University of Idaho

ECE 525

POWER SYSTEM PROTECTION AND RELAYING

SESSION no. 8

Simple Digital Filter Calculation

$RS := 16$ — Enter the number of samples per cycle of the relay

$LPW := \text{floor}\left(\frac{2}{60 \cdot \Delta t \cdot RS}\right)$ — Calculate the number of samples to create an averaging LP filter with at cutoff frequency at 1/2 the sampling frequency.

$LP(a) := \left(1 + \frac{1}{RS}\right) \cdot \sum_{k=0}^{LPW-1} \frac{Is_{a-LPW+k}}{LPW}$ — Averaging Filter

$ii := LPW .. \text{ceil}\left(\frac{CY}{f \cdot \Delta t}\right)$

$I_{ii} := LP(ii)$ — Calculate filtered current

cycles

$S := CY \cdot RS$ — Calculate the number of relay samples available in the data and create an index "s" as a row pointer

$s := 2 .. S$

$Ia_s := \text{linterp}\left(t, I, \frac{s}{RS \cdot 60}\right)$ — Create a vector "Ia" representing the relay's sampled values

$if := (RS - 1) .. S$ — Create a filter index, "if" and apply a full cycle cosine filter, "IF" to vector "Ia"

$IF_{if} := \frac{2}{RS} \cdot \sum_{k=0}^{RS-1} \left[\cos\left(k \cdot \frac{2 \cdot \pi}{RS}\right) \cdot Ia_{[if-(RS-1)]+k}\right]$ — Cosine Filter

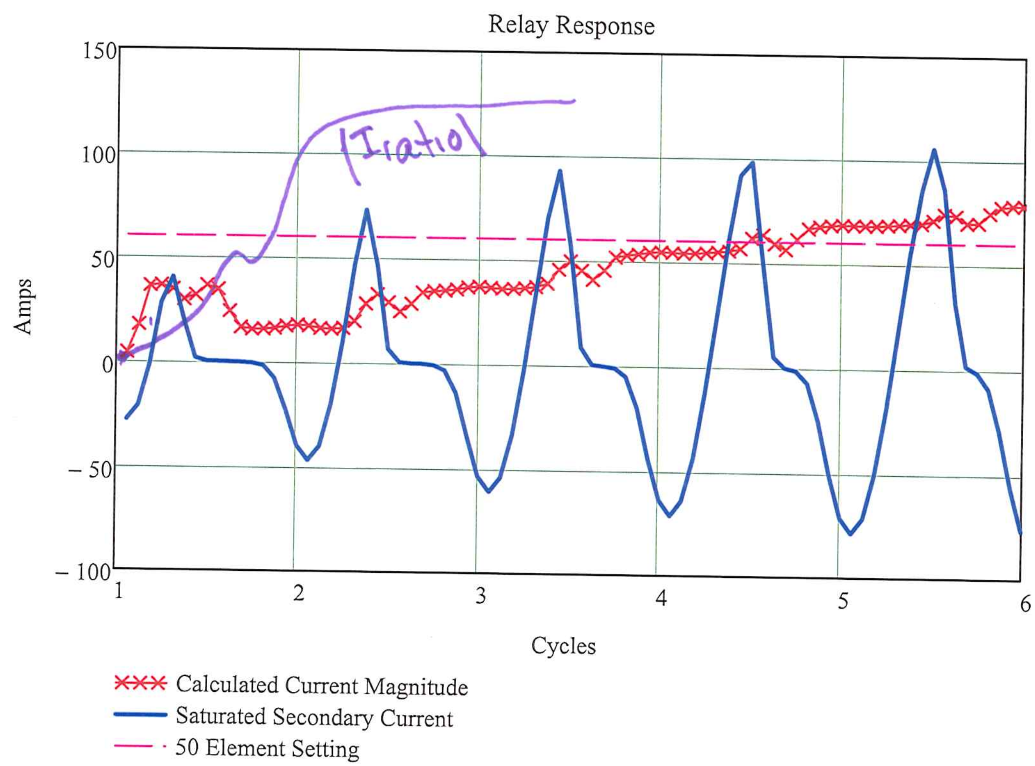
digital cosine filter

$iv := (RS + 1) .. S$ — Create a vector index, "iv" and form a complex vector, "Icpx" from filtered quatities at 90 degree intervals

$Icpx_{iv} := IF_{iv} + j \cdot IF_{iv - \frac{RS}{4}}$

Iphasor = cosine + j sine

cosine filter outp — delayed by 90° — output of cosine filte


Relay Response
150
100
50
0
– 50
– 100
Amps
1
2
3
4
5
6
Cycles
|Iratio|
Calculated Current Magnitude
Saturated Secondary Current
50 Element Setting

L8 3/18

ECE 525: Lecture 6

ORIGIN := 1

CT Data: C600 class, 1200/5

Full ratio: $N_{full} := \frac{1200}{5}$ $N_{full} = 240$

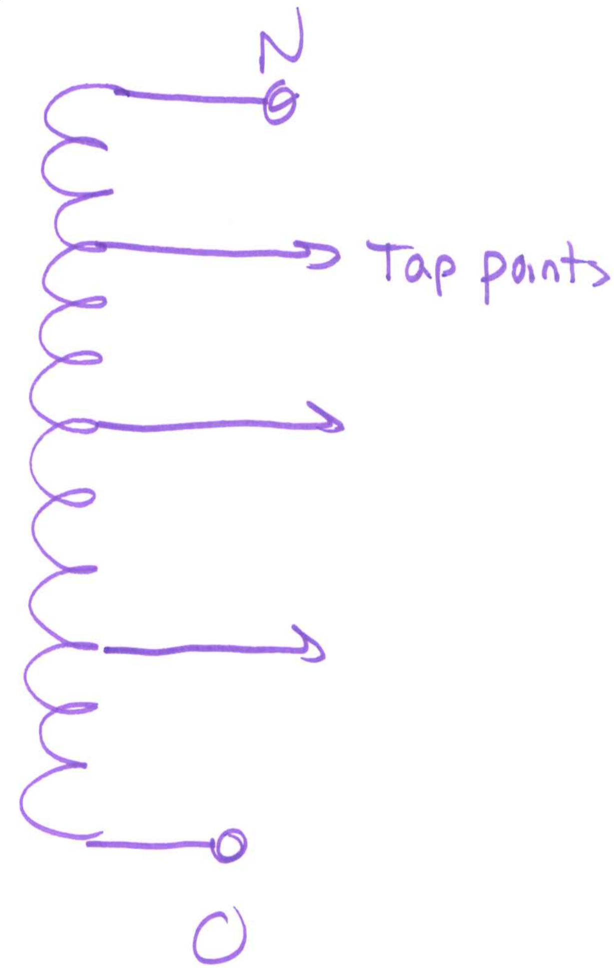
CT Excitation Curve

Im V

$$\text{excitation} := \begin{pmatrix} .001 & 0.09 \\ .04 & 90 \\ .1 & 428 \\ .12 & 520 \\ .14 & 600 \\ .2 & 700 \\ .3 & 780 \\ .4 & 800 \\ 40 & 927 \end{pmatrix}$$

