Current Transformers

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Power System Protection

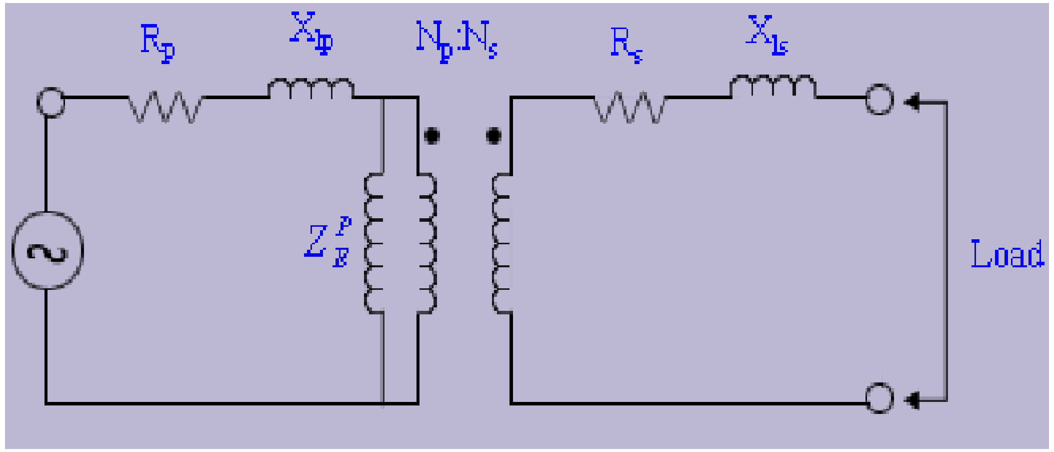
Introduction to Current Transformer

- Current and voltage signals are derived for all electrical measurements and relaying decisions
- Since relaying hardware works with smaller range of current (in amperes and not kA) and voltage (volts and not kV), real life signals (feeder or transmission line currents) and bus voltages have to be scaled to lower levels and then fed to the relays. This job is done by current and voltage transformers (CTs and VTs).
- CTs and VTs also electrically isolate the relaying system from the actual power apparatus and thus provides safety of both human personnel and the equipment as well.

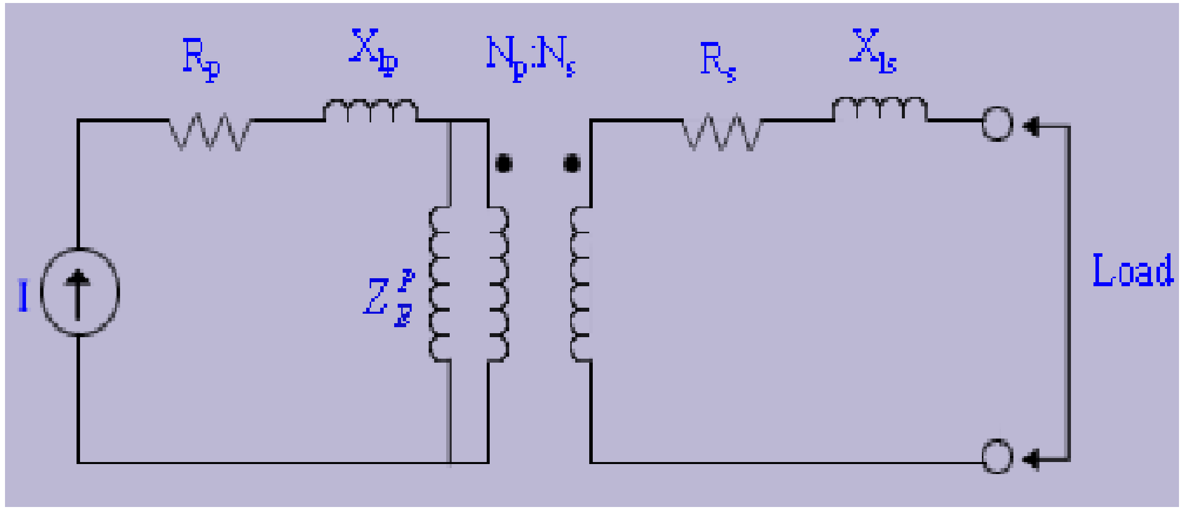
Introduction to Current Transformer

- CT and VTs are the sensors for the relay.
    - They function like ‘ears' and the ‘eyes' of the protection system. They listen to and observe all happening in the external world.
- Relay itself is the brain which processes these signals and issues decision commands implemented by circuit breakers, alarms etc.
- Clearly, quality of the relaying decision depends upon ‘faithful' reproduction on the secondary side of the transformer.

Equivalent Circuit of CT



<u>**Fundamental difference:**</u> **regular power transformers are excited by a voltage source, a current transformer has current source excitation**

