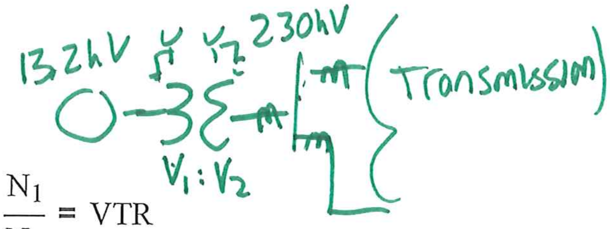
ECE 525

POWER SYSTEM PROTECTION AND RELAYING

SESSION no. 5

Comparing Primary and Secondary Ohms and Converting to Per Unit on Secondary When CTR and VTR Don't Cancel

- First look at a regular transformer



We know the following:

$$\frac{V_1}{N_1} = \frac{V_2}{N_2} \quad \text{which can be rearranged as:} \quad \frac{V_1}{V_2} = \frac{N_1}{N_2} = VTR$$

Similarly (using power transformer polarity)

$$I_1 \cdot N_1 - I_2 \cdot N_2 = 0 \quad \text{which can be rearranged as:} \quad \frac{I_1}{I_2} = \frac{N_2}{N_1} = CTR$$

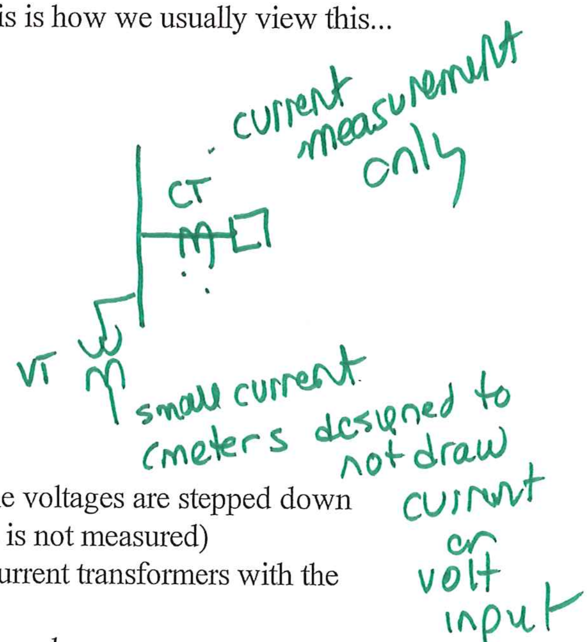
- Now if we wanted to relate an impedance across the transfomer

$$Z_2 = \frac{V_2}{I_2} = \frac{V_1 \cdot \left(\frac{N_2}{N_1}\right)}{I_1 \cdot \left(\frac{N_1}{N_2}\right)} = \frac{V_1}{I_1} \cdot \left(\frac{N_2}{N_1}\right)^2 = Z_1 \cdot \left(\frac{N_2}{N1}\right)^2$$

This is how we usually view this...

Alternate simplification

$$Z_2 = \frac{V_2}{I_2} = \left[\frac{V_1 \cdot \left(\frac{N_2}{N_1}\right)}{I_1 \cdot \left(\frac{N_1}{N_2}\right)}\right] = \frac{V_1 \cdot CTR}{I_1 \cdot VTR} = Z_1 \cdot \frac{CTR}{VTR}$$



- In the case of the measurements seen at the protective relay, the voltages are stepped down through a set of voltage transformers with little current (which is not measured)
- And the currents are stepped down through a separate set of current transformers with the voltage not measured
- The measured voltage and current go into different inputs to the relay
- The relay "sees" and effective secondary impedance based on the voltages and currents stepped down by these separate VTs and CTs
- This will be more important when we look at distance relays, but it also matters for fault location calculations

CT's are sized (CTR)

- based on the rated current in the primary circuit
- and desired rated current on secondary