TAPS

$$t := \begin{pmatrix} 240 \\ 200 \\ 180 \\ 160 \\ 120 \\ 100 \\ 80 \\ 60 \\ 40 \\ 20 \end{pmatrix}$$



$$v_t(N2) := \left(\frac{N2}{t_1}\right) \cdot \text{excitation}^{\langle 2 \rangle}$$

$$Im_t(N2) := \left(\frac{t_1}{N2}\right) \cdot \text{excitation}^{\langle 1 \rangle}$$

$t_{[1}$ ~ 1st point in vector t

$turn := 1$

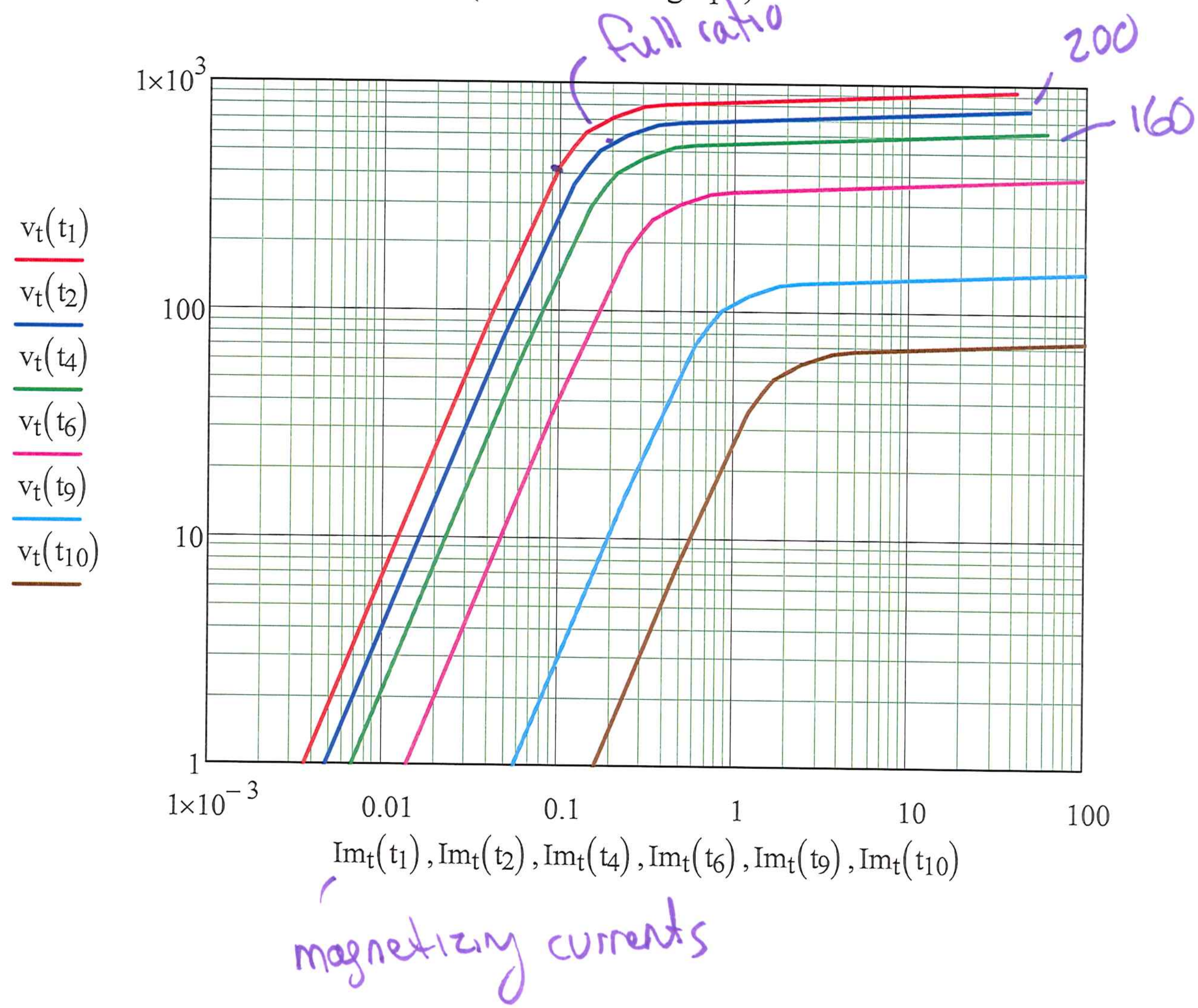
$R_{turn} := 0.0024 \frac{ohm}{turn}$ Full winding: $R_{secondary} := R_{turn} \cdot 240turn$ $R_{secondary} = 0.58\,\Omega$

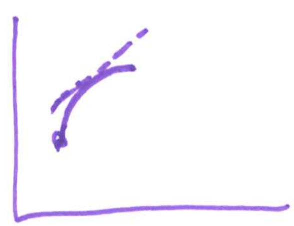
$V_{1200} := 428V$ at the bottom of the knee of the saturation curve (read from the graph)

$V_{per\_turn} := \frac{V_{1200}}{240turn}$

$V_{per\_turn} = 1.783\,V$

- Notice that the knee is at 600V for full tap





L8 8/8

ECE 525: Lecture 8

- For C-class current transformers, the CT is rated such that the error in the secondary current will be less than 10% if the 20 times rated current flows through a standard burden.
- This should be adjusted to account for the effect of the decaying offset.
- So the equation to never saturate is:

$$R_{totalburden\_pu} \cdot I_{f\_pu} \cdot \left(1 + \frac{X_{system}}{R_{system}}\right) < 20$$

Assuming that the inductance in the CT secondary windings, lead wire and relay can be neglected, the voltage across the CT equivalent circuit magnetizing branch is:

$$v_m(t) = i_{secondary}(t) \cdot (R_{ct} + R_b) \qquad \text{where:} \qquad R_b = R_{lead} + R_{relay}$$

We want to get a measure of how long it takes the CT to saturate if it not sized to meet the above equation.