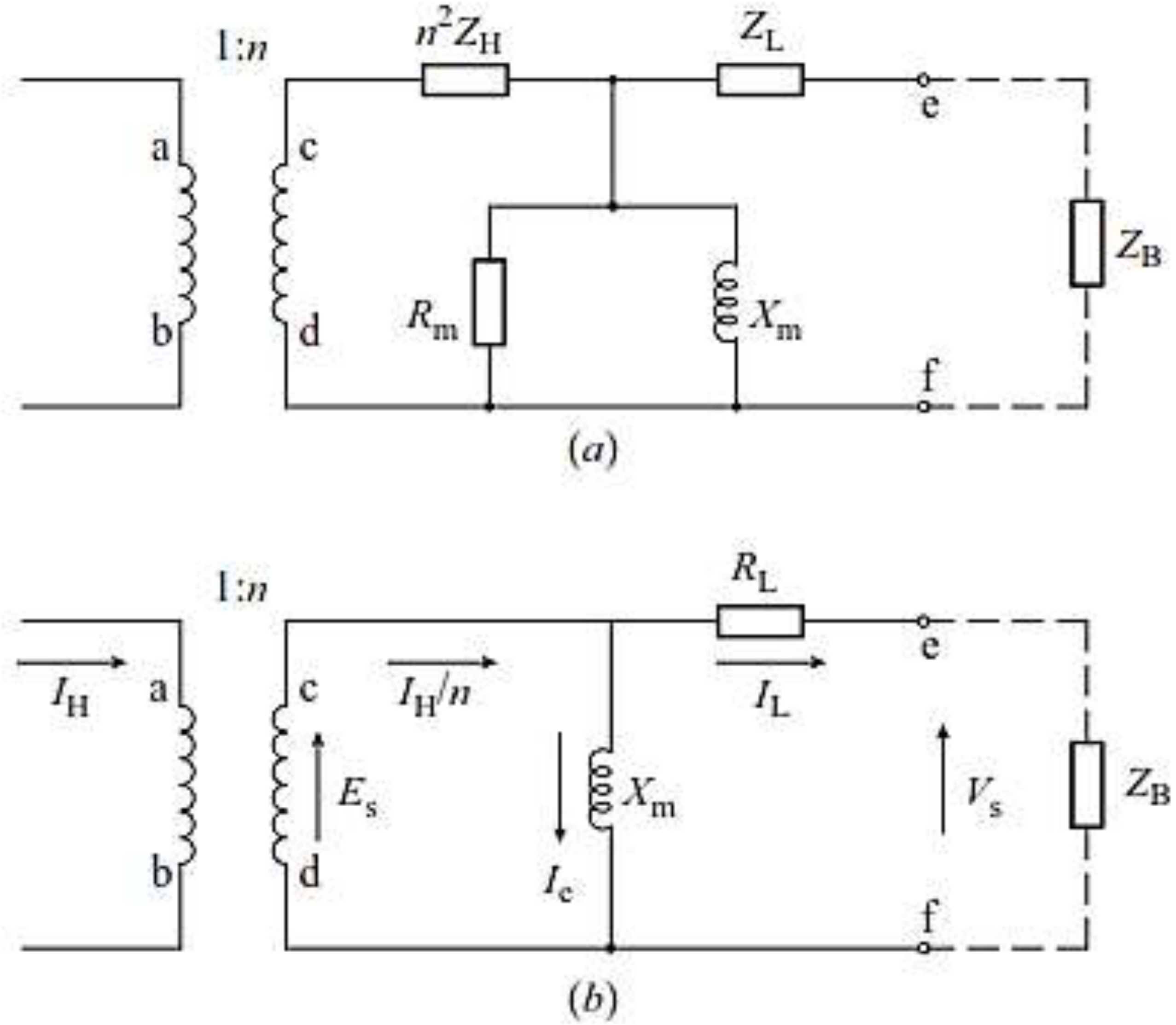


Primary winding of the CT is connected in series with the transmission line. The load on the secondary side is the relaying burden and the lead wire resistance.

Equivalent Circuit of CT

- Total load in ohms that is introduced by CT in series with the transmission line is insignificant and hence, the connection of the CT does not alter current in the feeder or the power apparatus at all.
- **From modeling perspectives:** reasonable to assume that CT primary is connected to a current source.
- The remaining steps in modeling are as follows:
  - As impedance in series with the current source can be neglected, we can neglect the primary winding resistance and leakage reactance in CT modeling.
  - For the convenience in analysis, we can shift the magnetizing impedance from the primary side to the secondary side of the ideal transformer

Equivalent Circuit of CT



Z_H can be ignored, since it does not influence either the current I/n *or the* voltage across $X_{m.}$. The current flowing through X_m is the excitation current I_e

Equivalent Circuit of CT

- Secondary winding resistance and leakage reactance is not neglected as it will affect the performance of CT.
- Total impedance on the secondary side is the sum of relay burden, lead wire resistance and leakage impedance of secondary winding.
- Therefore, the voltage developed in the secondary winding depends upon these parameters directly.

$$E = 4.44\, f\, N_2\, \Phi_m$$

Equivalent Circuit of CT

- Φ_m is the peak sinusoidal flux developed in the core. If corresponding to this flux is above B_m (magnetic flux density) the knee point, it is more or less obvious that the CT will saturate
- During saturation, CT secondary winding cannot replicate the primary current accurately and hence, the performance of the CT deteriorates.
- Thus, in practice, while selecting a CT we should ascertain that it should not saturate on the sinusoidal currents that it would be subjected to.

Equivalent Circuit of CT

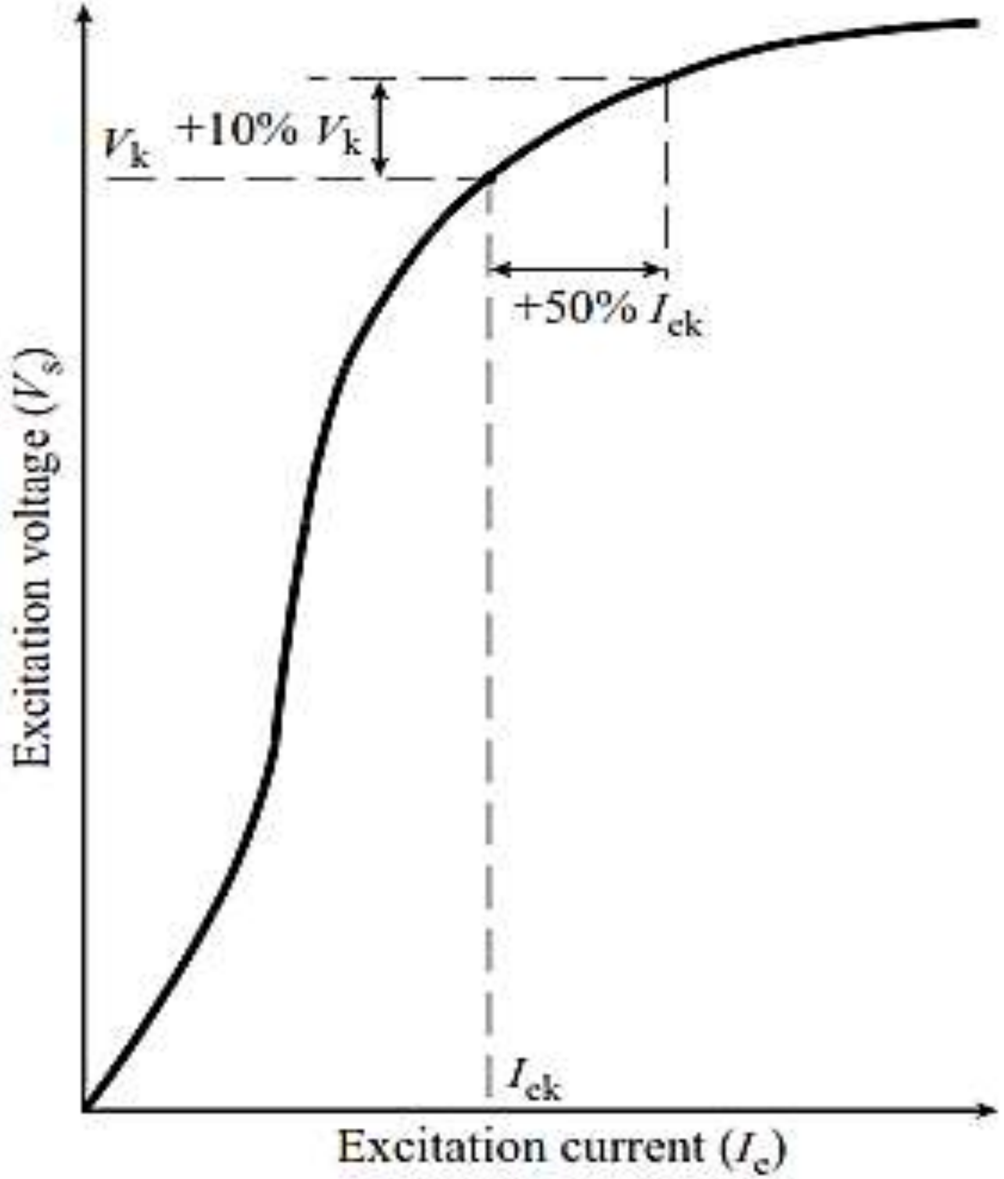
- Use of numerical relays due to their very small burden improves the CT performance.
- CT is to be operated always in closed condition. If the CT is open circuited, all the current Ip/N, would flow through Xm.
  - This will lead to the development of dangerously high level of voltage in secondary winding which can even burn out the CT.
- One of the major problems faced by the protection systems engineer is the saturation of CT on large ac currents and dc offset current present during the transient.
  - When the CT is saturated, primary current source cannot be faithfully reflected to the secondary side.

