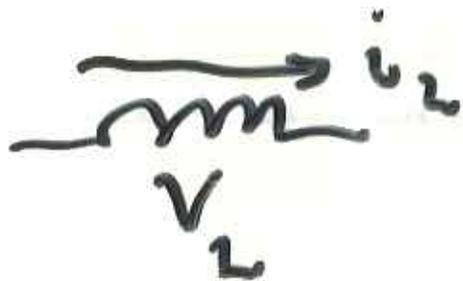
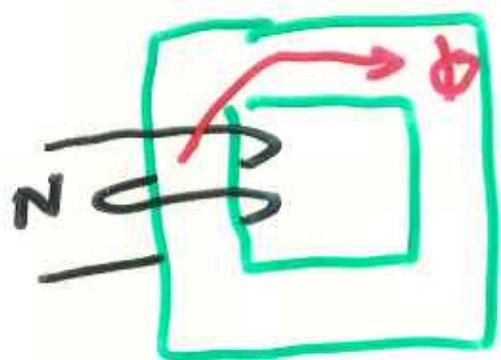
i_c (critical) saturates the core

L_m reduces by $\frac{\mu_c}{\mu_0} \sim \frac{100}{1000}$

\Rightarrow Shorted input
 L_m too small

Inductance:

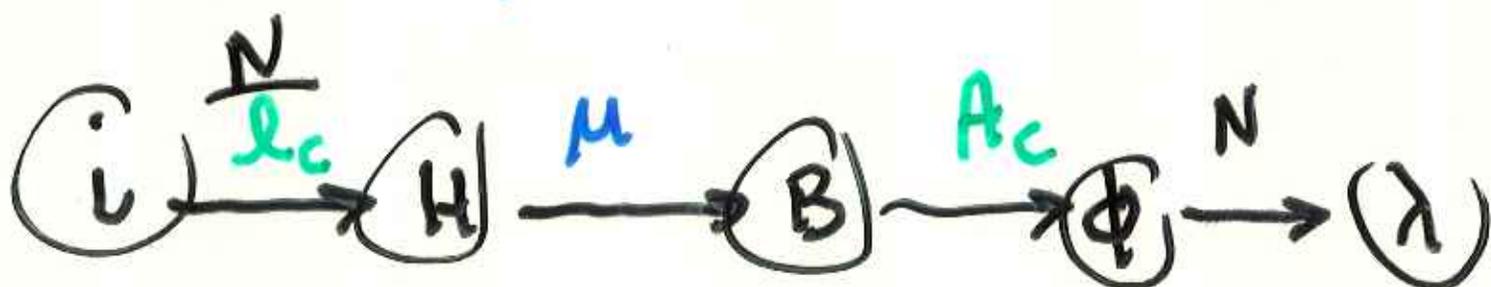
$$V_L = L \frac{di_L}{dt}$$



$$L_m \equiv \frac{\text{flux linkage}}{i_m}$$

$$\equiv \frac{N^2}{R_m} \text{ magnetic reluctance}$$

$$R_m = \frac{l_c}{\mu A_c}$$



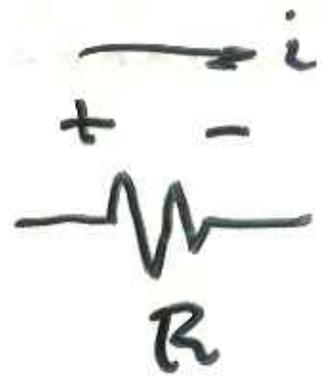
$$L = \frac{\lambda}{i} = \frac{N^2 \mu A}{l_c}$$

$$= \frac{N^2}{R_m} \leftarrow \frac{l}{\mu A}$$

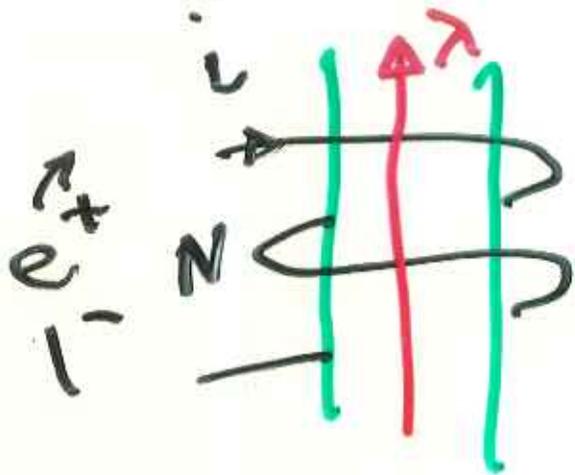
flux linkage

Faradays Law

$e^- \oplus$ convention



magnetic convention



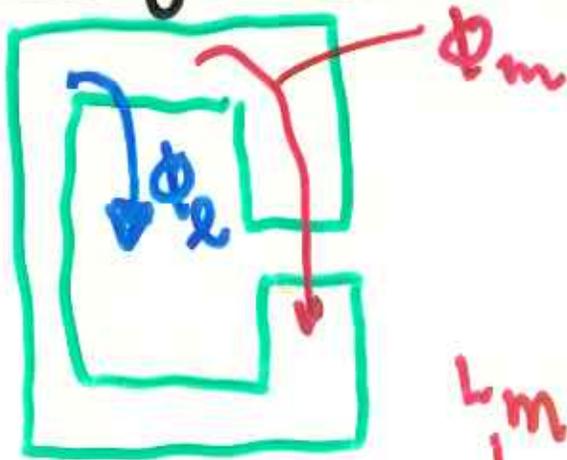
$$e = \frac{d\lambda}{dt}$$

$$= N \frac{d\phi}{dt}$$

No current involved

if all turns are linked

Leakage Inductance: L_l



$\mu_{\text{core}} \leq 10 \mu_0$
 \Rightarrow lots of flux leakage!