Equation for current with the DC offset: dc offset

$$i_{secondary}(t) = I_{fmax\_sec} \cdot \left(e^{\frac{-t}{T_p}} - \cos(\omega \cdot t)\right)$$

60Hz

- Assumes fault timing for worst DC offset.

The paper: Juergen Holbach, "Modern Solutions to Stabilize Numerical Differential Relays for Current Transformer Saturation during External Faults", *2006 Power Systems Conference: Advanced Metering, Protection, Control, Communication, and Distributed Resources*, gives the following three equations for estimating the time to saturation for a CT:

The notes included several equations that could be used to describe what the author called "V_{knee}".

$$v_{sat1}(t_s) = I_{fmax\_sec} \cdot R_b \cdot \left[(-XoverR) \cdot \left(e^{\frac{-t_s}{T_p}} - 1\right) + 1\right]$$

Saturation free > 12 ms

not per unit

$$v_{sat2}(t_s) = I_{fmax\_sec} \cdot R_b \cdot \left[(-XoverR) \cdot \left(e^{\frac{-t_s}{T_p}} - 1\right) - \sin(\omega \cdot t_s)\right]$$

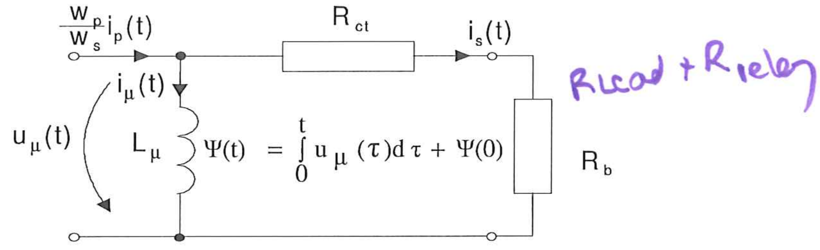
Saturation free 7-12 ms

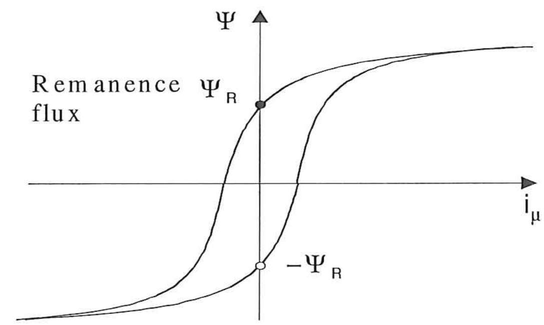
$$v_{sat3}(t_s) = I_{fmax\_sec} \cdot R_b \cdot (1 - \cos(\omega \cdot t_s))$$

Saturation free < 7ms

L8 6/18

Current transformer equivalent circuit and magnetising characteristic



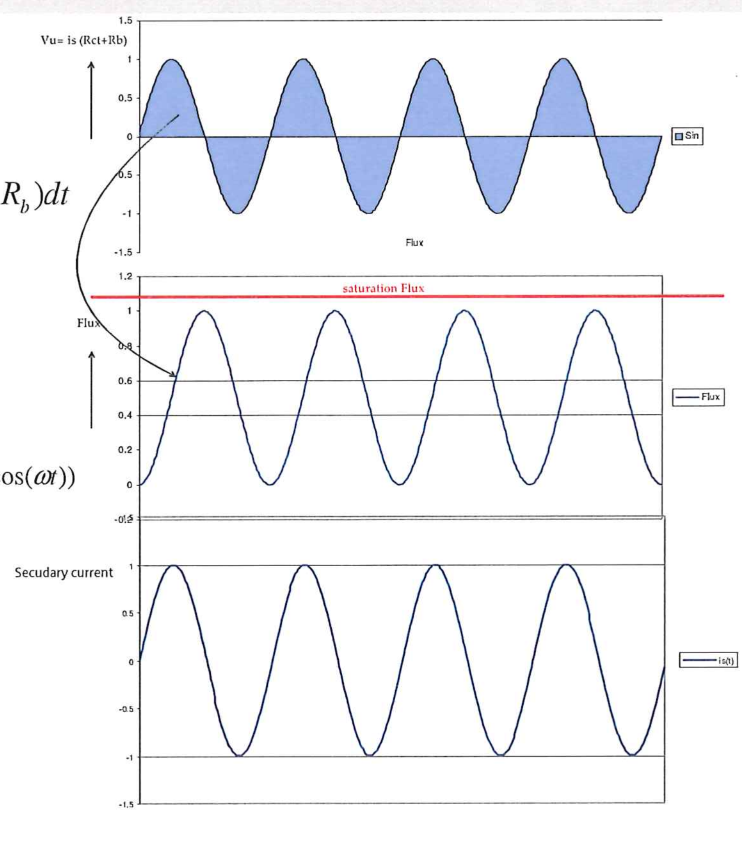


Voltage and flux under unsaturated condition

$$Flux = \int v_\mu(t)dt$$
$$= \int i_s(t) \cdot (R_{CT} + R_b)dt$$

$$for \quad i_s(t) = I\sin(\omega t)$$

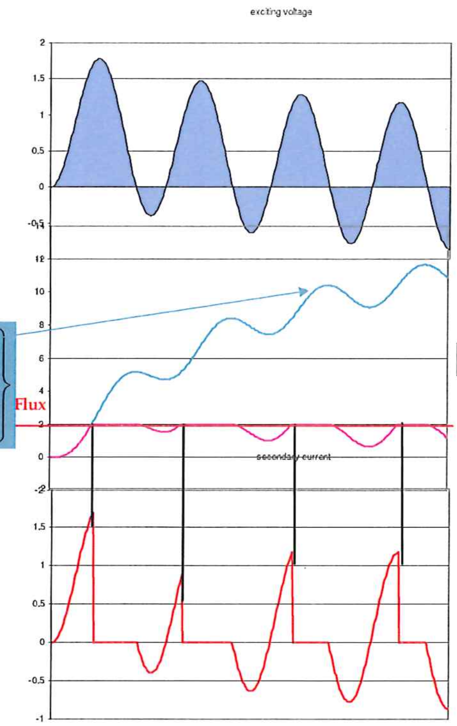
$$Flux = \frac{I \cdot (R_{CT} + R_b)}{\omega}(1 - \cos(\omega t))$$