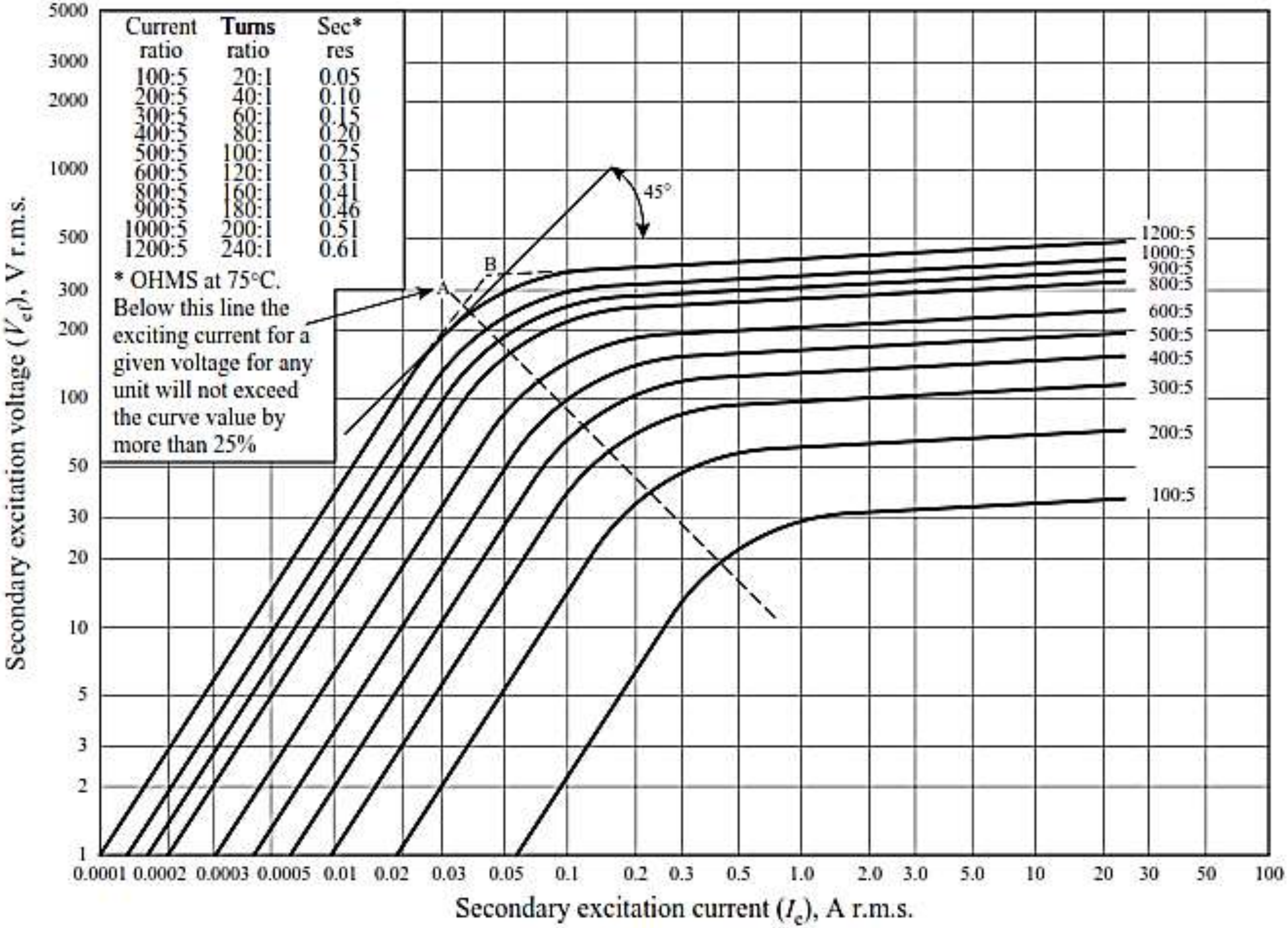
CT saturation

- Excitation current results in CT errors
  - excitation curve are calculated for proper functioning of CTs.
- Magnetization current of a CT depends on
  - cross-section and length of the magnetic circuit, number of turns in the windings and the magnetic characteristics of the material.
- Voltage across the magnetization impedance is directly proportional to the secondary current.
  - *Voltage* reaches the so-called saturation voltage when the peak induction just exceeds the saturation flux density and the magnetization current becomes sufficiently high enough to produce an excessive error.

CT saturation

- Curve is called the saturation at which an increase in the excitation voltage of 10% produces an increase of 50% in the excitation current.





Current ratio	**Turns** ratio	Sec* res
100:5	20:1	0.05
200:5	40:1	0.10
300:5	60:1	0.15
400:5	80:1	0.20
500:5	100:1	0.25
600:5	120:1	0.31
800:5	160:1	0.41
900:5	180:1	0.46
1000:5	200:1	0.51
1200:5	240:1	0.61

* OHMS at 75°C.

Below this line the exciting current for a given voltage for any unit will not exceed the curve value by more than 25%

Types of CTs

- Based on construction, types of CTs are:
  - Wound Current Transformer
  - Bar-type Current Transformer
  - Toroidal Current Transformer
- **Wound Current Transformer**
  - transformers primary winding is physically connected in series with the conductor that carries the measured current flowing in the circuit
  - magnitude of the secondary current is dependent on the turns ratio of the transformer.

