Current Transformers

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

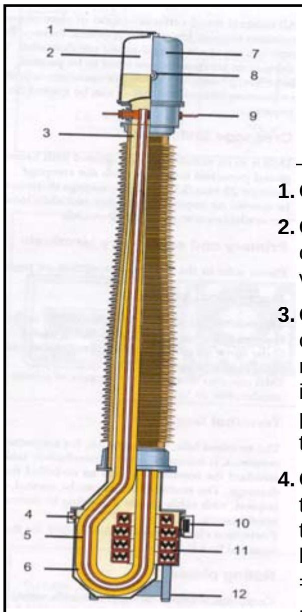
CT Construction

- 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.

CT Construction

- 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.

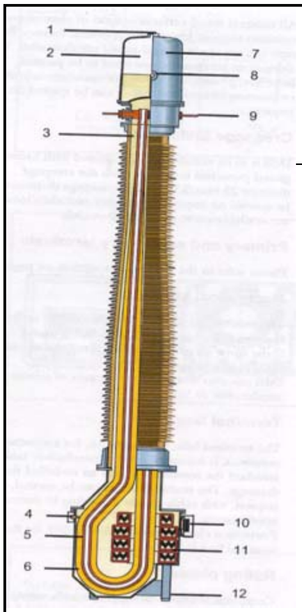
Common HV CT



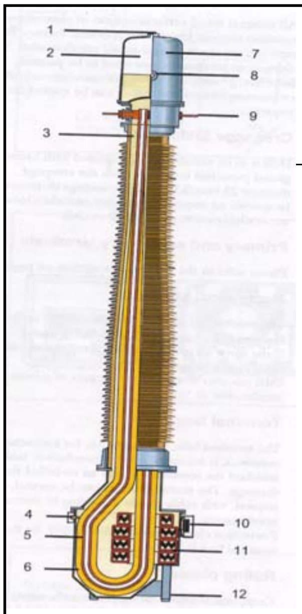
CT Construction

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 δ = $\varepsilon''/\varepsilon'$). 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)..

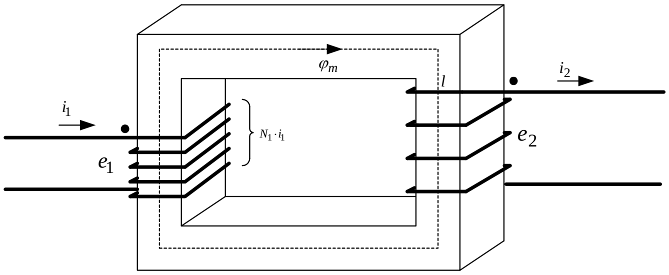


5. **Primary Conductor**. The primary winding consists of one or more parallel aluminum (Al) or copper (Cu) bars bent in a hairpin shape as shown. (*therefore, the name hairpin CT*) .
6. **Paper Insulation**. The conductor(s) is insulated with a special paper (Kraft paper). This paper has a high dielectric 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**.



10. **Secondary Terminal Box**. The secondary windings' terminals are brought out to the terminal box. It is here that the CT ratio is selected and where the relay cables are terminated.
11. **Cores/Secondary Windings**. Cores for metering purposes are usually made of a nickel alloy, which provides low saturation levels and low losses, resulting in high accuracy. Protection cores are made of high grade grain-oriented steel. Protection cores with air gaps for special applications can be included. The secondary winding consists of double-enameled copper wire, evenly distributed around the whole periphery of the core. The leakage reactance in the winding and also between taps in the secondary winding is therefore negligible.
12. **Earth Terminal**. This is the earthing terminal for the current transformer and **not** the earth terminal for the secondary winding.

Theory of Operation

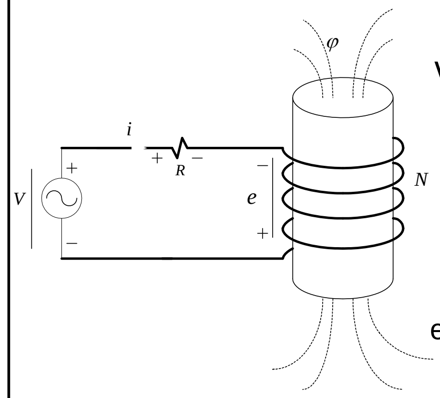


$$e_1 := N_1 \cdot \frac{d\varphi}{dt} \qquad \varphi_m := \frac{N_1 \cdot i_1}{\Re}$$