DC-Offset

$$Flux = \int v_{\mu}(t)dt$$
$$= \int i_s(t) \cdot (R_{CT} + R_b)dt$$
$$i_s(t) = I\left(e^{-\frac{t}{T_P}} - \cos(\omega t)\right)$$

$$V_{knee} = I(R_{CT} + R_b)\left\{\left[-\omega T_p\right]\left(e^{-\frac{t}{T_P}} - 1\right) - \sin(\omega t)\right\}$$

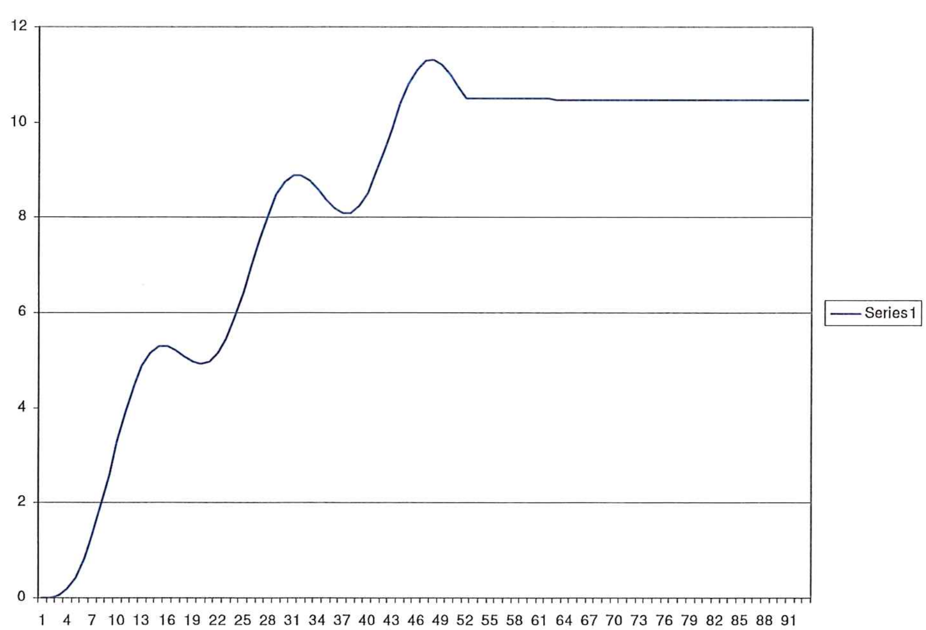


For no saturation at all : Set t=infinitive and -sin(wt)=1

$$V_{knee} = I(R_{CT} + R_b)\left[1 + \omega T_p\right] or$$
$$V_{knee} = I(R_{CT} + R_b)\left[1 + \frac{X}{R}\right]$$

Remanence

The flux inside the CT will not go to zero after the fault current is interrupted!



Considering remanence flux

$$K_{\text{Remanece}} = \frac{100}{100 - \text{Prozent } of \text{ Remanence}}$$

Percent

Example: Worst case of remanence (iron closed CT's) = 80%

$$K_{\text{Re}manece} = \frac{100}{100-80} = 5$$

CT dimensioning for no saturation under all worst case condition

Example: Isc=20000A, CT ratio =1000/5, RCT=0.5 Ohm, Rb=0.5 Ohm
Tp=60ms, iron closed CT

1. considering DC offset

$$V_{knee} = I(R_{CT} + R_b)[1 + \omega T_p]$$
$$V_{knee} = 100A \cdot 1Ohm(1 + 22.6) = 2260V$$

2. considering 80% remanence

$$K_{\text{Re}manece} = \frac{100}{100-80} = 5 \qquad \Rightarrow \quad V_{knee} = 5 \cdot 2260V = 11300V$$

The dimension of a CT that will not saturate for the maximum short circuit current that has a full DC offset with a long time constant and is at 80% in remanence, will lead to uneconomical and oversized CT's.

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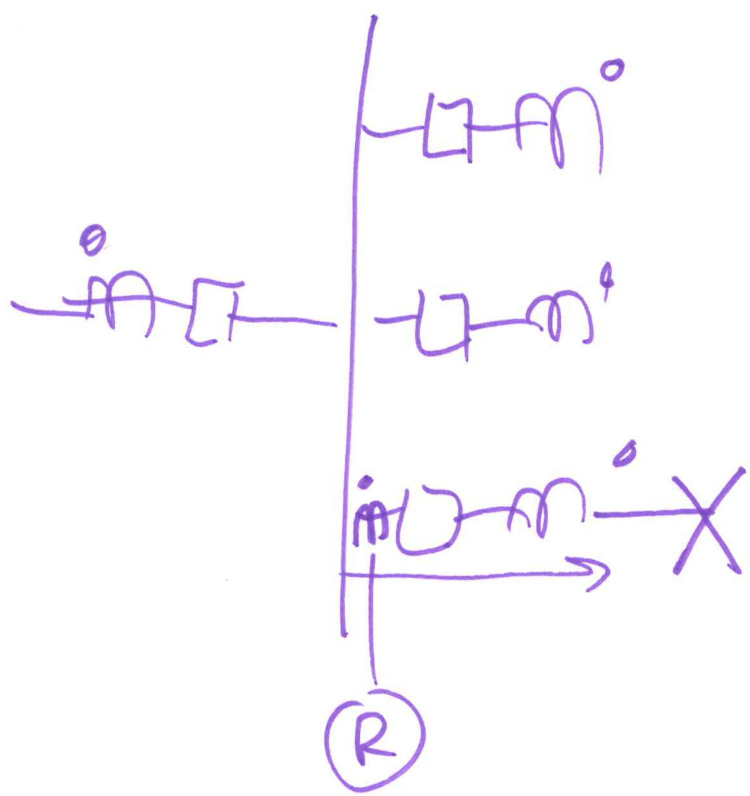
L8 9/18



