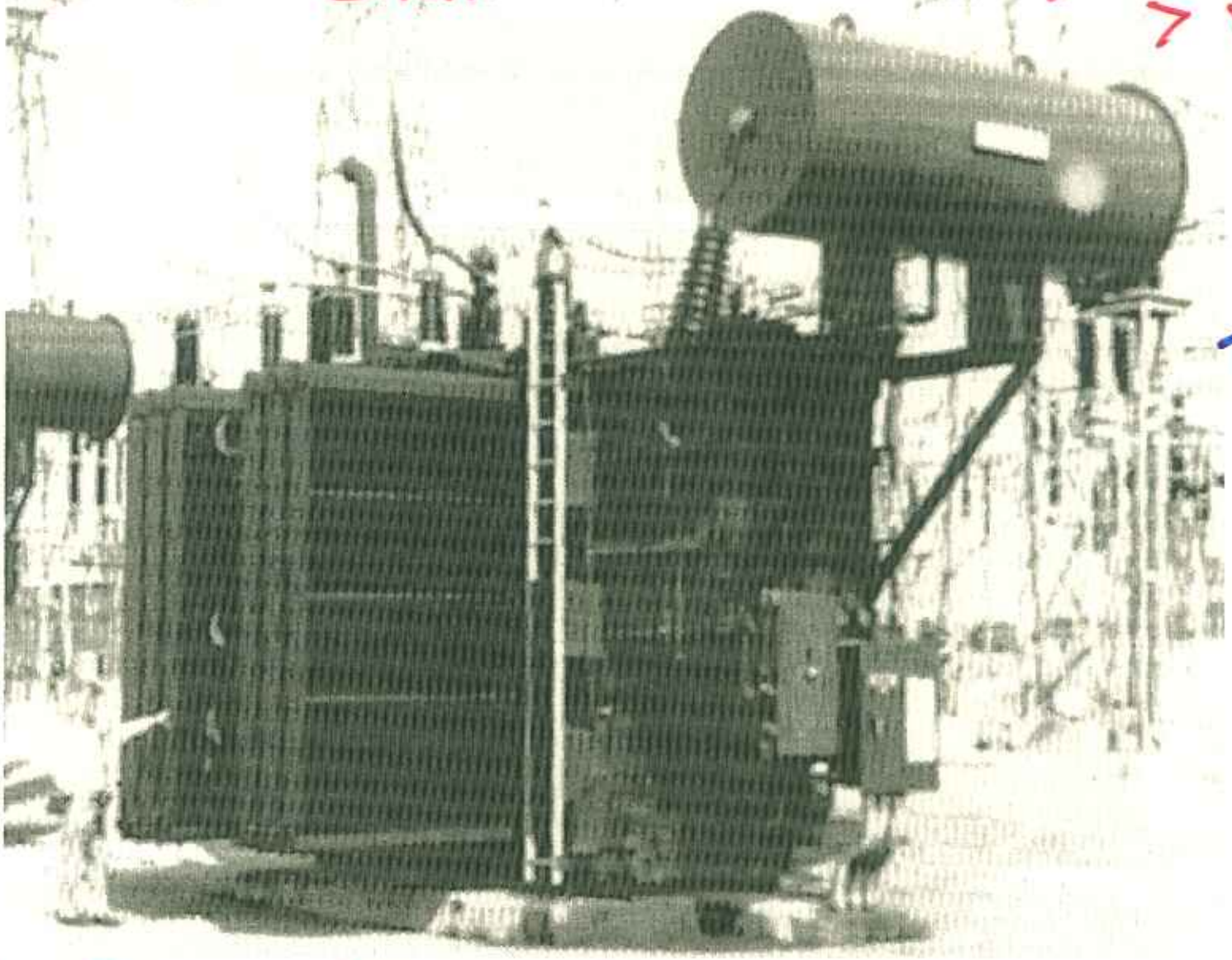
Chapter 9b Transformers

- Infrastructure Vulnerability/Lighting/Alt Energy Preaching
- Ideal vs. Real Transformer
- Homework
- Transformer Per Unit

TARGETS

No protection beyond Chain link fence } Only 10^5 transformers > 100KV



Cu Thieves

Only Protected by chain length fence

Lighting

Commercial Buildings

40% total energy use is ?

New buildings

more daylight

Windows

light pipes

CFL and LED's

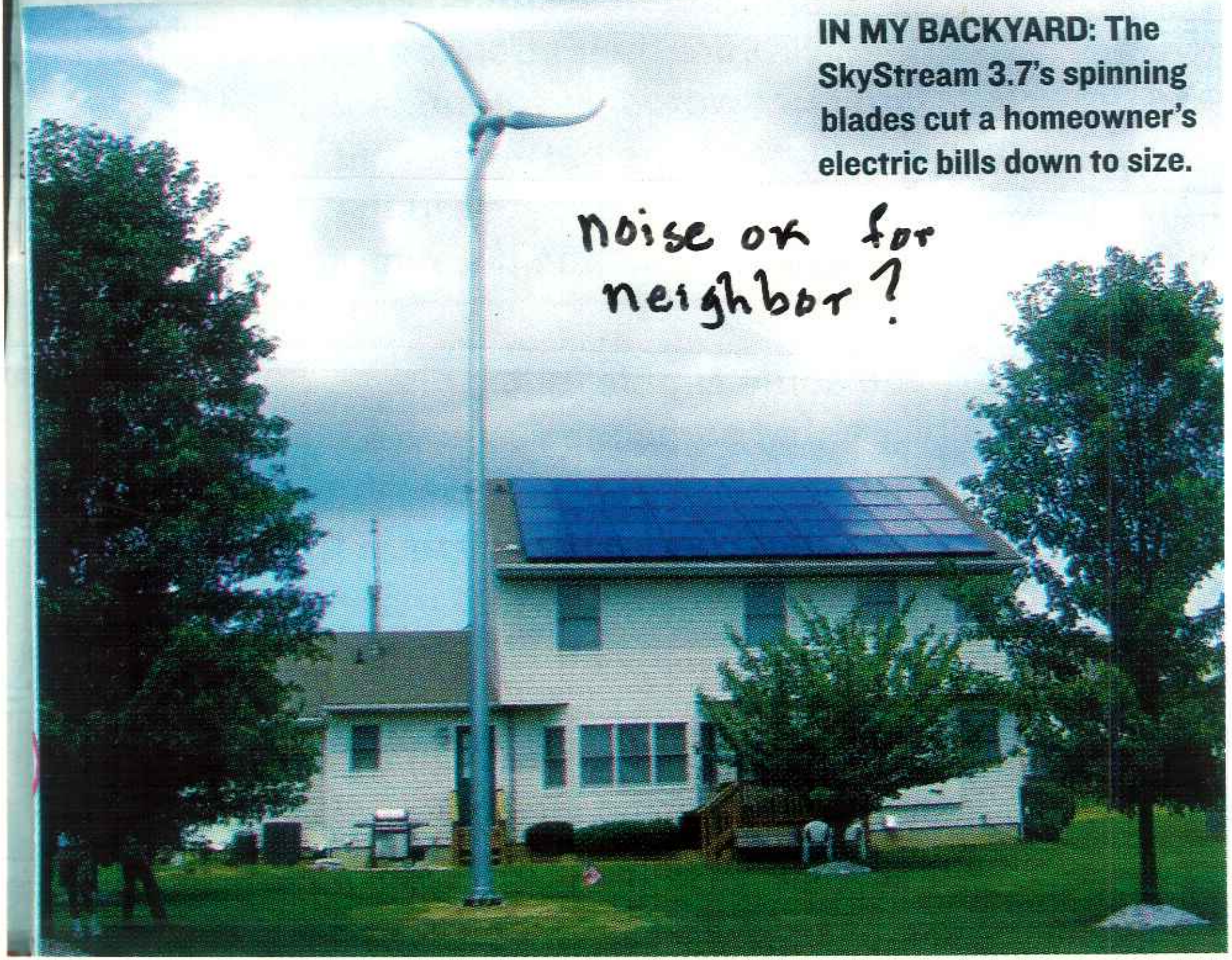
Federal Law

100 W incandesent

illegal 2012

75 W 2013

60 W 2014
40



IN MY BACKYARD: The SkyStream 3.7's spinning blades cut a homeowner's electric bills down to size.

noise ok for neighbor?

Smart Meters : Texas, Calif, Colo

① Measure P(t)

② Communicate two way

consumer devices ⟷ Power company

e.g. Tendril Networks Boulder Colo

home energy display

Controllers

Communication Protocols

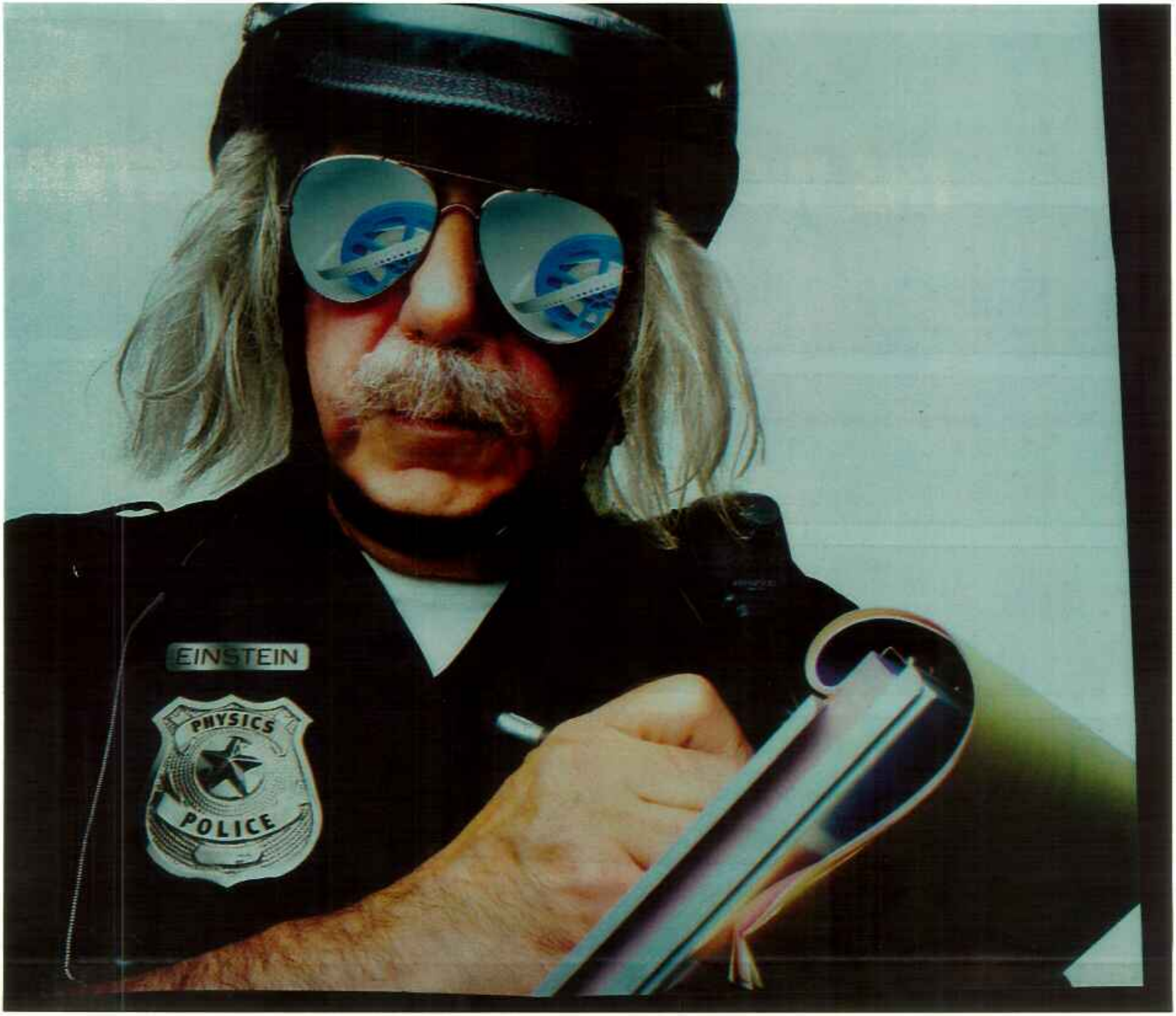
① Zig Bee non-profit — Intron, Tendril, Greenbox Technology