$$\Phi_T = \Phi_m + \Phi_l$$

Why no leakage resistance?

$$L_m \equiv \frac{R}{N^2}$$

$N \uparrow \quad L_m \uparrow$
 $i_m \downarrow$



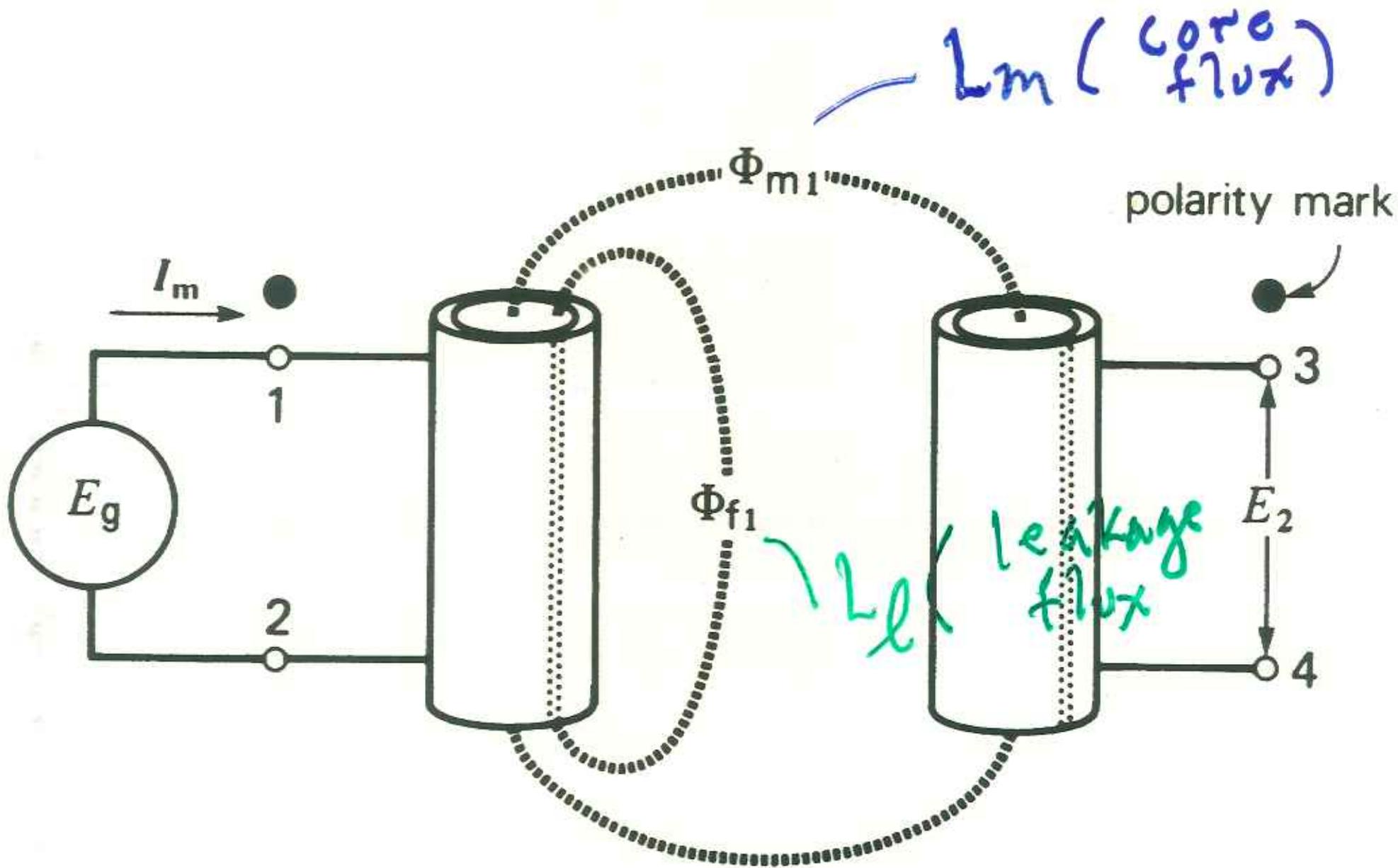
Core Fe
 Winding Cu
Winding Insulation

$$\frac{N_2}{N_1} = \frac{3}{1}$$

vs $\frac{600}{200}$

vs $\frac{6000}{2000}$

What's the difference?



We apply ONLY 50 KVA irr $V_p = 480$, $V_s = 120$
our choice step-down

9-7



3 turns

0.93V

MEASURE V

$$0.93V = 3 \text{ turns}$$

$$\therefore 1V = \frac{3}{0.93} = 3.226 \text{ turns}$$

$$\frac{.93}{3} = \frac{76}{?}$$

$$\frac{V}{\text{turns}} \approx \frac{.93}{3}$$

$$76V = 76 \times 3.226 = 245 \text{ turns}$$

The 120V winding has therefore 245 turns

The 480V winding has $245 \times \frac{480}{120} = 980$ turns.