  → 5 A rms

VT's have VTR sized based

- on primary voltage
- secondary voltage

  → $\frac{115V}{\sqrt{3}}$

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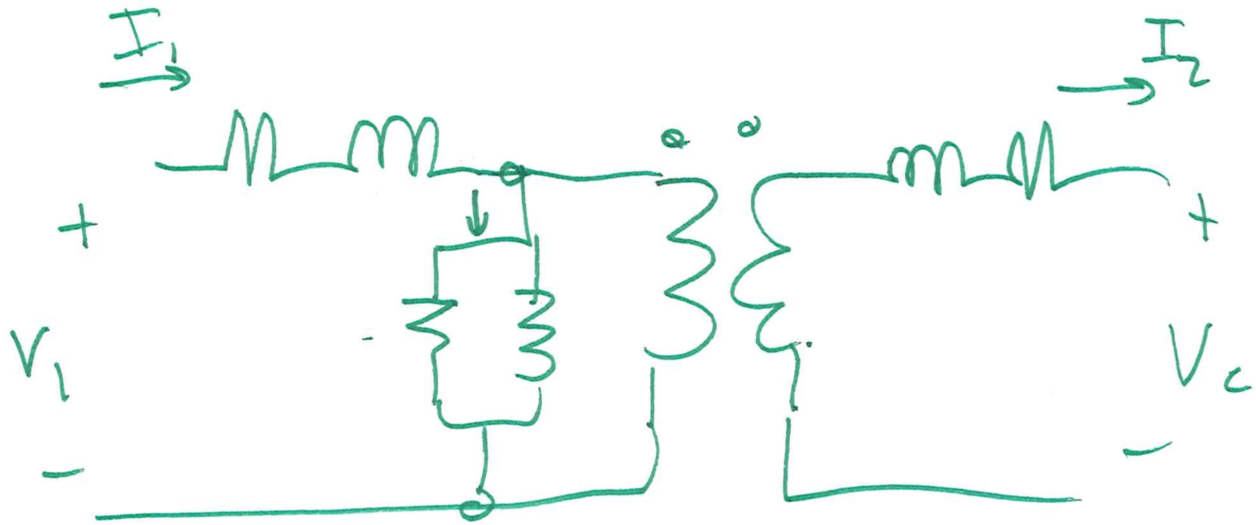

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U I Current Transformers

- CT Basics
  - » Construction
  - » Theory of Operation
  - » Polarity
  - » Equivalent Circuit Model
  - » Accuracy
- CT Transient Performance ⇒ saturation
- Impact on relay element performance

U I CT Construction

- Bar-Type
  - » A fixed insulated straight conductor that is a single primary turn passing through a core assembly with a permanently fixed secondary winding.
- Bushing Type
  - » A secondary winding insulated from and permanently assembled on an annular core with no primary winding or insulation for a primary winding.

