Chapter 9b Transformers

- Infrastructure Vulnerability/Lighting/Alt Energy Preaching
- Ideal vs. Real Transformer
- Homework
- Transformer Per Unit
No protection beyond
Chain link fence

TARGETS
Only 105 transformers
> 100kV

Only Protected by chain length fence
Lighting

Commercial Buildings
40% total energy use is?

New buildings
more daylight
CFL and LED's

Windows
light pipes

Federal Law
100 W
Incompliant
75 W 2013

Illegal 2012
60 W 2014
40 W 2014
IN MY BACKYARD: The SkyStream 3.7’s spinning blades cut a homeowner’s electric bills down to size.

noise on for neighbor?
Smart Meters: Texas, Calif, Colo

1. Measure P(t)
2. Communicate two way consumer → Power company devices

E.g. Tendril Networks Boulder Colo

Home energy display controllers

Communication Protocols

1. Zig Bee non-profit Intron, Tendril
2. z-wave Greenbox Technology Intel, Leviton
   by Universal Electron

Goal program home devices

To use less power cheaper power

Gridpoint Inc. diagnosed recommend
Real Transformer

Gives rise to $L_m$ $X_m$ magnetizing

Flux paths matter You choose

Flux leakage gives rise to $L_e$ $X_e$ leakage
Role of $X_2$ & wire $R$

$E_1 = E_{g} - I_{1}(Z_{1})$

$E_2 = E_{s} + I_{2}(R_{2})$

$\text{ideal Trf}$

Keep

$\frac{N_1 u_1}{N_2 u_2} = Z_{\text{eff}} = \left(\frac{N_1}{N_2}\right) R_2$

$\frac{E_1}{N_1} = \frac{E_2}{N_2}$
\[ L_m = \frac{N_p^2}{Q_{core}} \quad Q_{core} = \frac{I_C}{\mu C A_C} \]

\[ \mu_C \to \infty \quad \Rightarrow \quad Q_C \to 0 \quad \Rightarrow \quad L_m = \infty \]

For finite \( \mu_C \) (\( N_p \)) matters to \( L_m \)

Want \( L_m \) large \( \Rightarrow \)

\[ |N_p| \] matters
Load in secondary: $i_2$

Ideal transformer arrow to $i_2$

$N_1, i_2$ in primary

Ampere's law causes Amp-turns equals $N_2 i_2$.

$N_1 i_2$ in primary

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

Input $i_1$ has two parts:

$\text{Input (total)} = l_2 + u_m$

So called ideal

$I_1, N_1 = I_2 N_2$ if neglect $l_m$
Add $R_l (\text{wire})$ to $L_l$, $R_2 (\text{wire})$ to $L_2$

Account for: (eddy current) losses

Another effective $I^2 R_{\text{eff}}$ loss

Test for all components
- Short secondary
- Open secondary

Lossless case

$Z_{\text{primary}} = Z_{\text{secondary}} \left( \frac{N_1}{N_2} \right)^2$
Measure $X_m, R_m$ by Test

ONLY LOSSES FOR $n$? Condition
Measure $X_e$ or $R_{wire}$ condition by $n$? $I_0 \ll I_1$ for $\frac{N_1}{N_2}$ condition.
Various Types of Transformers have a range of use.

Fig 10.8
Page 202

"Let's go on a transformer tour!"

\[
\frac{E_1}{N_1} = \frac{E_2}{N_2}
\]

\[
\frac{I_2}{N_2} = \frac{I_1}{N_1}
\]
Small Distribution Transformers & KW

$L_e$ is parasitic

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

You choose size?

Let's follow transformers to generator.
Large Substation Trf
128KV

large amount of insulation wire to core

200-300A = D large diameter of wires

often ≠ not wires

Fig 10.9
PG 204
$S = 1.3 \text{ GVA}$
\[ V \rightarrow 24.5 \text{ kV} / 345 \text{ kV} \]

AC. Trf

A.C. Transmission Line
\[ I = ? \]

Air flow cools $\text{H}_2\text{O}$

$\text{H}_2\text{O}$ flow cools oil in trf

Fig 10.18
g209
Renco’s quality transformers
will make you smile

Renco transformers
trusted in milking
machines
Does $I_1$ saturate core?