Types of CTs

- **Bar-type Current Transformer**
  - uses the actual cable or bus-bar of the main circuit as the primary winding, which is equivalent to a single turn.
  - fully insulated from the high operating voltage of the system and are usually bolted to the current carrying device.
- **Toroidal Current Transformer**
  - do not contain a primary winding. Instead, the line that carries the current flowing in the network is threaded through a window or hole in the toroidal transformer.
  - Some current transformers have a “split core” which allows it to be opened, installed, and closed, without disconnecting the circuit to which they are attached.

Classification of CT

- Measurement CTs
  - It has much lower VA capacity than a protection grade CT.
  - accurate over its complete range e.g. from 5% to 125% of normal current. In other words, its magnetizing impedance at low current levels.
  - due to non-linear nature of B-H curve, magnetizing impedance is not constant but varies over the CT's operating range. It is not expected to give linear response (secondary current a scaled replica of the primary current) during large fault currents.
- Protection CTs
  - linear response is expected up to 20 times the rated current
  - performance has to be accurate in the range of normal currents and up to fault currents
  - magnetizing impedance should be maintained to a large value in the range of the currents of the order of fault currents

Classification of CT

- When a CT is used for both the purposes, it has to be of required accuracy class to satisfy both accuracy conditions of measurement CTs and protection CTs.
  - In other words, it has to be accurate for both very small and very large values of current. Typically, CT secondary rated current is standardized to 1A or 5A (more common).
- Unreasonable to assume that the linear response will be independent of the net burden on the CT secondary.
  - quite obvious that the driving force required to drive the primary current replica will increase as this burden increases.
  - If this voltage exceeds the designer's set limits, then the CT core will saturate and hence linear response will be lost. Hence, when we say that a CT will give linear response up to 20 times the rated current, there is also an implicit constraint that the CT burden will be kept to a low value.
  - In general, name-plate rating specifies a voltage limit on the secondary (e.g., 100 V) up to which linear response is expected. If the CT burden causes this voltage to be exceeded, CT saturation results

Relay Burden

- Burden of a CT is the value in ohms of the impedance on the secondary side of the CT due to the relays and the connections between the CT and the relays.