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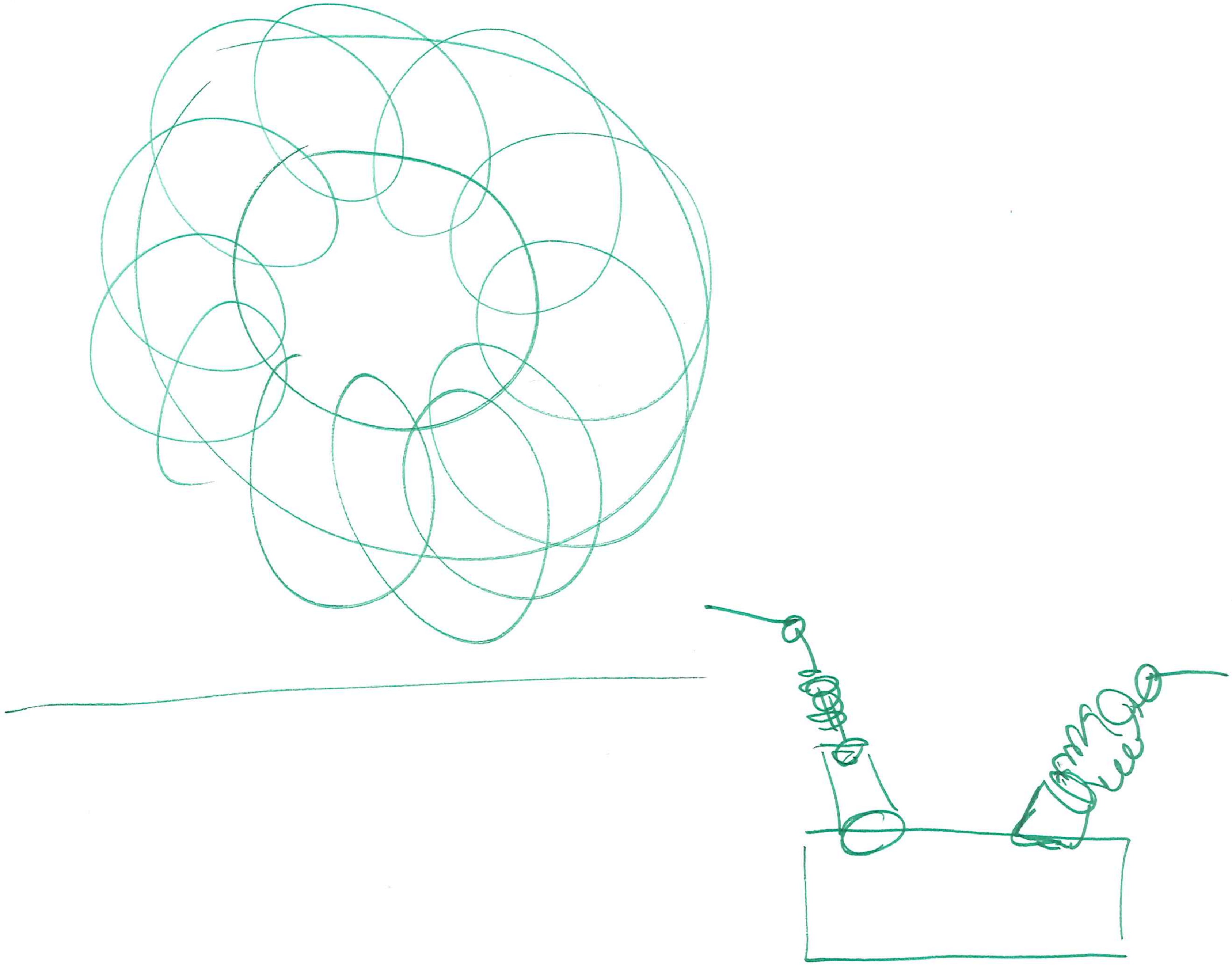

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CT Construction

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- Window Type
  - » A secondary winding insulated from and permanently assembled on the core with no primary winding but with complete insulation for a primary winding.
- Wound Type
  - » A primary and secondary winding insulated from each other consisting of one or more turns encircling the core. Constructed as multi-ratio CTs by the use of taps on the secondary winding.

Common HV CT

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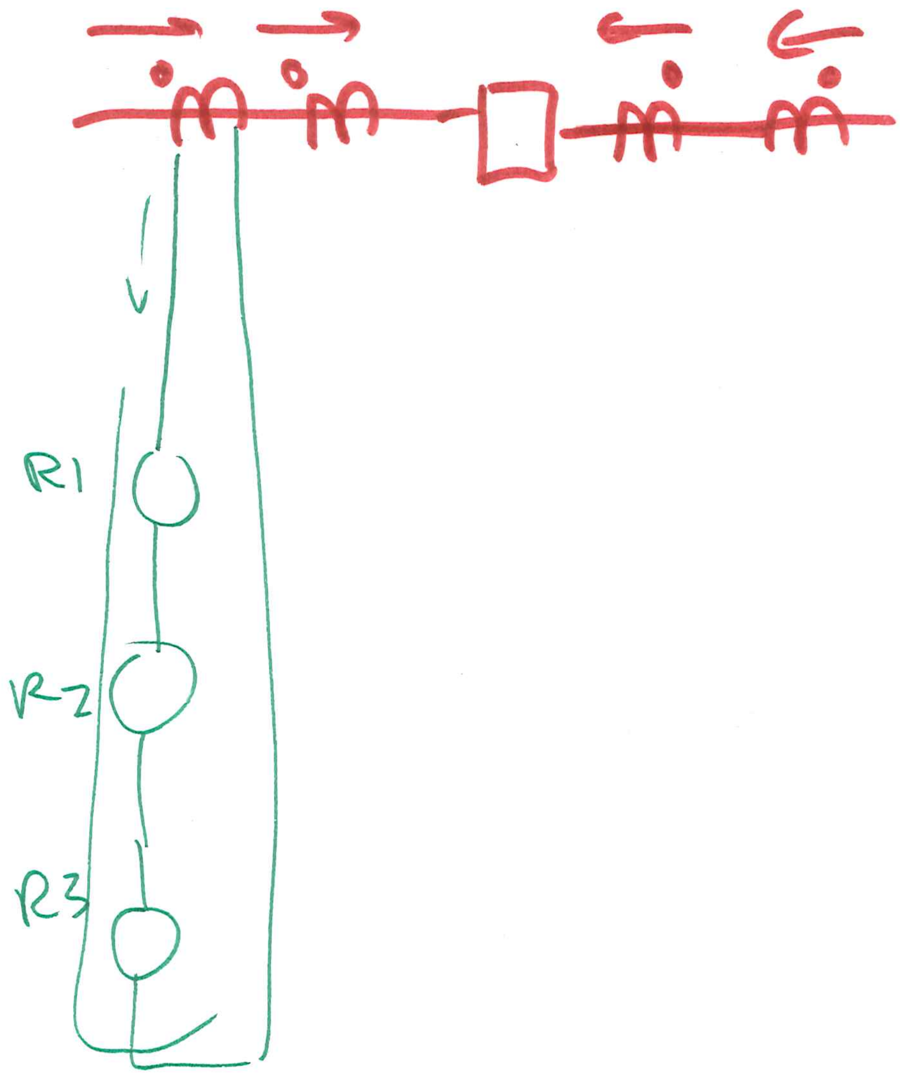
CT Construction

