Current Transformers

Imagination at work.

Current Transformer Function

- Reduce power system current to lower value for measurement.
- Insulate secondary circuits from the primary.
- Permit the use of standard current ratings for secondary equipment.

REMEMBER :

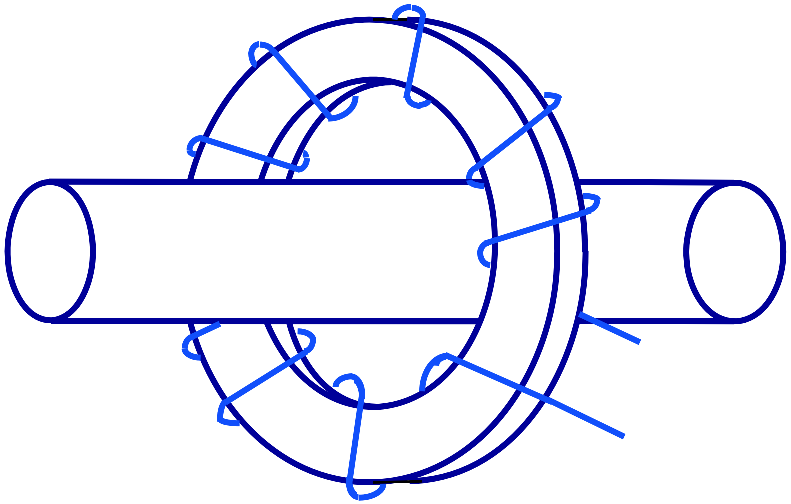
The relay performance DEPENDS on the C.T which drives it !

Instrument Transformer Standards

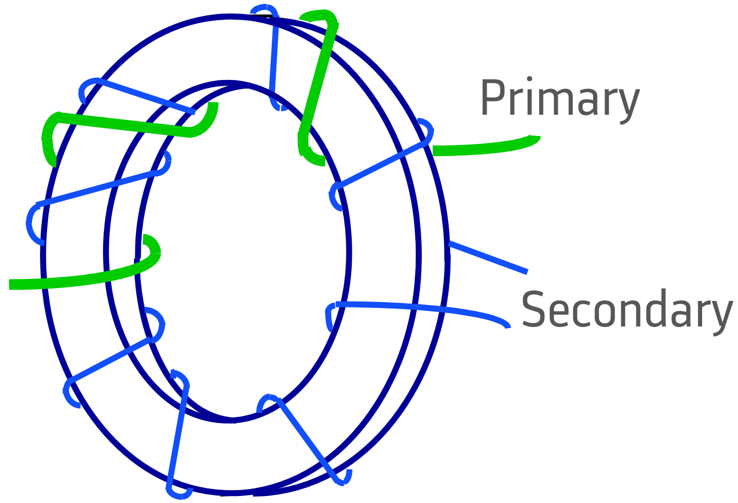
IEC	IEC 185:1987	CTs
	IEC 44-6:1992	CTs
	IEC 186:1987	VTs
EUROPEAN	BS 7625	VTs
	BS 7626	CTs
	BS 7628	CT+VT
BRITISH	BS 3938:1973	CTs
	BS 3941:1975	VTs
AMERICAN	ANSI C51.13.1978	CTs and VTs
CANADIAN	CSA CAN3-C13-M83	CTs and VTs
AUSTRALIAN	AS 1675-1986	CTs