② Z-wave by Zensys — Intel, Levitron, Universal Electronics

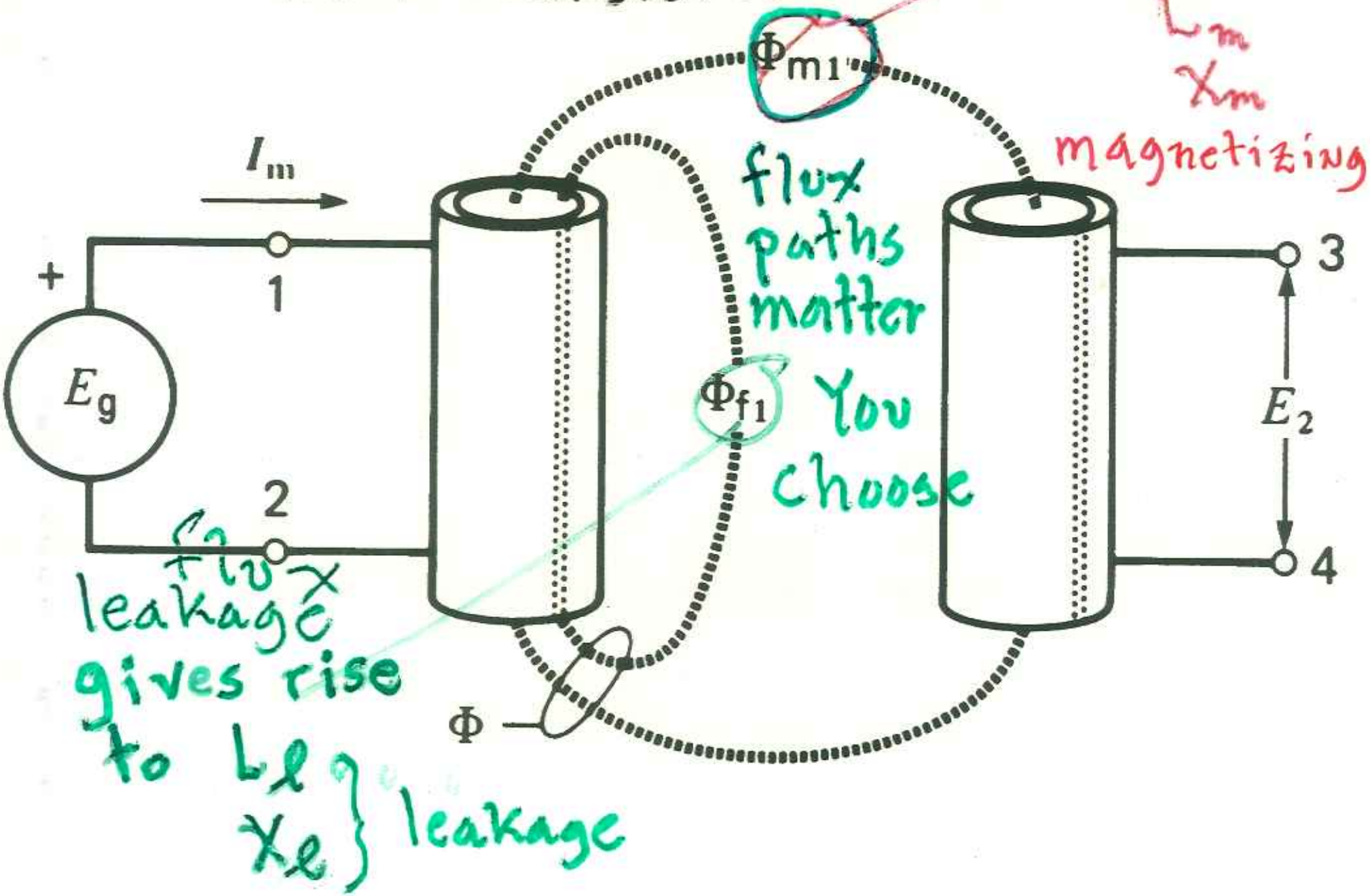
Goal program home devices to use less power

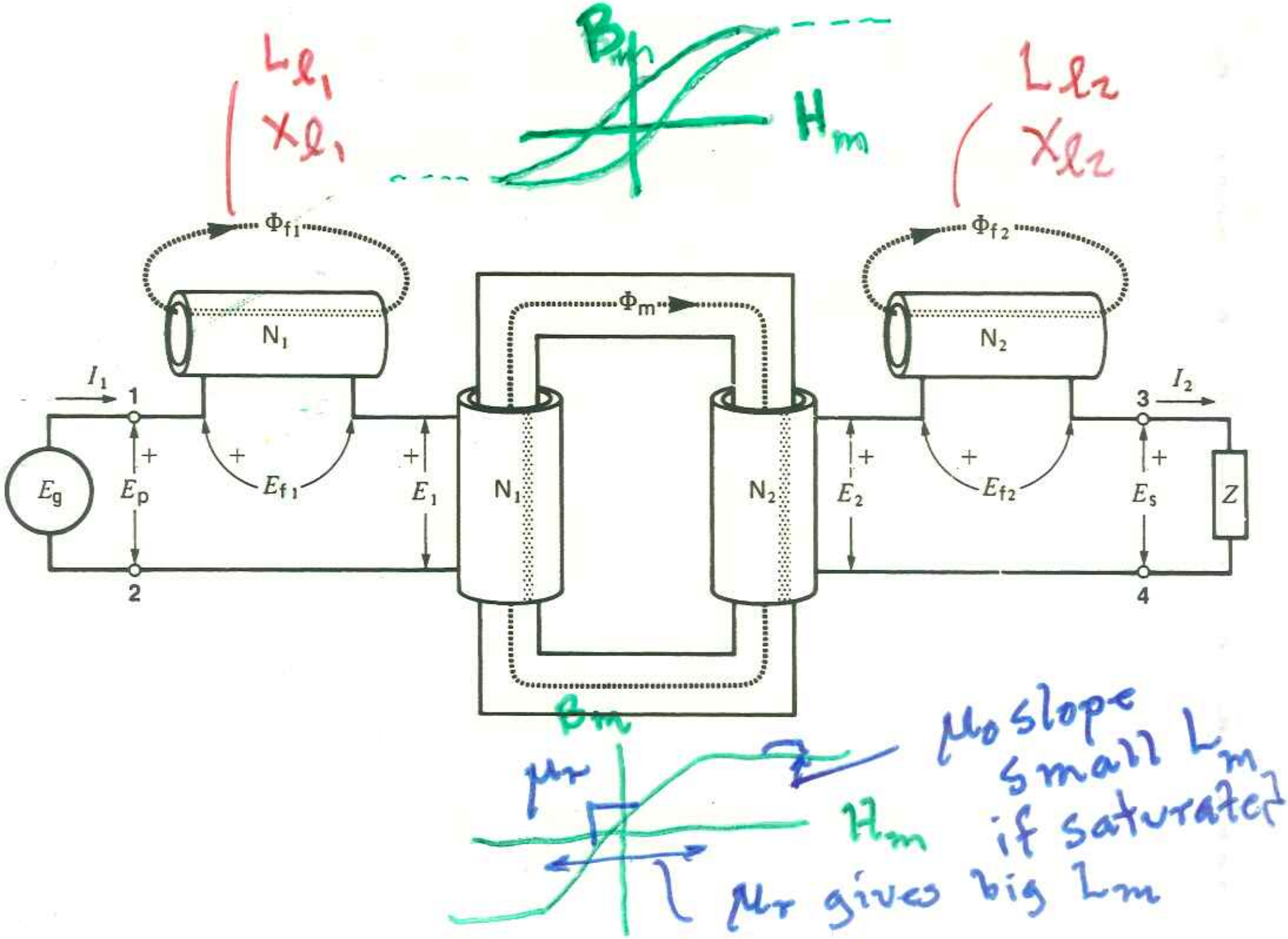
cheaper power

Gridpoint Inc. diagnose & recommend


EINSTEIN
PHYSICS
POLICE

Real Transformer

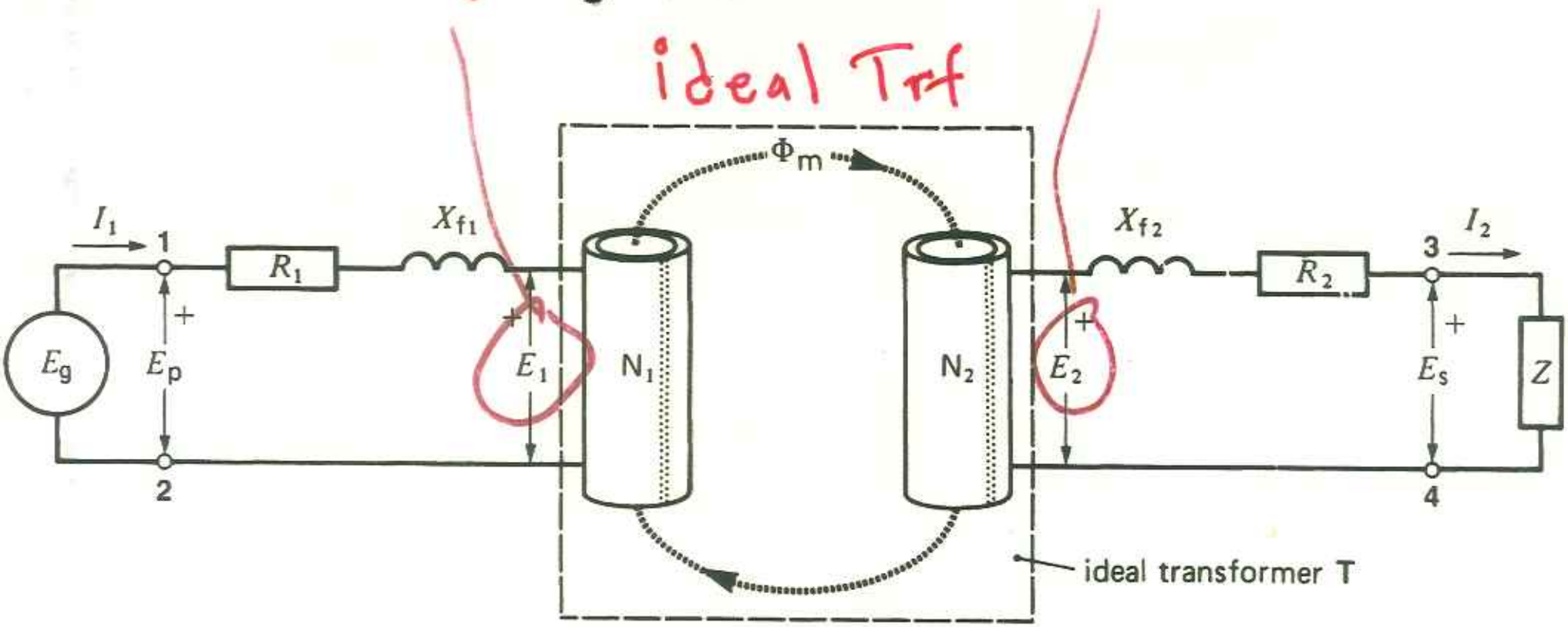



$L_{\ell 1}$
$X_{\ell 1}$
B_m
H_m
$L_{\ell 2}$
$X_{\ell 2}$
Φ_{f1}
Φ_m
Φ_{f2}
N_1
N_2
I_1
I_2
1
2
3
4
E_g
E_p
E_{f1}
E_1
E_2
E_{f2}
E_s
Z
B_m
μ_r
H_m
μ_0 slope
small L_m
if saturated
μ_r gives big L_m

Role of X_ℓ & wire R

$E_1 = E_g - I_1(Z_1)$

$E_2 = E_s + I_2(Z_2)$



Keep

$N_1 i_1 = N_2 i_2$

$\frac{E_1}{N_1} = \frac{E_2}{N_2}$

$Z_1^{eff} = \left(\frac{N_1}{N_2}\right)^2 Z_2$

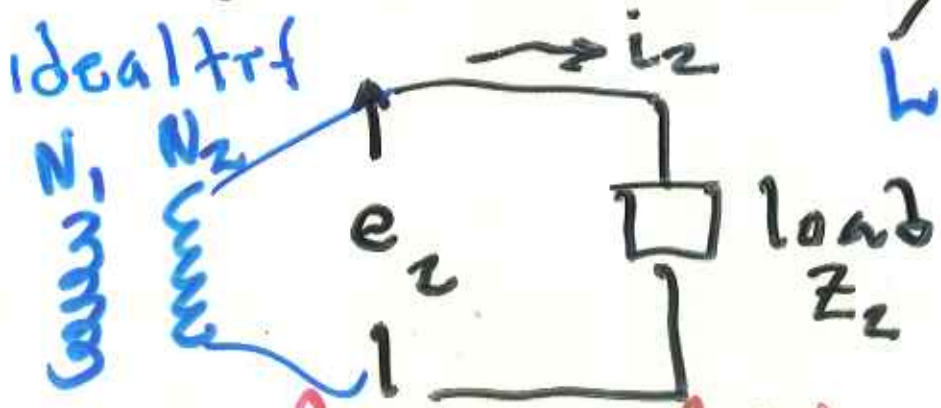
$$L_m \equiv \frac{N_p^2}{\mathcal{R}_{core}} \qquad \mathcal{R}_{core} = \frac{l_c}{\mu_c A_c}$$

$$\mu_c \to \infty \to \mathcal{R}_c \to 0 \to L_m = \infty$$

For finite μ_c $|N_p|$ matters to L_m

Want L_m large $\Rightarrow$ $|N_p|$ matters

Load in secondary i_2



Load sets i_2

$$i_2 = \frac{e_2}{Z_2}$$

Amperes Law

Causes Amp-turns $N_2 i_2$

equals $\Rightarrow i_1' = \frac{i_2 N_2}{N_1}$

$N_1 i_2'$ IN primary

$$i_2'(\text{primary}) = \frac{N_2}{N_1} i_2(\text{load})$$

Input i has two parts!