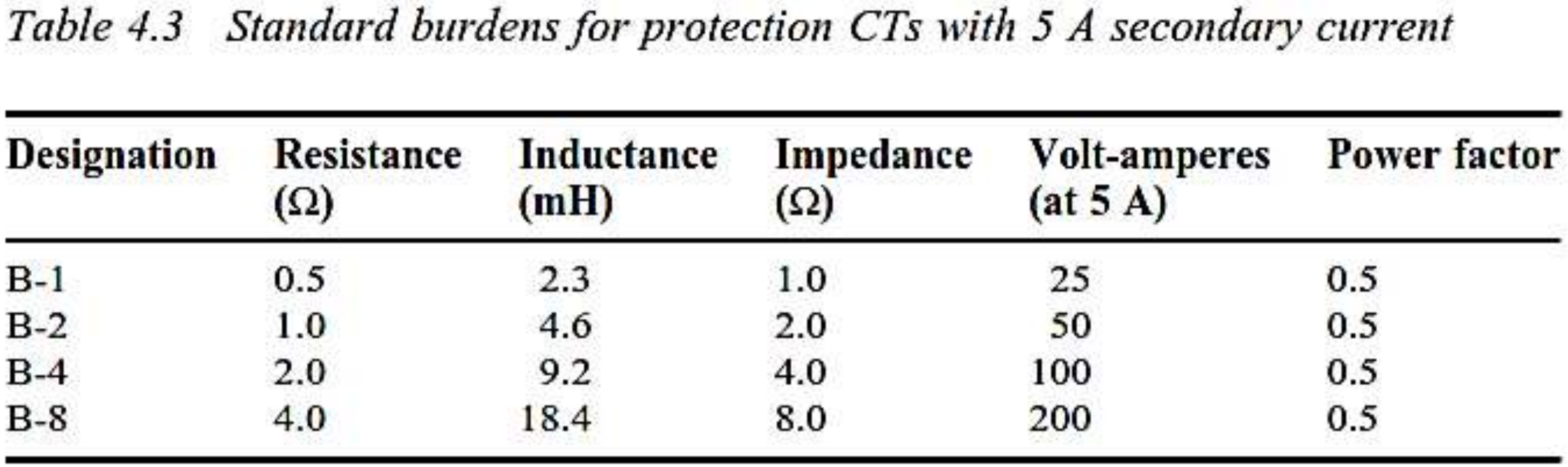


Table 4.3 Standard burdens for protection CTs with 5 A secondary current

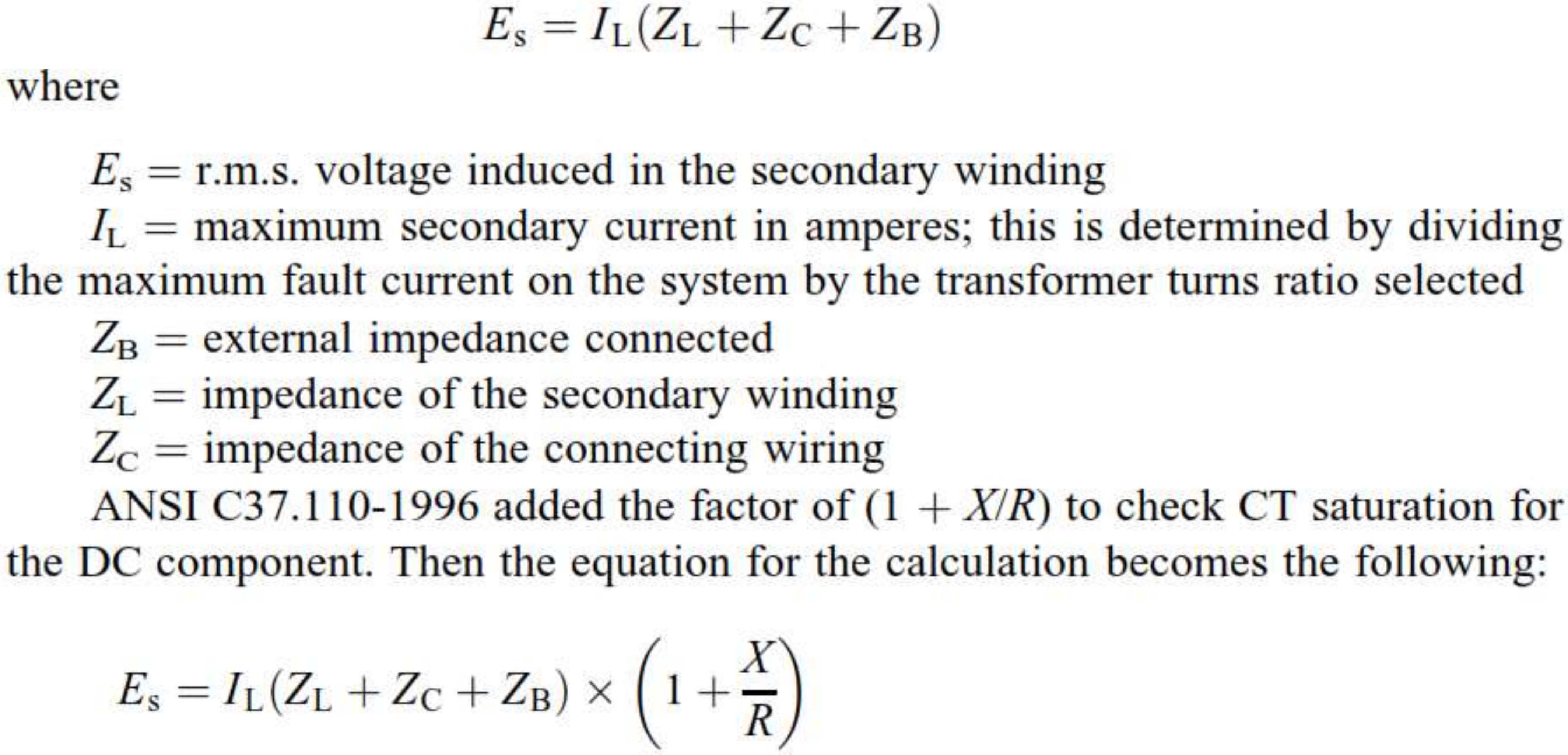
Designation	Resistance (Ω)	Inductance (mH)	Impedance (Ω)	Volt-amperes (at 5 A)	Power factor
B-1	0.5	2.3	1.0	25	0.5
B-2	1.0	4.6	2.0	50	0.5
B-4	2.0	9.2	4.0	100	0.5
B-8	4.0	18.4	8.0	200	0.5

- Secondary terminal voltage rating is the CT secondary voltage that the CT will deliver when it is connected to a standard secondary burden, at 20 times rated secondary current, without exceeding a 10% ratio error

Selection of CTs

- Important to ensure that the maximum load is equal or lower than the rated current of the CT
    - fault levels do not result in saturation of the core.
- Fundamental concept about CT saturation checking is to guarantee an operating point on the CT such that the excitation voltage lies within the linear portion, or below the so-called ‘knee point’ of the CT saturation curve.
- Saturation can be caused due to the AC and DC components.
- Secondary excitation voltage has to be calculated with the secondary excitation current multiplied for the total burden that represents the summation of the impedances of the CT windings, the wires and the impedances of the instrument connected

Selection of CTs



$$E_s = I_L(Z_L + Z_C + Z_B)$$

where

E_s = r.m.s. voltage induced in the secondary winding

I_L = maximum secondary current in amperes; this is determined by dividing the maximum fault current on the system by the transformer turns ratio selected

Z_B = external impedance connected

Z_L = impedance of the secondary winding

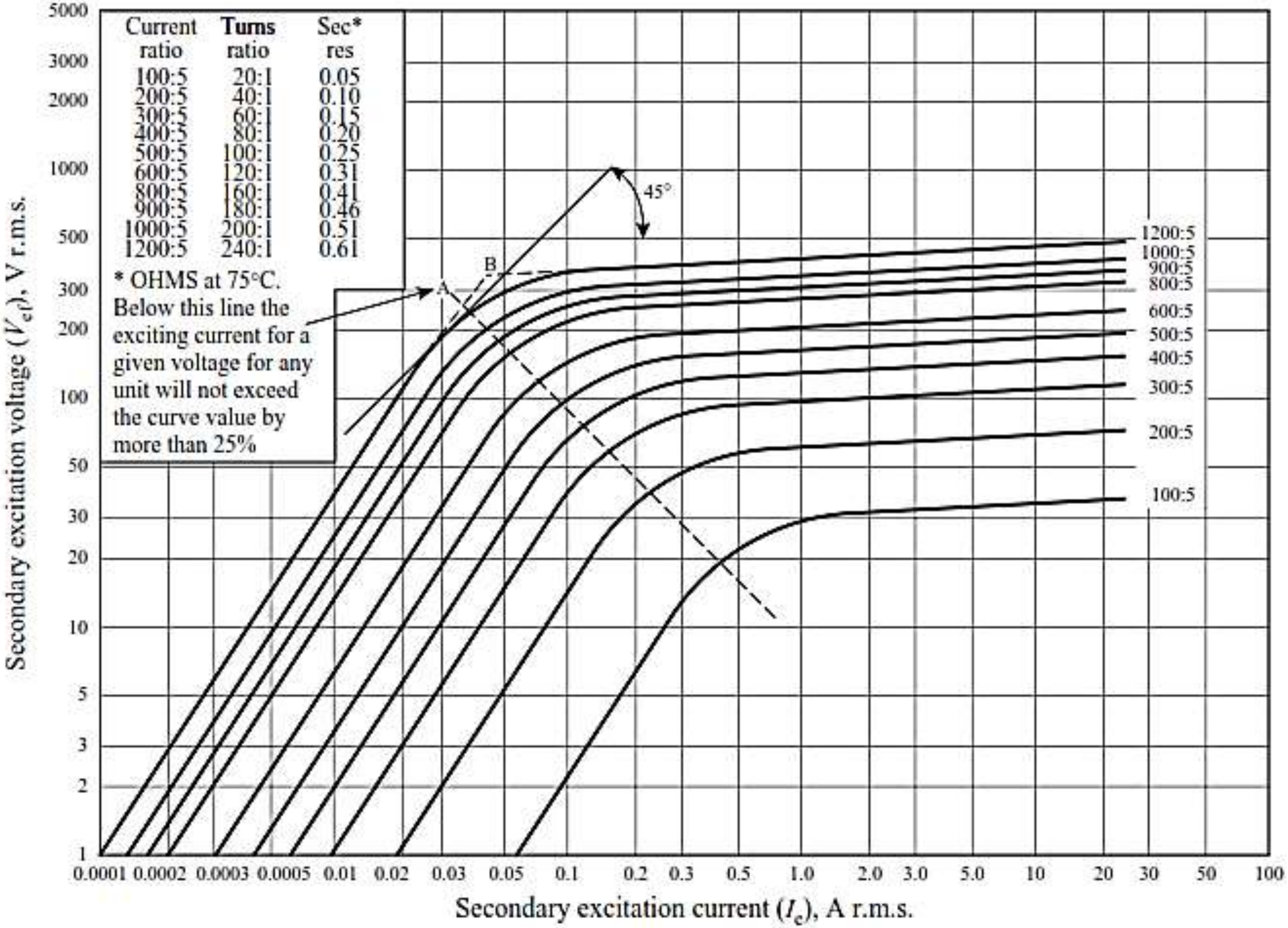
Z_C = impedance of the connecting wiring