Current Transformer Construction

BAR PRIMARY

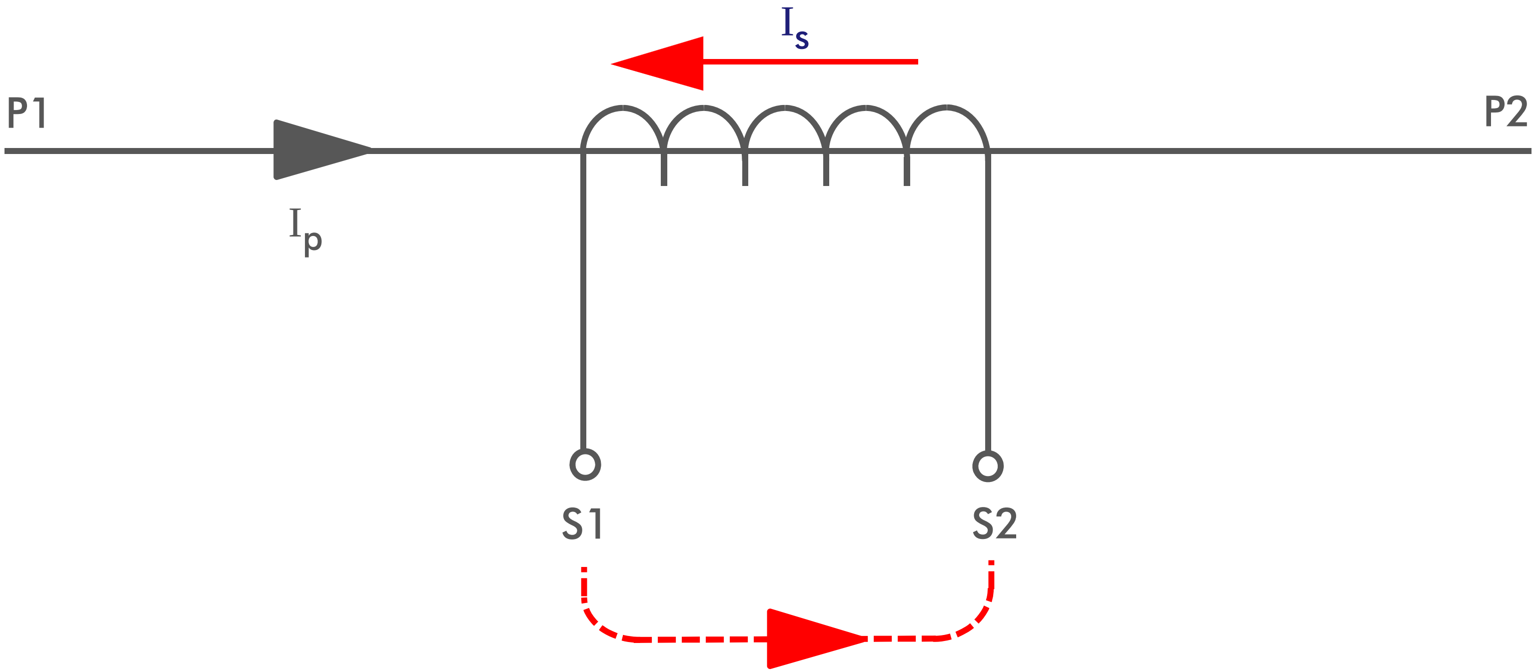


WOUND PRIMARY



Polarity

As per IEC 60044-1

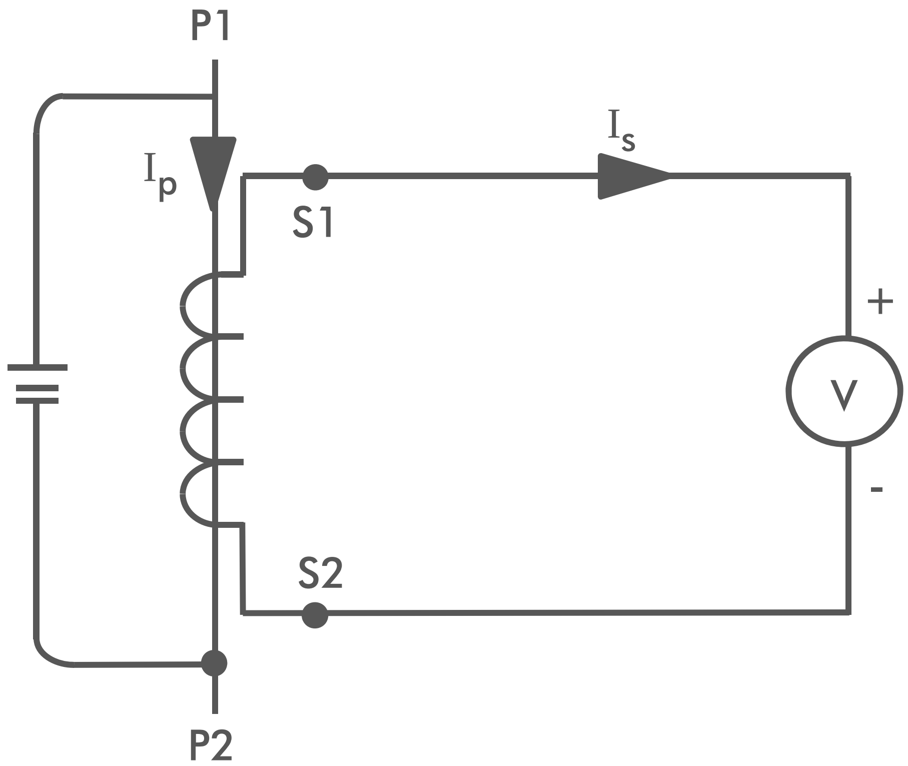


Inst. Current directions :-

P1 ➔ P2

S1 ➔ S2 <u>Externally</u>

Flick Test



FWD kick on application,

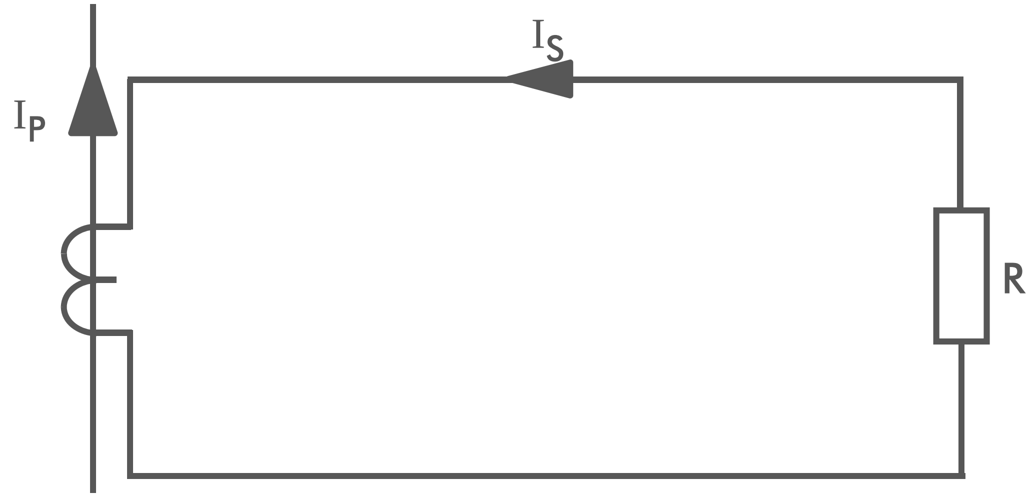