With consideration of saturation free time tsat

The requirement that no saturation is allowed will lead to uneconomical and oversized CT's

$$V_{knee} = I(R_{CT} + R_b)\left[1 + \frac{X}{R}\right]$$

Modern numerical relays only require a certain saturation free time tsat. The following formula takes this into consideration:

$$V_{knee} = I(R_{CT} + R_b)\left\{\left[-\omega T_p\left(e^{-\frac{t_{sat}}{T_P}} - 1\right) - \sin(\omega t_{sat})\right\}$$

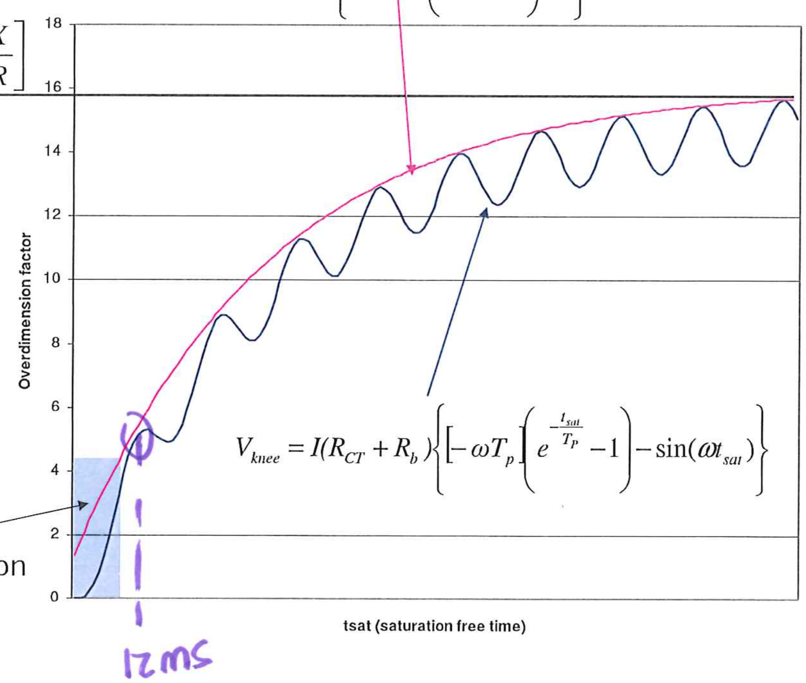
Many times a simplified version where –sin(wt) is replaced by 1 is used

$$V_{knee} = I(R_{CT} + R_b)\left\{\left[-\omega T_p\left(e^{-\frac{t_{sat}}{T_P}} - 1\right) + 1\right\}$$

What does the different formulas describe?

$$V_{knee} = I(R_{CT} + R_b)\left\{\left[-\omega T_p\left(e^{-\frac{t_{sat}}{T_P}} - 1\right) + 1\right\}$$

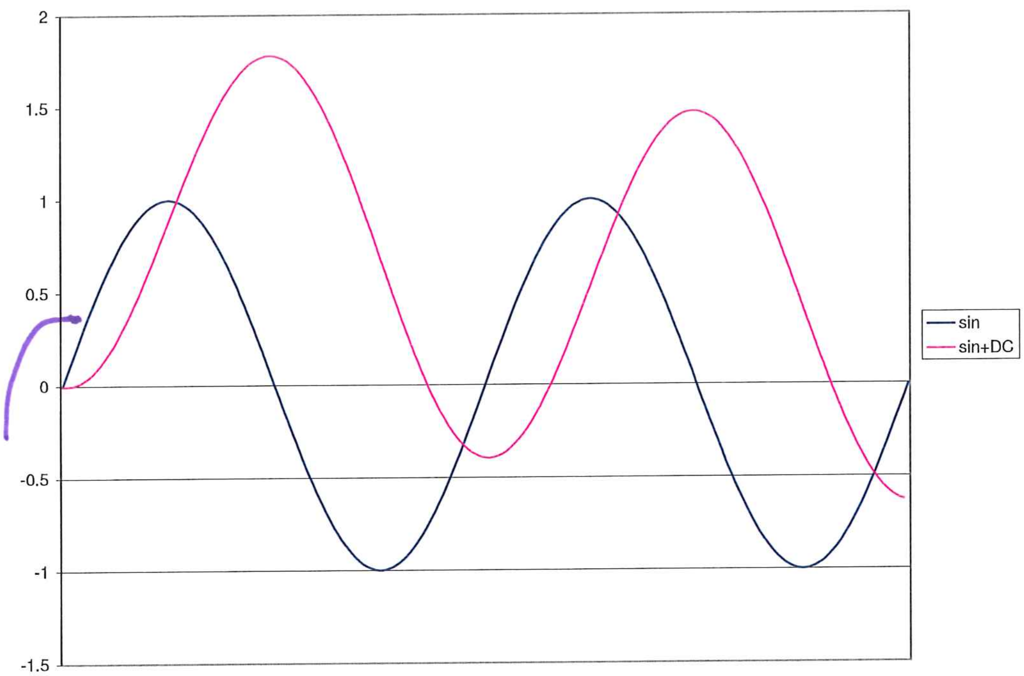
$$V_{knee} = I(R_{CT} + R_b)\left[1 + \frac{X}{R}\right]$$