$$e_2 := N_2 \cdot \frac{d\varphi}{dt} \qquad \varphi_m := \frac{N_2 \cdot i_2}{\Re}$$

$$\frac{e_1}{e_2} := \frac{N_1}{N_2} \qquad \frac{N_1}{N_2} := \frac{i_2}{i_1}$$

Basic Transformer



$$v := iR - e$$

$$e := -N\frac{d\varphi}{dt}$$

$$\varphi := \varphi_{MAX} \cdot \sin(\varpi t)$$

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

$$B := \varphi \cdot Area$$

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

$$\varpi := 2\pi f$$

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

Theory of Operation

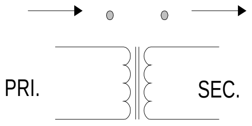
- When a time varying current I_p flows, a magnetomotive force (mmf) is developed by: MMF = $I_p * N_p$.
- The primary mmf creates a magnetic flux Φ_p in the core given by: Φ_p = MMF/R_m where R_m is the core reactance.
- The direction of Φ_p is determined by the right hand rule.
- Φ_p Links the secondary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

Theory of Operation

- 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
  - » $I_e * N_p/N_s = I_p * N_p/N_s - {}_{Is}$
  - » $I_s = I_p * N_p/N_s$ if I_e is small

Polarity

- 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:

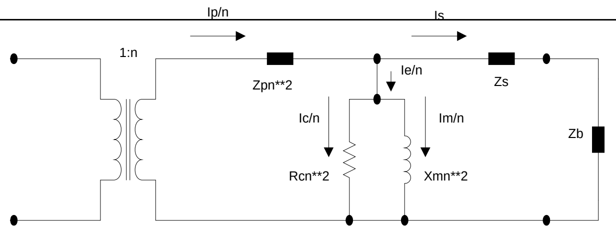


Hint: Direction of the secondary current can determined as if the two polarity terminals formed a continuous circuit

Equivalent Model

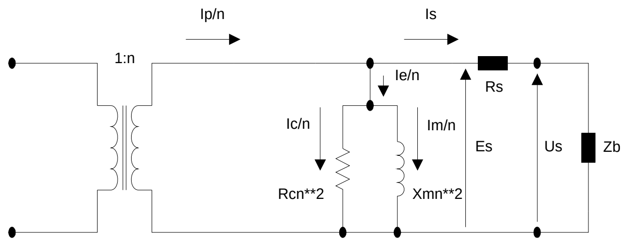
- The transformation of current induces errors. Some energy form the primary winding is used to:
  - » Establish magnetic flux in the core.
  - » Change the direction of the magnetic flux in the core named hysteresis losses.
  - » Generate heat due to eddy currents.
  - » Establish leakage flux.
- To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

Equivalent Model



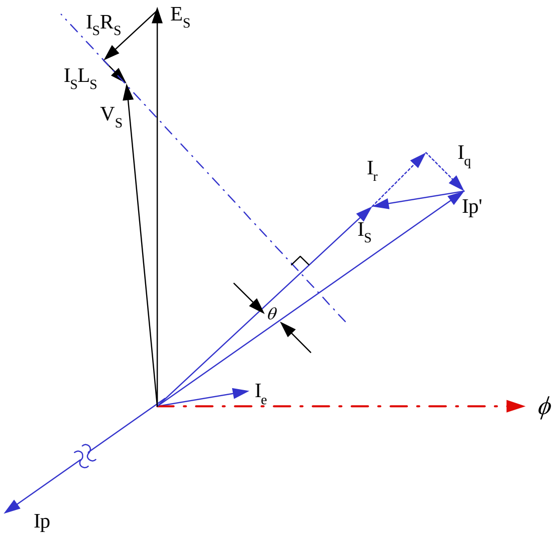
- The primary current Ip is stepped down in magnitude by 1:n through a no-loss transformer.
  - » Zpn**2 - primary winding impedance
  - » Zs - secondary winding impedance
  - » Rcn**2 - hysteresis and eddy current losses referred to the secondary
  - » Xmn**2 - magnetic reactance accounting for losses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