REV kick on removal of test lead.

Battery (6V) + to P1

AVO +ve lead to S1

Basic Theory

Basic Theory (1)



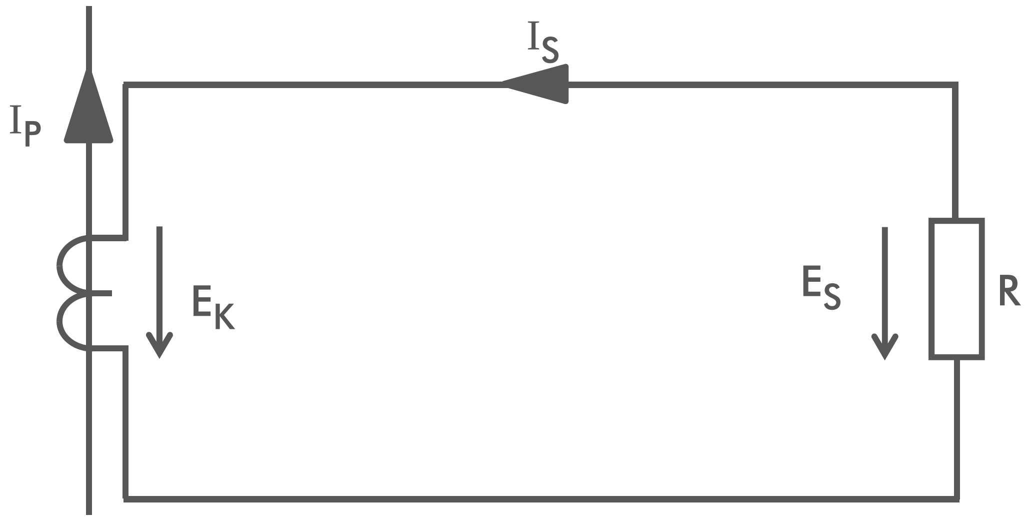
1 Primary Turn
N Secondary Turns

For an ideal transformer :-

PRIMARY AMPERE TURNS = SECONDARY AMPERE TURNS

$$\Rightarrow I_P = N \times I_S$$

Basic Theory (2)