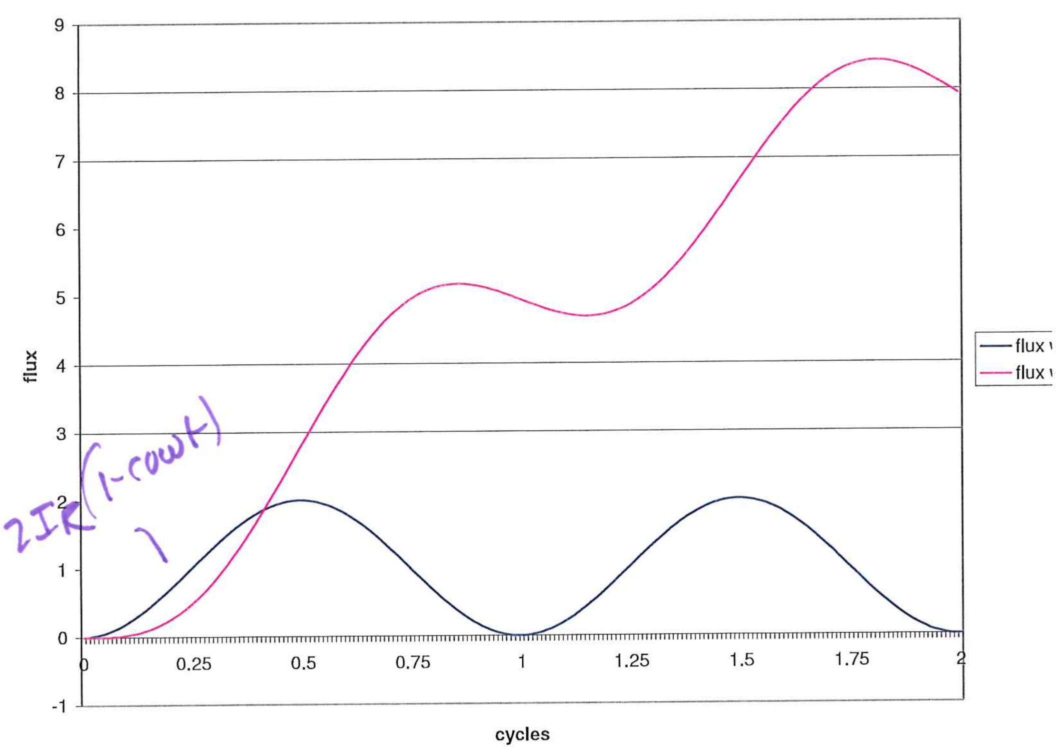
$$V_{knee} = I(R_{CT} + R_b)\left\{\left[-\omega T_p\left(e^{-\frac{t_{sat}}{T_P}} - 1\right) - \sin(\omega t_{sat})\right\}$$

Special consideration needed

Saturation free times < 7ms



Flux for saturation free time <7 ms



Which formula should be applied

No saturation

$$V_{knee} = I(R_{CT} + R_b)\left[1+\frac{X}{R}\right]$$

Saturation free time > 12ms

$$V_{knee} = I(R_{CT} + R_b)\left\{\left[-\omega T_p\right]\left(e^{-\frac{t_{sat}}{T_P}} - 1\right) + 1\right\}$$

Saturation free time between 7-12 ms

$$V_{knee} = I(R_{CT} + R_b)\left\{\left[-\omega T_p\right]\left(e^{-\frac{t_{sat}}{T_P}} - 1\right) - \sin(\omega t_{sat})\right\}$$

Saturation free time < 7ms

$$V_{knee} = I(R_{CT} + R_b)[1 - \cos(\omega t_{sat})]$$

Influence of CT saturation on protection

- Distance protection
  - Close in faults
    - Direction has to be correct
    - High speed tripping decision before saturation
  - Zone end fault
    - Accuracy and timing will be effected
- Overcurrent protection
  - based on RMS or fundamental
  - 50 element not influenced if remaining current is above pickup
  - 51 element experienced an additional time delay
- Differential protection
  - Critical for the security of the protection!

L8 12/18

- They are not exactly a voltage. This is better described as the ***Volt-Time Area***
- If you are working from measured data:

$$VTA(x) = \sum_{j=0}^{x} \left(V_{sec_j} \cdot \Delta t\right)$$

Δt is the sampling rate

- A more general equation is

$$B_s \cdot N \cdot Area \cdot \omega = \omega \cdot I_{fmax\_sec} \cdot R_b \cdot \left(e^{\frac{-t}{T_p}} - \cos(\omega \cdot t)\right)$$

  - So this works out to be the flux as a function of time, multiplied times the frequency
  - Adding the frequency covers the summation of time slices

Example

total burden

$R_b := 5ohm$ $\qquad CTR := \frac{1200}{5}$ $\qquad CTR = 240$

$I_{fmax\_sec} := 18 \cdot 5A$ $\qquad I_{fmax\_sec} = 90\,A$ RMS

$I_{fP} := CTR \cdot I_{fmax\_sec}$ $\qquad I_{fP} = 21.6 \cdot kA$

- Fault current referred to primary

$I_{fmax\_sec} \cdot \left(R_b\right) = 450\,V$

- If no DC offset needs to be included

$XoverR := 12$ $\qquad \omega := 2 \cdot \pi \cdot 60Hz$

$T_p := \frac{XoverR}{\omega}$ $\qquad T_p = 31.83 \cdot ms$

$I_{fmax\_sec} \cdot \left(R_b\right) \cdot (1 + XoverR) = 5850 \cdot V$

- Expensive custom order

- pu equation: $\frac{I_{fmax\_sec}}{5A} \cdot \left(\frac{R_b}{8ohm}\right) \cdot (1 + XoverR) = 146.25$