Equivalent Model

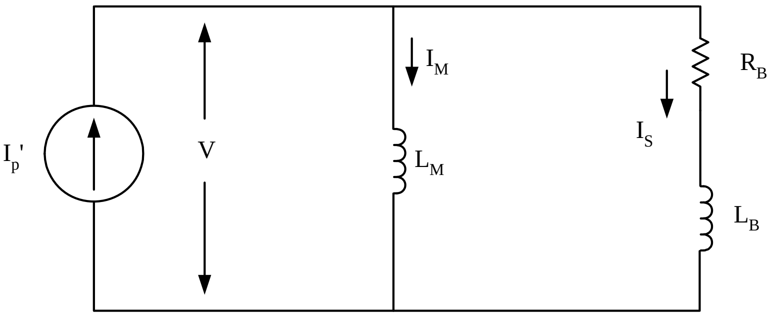


- If the secondary winding is uniformly distributed on the core, Zs is resistive = Rs.
- The voltage drop across the primary winding is negligible to the source voltage to which it is connected and does not effect current flow, Zp/n**2 = 0.
- The secondary current is reduced by the shunting current of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

Phasor Diagram CT



Simplified CT Equivalent Circuit



Voltage Equations

From Simplified Circuit

$$V = N_S\,\dot{\phi} = L_M\,\dot{I}_M \;....(1)$$

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

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

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

where:

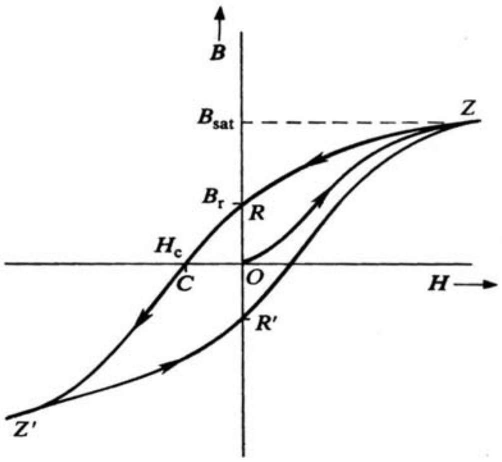
$$\mu = \frac{dB}{dH} := \frac{\Delta B}{\Delta H}$$

$A = \text{Area}$

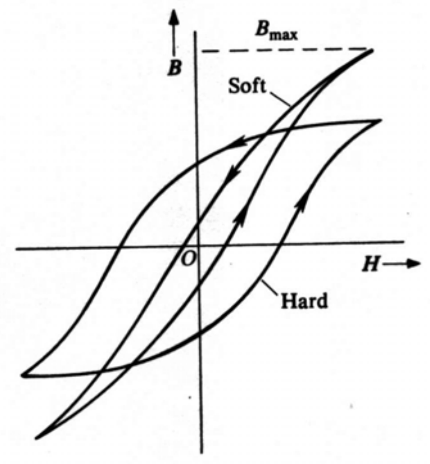
$\ell = \text{length}$

$\mathfrak{R} = \text{Reluctance}$

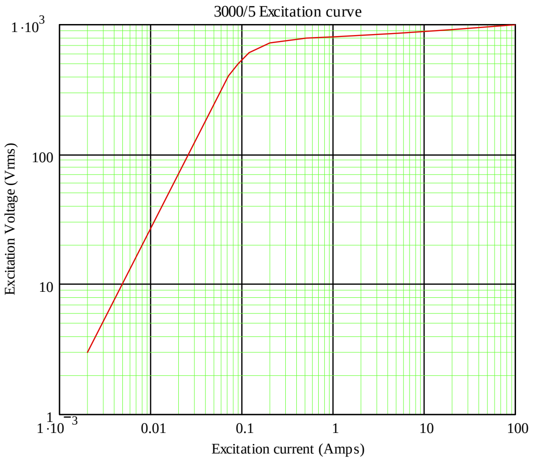
Complete Hysteresis Loop of Ferromagnetic Material