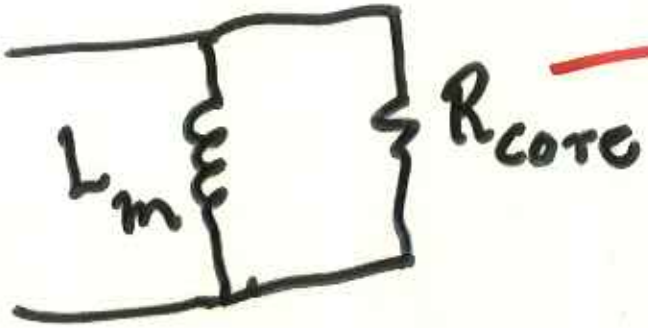
$$i_{IN}(\text{total}) = i_2' + i_m$$

"So called" ideal

$I_1 N_1 = I_2 N_2$ if neglect L_m

Add R_1 (wire) to L_{ℓ_1}
R_2 (wire) to L_{ℓ_2} } real I^2R loss

Account for: (eddy current, hysteresis) losses



another effective $I^2 R_{eff}$ loss

Test for all components

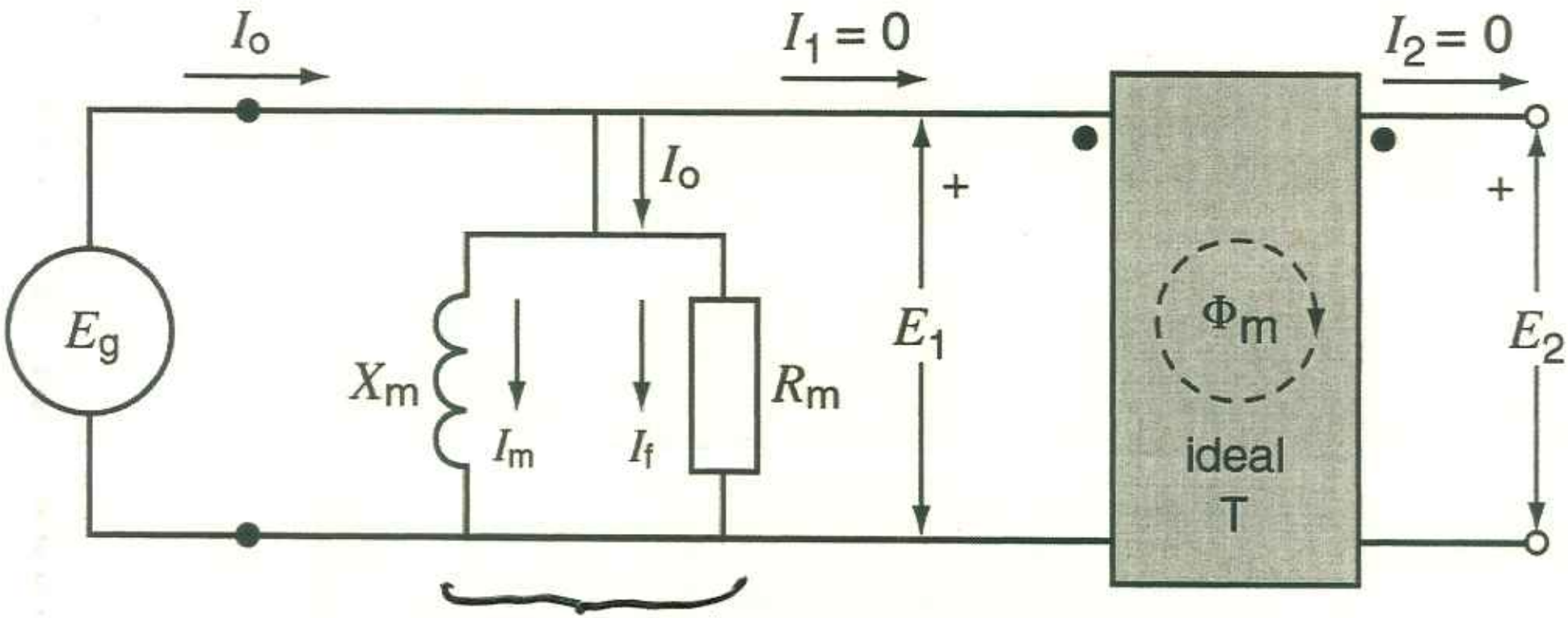
Short Secondary

Open Secondary

<u>Lossless case</u>

$$Z_{primary} = Z_{secondary}\left(\frac{N_1}{N_2}\right)^2$$

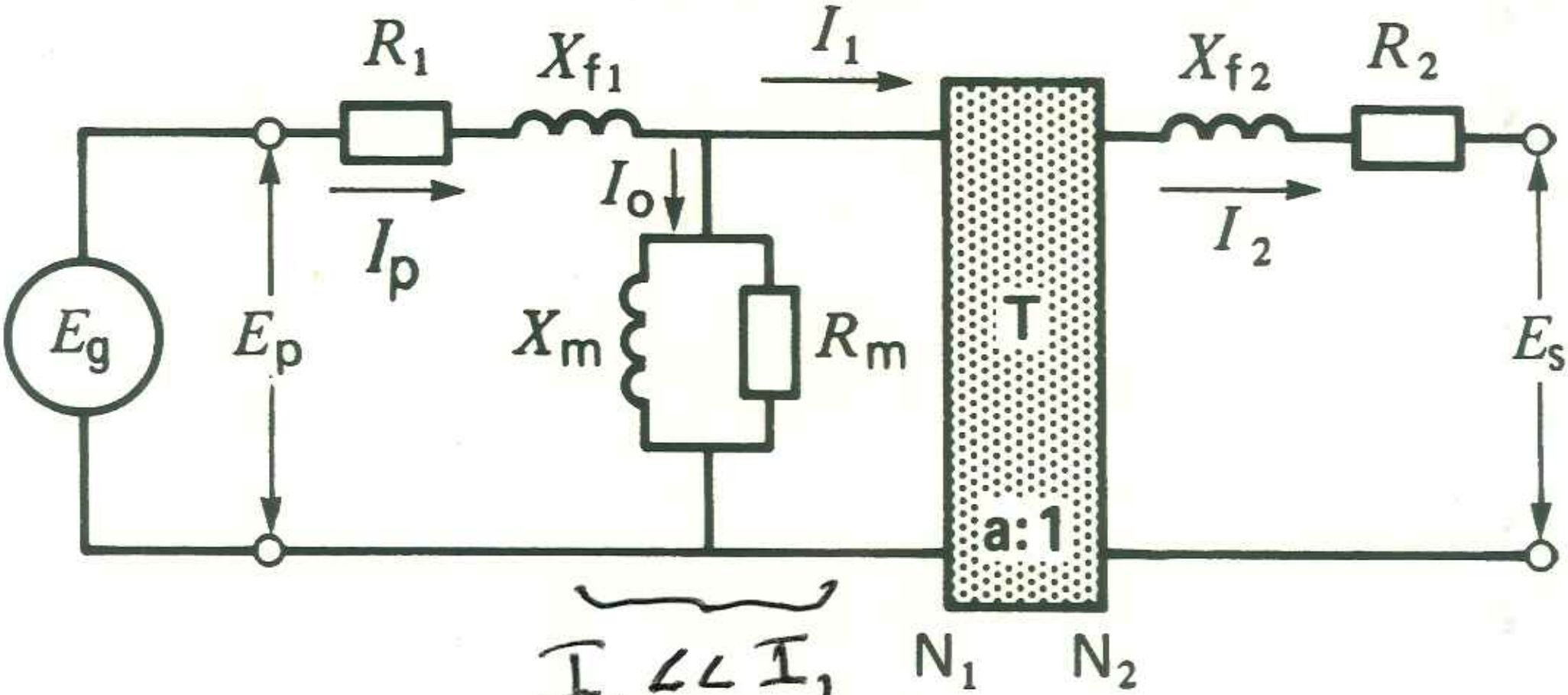
Measure X_m, R_m by
" ? " Test



Only losses
for " ? "
condition

Measure X_l R_{wire}

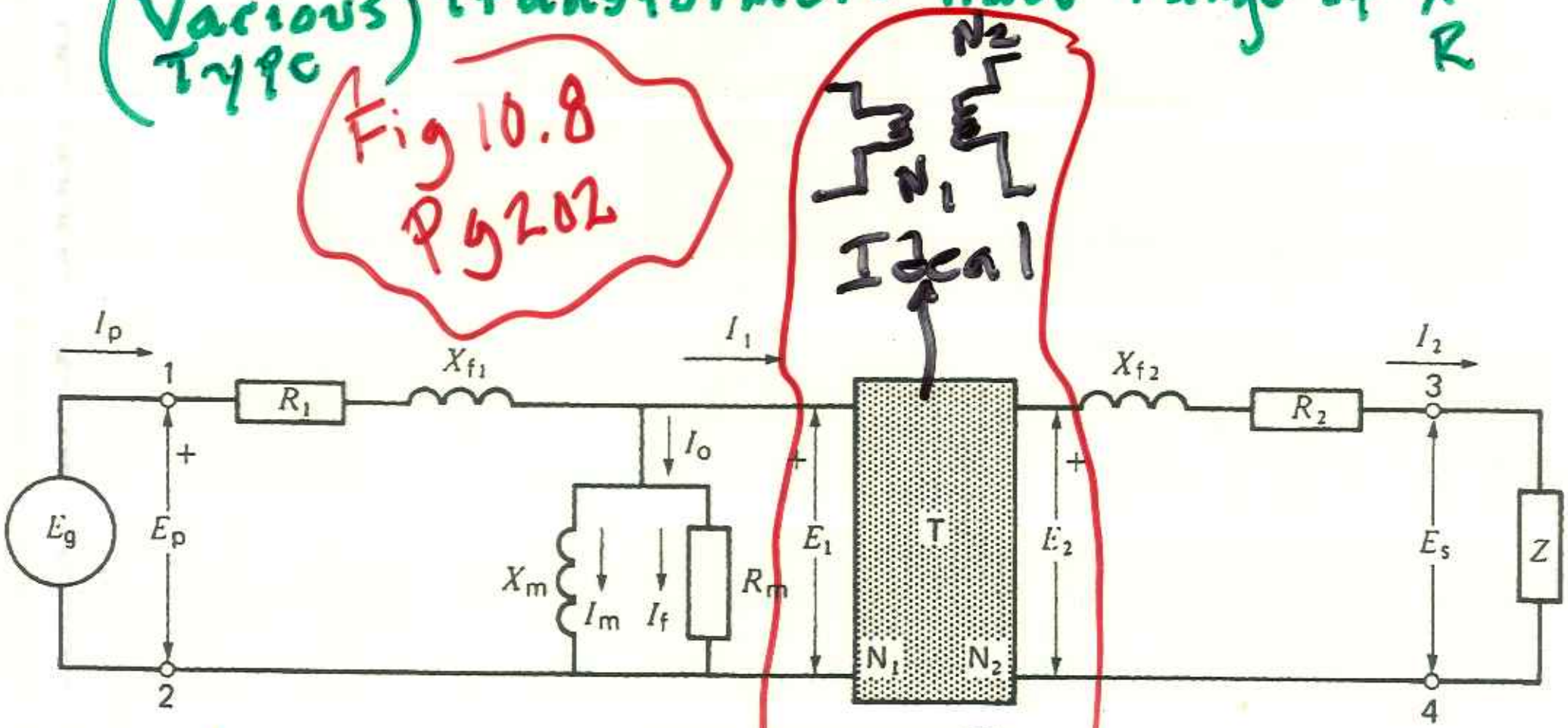
by " ? " condition



$I_o << I_1$ for " ? " condition

(Various Type) Transformers have range of $\frac{X}{R}$

Fig 10.8
Pg 202

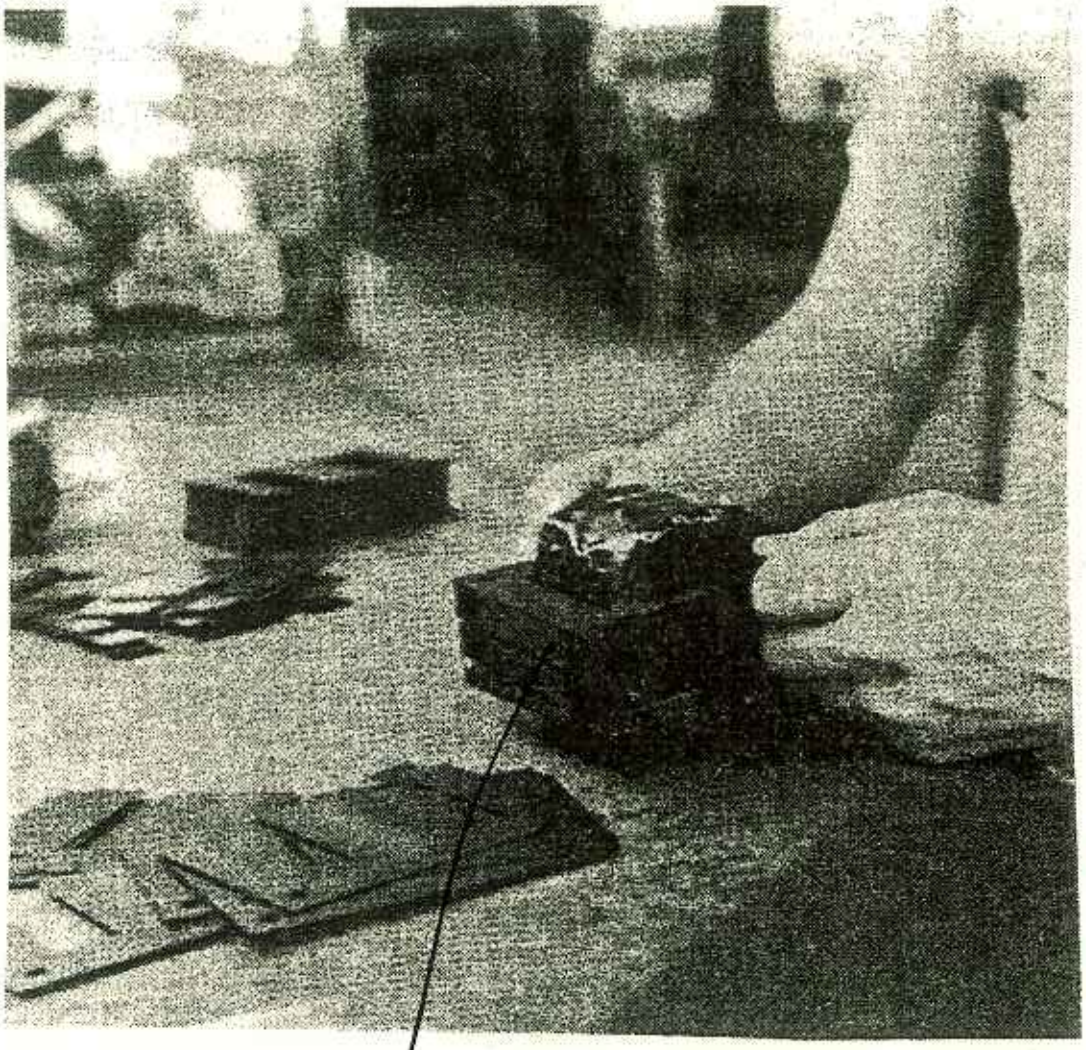


$$\frac{E_1}{N_1} = \frac{E_2}{N_2}$$

$$\frac{I_2}{N_1} = \frac{I_1}{N_2}$$

"Lets go on a transformer tour"