1. **Oil Filling Valve**.
2. **Gas Cushion**. An hermetically sealed expansion system compensates for any volume changes due to temperature variations. Nitrogen gas is used.
3. **Quartz Filling**. The free space inside the transformer is filled with clean dry quartz sand. The quartz sand reduces the amount of oil required inside the transformer thereby ensuring a long life for the insulating paper (Kraft paper). The quartz sand, in addition to providing isolation, also provides mechanical strength for the transformer core and primary winding.
4. **Capacitive Voltage Tap**. A tap is brought out from the second to the last capacitive layer in the HV insulation through a bushing on the transformer tank. It is used to check condition of the insulation by measuring the loss angle (commonly known as the tanδ => $\tan\delta = \varepsilon''/\varepsilon'$). It can also be used for voltage indication.

Note: Due to its low capacitive value, the output is limited, (cannot drive a protective relay from this tap)..

5. **Primary Conductor**. The primary winding consists of one or more parallel aluminum (Al) or copper (Cu) bars bent in a hairpin shape as shown. (*therefore, the name hairpin CT*) .
6. **Paper Insulation**. The conductor(s) is insulated with a special paper (Kraft paper). This paper has a high dielectric and mechanical strength. It has a low dielectric loss (low tan δ) and has a good resistance to aging. The winding is dried and heated in a vacuum before assembly.
7. **Expansion Vessel**. A nitrogen gas cushion is used for this purpose because the tank-type design provides a large distance between the active part and the expansion vessel. In addition, the quartz filling significantly reduces the oil volume inside the transformer and a relatively large gas volume minimizes pressure variations. This type of expansion system increases operating reliability and minimizes the need of maintenance and inspections.
8. **Oil Sight Glass**.
9. **Primary Terminal**.


R1
R2
R3

Theory of Operation

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- Since the magnetic flux is proportional to the mmf we get:
  - » $F_e = F_p - F_s$ or
  - » $I_e * N_p = I_p * N_p - I_s * N_s$ dividing by N_s
  - » $I_e * N_p/N_s = I_p * N_p/N_s - I_s$
  - » $I_s = I_p * N_p/N_s$ if I_e is small

Polarity

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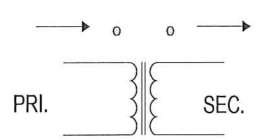
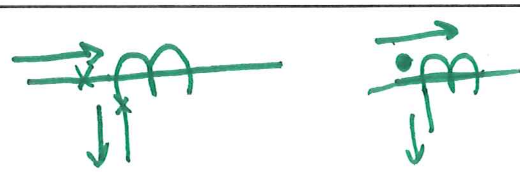
- The CT primary and secondary terminal is physically marked with a polarity.
- The marking indicates the instantaneous direction of the secondary current in relation to the primary current.
- When current flows in at the marked primary, current is flowing out of the marked secondary:



Hint: Direction of the secondary current can determined as if the two polarity terminals formed a continuous circuit



U_I Basic Transformer

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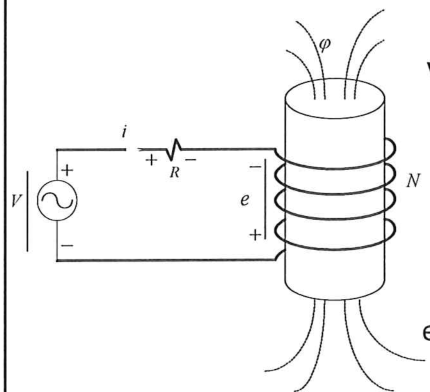

$$v := iR - e$$

$$e := -N\frac{d\varphi}{dt} \qquad \varphi := \varphi_{MAX} \cdot \sin(\varpi t)$$

$$e := -\varpi \cdot N \cdot \varphi_{MAX} \cdot \cos(\varpi t) \qquad B := \varphi \cdot Area$$

$$e := -\varpi \cdot N \cdot B_{MAX} \cdot A \cdot \cos(\varpi t) \qquad \varpi := 2\pi f$$

$$E := 4.44 \cdot N \cdot B_{MAX} \cdot f \cdot A \cdot$$

U_I Theory of Operation

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- When a time varying current I_p flows, a magnetomotive force (mmf) is developed by: MMF = $I_p * N_p$.
- The primary mmf creates a magnetic flux Φ_p in the core given by: Φ_p = MMF/R_m where R_m is the core ~~reactance~~. reluctance
- The direction of Φ_p is determined by the right hand rule.
- Φ_p Links the secondary winding, inducing an electromotive force E_s (emf), resulting in a secondary current Is flowing through burden Z_b.

Equivalent Model

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- The transformation of current induces errors. Some energy form the primary winding is used to:
  - » Establish magnetic flux in the core.
  - » Change the direction of the magnetic flux in the core named hysteresis losses.
  - » Generate heat due to eddy currents.
  - » Establish leakage flux.
- To account for losses a fictitious component is introduced, the exciting current Ie.

Equivalent Model

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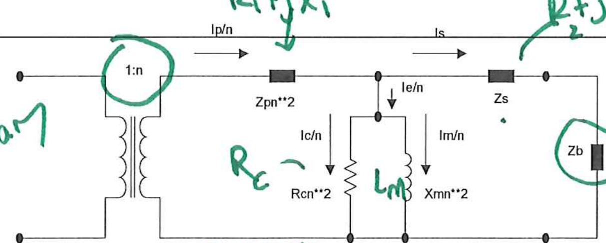
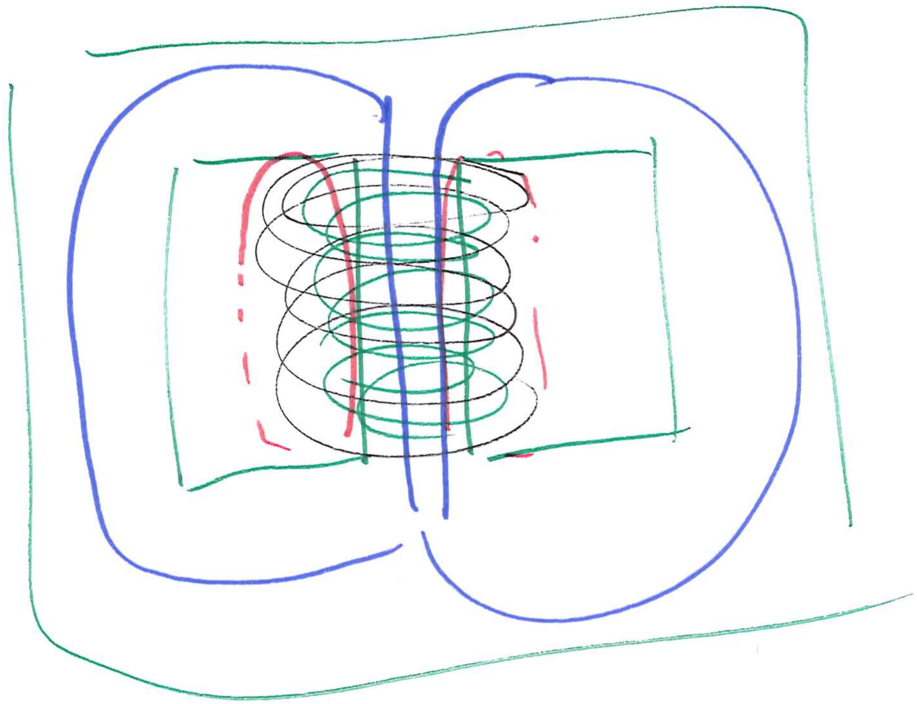