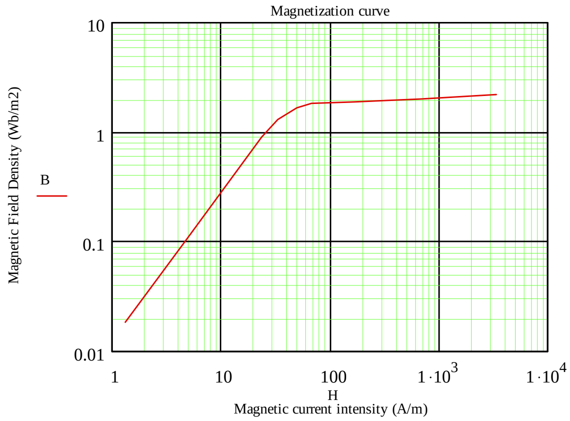
Hysteresis Loops for Hard and Soft Magnetic Material



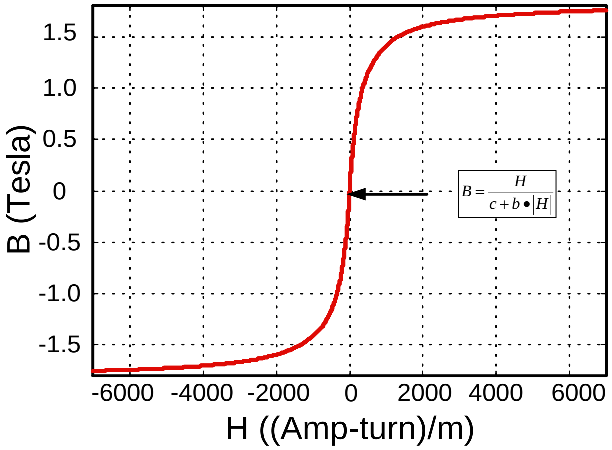
Magnetization Curve (1): Excitation Curve



Magnetization Curve (1)



Magnetization Curve (2)



Determining the Permeability Using the Frolich Equation

$$\mu = \frac{\left(1 - b\left|B\right|\right)^2}{c}$$

$$c = \frac{1}{\mu_i \mu_0}$$

$$b = \frac{1 - \frac{1}{\sqrt{\mu_i}}}{B_{SAT}}$$

Secondary Current

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

$$---- := L_M \cdot \frac{N_P}{N_S} \cdot \dot{I}_P - L_M \cdot \dot{I}_S$$

$$N_S \cdot \dot{B} \cdot A := L_M \cdot \left[\frac{N_P}{N_S} \cdot \dot{I}_P - \dot{I}_S\right]$$

$$\dot{B} := \frac{L_M}{N_S \cdot A} \cdot \left[\frac{N_P}{N_S} \cdot \dot{I}_P - \dot{I}_S\right] \text{.........(3)}$$

$$N_S \cdot \dot{\phi} := I_S \cdot R_S + \dot{I}_S \cdot L_S$$

$$N_S \cdot \dot{B} \cdot A := I_S \cdot R_S + \dot{I}_S \cdot L_S$$

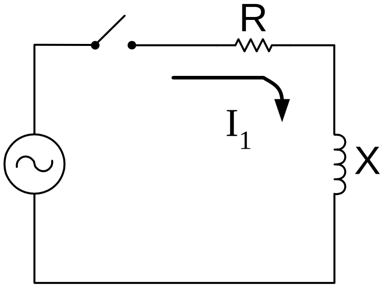
$$\dot{I}_S := \frac{1}{L_S} \cdot \left[N_S \cdot \dot{B} \cdot A - I_S \cdot R_S\right] \text{.........(4)}$$

Flux Density and Secondary Current

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

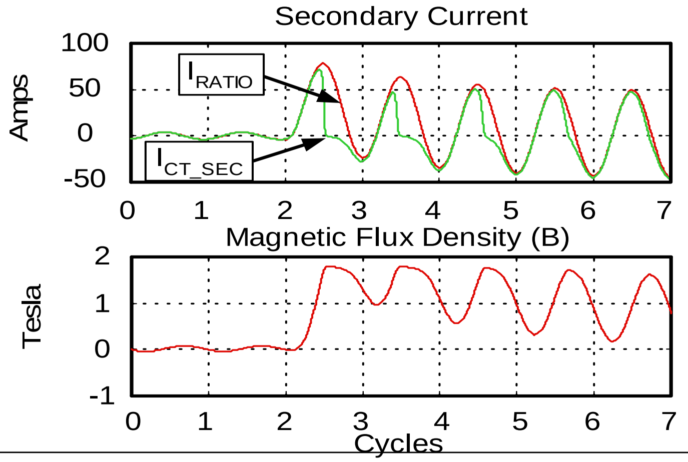
$$\dot{I}_S = \frac{N_P N_S \mu A \dot{I}_P - \ell R_S I_S}{\ell L_S + N_S{}^2 \mu A}$$