What saturates a core?
Saturation occurs!

\( \mu_r \rightarrow \mu_0 \rightarrow L_m \text{ falls by causes; } \frac{\mu_r}{\mu_0} \)

Short across \( V_i \)

\( V \) across \( N_1 \rightarrow 0 \)

Transformer becomes short

\( i_{in} \rightarrow \infty \)
What if $R \to \infty$? Open circuit $ct$?

$V_{out} \leftarrow I_{in}$

Choose $R_{out}$ to give $V_{out}$.

Given:

$V_{in} = 2$ V

$R_{out} = \frac{3}{2}$
Use Torroid Core "around" wire carrying i

Low & voltage terminal is usually "shorted" $E_2 \rightarrow 0$

Next simple CT #5
\[ V_{in} \]

\[ I_{in} \]

\[ V_L = L \frac{di_i}{dt} \] \{ OPEN secondary only \[ L_m \]

\[ \int \frac{V_L}{L} dt \rightarrow i(t) \]

\[ B(t) \]

\[ | \begin{array}{c} B \text{ flatlines} \\
H = i \end{array} | \]

\[ i > i_{\text{max}} \]

\[ = D \frac{dB}{dt} = 0 \]

\[ V_{in} \]

\[ V_L = V_{in} \]

\[ i_{\text{in}} \]

\[ i_{\text{lim}} \]

\[ i_{\text{max}} \]

\[ \text{drives } i + \]

\[ \text{Always} \]

\[ \text{drives } i_{\text{in}} \text{ to } L \]

\[ \text{returns } i \text{ to } \text{zero.} \]
Two coupled coils

\[ E = 4.44 fN, \phi_p \]

\[ S_1 = 4.44 \times 60 \times 320 \times \phi_p \rightarrow \phi = 0.00057 \text{ wb} \]

Also on secondary side:

\[ E_s = N_s \frac{d\phi}{dt} \]

\[ 22 = 4.44 \times 60 \times 160 \times \phi_{mi} \rightarrow \phi_{mi} = 0.516 \text{ mwb} \]

Consequently

\[ \phi_{f1} = \phi - \phi_{mi} \]

\[ = (0.657 - 0.516) = 0.141 \text{ mwb} \]

Amazing measure

\[ V_P = D \text{ get leakage flux} \]
Making the C we need

Use parallel caps or use transformers

\[ \text{Goal} \]

Ratio of capacitances = \( \frac{300 \mu F}{40 \mu F} = 7.5 \)

Hence ideal transformer turns ratio = \( \sqrt{7.5} \)

= 2.7386

Ratios available:

\[ \frac{330 \text{V}}{120 \text{V}} = 2.75 \]
\[ \frac{450 \text{V}}{60 \text{V}} = 7.5 \]
\[ \frac{480 \text{V}}{150 \text{V}} = 3.2 \]

Your Trf pile

Choose 1 best

The 330V/120V transformer is the most appropriate choice. The 40 \( \mu F \) capacitor must be connected to the 330V winding.

\[ \frac{N_1}{N_2} \]

\[ z_c = \frac{1}{\omega C} \]

\[ z_p = \frac{z_{sec}}{(\frac{N_2}{N_1})^2} \]

\[ D_{cp} = C_s \left( \frac{N_2}{N_1} \right)^2 \]
Figure 21-8  Potential across a capacitor.

Pbm 9.10

How to make C↑

C

7

I

Appeaver bigger?

8
For $X_m \gg X_e$

$E \rightarrow \frac{M}{X_{pu}}$

$S_{prim} = 5 \text{ sec} = S_{rating}$

$\frac{x_{e1}}{x_{e2}}$

Real

$\Rightarrow$

3 3

real

(trf)

$\left\{ \begin{array}{l}
\text{Real values are not equal} \\
\text{Payoff for pu is}
\end{array} \right.$

System simplicity of trf model

Especially transformer cascades

because in pu $X_{pu}^1 = X_{pu}^2$
Transformers in pu

Ch 10

\[ X_{lpri}^{pu} = X_{lsec}^{pu} \] in per unit

Base Base2

Surprise! Same value in pu!