ANSI C37.110-1996 added the factor of $(1 + X/R)$ to check CT saturation for the DC component. Then the equation for the calculation becomes the following:

$$E_s = I_L(Z_L + Z_C + Z_B) \times \left(1 + \frac{X}{R}\right)$$

Example 1

- A 1200/5, C400 CT with excitation curves, is connected to a 2.0 Ω burden. Based on the accuracy classification, what is the maximum symmetrical fault current that may be applied to this CT without exceeding a 10% ratio error?



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* OHMS at 75°C.
Below this line the exciting current for a given voltage for any unit will not exceed the curve value by more than 25%
A
B
45°
1200:5
1000:5
900:5
800:5
600:5
500:5
400:5
300:5
200:5
100:5
Secondary excitation voltage (V_e), V r.m.s.
5000
3000
2000
1000
500
300
200
100
50
30
20
10
5
3
2
1
0.0001
0.0002
0.0003
0.0005
0.01
0.02
0.03
0.05
0.1
0.2
0.3
0.5
1.0
2.0
3.0
5.0
10
20
30
50
100
Secondary excitation current (I_e), A r.m.s.

Example 2

- A 1200/5, C400 CT is connected on the 1000/5 tap. What is the maximum secondary burden that can be used and we can maintain rated accuracy at 20 times rated symmetrical secondary current?

Example 3

- Assume that secondary burden of a 300:5 class C CT is 5 Ω. The relay setting is 2A and the CT ratio is 300/5. Using figure of slide 12 for Class C CT, calculate the primary current required to operate the relay?

Example 4

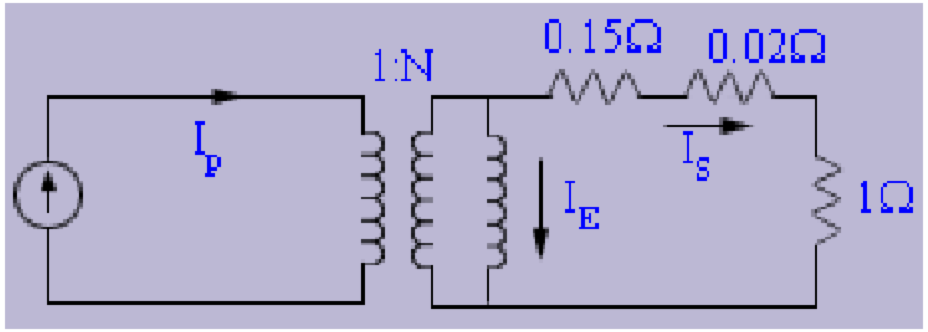
- A relay is expected to operate for 7000A primary current. The class C CT ratio is 600/5 (see figure). Secondary burden is 3.5 Ω. Will the CT saturate at this burden? Also, comment on the ratio error.

Example 5

- What will be the approximate % error if a 500:5 class C CT is connected to a secondary burden of 2.5 Ω and the secondary current is 68A.

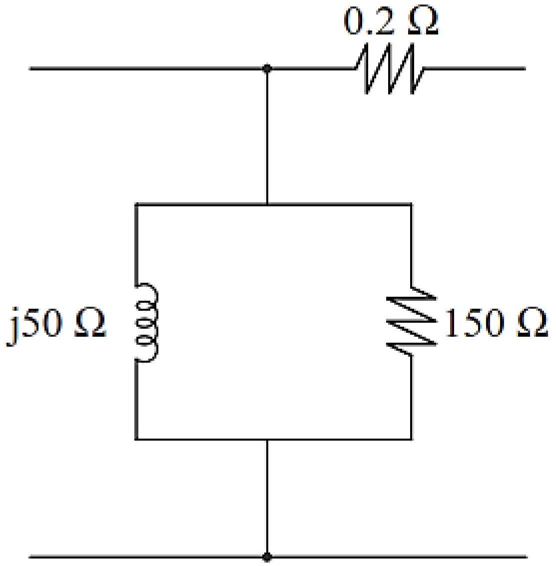
Example 6

- If a 300:5 class C CT is connected to a meter with resistance 1Ω and secondary current in the CT is 4.5A; find out the primary current, voltage developed across the meter and % ratio error. Lead wire resistance secondary resistance R_L = 0.02 Ω of a 300:5 CT = 0.15 Ω



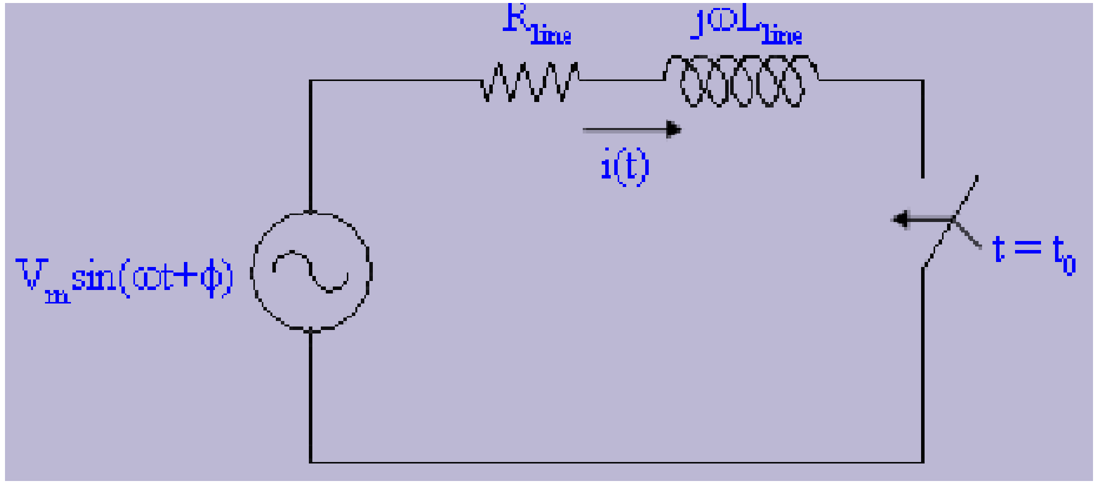
Example 7

Consider a 13.2-kV feeder that is carrying a load of 10 MVA at 1.0 power factor. Associated with this circuit is a 500/5 CT feeding a measurement system whose total load is 10 VA. The equivalent circuit of the CT referred to the secondary side is shown in below Figure. Calculate the voltage that would occur in the secondary circuit of the CT if the measurement system was accidentally opened.