Actual transformer

Problem is

How to make measurements to find

N_p & N_s

You wind auxiliary winding with known # turns



9-8 (a) $Z = 42V / 1.24A = 33.87 \Omega$ Z_{AC} Z_{DC}

(b) $X_L = \sqrt{33.87^2 - 14.7^2} = 30.5 \Omega$

$L = 30.5 / (2\pi \times 60) = 0.0809H = 80.9mH$

(c) $\theta = \arctan \frac{X_L}{R} = \arctan \frac{30.5}{14.7} = 64.3^\circ$

R_{DC} of (primary coil)
Simple

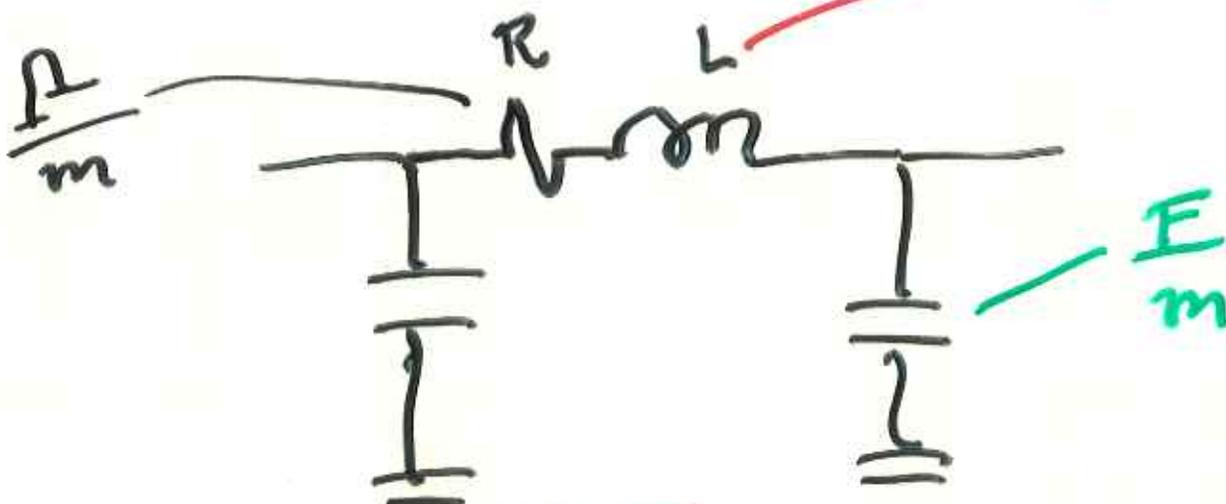
Known

Next Apply V_{AC} measure
 I_{AC}

$L = ?$
 $R = ?$

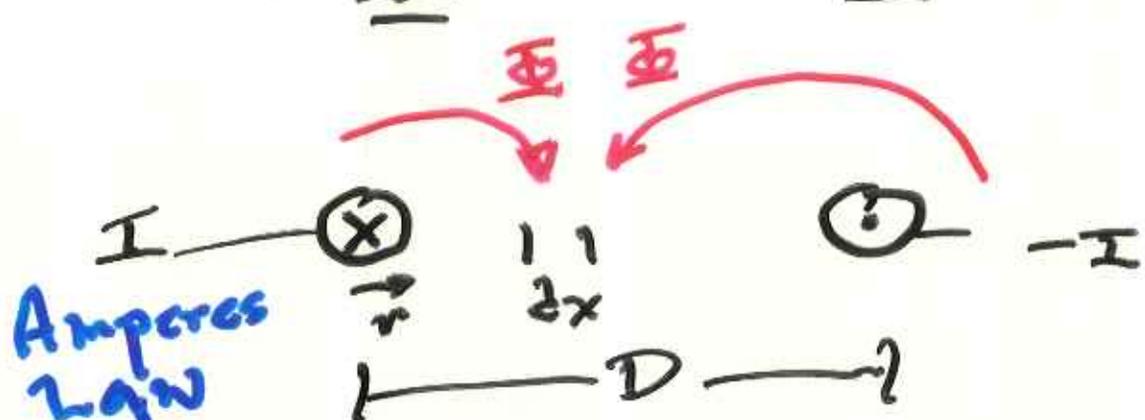
TRANS. Line

$$L \equiv \frac{\lambda}{I} \text{---?}$$



H/m

Ampere's Law



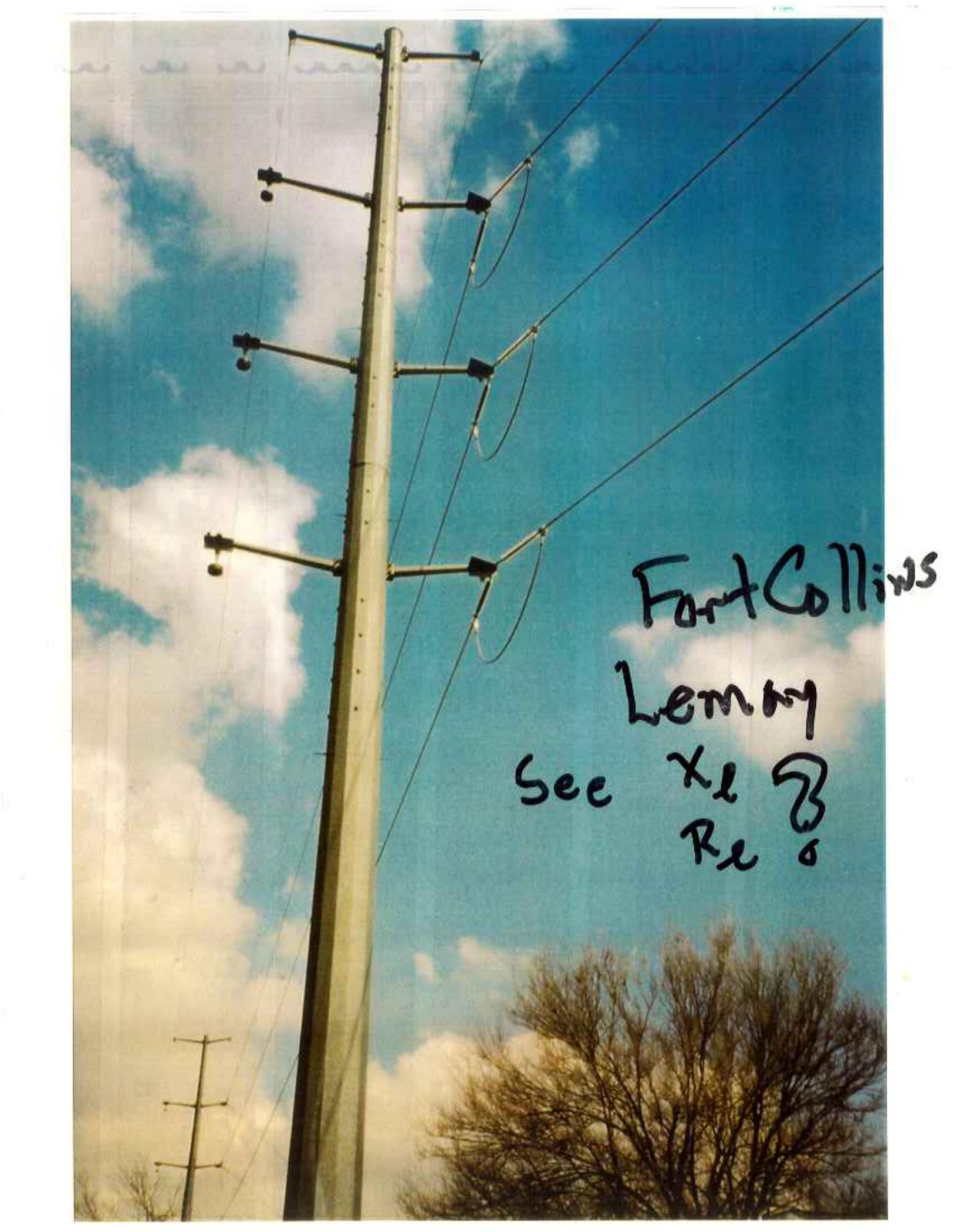