If nameplates given in pu

\[ X^{pu} = 2.69\% = 0.026\text{ pu} \]

to get actual \( X_{real} \)

\[ X_{real} = X_{pu} \left( \frac{\text{Base Base1}}{\text{Base Base2}} \right) \]

differs in Base 1 primary Base 2 secondary

Note well! \( X_{base} \) takes into account

\( \left( \frac{N_2}{N_1} \right)^2 \) ctc
Trf Reality

Coming Ch10: Fig 10.31 pg 217

1. Complex Trf

Get all approx values for unknown trf

2. Power Approx V_{e(60)}

1. Get $S$
2. Typical pu values
3. Use $R_{(pri)}/Z_{g}(sec)$
Composite Single-Line Diagram for Typical Large Industrial Power System
Per Unit System

\[ Z_{\text{actual}} = \frac{Z^\text{R}}{Z^\text{(base)}} \]

\[ Z_{\text{actual \ pu}} = \frac{V}{I} \]

\[ Z = \frac{S}{V^2} \quad \text{ok?} \]
\[ z_{op}(\text{base}) = \frac{V_{op}^2}{S_{op}} \cdot \quad z_{\text{rated}} (\text{base}) = \frac{V_{\text{rated}}^2}{S_{\text{rated}}} \]

\[ z_{\text{Actual}} \equiv z_{\text{pu}} \quad z_{\text{base}} \]

\[ \Rightarrow \quad z_{\text{op}} + \frac{V_{op}^2}{S_{op}} = z_{\text{pu}} + \frac{V_{\text{rated}}^2}{S_{\text{rated}}} \]

\[ \Rightarrow \quad z_{\text{pu}} = z_{\text{pu (rated)}} \quad ? \]
Per Unit Changes from rated base to operating base.

From: Equipment Nameplate has rated $S_R$, $V_R$.

From manufacturer $V_{op}$.

To: Actual Operation User.

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

Operate below rating is best.

$Z_{pu\ (op)} = Z_{pu\ (rating)} = ?$

$\frac{(V_R^2)}{(V_{op})^2} \frac{S_{op}}{S_R}$
3 Components all pu in operating system

Each component has specs in manufactures rating

How to do it?

\[
X_{pu}^{op} = X_{pu} \left( \frac{V}{V_{op}} \right) \frac{S_{op}}{S_{rat}}
\]
\[ Z_{\text{Base}} = \frac{V_{\text{Base}}}{I_{\text{Base}} \times \frac{S}{V_{\text{base}}}} = \frac{(V_{\text{Base}})^2}{S_{\text{Base}}} \]

High \( S_{\text{Base}} \)  \( \Rightarrow \)  \( Z_{\text{B}} \downarrow \)

Low \( S_{\text{B}} \)  \( \Rightarrow \)  \( Z_{\text{B}} \uparrow \)

Trends

1. \( R_x(\text{low} S_{\text{B}}) \) \( \text{in p.u.} \) > \( R_x(\text{high} S_{\text{B}}) \) \( \text{in p.u.} \)
TABLE 10A  ACTUAL TRANSFORMER VALUES