CT Saturation and DC Offset Current

- Typically, fault current consists of symmetrical ac component and a dc offset current.
- To understand this issue, consider an unloaded transmission line excited by a voltage source. The fault strikes at time t=to.
- This can be simulated by closing the switch. If R + jωL models the line impedance, then the fault current in the line is given by

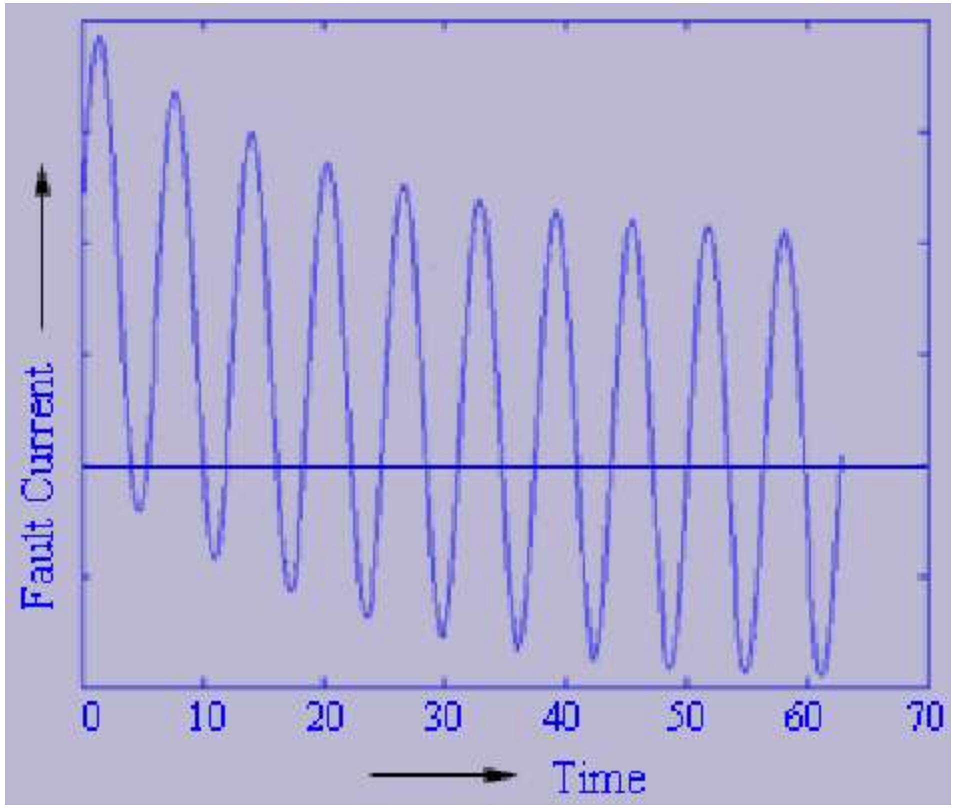


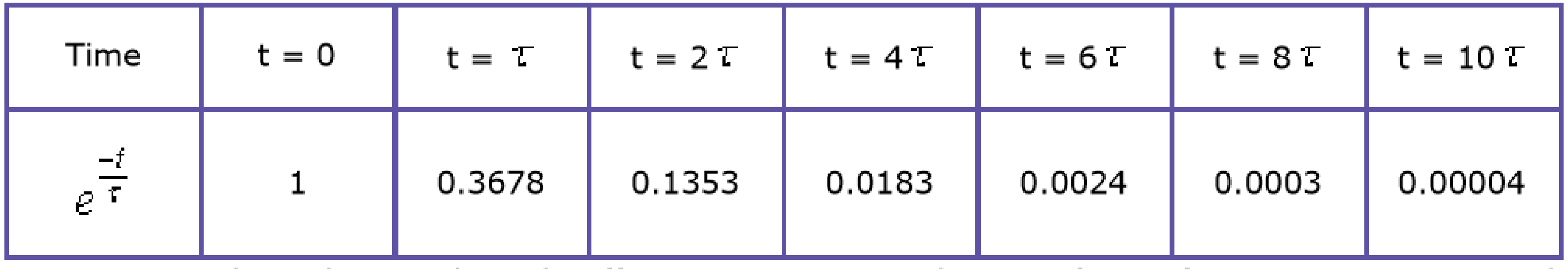
$$i(t) = \frac{V_m \sin(\omega t + \phi - \theta)}{|Z_{line}|} + I_0 e^{-\left(\frac{t-t_0}{\tau}\right)}$$

$\tau = L_{line}/R_{line}$

DC offset current

- Fault current can be decomposed into two components
  - steady state sinusoidal ac response
  - dc offset current due to the presence of inductance in the circuit and therefore a consequence of maintaining initial condition





Time	t = 0	t = τ	t = 2τ	t = 4τ	t = 6τ	t = 8τ	t = 10τ
$e^{\frac{-t}{\tau}}$	1	0.3678	0.1353	0.0183	0.0024	0.0003	0.00004

DC offset current

- The peak value of dc offset current I_0 can be worked out by setting the current $i(t_0)$ to zero

This implies that $I_0 = \frac{-V_m}{|Z_{line}|}\sin(\omega t_0 + \phi - \theta)$

Thus $i(t) = \frac{V_m}{|Z_{line}|}\sin(\omega t + \phi - \theta) - \frac{V_m}{|Z_{line}|}\sin(\omega t_0 + \phi - \theta)e^{-\left(\frac{t-t_0}{\tau}\right)}$