- The primary current Ip is stepped down in magnitude by 1:n through a no-loss transformer.
  - » Zpn**2 - primary winding impedance
  - » Zs - secondary winding impedance
  - » Rcn**2 - hysteresis and eddy current losses referred to the secondary
  - » Xmn**2 - magnetic reactance accounting for losses to establish flux referred to the secondary



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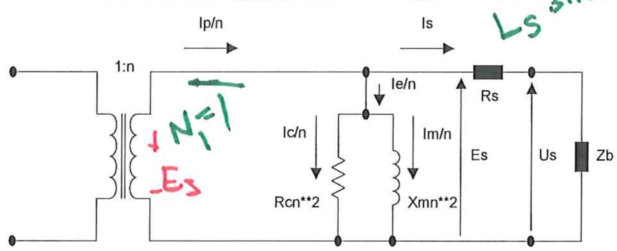
Equivalent Model



- If the secondary winding is uniformly distributed on the core, Zs is resistive = Rs.
- The voltage drop across the primary winding is negligible to the source voltage to which it is connected and does not effect current flow, Zp/n**2 = 0.
- The secondary current is reduced by the shunting current of the exciting branch. The greater Ie the less accurate Is represents Ip.

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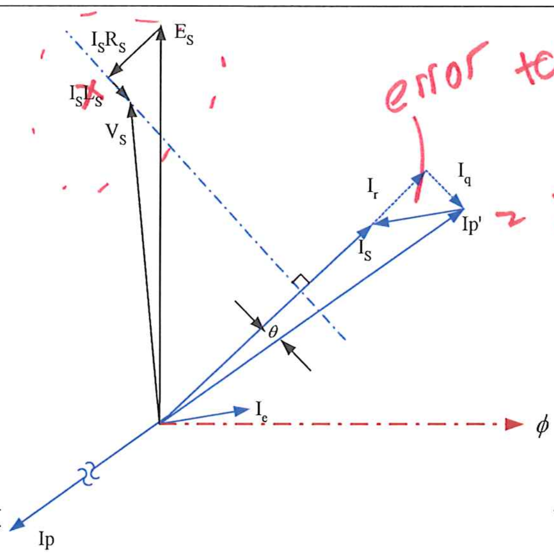
Phasor Diagram CT



Simplified CT Equivalent Circuit

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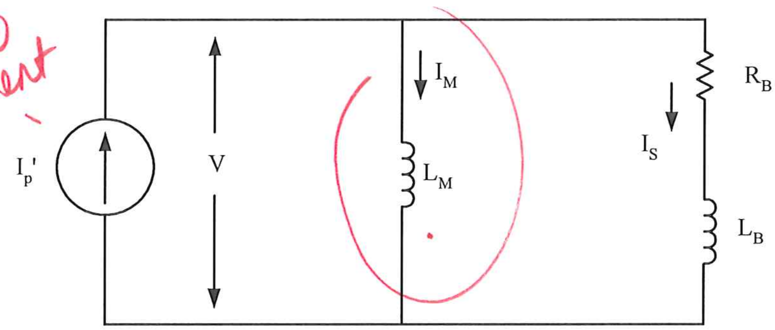