Fault Current Components

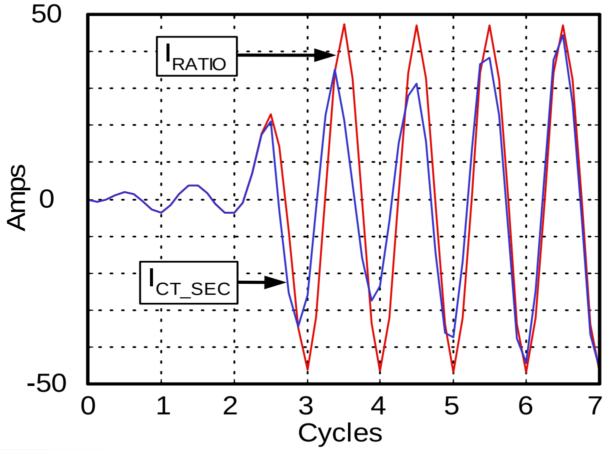


$$I = \sqrt{2} I_1 \left[\sin(\omega t + \phi - \theta) - e^{-\frac{t}{\tau}} \sin(\phi - \theta) \right] \qquad \theta = \tan^{-1}\left(\frac{X}{R}\right)$$

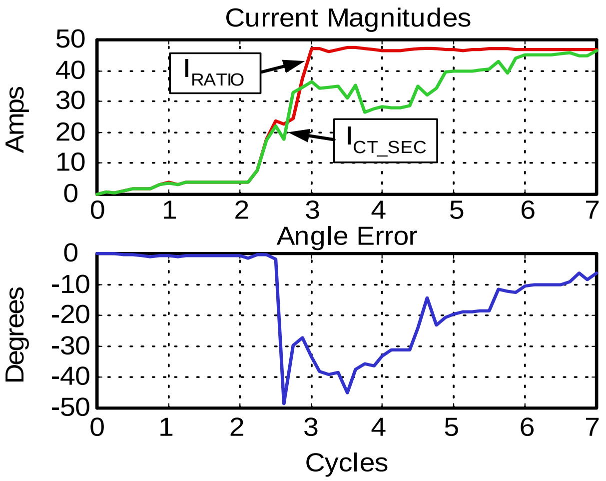
CT Response During Fault Condition



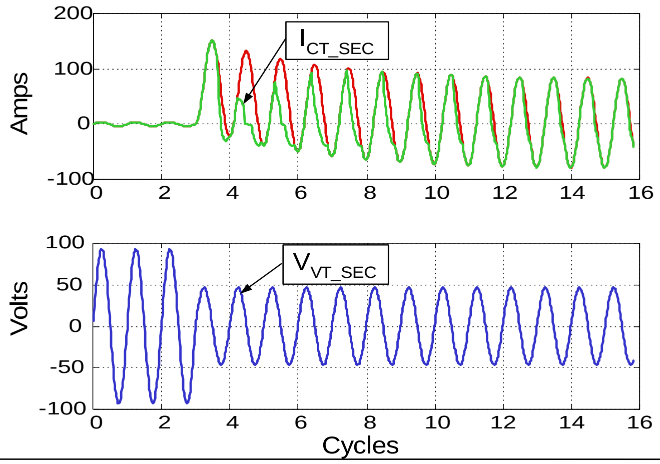
Filtered Currents



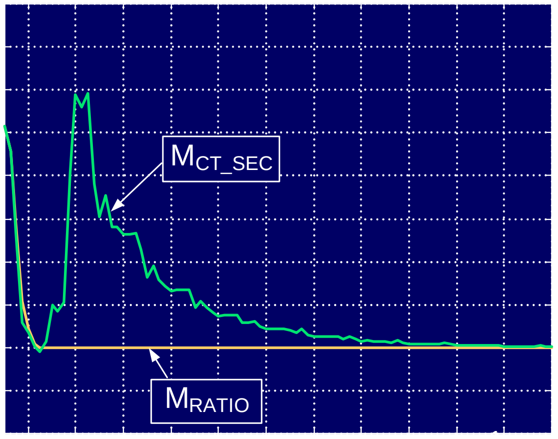
Current Mag. and Angle Error



Secondary Current and Voltage Signals



Distance Element Response



Effects of CT Saturation

Current signal has reduced magnitude

Current signal has angle error

CT saturation causes distance element underreach

What Do I Need to Know to Select a Correct CT

- Maximum fault current
- Systems X/R ratio
- CT burden

CT Core Flux

$$i_S := I\hat{s} \cdot [(\sin \varpi t - \frac{\pi}{2}) + e^{-\frac{R}{L} \cdot t}]$$