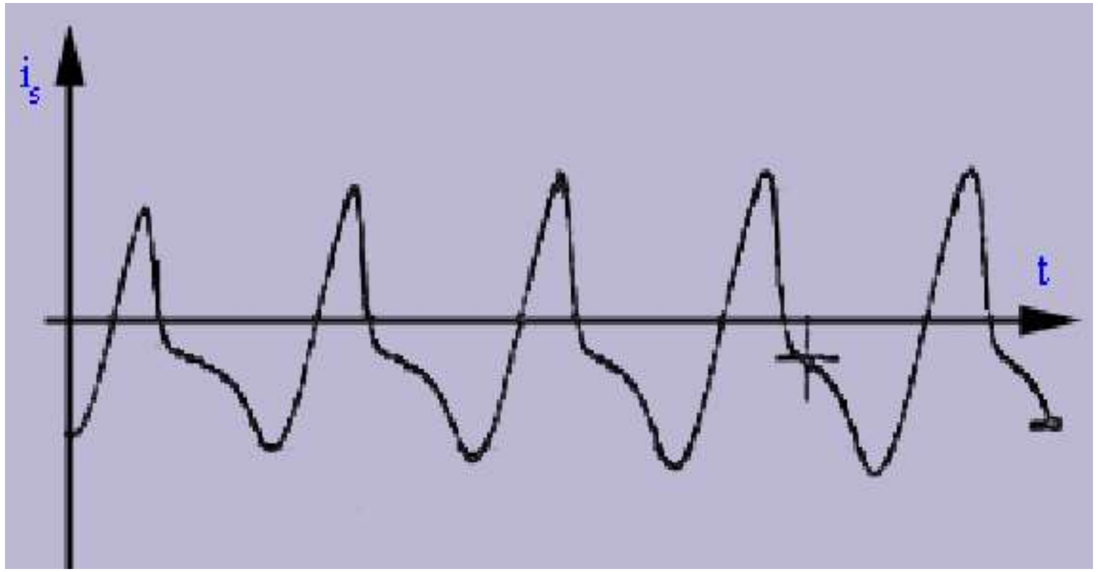
Clearly, the peak value of dc offset current depends upon the following parameters:

- Time at which fault strikes,
- Phase angle ϕ of ac voltage and
- $|Z_{line}|$ and θ of transmission line.
- Voltage V_m

We have considered a single phase current, a 3 phase fault on a 3 phase transmission line would always induce dc offset current in at least two phases. **DC offset has adverse impact on CT performance.**

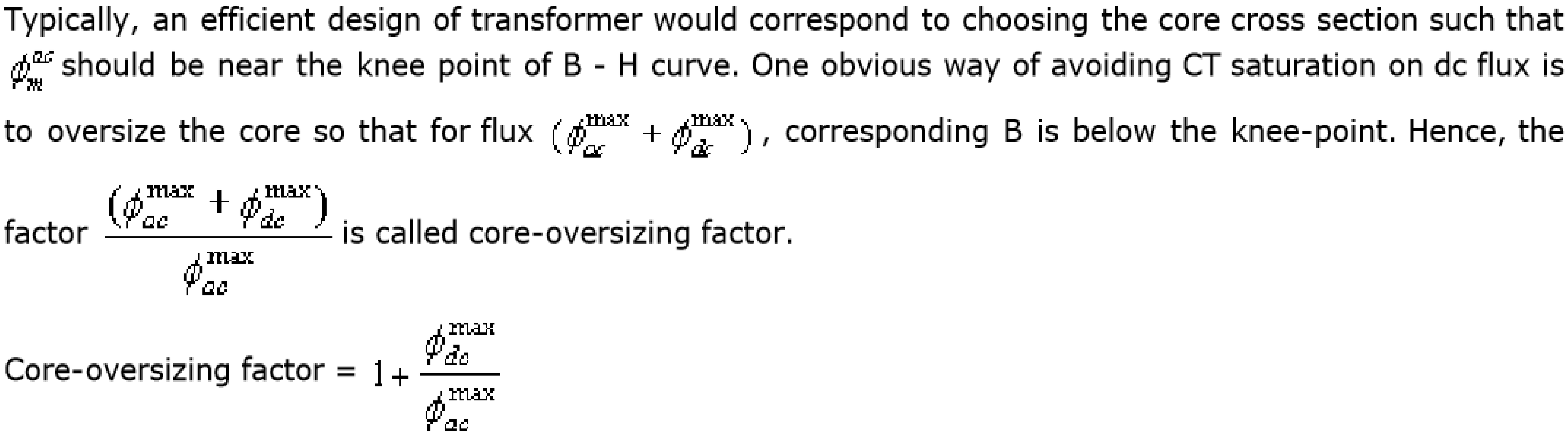
CT Saturation due to DC - Offset Current

- Due to CT core saturation, the secondary current would not faithfully replicate the primary current. In fact, in practice it is observed that CT secondary current is clipped that leads to “blinding” of the relay which cannot function any further. Hence, CT saturation in presence of dc offset current is a serious problem which relay designers have to face.



CT Saturation due to DC - Offset Current

- AC voltage induced flux has zero average value. However, dc offset induced flux does not have this nice feature. The total instantaneous flux in ideal CT core is a summation of ac flux and dc flux
- DC flux accumulates gradually depending upon the transmission line time constant (Ƭ).



Typically, an efficient design of transformer would correspond to choosing the core cross section such that ϕ_m^{ac} should be near the knee point of B - H curve. One obvious way of avoiding CT saturation on dc flux is to oversize the core so that for flux $(\phi_{ac}^{\max}+\phi_{dc}^{\max})$, corresponding B is below the knee-point. Hence, the factor $\frac{(\phi_{ac}^{\max}+\phi_{dc}^{\max})}{\phi_{ac}^{\max}}$ is called core-oversizing factor.

Core-oversizing factor = $1+\frac{\phi_{dc}^{\max}}{\phi_{ac}^{\max}}$

CT Over sizing Factor

- X/R is the transmission line X/R ratio.
- For a 220KV line with X/R = 10, this would imply that transformer core should be oversized by a factor of 11. For a EHV line, with X/R is 20, this would imply an oversizing requirement of about 21 times the usual design.
- Clearly, this high amount of oversizing is not practical. Thus, an important conclusion is that, protection engineers have to live with the saturation problem. Under the situation one should try to quickly reach the decision, before CT saturates. However, this brings in the picture, the well discussed 'speed vs accuracy conflict'.

Caution in CT selection

1. The CT rating and continuous load current should match. For example, if maximum load current is 90A, a 100:5 CT may be acceptable but 50:5 is not acceptable.
2. The maximum fault current should be less than 20 times the CT rated current. For example, 100:5 CT can be used, so long as burden on the CT is within the rated values and maximum primary fault current is below 2000A.
3. The voltage rating of CT should be compatible. For example, 100:5 C100 would give linear response, upto 20 times rated current provided CT burden is kept below(100/20 x 5 = 1Ω). With 2 Ω burden, this CT can be used only if maximum current is limited to 1000A. Paralleling of CT's e.g. in differential protection, or with SLG fault can create significant errors in CT performance. One should generally ascertain that magnetizing current is kept much below the pick up value