Voltage Equations

From Simplified Circuit

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$$V = N_S \dot{\phi} = L_M \dot{I}_M \ldots (1)$$

$$V = N_S \dot{\phi} = R_S I_S + L_S \dot{I}_S \ldots (2)$$

From equation (1)

$$L_M \cdot \dot{I}_M := N_S \cdot \dot{\phi}$$

$$L_M := N_S \cdot \frac{\dot{\phi}}{\dot{I}_M}$$

$$L_M := N_S^2 \cdot \frac{\Delta B \cdot A}{\Delta H \cdot l}$$

Magnetizing Inductance

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$$L_M = N_S{}^2 \frac{\mu A}{\ell} \qquad \text{OR} \qquad L_M := \frac{N_s{}^2}{\Re}$$

where:

$$\mu = \frac{dB}{dH} := \frac{\Delta B}{\Delta H}$$

A = Area

ℓ = length

$\Re$ = Reluctance

Complete Hysteresis Loop of Ferromagnetic Material

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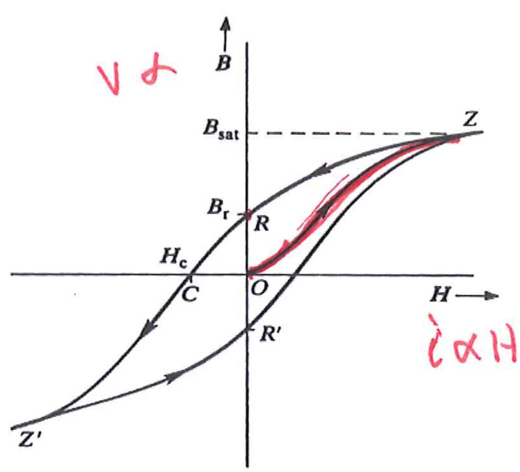

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Hysteresis Loops for Hard and Soft Magnetic Material

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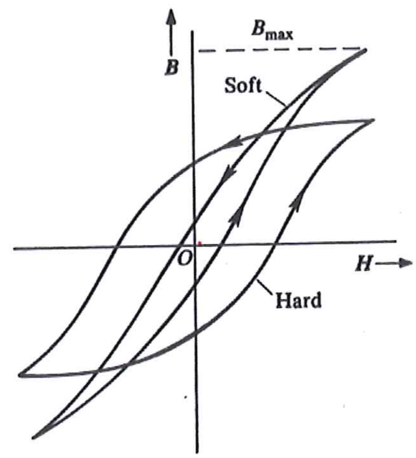

Current Transformers Fall 2018

Magnetization Curve (1): Excitation Curve

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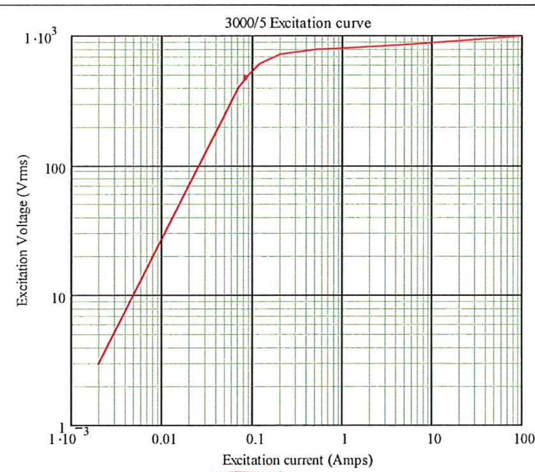
CT curve → C-class CT



Current Transformers Fall 2018

C800 800V knee point → If Rated "Burden"
C600 - 8Ω -
C400 - 20x rated current
⋮ error < 10%

Flux Density and Secondary Current

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$$\dot{B} = \frac{\mu\left(N_P L_S \dot{i}_P + N_S R_S I_S\right)}{\ell L_S + N_S^{2}\mu A}$$

$$\dot{i}_S = \frac{N_P N_S \mu A \dot{i}_P - \ell R_S I_S}{\ell L_S + N_S^{2}\mu A}$$