Small Distribution Transformers < KW



You Choose

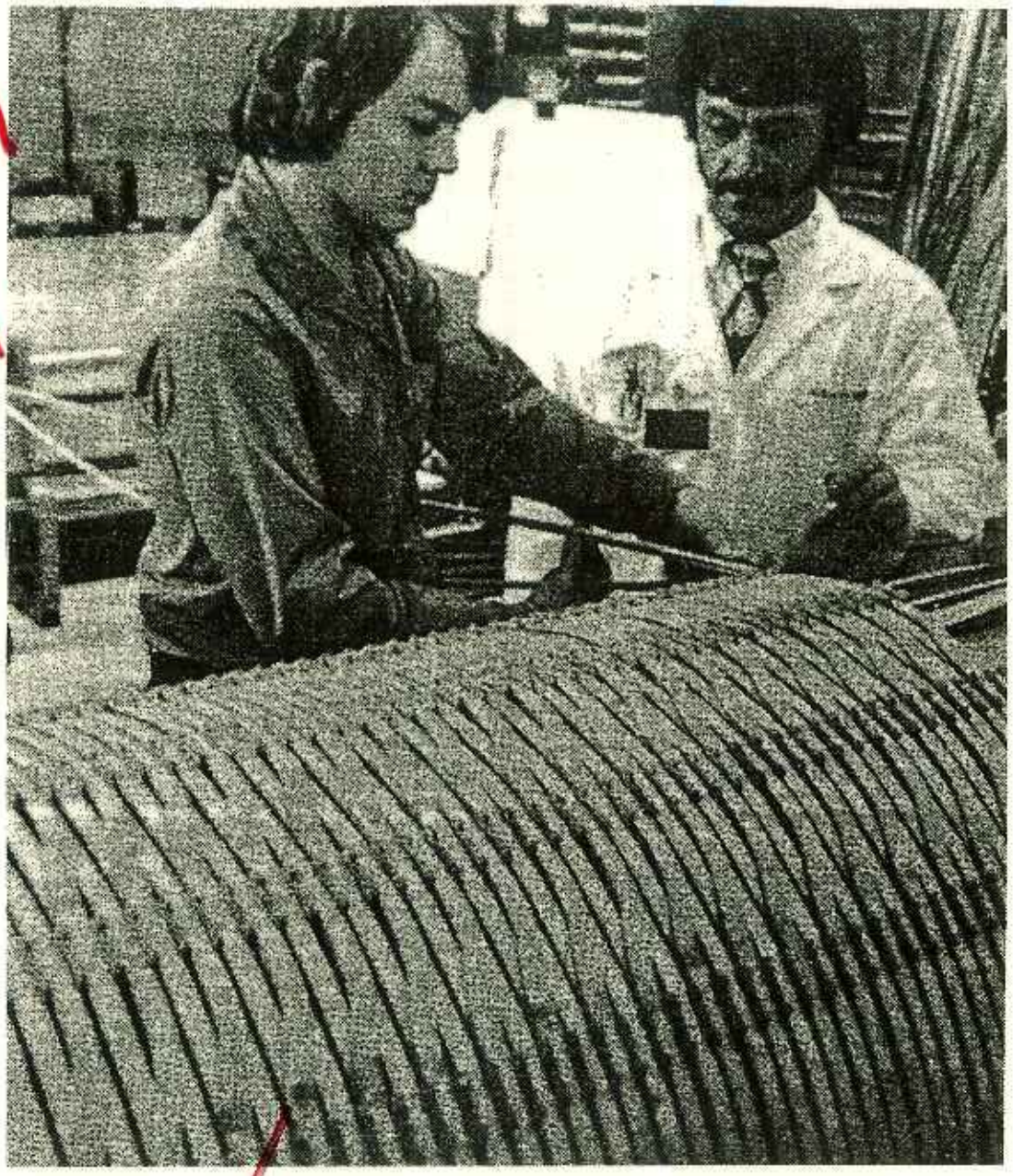
L_ℓ is parasitic Size

L_m is $= \frac{N^2}{R_{core}}$ Size?

Lets follow transformers to generator

Large Substation Trf
128KV ← large amount of insulation wire to core

Fig 10.9 c Pg 204



200 – 300A ⇒ Large diameter wires
often not

$S = 1.3\ GVA$

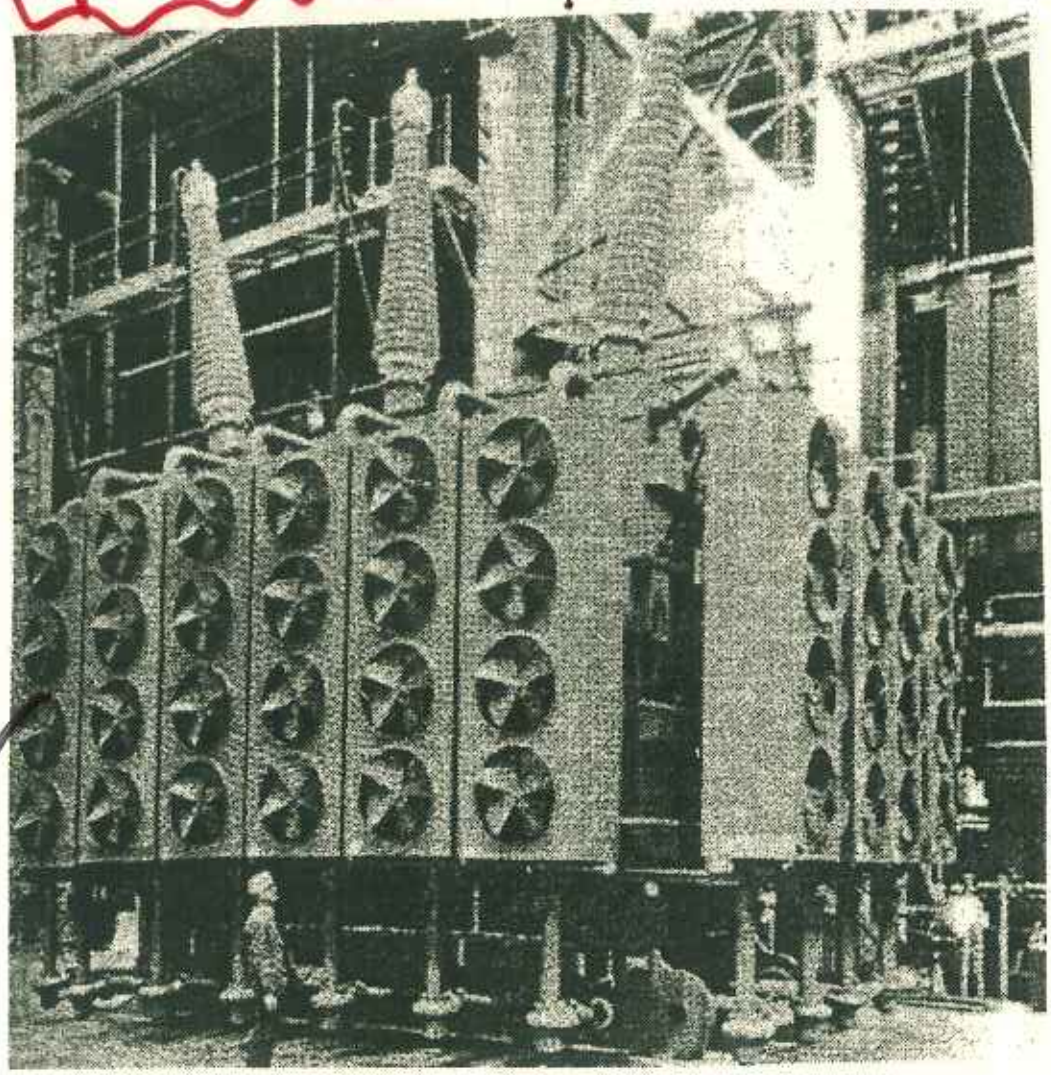
$V \rightarrow 24.5\ KV / 345\ KV$ } Big Trf