C800

L8 10/15

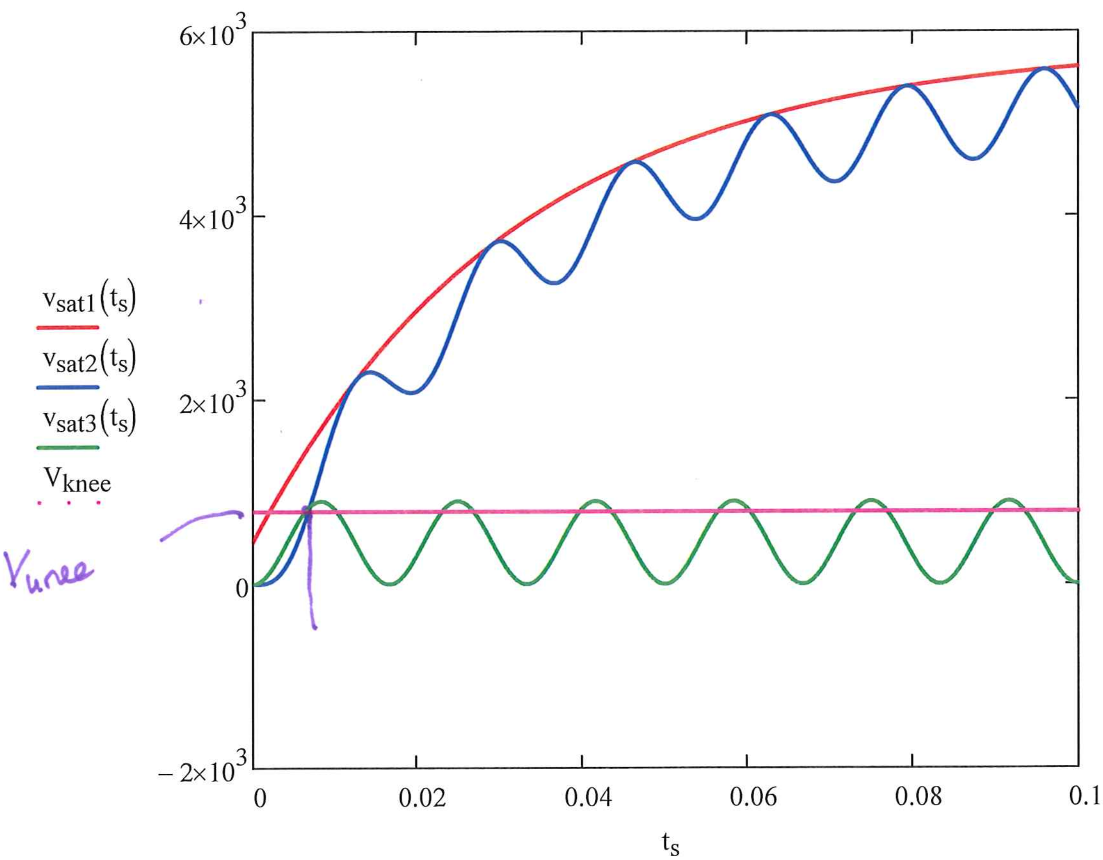
Now lets say we want $V_{knee} := 800V$

$$v_{sat1}(t_s) := I_{fmax\_sec} \cdot R_b \cdot \left[(-XoverR) \cdot \left(e^{\frac{-t_s}{T_p}} - 1\right) + 1\right]$$

$$v_{sat2}(t_s) := \left[I_{fmax\_sec} \cdot R_b \cdot \left[(-XoverR) \cdot \left(e^{\frac{-t_s}{T_p}} - 1\right) - \sin(\omega \cdot t_s)\right]\right]$$

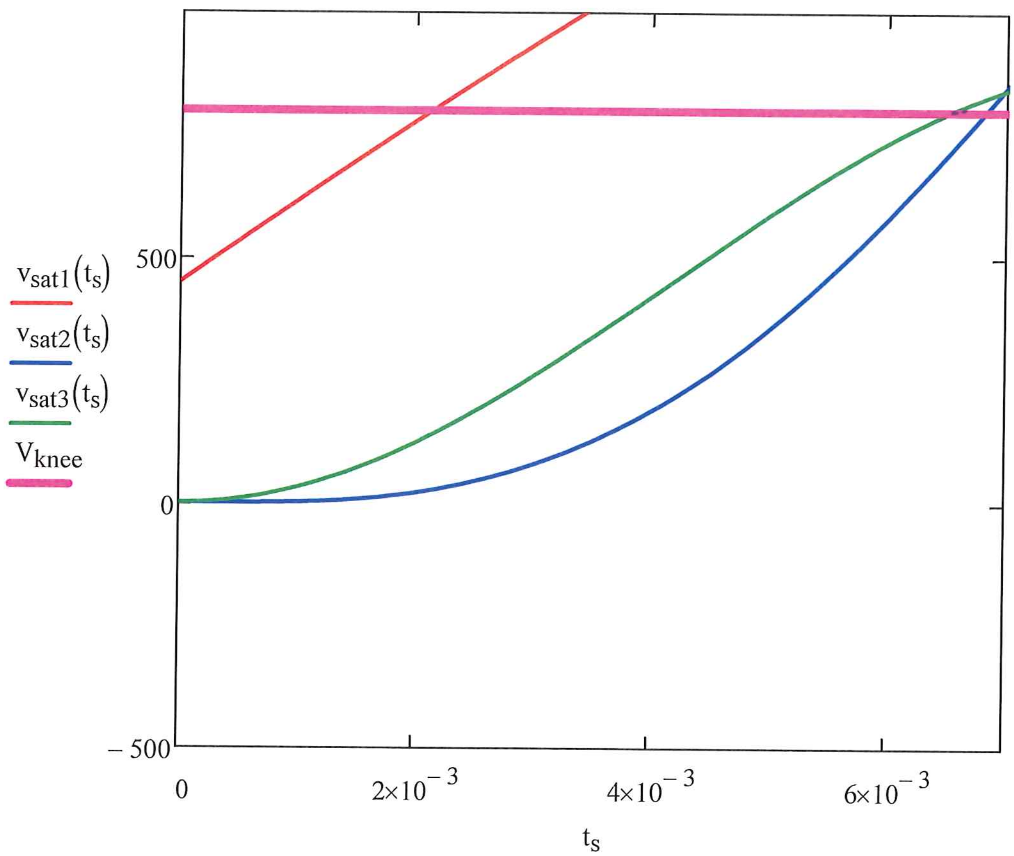
$$v_{sat3}(t_s) := I_{fmax\_sec} \cdot R_b \cdot (1 - \cos(\omega \cdot t_s))$$