Choices
↓
Consequences

$$H = \frac{I}{2\pi r}, \quad B = \frac{\mu_0 I}{2\pi r}, \quad d\phi = B dx$$

$$\lambda(\text{flux linkage}) = \frac{\mu_0 I}{2\pi} \int_r^D \frac{dx}{x} \quad \leftarrow L_{ext}$$

$$2\phi_{add} \Rightarrow \lambda_{total} = \frac{\mu_0 I}{\pi} \ln \frac{D}{r}$$

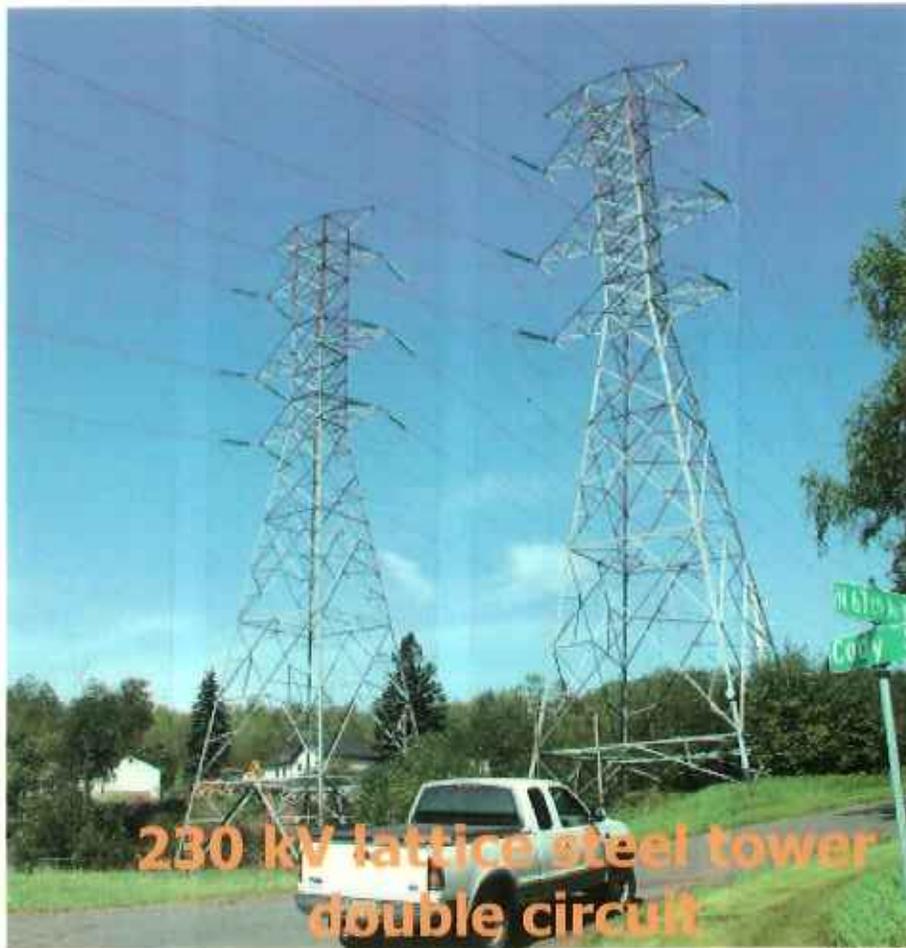
$$\frac{\lambda_T}{I} = L_{total} = \frac{\mu_0}{\pi} \ln \frac{D}{r} \neq f(I)$$



Fort Collins

Lenny

See X1 3
Re 0



February 11 - 13

First Class in Power Engineering
Power Systems Landscape

40

- P** flow on lines set by
1. Kirchoff's Laws
 2. Power Contracts (LAW^{Legal}S)
 3. Intermittant Alternative Energy