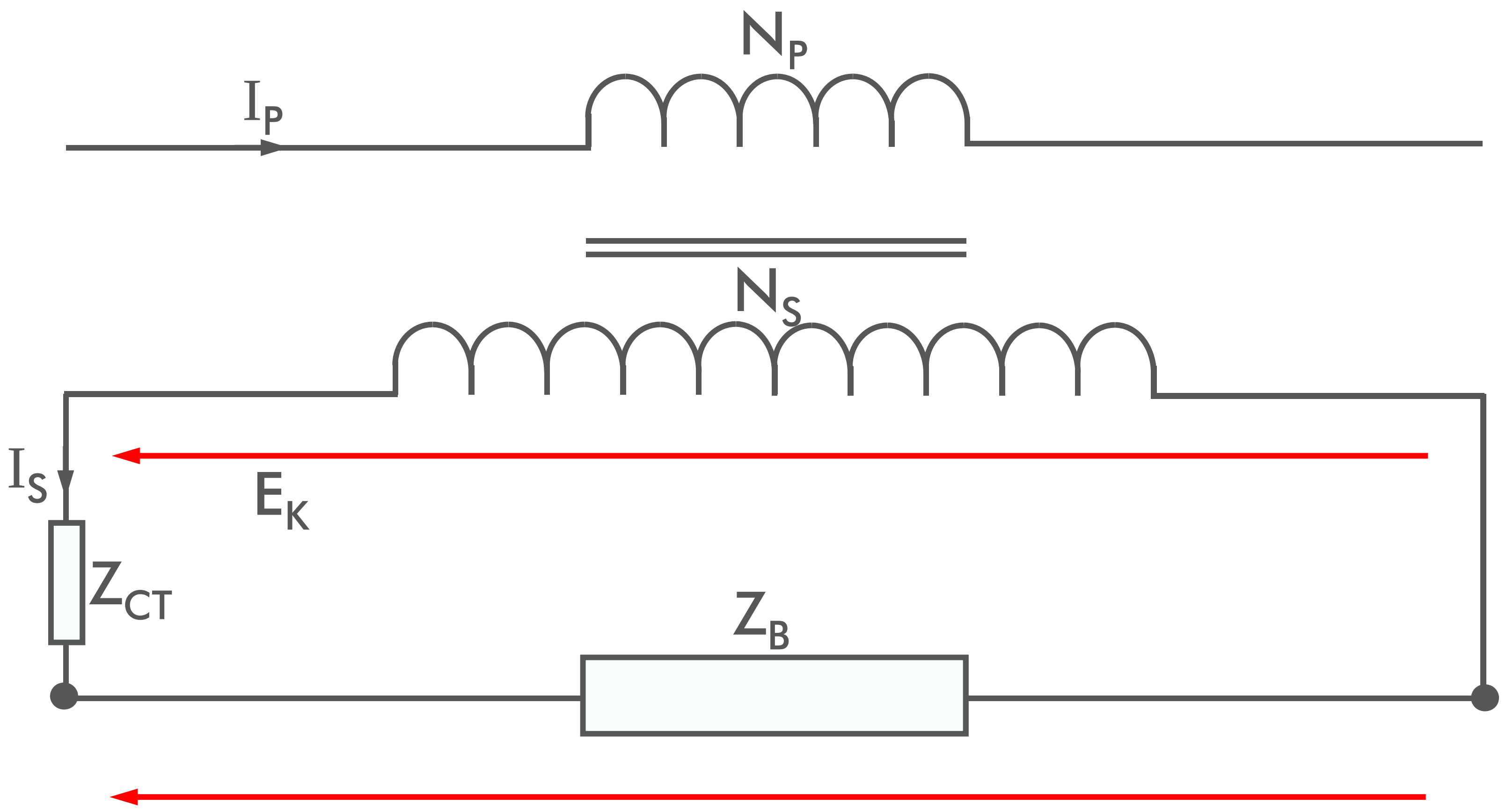
For I_S to flow through R there must be some potential difference E_K : E.M.F.

$$E_S = I_S \times R$$

E_K is produced by an alternating flux in the core.