A.C. GEN $I = ?$

A.C. Transmission Line $I = ?$

Fig 10.18 pg 209

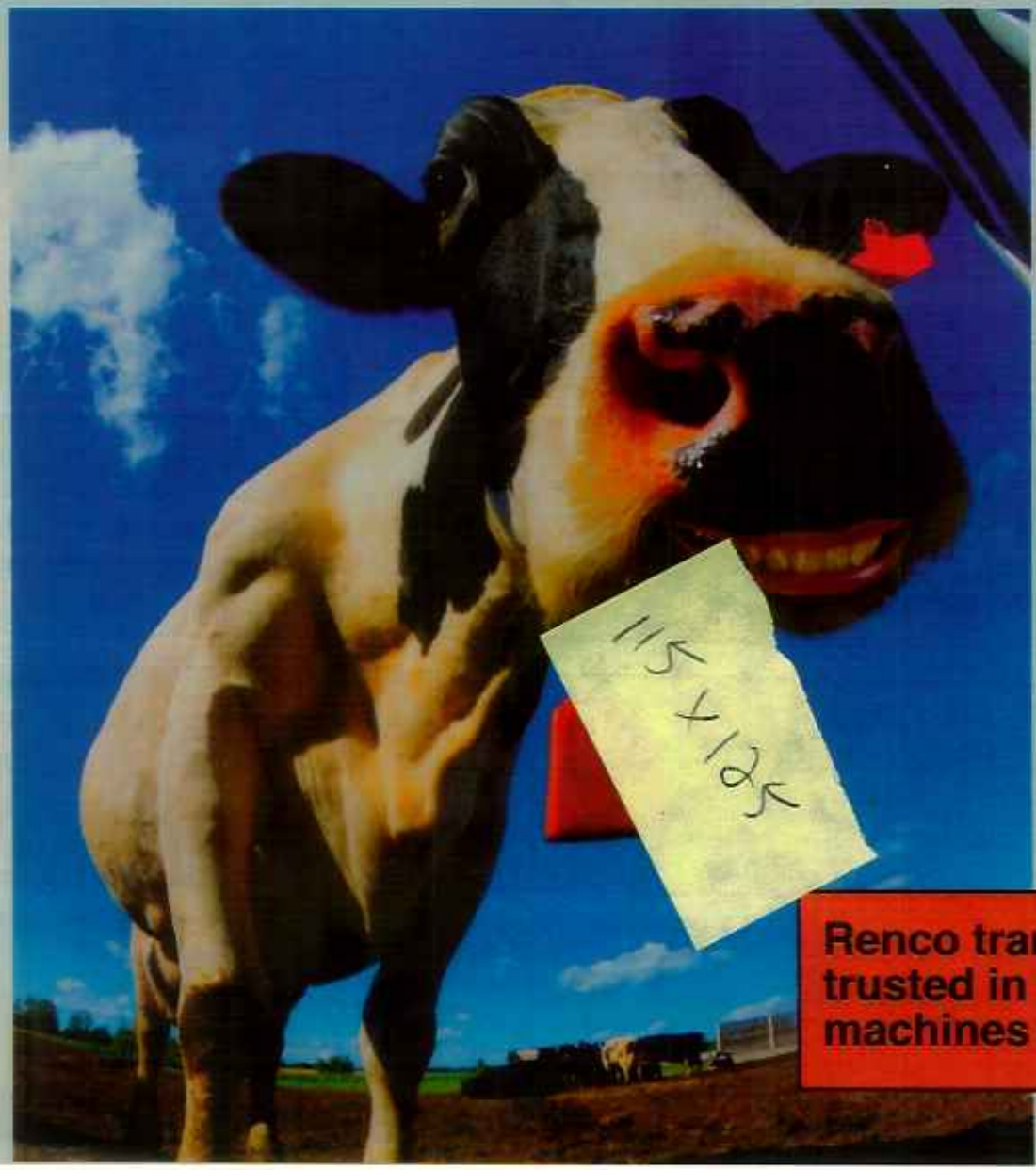
30 kt to fill oil in



Air flow cools H_2O

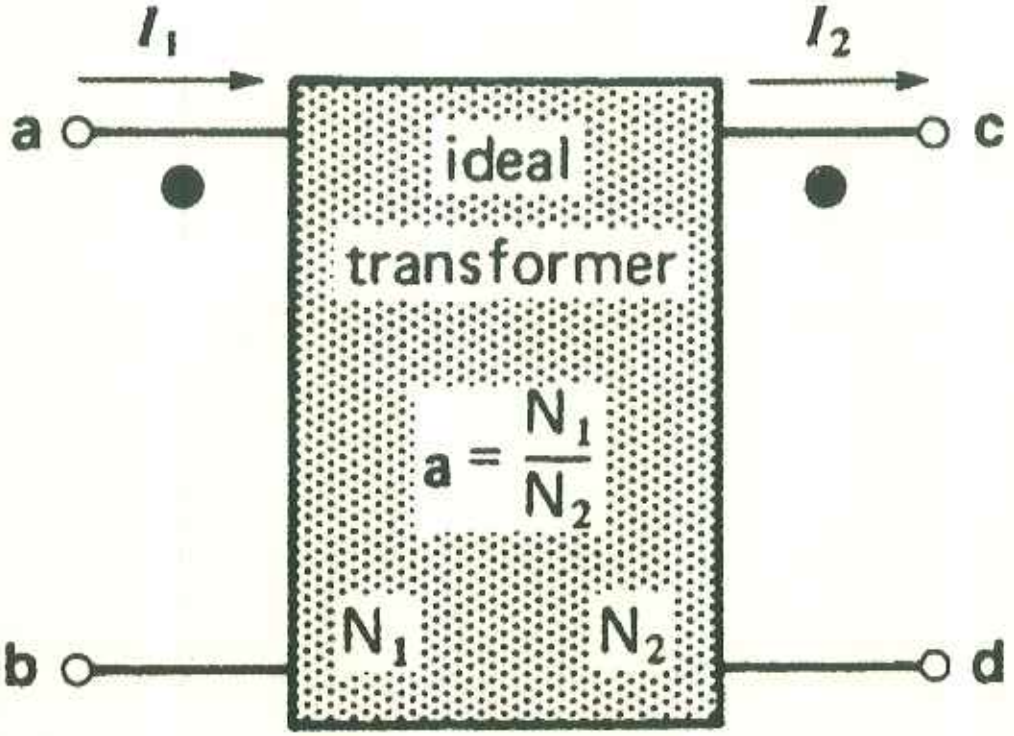
H_2O flow cools mineral oil in trf

Renco's quality transformers will make you smile

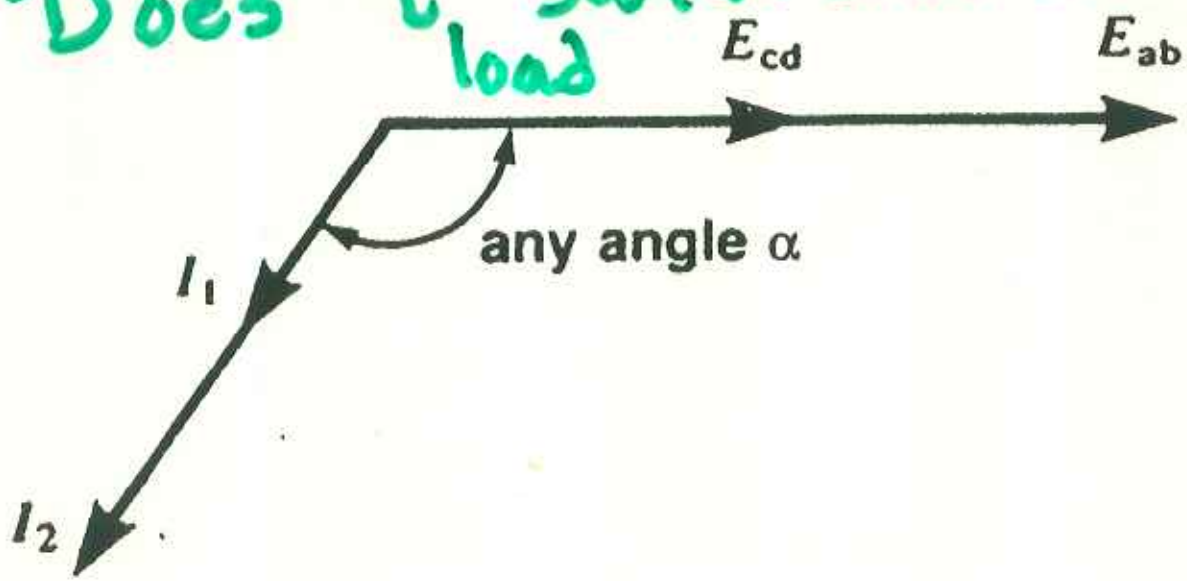


Renco transformers trusted in milking machines

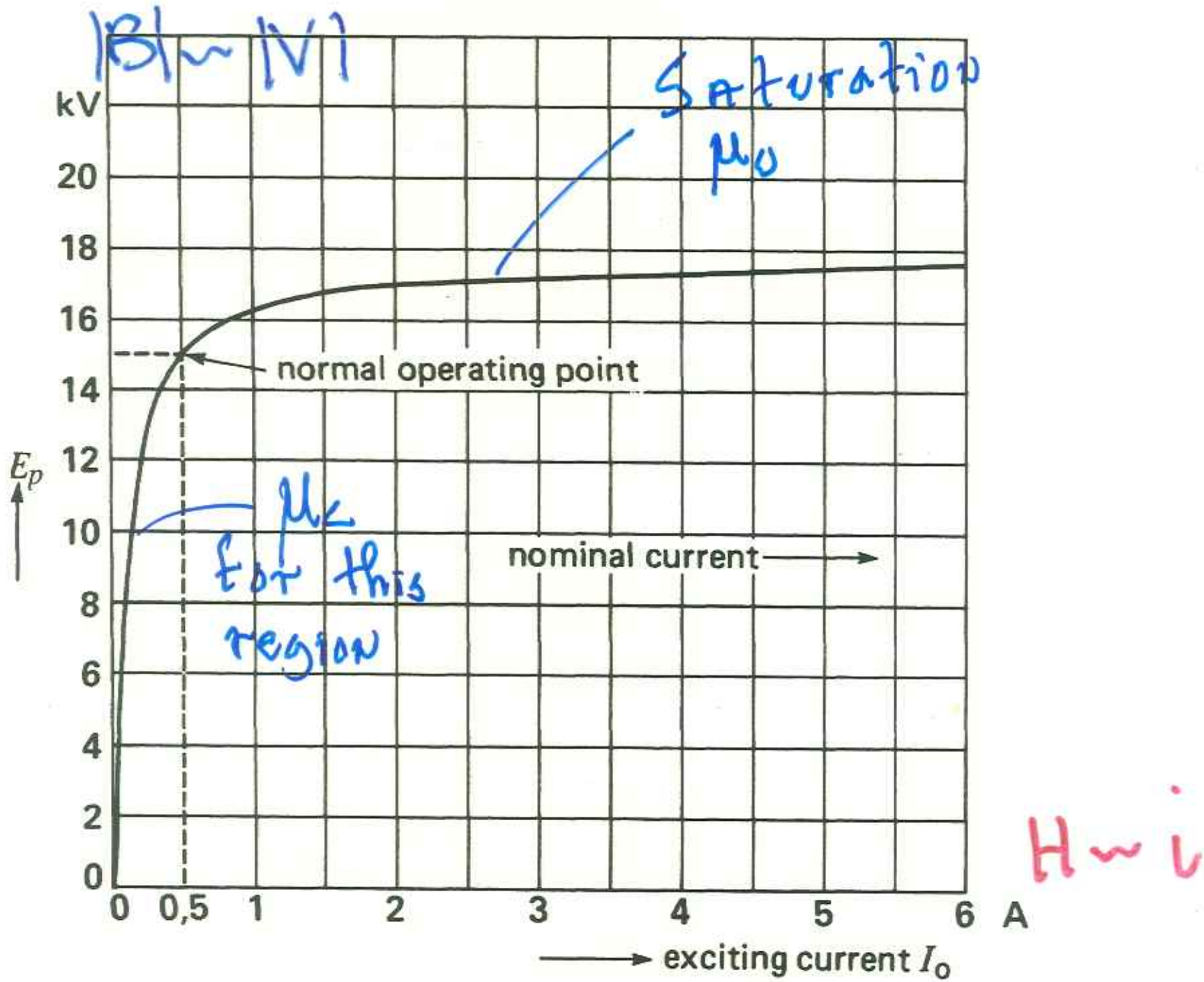
011

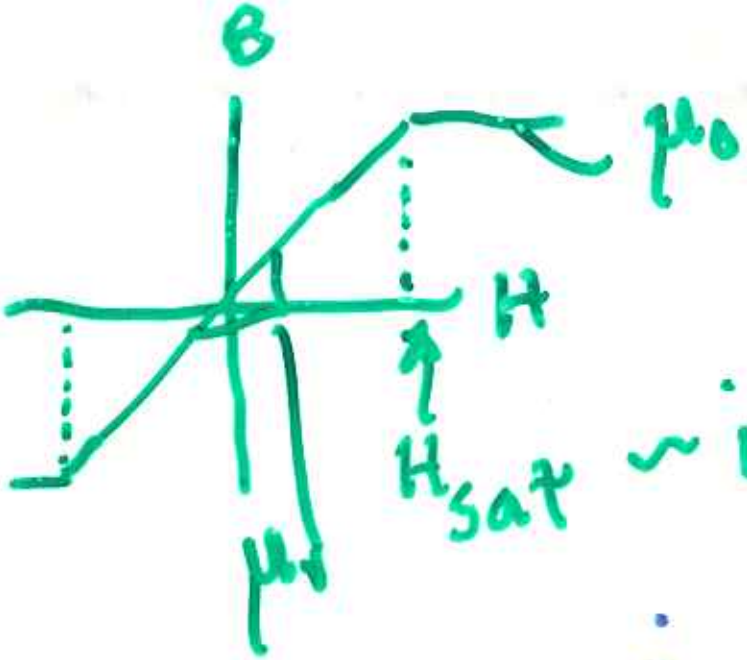


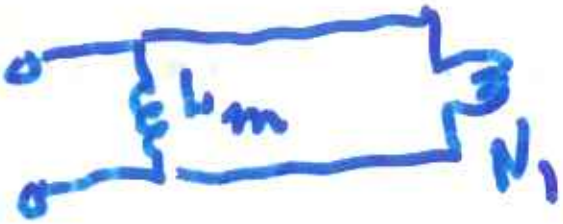
Does i_{load} saturate core?



What saturates a core?


|B| ~ |V|
Saturation
μ_0
kV
20
18
16
14
12
10
8
6
4
2
0
E_p
normal operating point
μ_r
for this region
nominal current
0
0,5
1
2
3
4
5
6
A
exciting current I_0
H ~ i

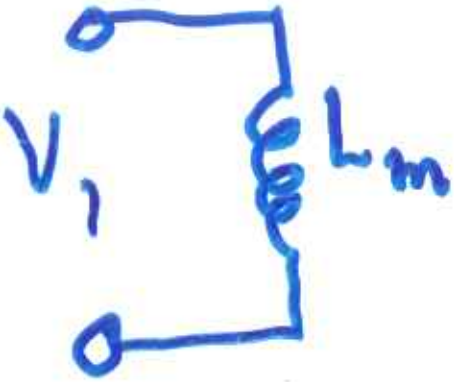




$\sim i_{sat}$

V-sec saturate

$$i_{L_m} = \left[\frac{V_1}{L_m}\right] dt$$



$i_{L_m} > i_{sat}$

Saturation occurs!

$\mu_r \rightarrow \mu_0 \longrightarrow L_m$ falls by $\frac{\mu_r}{\mu_0}$ causes:

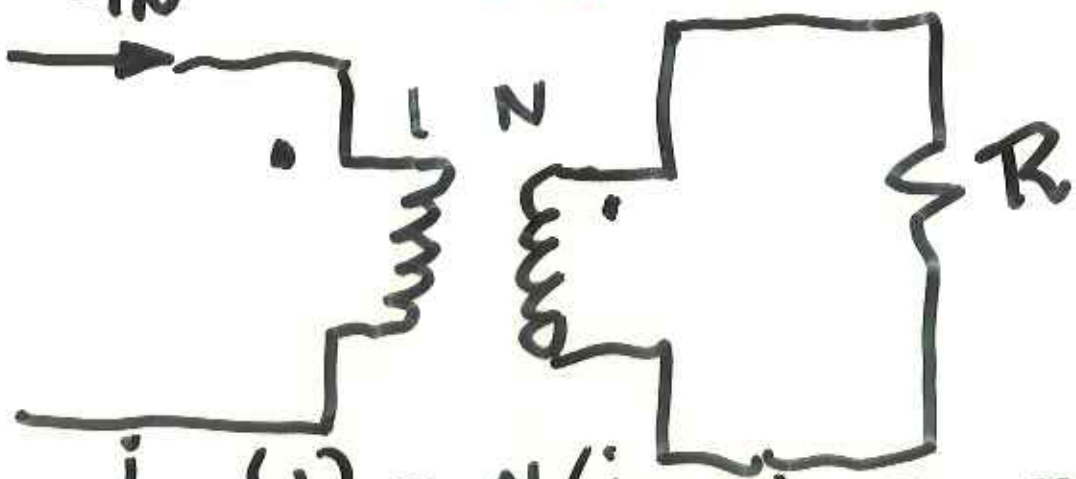
Short across V_1

V across $N_1 \rightarrow 0$ ☹

Trf becomes short

$i_{1N} \longrightarrow \infty$

C.T. $\rightarrow i_{out} \approx \frac{i_{IN}}{N}$



$i_{IN}(1) \approx N(i_{out})$ no net mmf

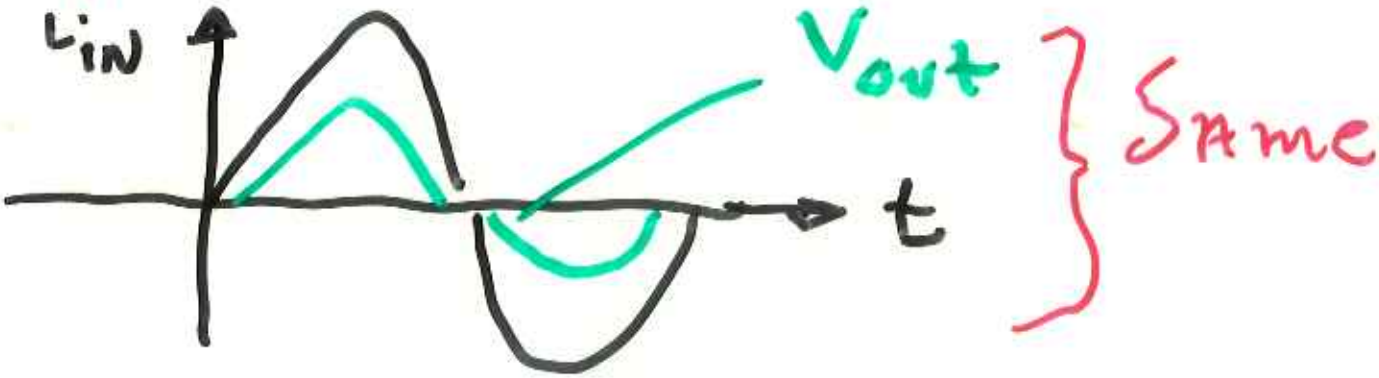
$V_{out} = i_{out} R_{out}$

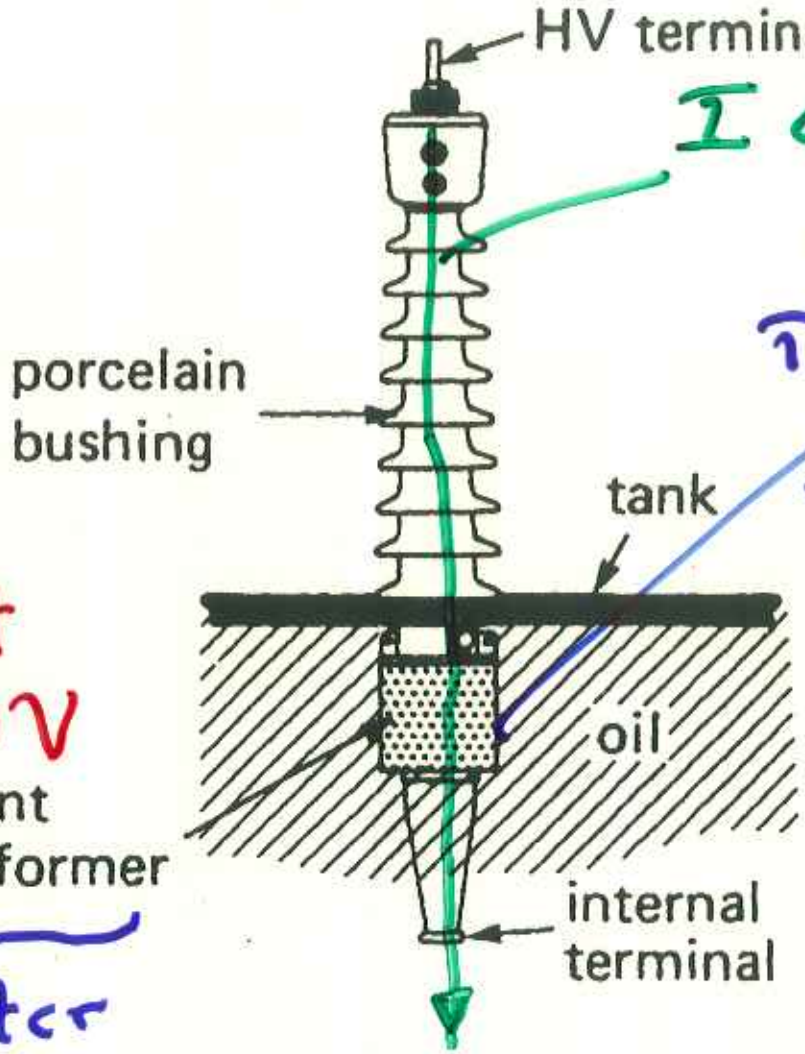
Given range

choose R_{out} to give $V_{out} \sim I_{IN}$

What if $R \rightarrow \infty$

open circuit CT ?





I at HV

Use Torroid core "around" wire carrying i

i at low V

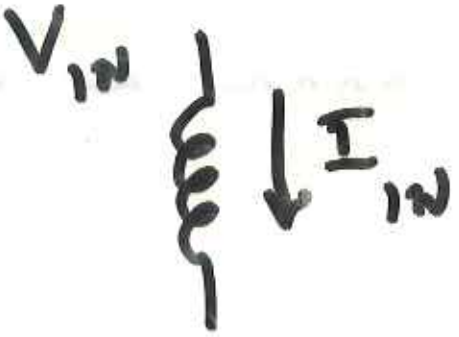
current transformer

better use V(standoff) >> V (max) line

or ?

Low voltage terminal is usually "shorted", $Z_L \to 0$

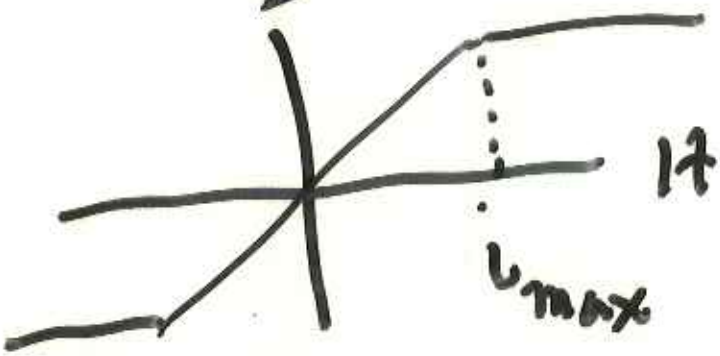
Next simple CT #5



$$V_L = L\frac{di_L}{dt}$$ } open secondary only L_m

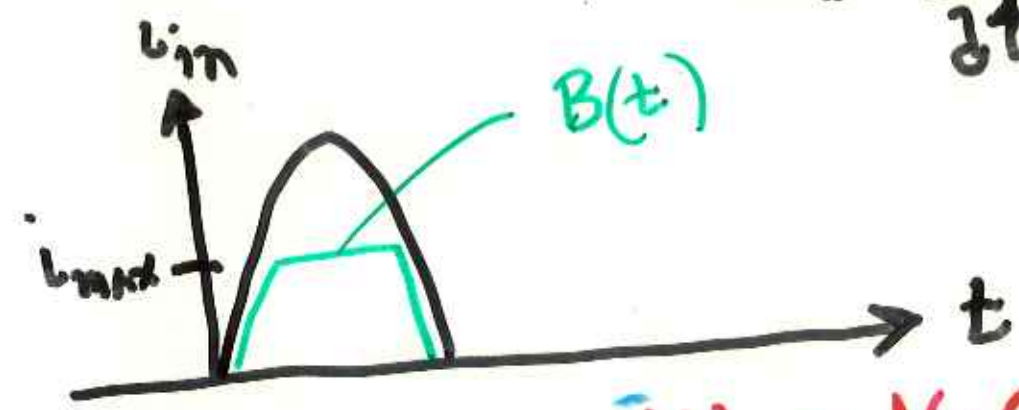
$$\int \frac{V_L\,dt}{L} \rightarrow i(t)$$

$B \sim V$

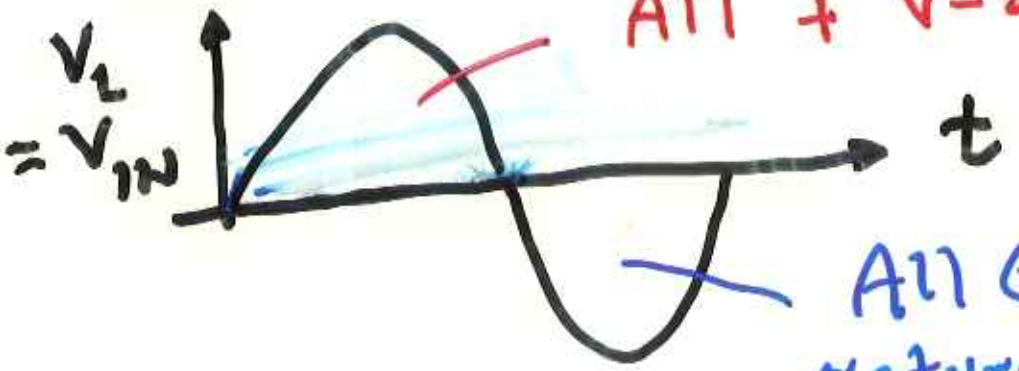


$H \sim i$ } $i > i_{max}$ B flatlines

$$\Rightarrow \frac{dB}{dt} = 0$$

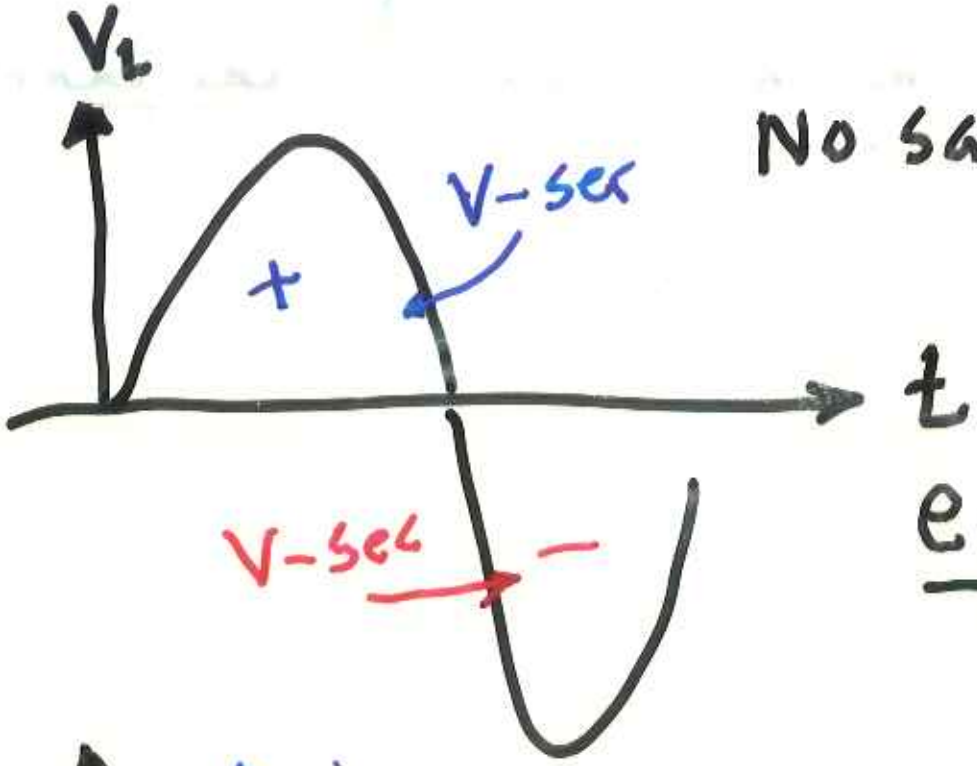


All + V-sec } drives i + Always



All ⊖ V-sec returns i to zero.

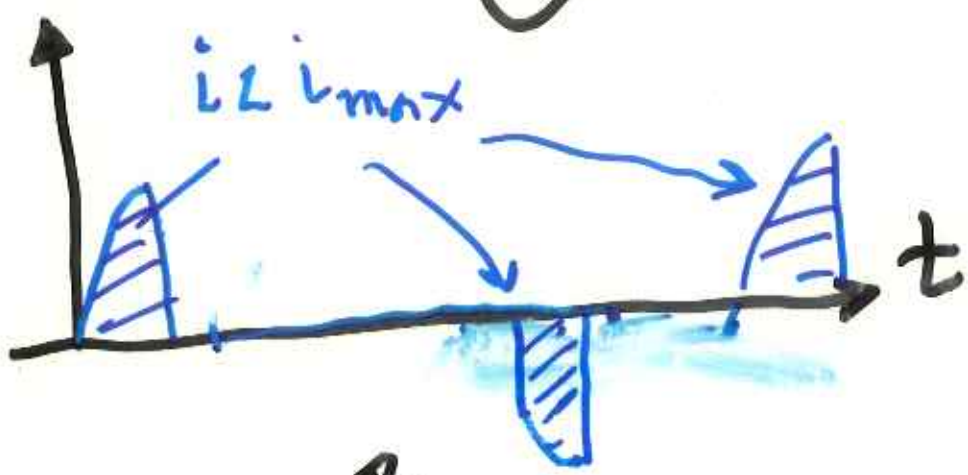
Drives i_{IN} L i_{max}



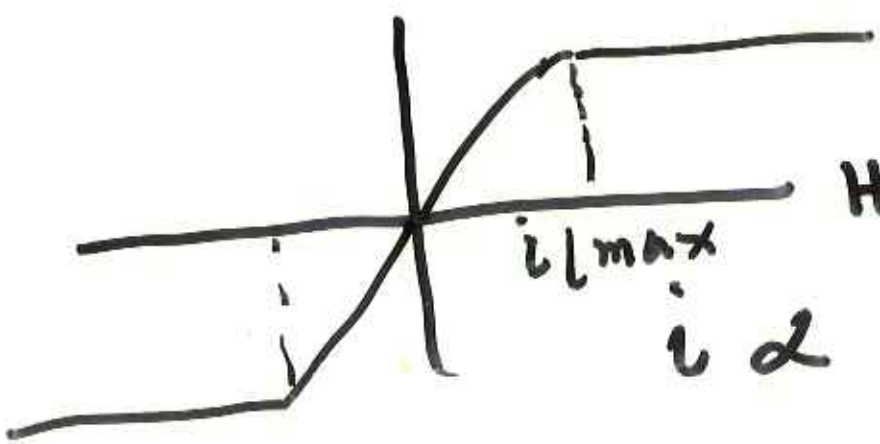
No saturation

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

$$\frac{e_L\,dt}{L} = \Delta i$$



Ch 21 for details V-sec



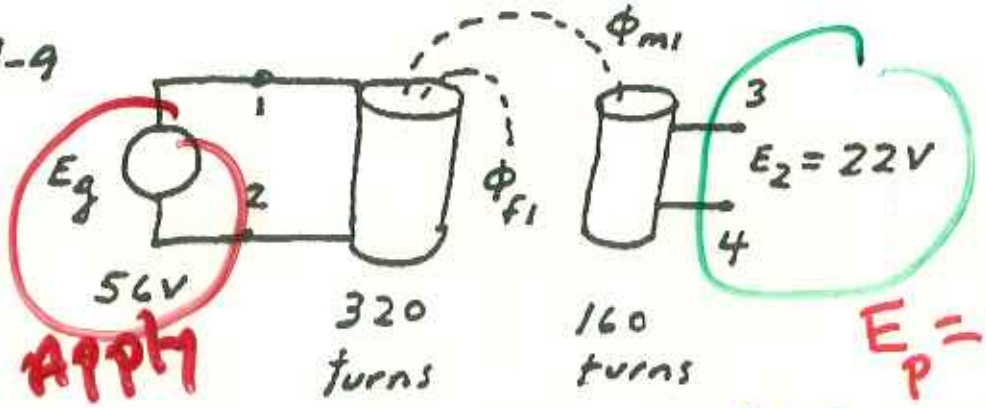
$H \sim i$

$$i \propto \frac{\int e_L\,dt}{L}$$

STOP

Two coupled coils

9-9



measure

Apply

$E_p = N \frac{d\phi_p}{dt}$

input L_m circuit

$E = 4.44 f N \phi_p$

$56 = 4.44 \times 60 \times 320 \times \phi_p \rightarrow \therefore \phi_p = 0.000657$ wb

$= 0.657$ mWb

also on secondary side $E_s = N_s \frac{d\phi_s}{dt}$

$22 = 4.44 \times 60 \times 160 \times \phi_{m1} \rightarrow \phi_{m1} = 0.516$ mWb

Consequently $\phi_{f1} = \phi_p - \phi_s$

$= (0.657 - 0.516) = 0.141$ mWb

Amazing measure

V_p, V_s $\Rightarrow$ get leakage flux

"Making" the C we need

① Use parallel caps
or Use Transformers

② 9-10 Ratio of capacitances = $\frac{300\,\mu F}{40\,\mu F} = 7.5$ WANT got

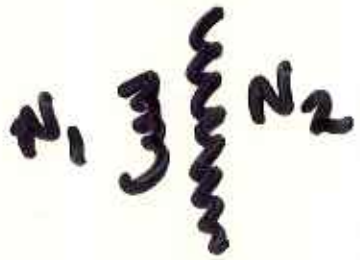
hence ideal transformer turns ratio = $\sqrt{7.5}$

$= 2.7386$ ← Goal

$$\left[\begin{array}{l} \text{Ratios available} = \frac{330\,V}{120\,V} = 2.75 \\ \text{and } \frac{450}{60} = 7.5 \\ \text{and } \frac{480}{150} = 3.2 \end{array}\right]$$

Your Trf pile
Choose 1 best

The 330V/120V transformer is the most appropriate choice. The 40 μF capacitor must be connected to the 330 V winding.