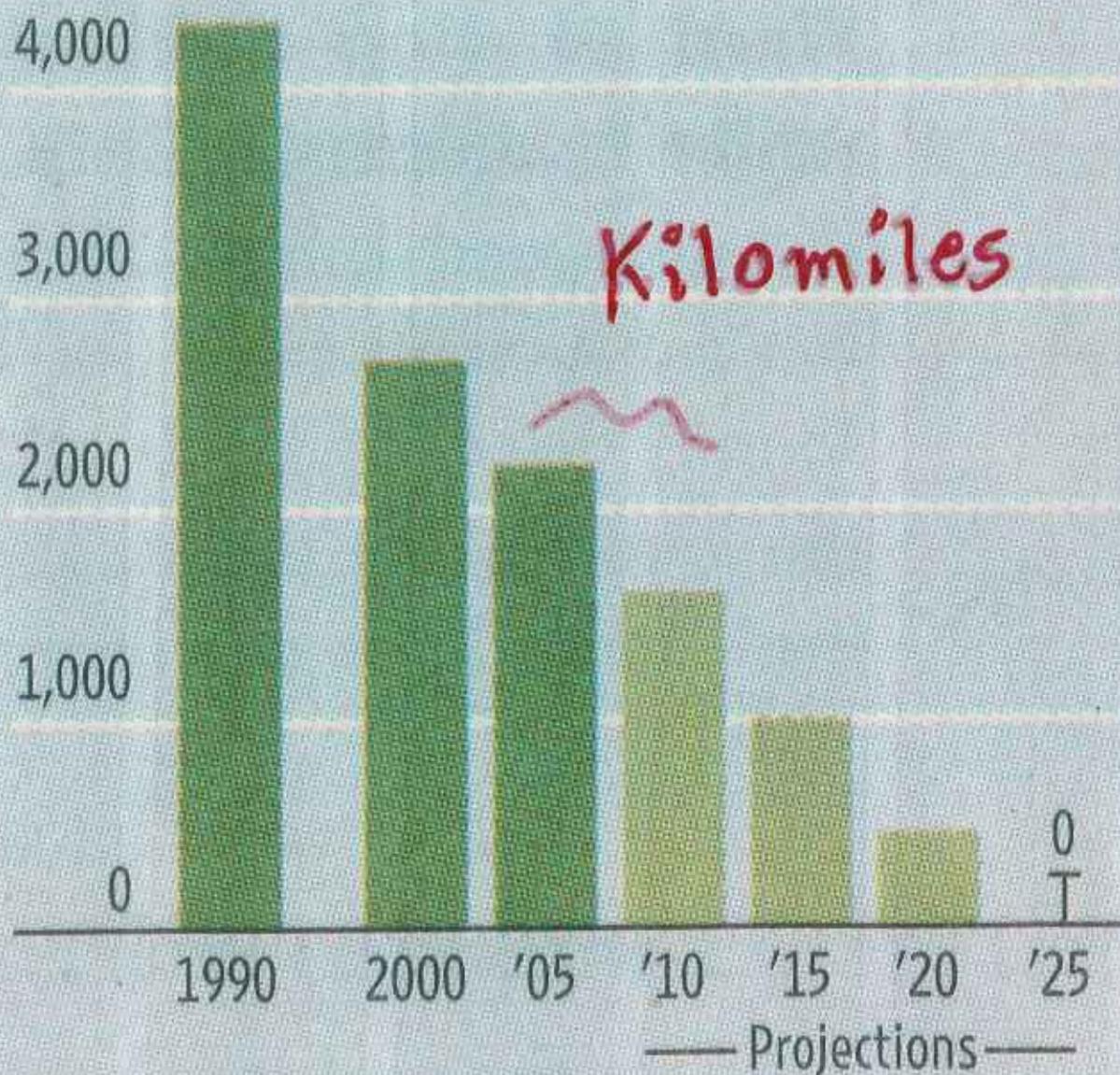
Bulk Transmission System

Hardware: Substations

- shunt capacitors
- communication equipment
 - telephone
 - microwave
 - power line carrier (PLC)
 - fiber optic
 - digital radio

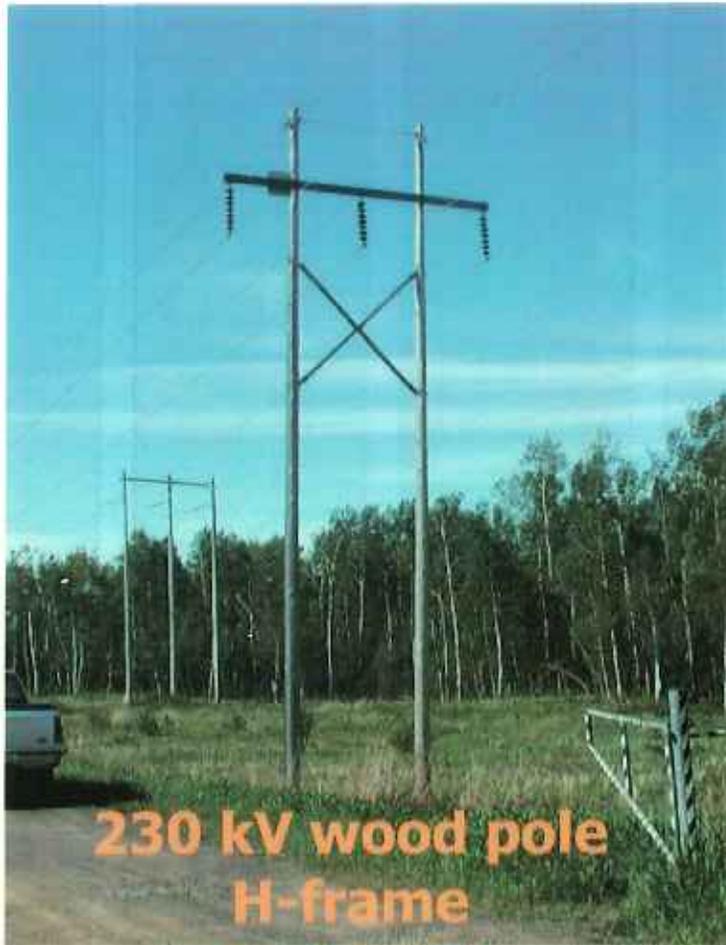
Discharged

Estimated number of circuit miles of outdated cable* in need of replacement in ConEd's network:



*Paper-insulated, lead-coated cable

Source: the company



February 11 - 13

First Class in Power Engineering
Power Systems Landscape

41

Transmission Lines: AC DC

Overhead lines: ^{230,345} 500, 765 KV AC

Underground / Undersea DC

99% lost in I^2R in USA.

corona in fog

3 ϕ wires

ground wires for lightning
 $2.6 \times 10^6 \Omega\text{-cm}$

ACSR

Al outer

$e(Al)$

Strands Iron Core

$\rho(Fe)$

Al outer

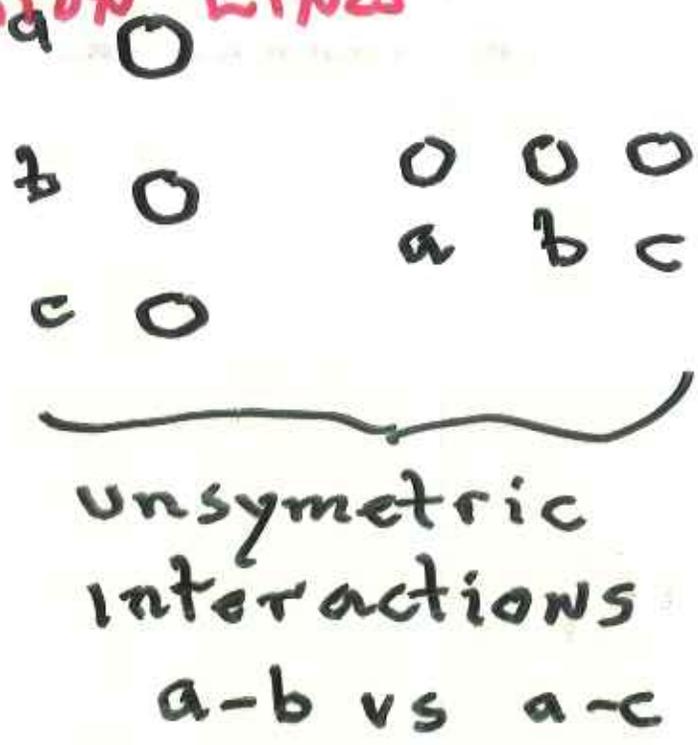
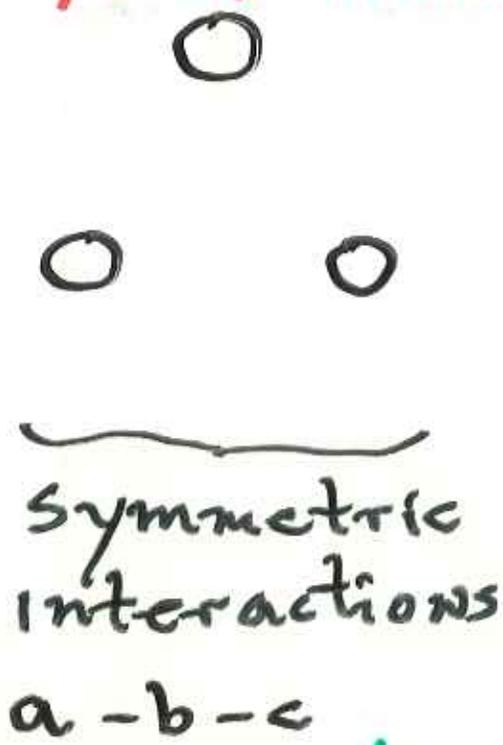
Skin Depth: $\delta = \sqrt{\frac{2}{\mu \omega \sigma}}$

$\mu(Al) = ?$

$\delta = 10 \text{ mm @ } 60 \text{ Hz} \Rightarrow ?$

I (inside wire on outside)

X of Transmission Lines



L effects Complex

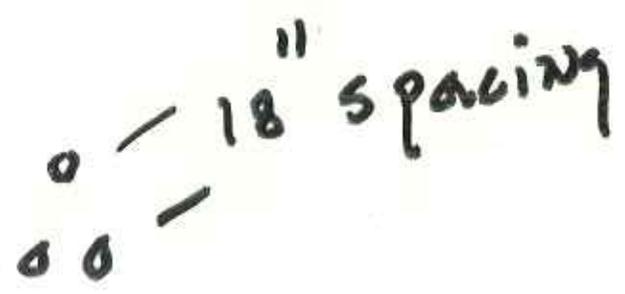
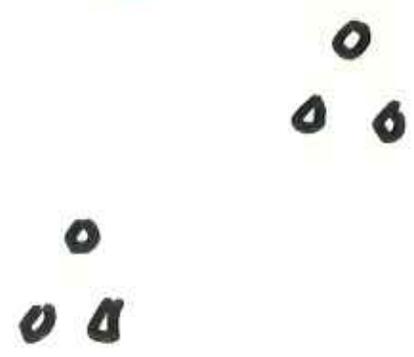
Need to transpose lines every 100 miles or get unbalanced currents

Calculate or Use Tables



difficult for ACSR!
Why?