$$E_K \propto \frac{d\text{Ø}}{dt}$$

Basic Theory (3)



$$V_{O/P} = I_S Z_B = E_K - I_S Z_{CT}$$

Basic Formulae

$$E_K \propto \frac{d\text{Ø}}{dt}$$

Flux required to produce Es :

$$\phi = B \,.\, A$$

where :-

B	=	Flux Density in the core (Wb/m^2)
A	=	Cross-sectional area of core (m^2)

$$E_K = 4.44\ N_S\ f\ A\ B$$

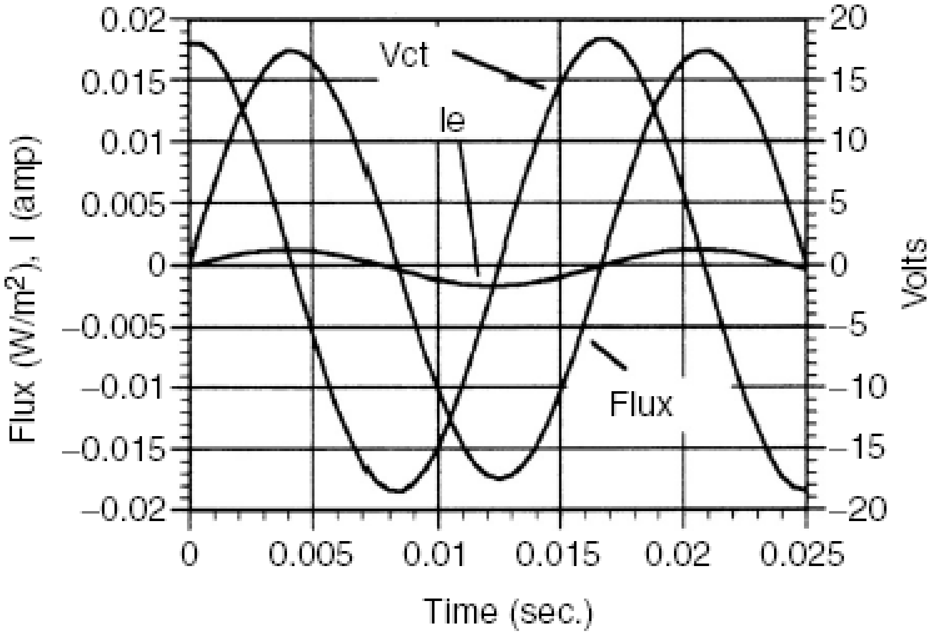
Basic Formulae

$$E_K \propto \frac{d\text{Ø}}{dt}$$

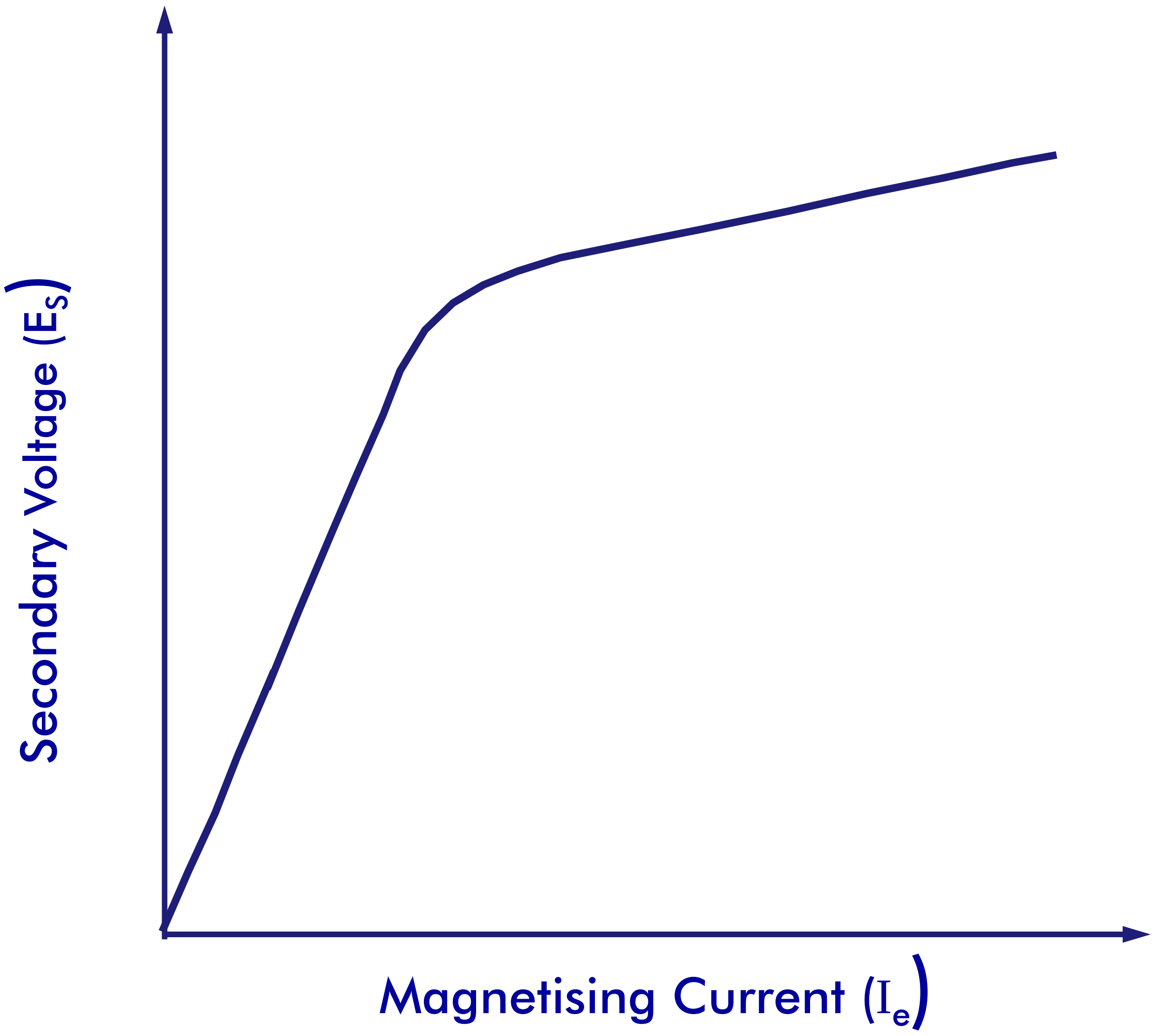
$$e(t) = E_K \cos(wt)$$

$$\text{Ø}(t) = \frac{E_K}{N_s} \int \cos(wt)$$

$$= \frac{E_K}{w N_s} \sin(wt)$$



Voltage Definition



Basic Formulae

Maximum Secondary Winding Voltage :

$$E_K = 4.44\ N_S\ f\ A\ B^*$$

where

E_K	=	‘ Knee-point Volts ‘
B^*	=	Saturation Flux Density (Tesla)
A	=	Cross-sectional area of core (m^2)
f	=	System Frequency (Hz)
N_S	=	Number of secondary turns

Basic Formulae

Circuit Voltage Required :

$$E_S = I_S (Z_B + Z_{CT} + Z_L) \quad \text{Volts}$$

where :-

I_S = Secondary Current of C.T. (Amperes)