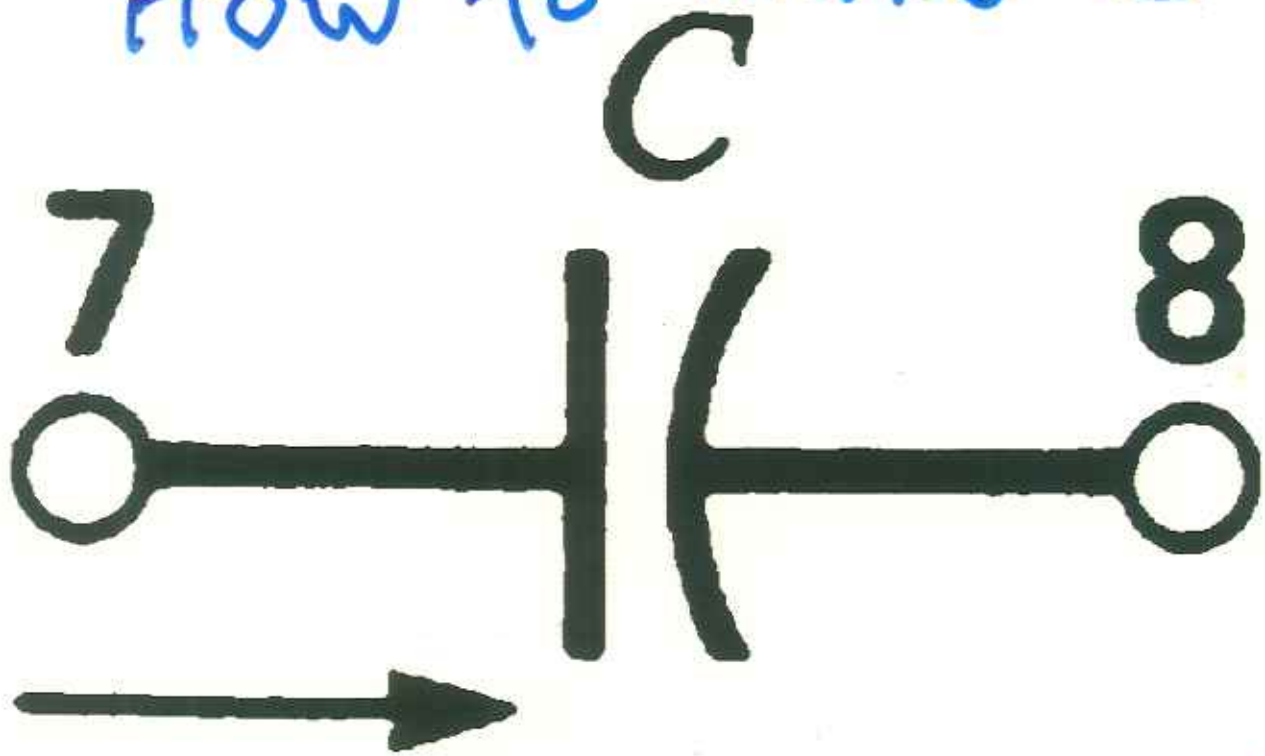
$$Z_c = \frac{1}{\omega C}$$

$$Z_p = \frac{Z_{sec}}{\left(\frac{N_2}{N_1}\right)^2} \Rightarrow C_p = C_s\left(\frac{N_2}{N_1}\right)^2$$

Pbm 9.10

How to make C ↑

Figure 21-8 Potential across a capacitor.



Appear bigger?

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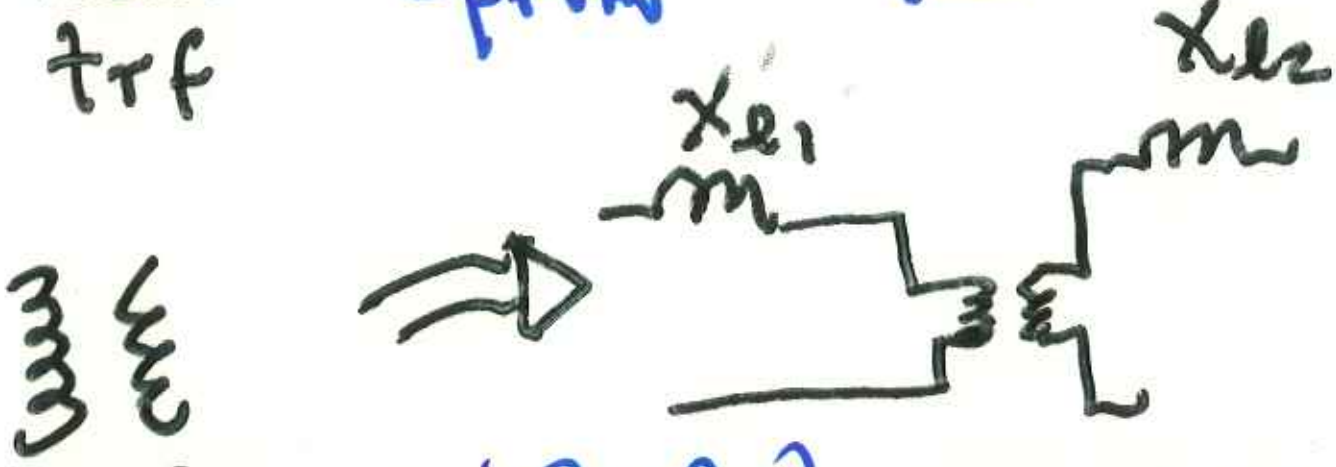
For $X_m >> X_\ell$

Real trf

$S_{prim} = S_{sec} = S_{rating}$



real trf } X_ℓ (Real actual) values are Not equal

Payoff for pu is

System simplicity of trf model

especially transformer cascades

because in pu $X^{pu}_{\ell_1} \equiv X^{pu}_{\ell_2}$

Transformers in pu
Ch 10

- $\underbrace{X^{pu}_{l_{pri}}}_{\text{Base 1}} = \underbrace{X^{pu}_{l_{sec}}}_{\text{Base 2}}$ in per unit

Suprise! Same value in p.u.!

Trf nameplates given in pu

$$X^{pu} = 2.6\% = 0.026 \text{ pu}$$

to get actual X_{real}

$$X_{real} = X_{pu} \underbrace{X_{base}}_{\text{differs in}}$$

Base 1 primary

Base 2 secondary

Note well!

X_{base} takes into account $(N_2/N_1)^2$ etc

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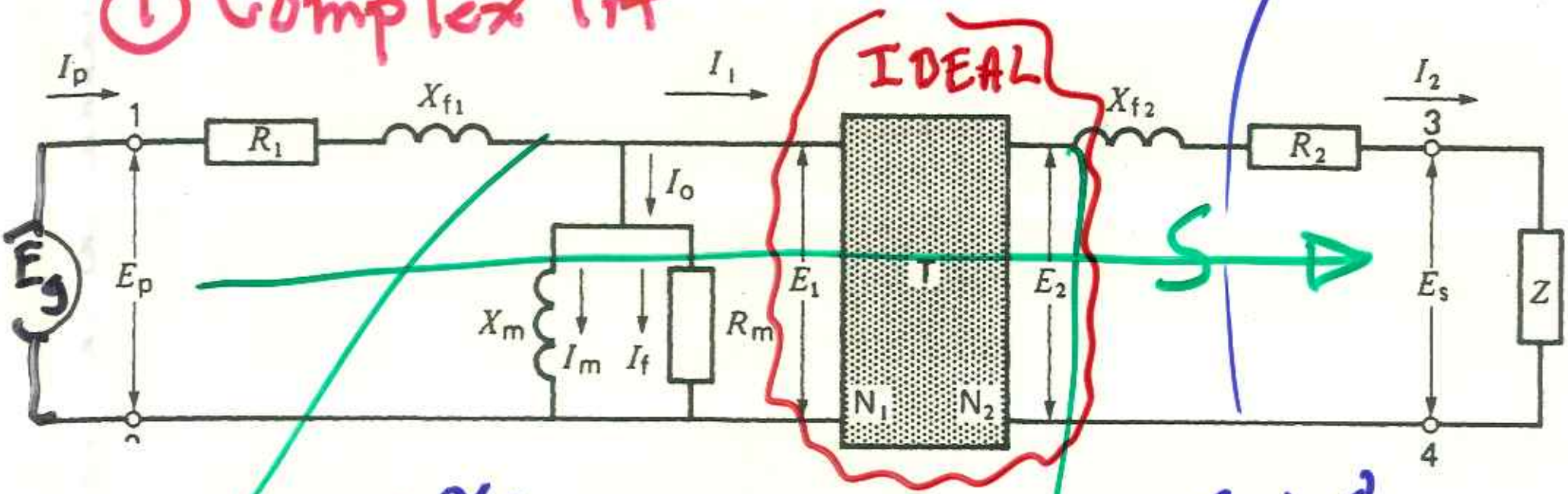
Trf Reality

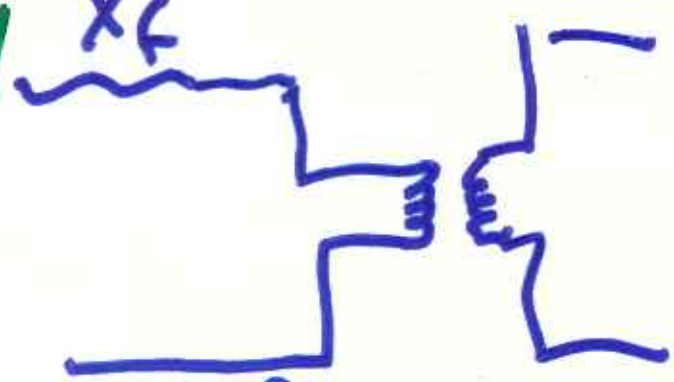
Coming Ch 10: Fig 10.31 Pg 217

① Complex Trf

How Get all approx values for unknown trf



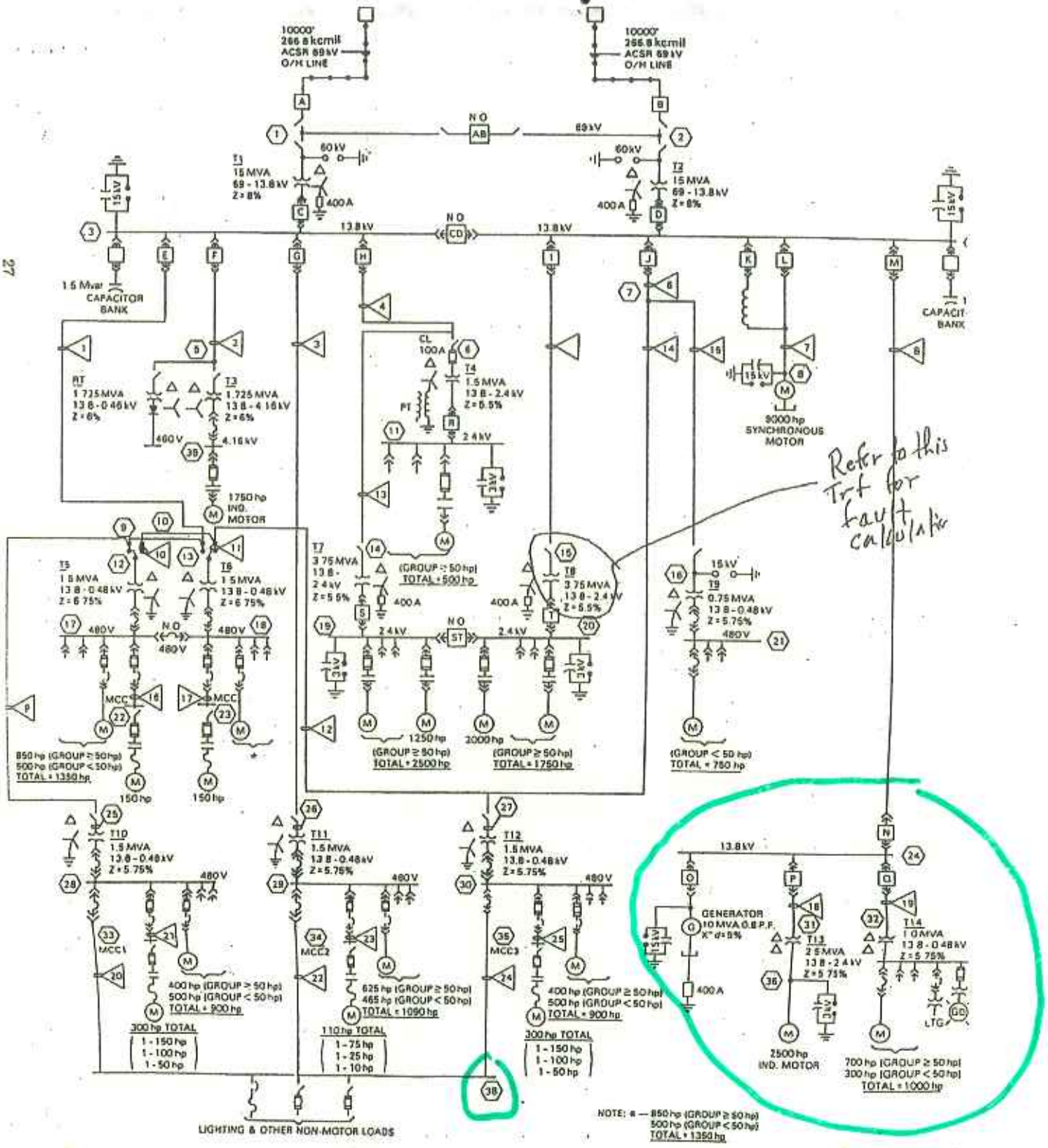
V_B(primary)