$$\phi := k \int v dt$$

$$\phi_{ss} := k \int I\hat{s} \cdot \sin(\varpi t - \frac{\pi}{2}) \cdot R_B dt$$

$$\phi_{ts} := k \int I\hat{s} \cdot e^{-\frac{R}{L} \cdot t} \cdot R_B dt$$

$$\frac{\phi_{ts}}{\phi_{ss}} := \frac{\varpi L}{R} := \frac{X}{R}$$

$$\phi_{ss} := \frac{k \cdot R_B \cdot I\hat{s}}{\varpi}$$

$$\phi_{ts} := \frac{k \cdot R_B \cdot I\hat{s} \cdot L}{R}$$

Total core flux:

$$\phi_c := \phi_{ss} + \phi_{ts} := \phi_{ss} \cdot \left[1 + \frac{X}{R}\right]$$

CT Requirement

When remanence is ignored:

$$V_S \geq \left[1 + \frac{X}{R}\right] \cdot I_S \cdot Z_{burden}$$

When remanence is considered:

$$V_S \cdot \left[1 - \frac{\%\mathrm{Remanance}}{100}\right] \geq \left[1 + \frac{X}{R}\right] \cdot I_S \cdot Z_{burden}$$

V_S = Saturation voltage

Accuracy

- Definition: Ability to reproduce the primary current in secondary amperes in both wave-shape and magnitude.
- ANSI/IEEE C57.13 designates two rating classes C or T describing capability.
  - » C: the ratio can be calculated, leakage flux is negligible due to uniform distribution of secondary winding.
  - » T: the ratio must be determined by test, leakage flux is appreciable due to undistributed windings.

Accuracy

- Designations are followed by a terminal voltage rating that the CT can deliver to a standard burden at 20 times rated secondary current without exceeding 10% ratio correction.
    - » Voltage classes are 100, 200, 400, 800

Accuracy

- The burdens are in ohms and at a .5 pf.
    - » Standard burdens are B-1, B-2, B-4, B-8
- Example:
    - » C800: 800 V/ 5 A * 20 = 8
    - » If current is lower the ohmic burden can be higher in proportion.
    - » Accuracy applies to the full winding. If a lower tap of a multiratio CT is used the voltage capability must be reduced proportionally.

ANSI Classification of CTs

At 800 V the CT will go into saturation

Rated burden calculation: $$Z_{\mathrm{rated}} := \frac{\mathrm{ANSI}_{\mathrm{Voltage}}}{20 \cdot I_{\mathrm{nom}}}$$

VA rating of CT calculated from rated burden:

$$VA_{\mathrm{rated}} := I_{\mathrm{nom}}^{2} \cdot Z_{\mathrm{rated}}$$

Percent error of the CT: by definition all C class CTs should not have more than 10% error at 20 x nominal current

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IEC Classification of CTs

Done by class, Accuracy Limit Factor, and VA

Example: 5P20, 40VA

- 5P = class
- 20 = Accuracy Limit Factor (ALF)
- At rated burden of 40VA, if current through CT is 20 x nominal current, maximum measurement error will be 5%

CT saturation voltage at rated burden:

$$V_{\mathrm{sat}} := \mathrm{ALF} \cdot \frac{VA_{\mathrm{rated}}}{I_{\mathrm{nom}}}$$

Open Circuit Voltage

- Open secondary causes Φs to go to zero.
- Ip drives the core to saturation each half cycle.
- The action of Ip changing from maximum to zero back to maximum causes Φp to change from saturation in one direction to its saturated value in the opposite direction.
- The rapid rise of Φp induces high voltage spikes in the secondary winding.
- A formula for peak voltage derived from CT tests is:

$$Vpeak = \sqrt{3.5 \times Zb \times Ip / n}$$

- Tests have shown values ranging fron 500 to 11,000 volts.