<table>
<thead>
<tr>
<th>Sn</th>
<th>kVA</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1000</th>
<th>400000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enp</td>
<td>V</td>
<td>2400</td>
<td>2400</td>
<td>12470</td>
<td>69000</td>
<td>13800</td>
</tr>
<tr>
<td>Ens</td>
<td>V</td>
<td>460</td>
<td>347</td>
<td>600</td>
<td>6900</td>
<td>424000</td>
</tr>
<tr>
<td>Inp</td>
<td>A</td>
<td>0.417</td>
<td>4.17</td>
<td>8.02</td>
<td>14.5</td>
<td>29000</td>
</tr>
<tr>
<td>Inn</td>
<td>A</td>
<td>2.17</td>
<td>28.8</td>
<td>167</td>
<td>145</td>
<td>943</td>
</tr>
<tr>
<td>Rn1</td>
<td>Ω</td>
<td>58.0</td>
<td>5.16</td>
<td>11.6</td>
<td>27.2</td>
<td>0.0003</td>
</tr>
<tr>
<td>Rn2</td>
<td>Ω</td>
<td>1.9</td>
<td>0.095</td>
<td>0.024</td>
<td>0.25</td>
<td>0.354</td>
</tr>
<tr>
<td>Xnf1</td>
<td>Ω</td>
<td>32</td>
<td>4.3</td>
<td>39</td>
<td>151</td>
<td>0.028</td>
</tr>
<tr>
<td>Xnf2</td>
<td>Ω</td>
<td>1.16</td>
<td>0.09</td>
<td>0.09</td>
<td>1.5</td>
<td>27</td>
</tr>
<tr>
<td>Xn</td>
<td>Ω</td>
<td>200000</td>
<td>29000</td>
<td>150000</td>
<td>505000</td>
<td>460</td>
</tr>
<tr>
<td>Rn</td>
<td>Ω</td>
<td>400000</td>
<td>51000</td>
<td>220000</td>
<td>432000</td>
<td>317</td>
</tr>
<tr>
<td>In</td>
<td>A</td>
<td>0.0134</td>
<td>0.0952</td>
<td>0.101</td>
<td>0.210</td>
<td>52.9</td>
</tr>
</tbody>
</table>

- Sn - Transformer rating
- Enp, Ens - Voltage
- Inp, Inn - Current
- Rn1, Rn2 - Resistance
- Xnf1, Xnf2 - Reactance
- Xn, Rn - Impedance
- In - Current

\[ I_{in} (i_{out}=0) = 53 \text{A} \quad \text{and} \quad V = 13.8 \text{kV} \]

\[ P_{loss} = \frac{1}{4000} = 70 \text{kVA} \]

- \( P_{loss} \) is the power loss in the transformer.
**Table 10B: Per Unit Transformer Values**

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

**Equations:**

- $Z_{pu}$ (primary) = $E_{pu} = \frac{E_{pu}}{I_{pu}} = \frac{E_{pu}^2}{S_{base}}$
- $Z_{pu}$ (secondary) = $E_{pu} = \frac{E_{pu}}{I_{pu}} = \frac{E_{pu}^2}{S_{base}}$

**Notes:**

- The same value is used in pu.
- Pu. = $X$ or $R$ (Nominal/Primary or Secondary)

**Explanation:**

$Z_{pu}$ (primary) = $Z_{pu}$ (secondary) = $E_{pu} = \frac{E_{pu}^2}{S_{base}}$.
### Rule of Thumb PV values: 2Group

\[
\frac{P_{out}}{P_{in}} (Fe:Si Trf) = 97\%
\]

5% Both \( R_{pu} \) and \( X_t(pu) \) in Dominator

<table>
<thead>
<tr>
<th></th>
<th>Low Power</th>
<th>High Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_1 ) or ( R_2 )</td>
<td>0.009–0.005</td>
<td>0.005–0.002</td>
</tr>
<tr>
<td>( X_{f1} ) or ( X_{f2} )</td>
<td>0.008–0.025</td>
<td>0.03–0.06</td>
</tr>
<tr>
<td>( X_m )</td>
<td>20–30</td>
<td>50–200</td>
</tr>
<tr>
<td>( R_m )</td>
<td>20–50</td>
<td>100–500</td>
</tr>
<tr>
<td>( I_o )</td>
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<tr>
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<td>0.05–0.03</td>
<td>0.02–0.005</td>
</tr>
</tbody>
</table>

\[
\frac{P_{out}}{P_{in}} (Ferrite Trf) = ?
\]

\[
\frac{P_{out}}{P_{in}} \text{ Fe:Si}
\]