1. Get S
2. Typical pu values
3. Use Z_B(pri) Z_B(sec)

② Power Approx V_B(sec)

Actual System



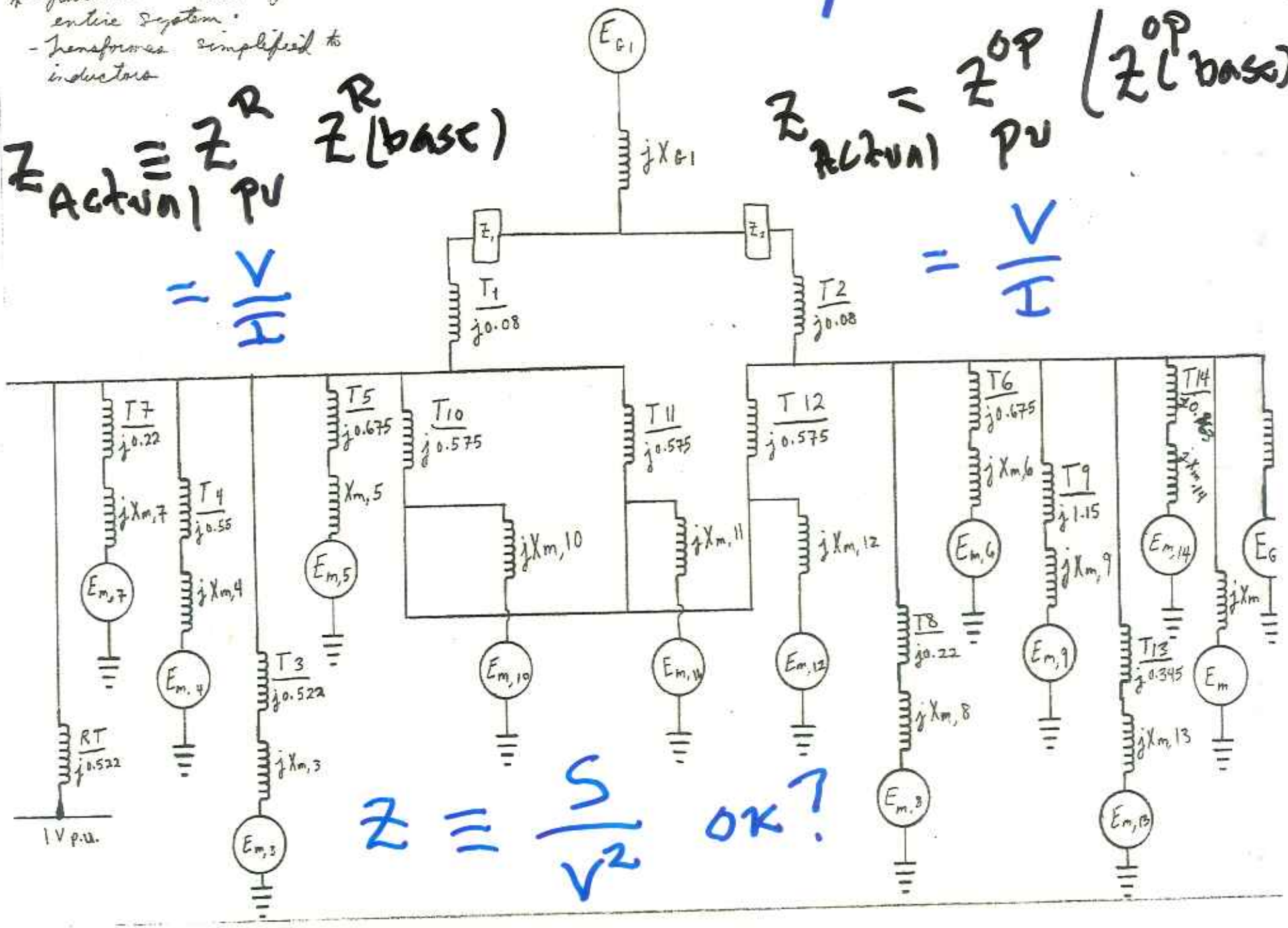
Composite Single-Line Diagram for Typical Large Industrial Power System

Per Unit System

* Equivalent circuit for entire system.
- Transformers simplified to inductors

$$Z_{Actual\,pu} \equiv Z^{R}\,Z^{R}(base) = \frac{V}{I}$$

$$Z_{Actual\,pu} = Z^{op}\left(Z^{op}(base)\right) = \frac{V}{I}$$



$$Z \equiv \frac{S}{V^2} \quad \text{OK?}$$

$$Z^{op}(\text{base}) = \frac{V_{op}^2}{S_{op}}$$

$$Z^{rated}(\text{base}) = \frac{V_{rated}^2}{S_{rated}}$$

$$Z_{Actual} \equiv Z_{pu} \, Z_{base}$$

$$\Longrightarrow$$

$$Z_{pu}^{op} * \frac{V_{op}^2}{S_{op}} = Z_{pu}^{rated} * \frac{V_R^2}{S_{Rated}}$$

$$\Longrightarrow$$

$$Z_{pu}^{op} = Z_{pu}(\text{rated}) * \ ?$$

Per Unit Changes

from rated base to actual operating base

From: Equipment Nameplate

has rated S_R, V_R — Motor, Gen, Trf

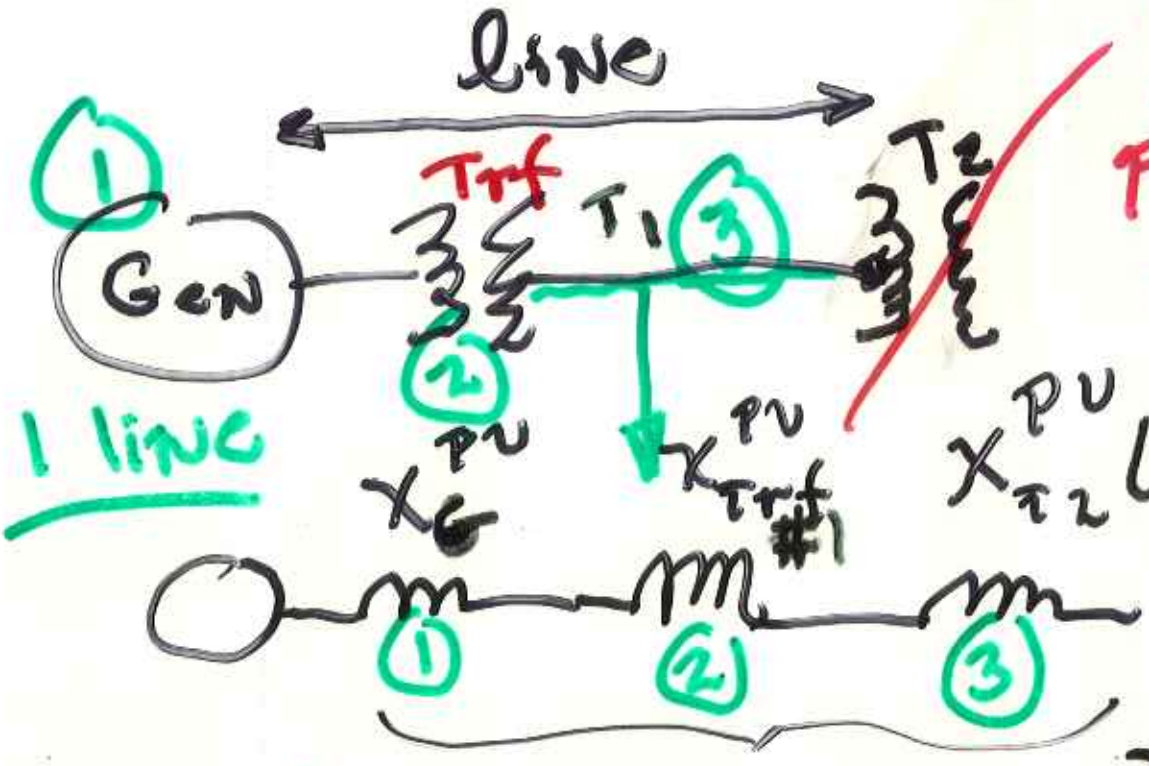
From manufacturer

To: Actual Operation — User

Equipment may be operated at S_{op}, V_{op}

Operate below rating is best

$$Z_{pu}(op) = Z_{pu}(rating) \left(\frac{V_R}{V_{op}}\right)^2 \frac{S_{op}}{S_R}$$



X_{trf}^{pu} same or different primary vs secondary?

?

3 components all pu

placed all in operating system

each component has specs in manufactures rating

How to do it?

$$X_{pu}^{op} = X_{pu}^{rat} \left(\frac{V^{rat}}{V^{op}}\right)^2 \frac{S^{op}}{S^{rat}}$$

$$Z_{Base} \equiv \frac{V_{Base}}{I_{Base}} = \frac{(V_{Base})^2}{S_{Base}}$$

$\uparrow S/V_{base}$

High S_{Base} $\Rightarrow$ $Z_B \downarrow$

Low S_B $\Rightarrow$ $Z_B \uparrow$

Trends

1. $\underbrace{\begin{matrix} R \\ X \end{matrix}(\text{low } S_B)}_{\text{IN P.U.}} > \underbrace{\begin{matrix} R \\ X \end{matrix}(\text{high } S_B)}_{\text{in P.U.}}$

ch 10 PU for Transformer 400 MVA Gen to Trans Line Trf

Distribution Trf

MVA Substation Trf

PJZ 15

$S_{prim} = S_{sec}$

TABLE 10A ACTUAL TRANSFORMER VALUES

S_n	kVA	1	10	100	1000	400000
E_{np}	V	2400	2400	12470	69000	13800
E_{ns}	V	460	347	600	6900	424000
I_{np}	A	0.417	4.17	8.02	14.5	29000
I_{ns}	A	2.17	28.8	167	145	943
R_1	Ω	58.0	5.16	11.6	27.2	0.0003
R_2	Ω	1.9	0.095	0.024	0.25	0.354
X_{f1}	Ω	32	4.3	39	151	0.028
X_{f2}	Ω	1.16	0.09	0.09	1.5	27
X_m	Ω	200000	29000	150000	505000	460
R_m	Ω	400000	51000	220000	432000	317
I_o	A	0.0134	0.0952	0.101	0.210	52.9

X_m ?

differ

differ

10^6 R trend

10^4 X_f trend

why? i drawn from V source applied to primary of Trf when $I_{out} = 0$ (open sec)

$I_{IN}(i_{out}=0) = 53A$ and $V_{IN} = 13.8KV$

loss ~ 1/4000 $\simeq 70KVA / 400,000 KVA$

30
3

PU for Transformer

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$$Z_{base}(\text{primary}) = \frac{E_p}{I_p} = \frac{E_p}{S/E_p} = \frac{E_p^2}{S}$$

$$Z_{base}(\text{secondary}) = \frac{E_s}{I_s} = \frac{E_s}{S/E_s} = \frac{E_s^2}{S}$$

TABLE 10B PER UNIT TRANSFORMER VALUES

S_n	kVA	1	10	100	1000	400000
E_{np}	V	2400	2400	12470	69000	13800
E_{ns}	V	460	347	600	6900	424000
I_{np}	A	0.417	4.17	8.02	14.5	29000
I_{ns}	A	2.17	28.8	167	145	943
Z_{np}	Ω	5760	576	1555	4761	0.4761
Z_{ns}	Ω	211.6	12.0	3.60	47.61	449.4
R_1 (pu)	–	0.0101	0.0090	0.0075	0.0057	0.00071
R_2 (pu)	–	0.0090	0.0079	0.0067	0.0053	0.00079
X_{f1} (pu)	–	0.0056	0.0075	0.0251	0.0317	0.0588
X_{f2} (pu)	–	0.0055	0.0075	0.0250	0.0315	0.0601
X_m (pu)	–	34.7	50.3	96.5	106	966
R_m (pu)	–	69.4	88.5	141.5	90.7	666
I_o (pu)	–	0.032	0.023	0.013	0.015	0.0018

Same value in PU

in Rn Sam

Why?

$$P.U. = \frac{X \text{ or } R}{\text{Nominal } Z}$$

Could be Primary or Sec

$$Z_{pu}(\text{prim}) = Z_{pu}(\text{Sec})$$

30 C

Rule of Thumb PV values: 2 Groups

$$\frac{P_{out}}{P_{IN}} \text{ (Fe:Si Trf)} \approx 97\%$$

S↑ Both R_{pu} and X_f(pu) ↑ } ⇒ X dominates

Typical per-unit values

	Low power 3 kVA to 250 kVA	High Power 1 MVA to 100 MVA
R_1 or R_2	0.009–0.005	0.005–0.002
X_{f1} or X_{f2}	0.008–0.025	0.03–0.06
X_m	20–30	50–200
R_m	20–50	100–500
I_o	0.05–0.03	0.02–0.005

Table 10.C Pg217

Pg217 Table 10C

$$\frac{P_{out}}{P_{IN}} \text{ (Ferrite Trf)} = ?$$

Fe : Si