$$t_s := 0ms, 0.1ms .. 100ms$$



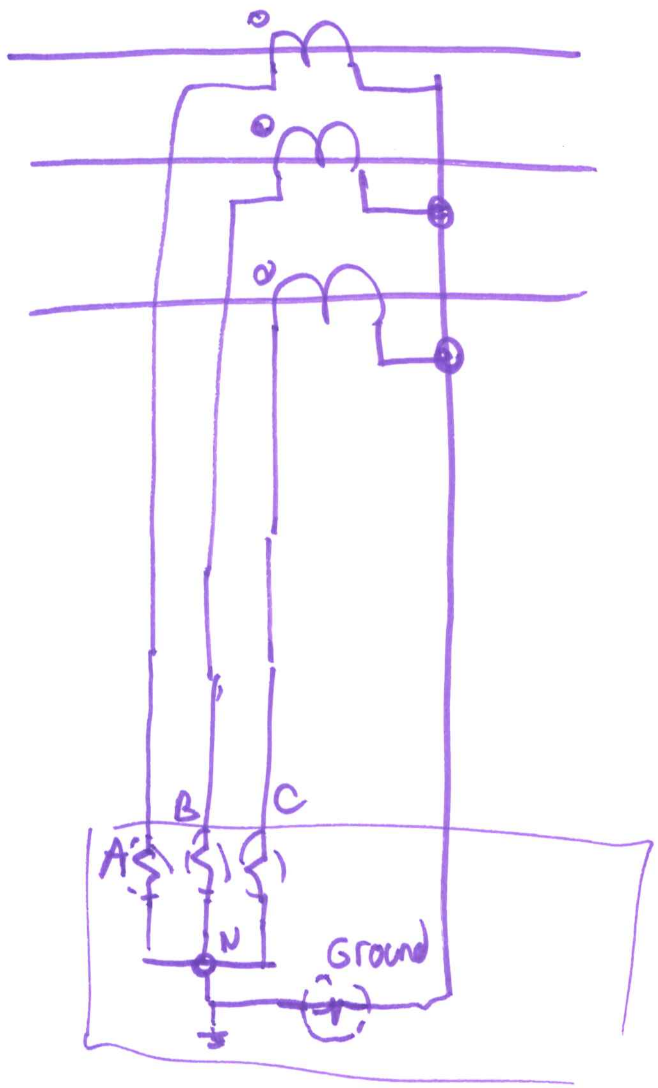
L8 8/15/18

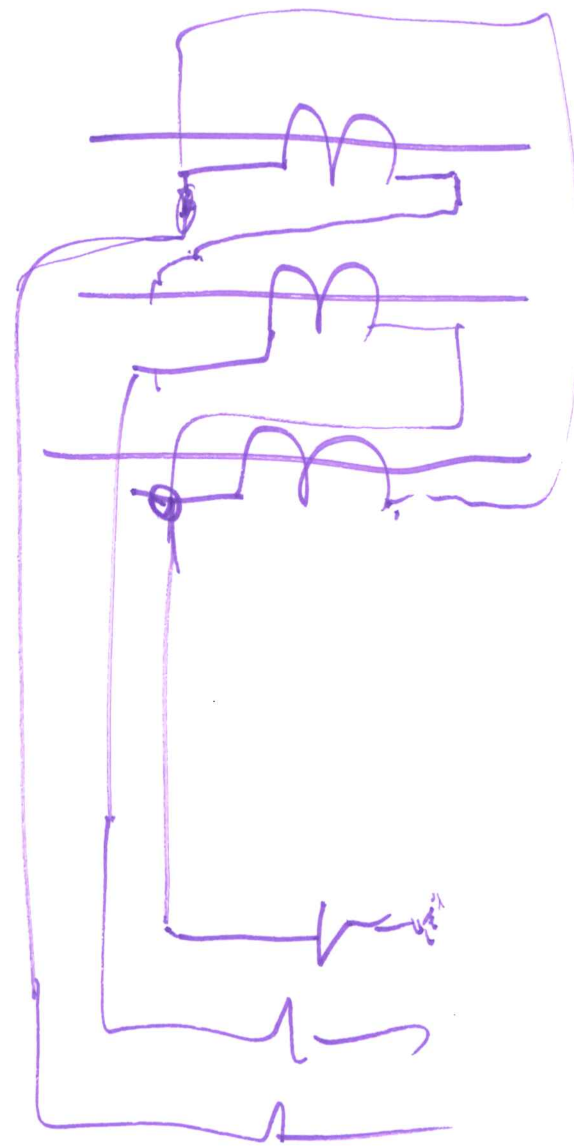
Zoom in to the beginning:

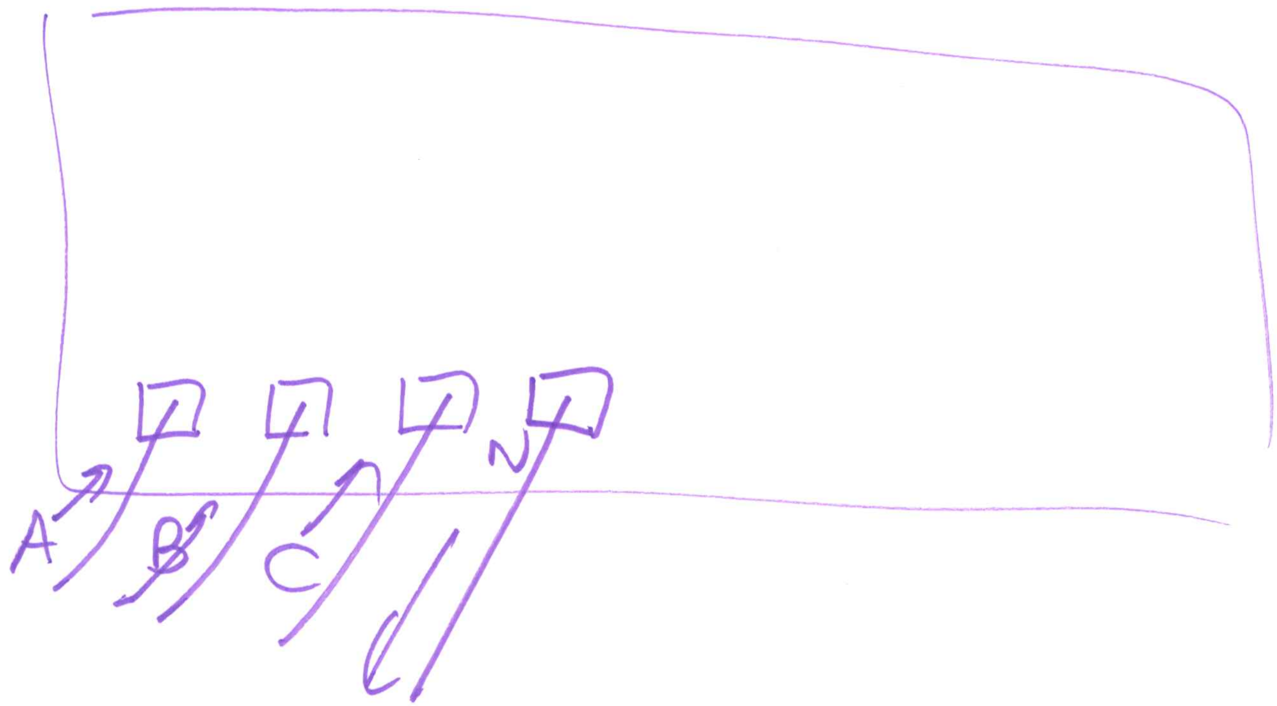


Saturation in 6.6 ms

CT connections






A
B
C
N

Ungrounded system (or high R grounded)