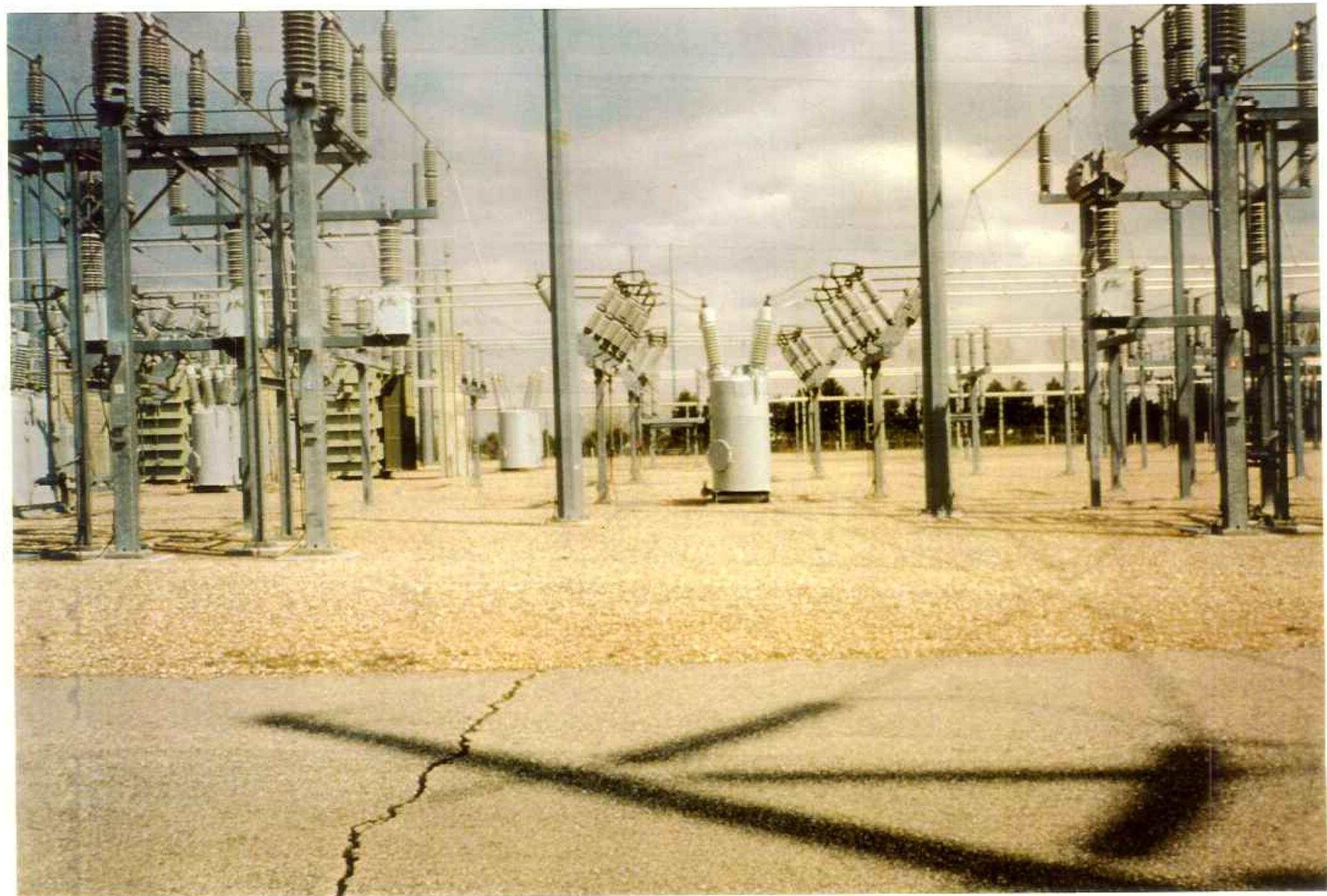
SKY WITH ground

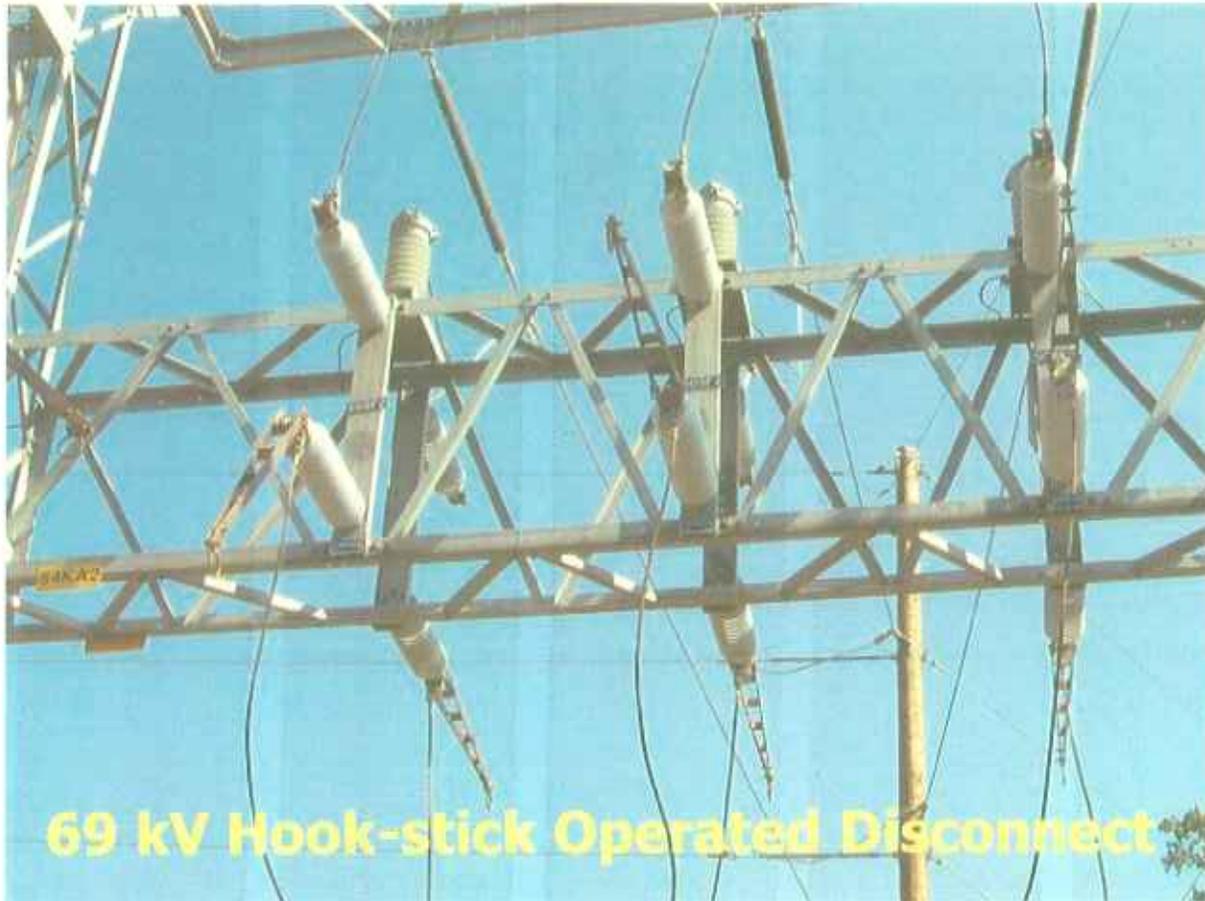


TO REPORT
PROBLEMS
CALL 1-800-455-7777

DANGER
HIGH
VOLTAGE





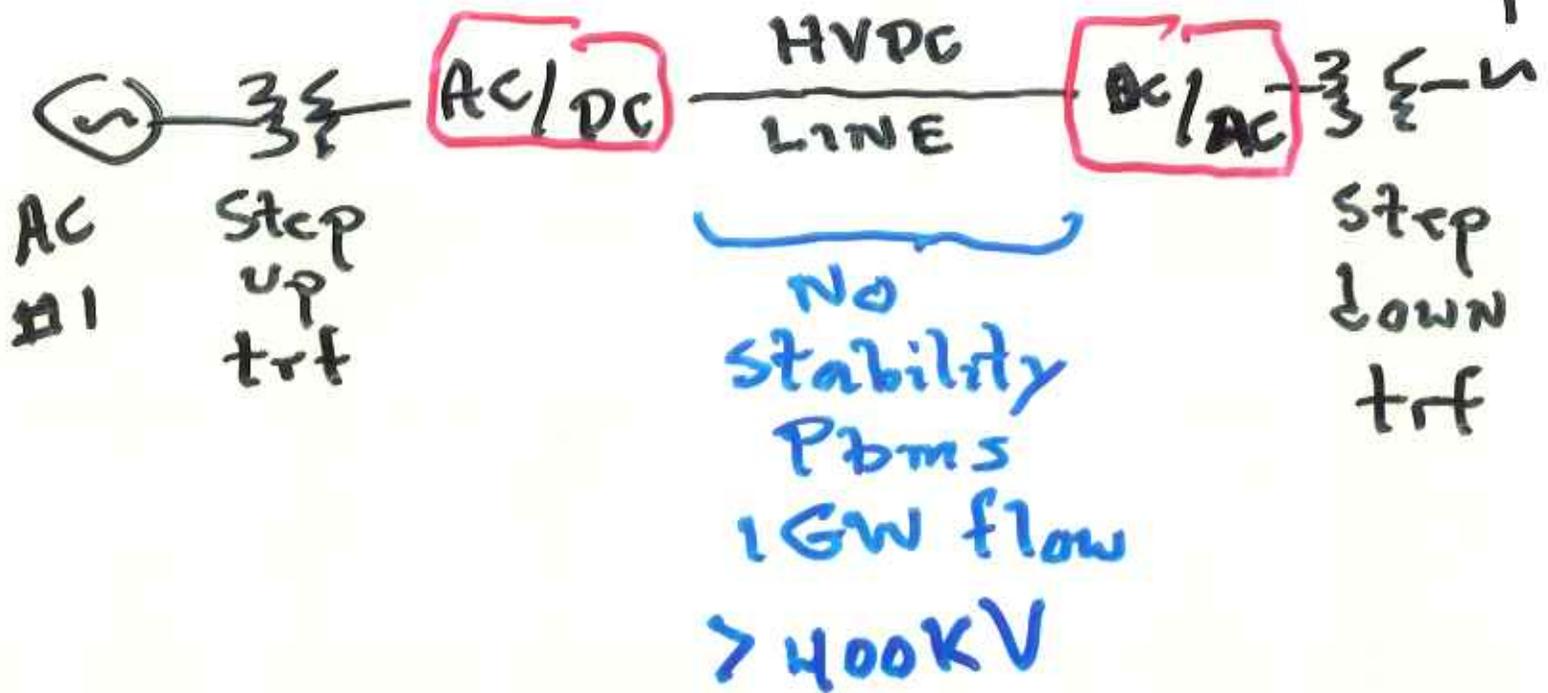


February 11 - 13

First Class in Power Engineering
Power Systems Landscape

46

HVDC Transmission



Texas buffers their AC from other grids by DC. No instability imported from other grids.

Control of power flow by

- Keep I unidirectional
- Vary V_{DC} \pm at ends

Current links use thyristors

Bulk Transmission System

Hardware: Transmission Lines

- **high voltage cable systems**
 - **oil filled (pipe type)**
 - **solid dielectric**