Fault Current Components

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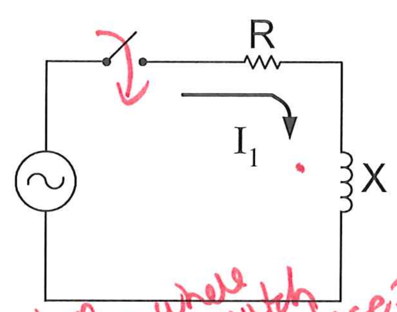
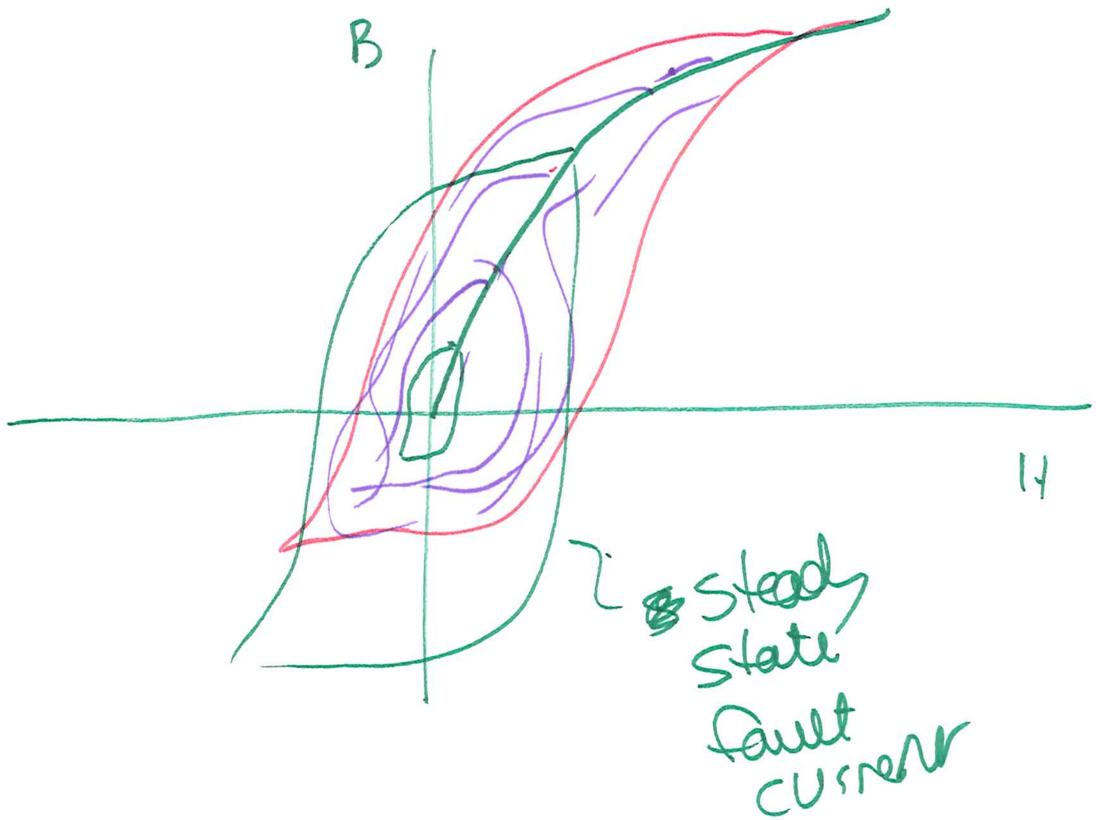


$$I = \sqrt{2} I_1 \left[\sin(\omega t + \phi - \theta) - e^{-\frac{t}{\tau}} \sin(\phi - \theta) \right] \qquad \theta = \tan^{-1}\left(\frac{X}{R}\right)$$


B
H
Steady
State
fault
current

CT Response During Fault Condition

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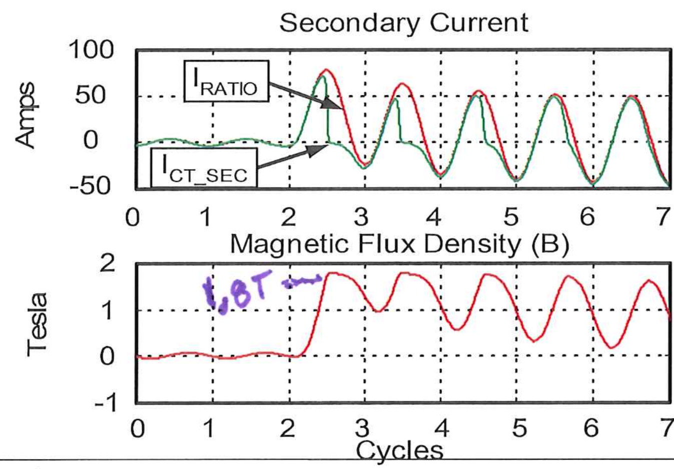

Filtered Currents

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