Z_B = Connected External Burden (Ohms)
Z_{CT} = C.T Winding Impedance (Ohms)
Z_L = Lead Loop Resistance (Ohms)

Require $\mathbf{E_K > E_S}$

Basic Formulae

Consider a 120/1 CT (Ns = 120), which is required to produce 200 volts :

$$B^* = 1.8 \text{ Wb / sq.m.}$$

$$\varnothing max = \sqrt{2} * 200 / (120 * 314)$$
$$= 0.0075 \text{ Wb}$$

$$\text{Core area} \quad A = 0.0075 / 1.8$$
$$= 0.0042 \text{ sq.m}$$

If this CT is used with a max fault level of 11 KA, and the burden is 3.2 ohm, the CT would need to produce

$$Es = 11000/120 * 3.2$$
$$= 293 \text{ volts}$$

This requires a flux density in excess of the material capability.

Basic Formulae

Example Calculation:

C.T. Ratio = 2000/5 A
R_S = 0.31 Ohms
I_{Max} Primary = 40 kA
Max Flux Density = 1.6 T
Core C.S.A = 20 cm^2

Find maximum secondary burden permissible if no saturation is to occur.

Basic Formulae

Solution:

$N = 2000/5 = 400$ Turns

$I_{S\ max} = 40{,}000/400 = 100$ Amps

From equation 1 the knee point voltage is :–

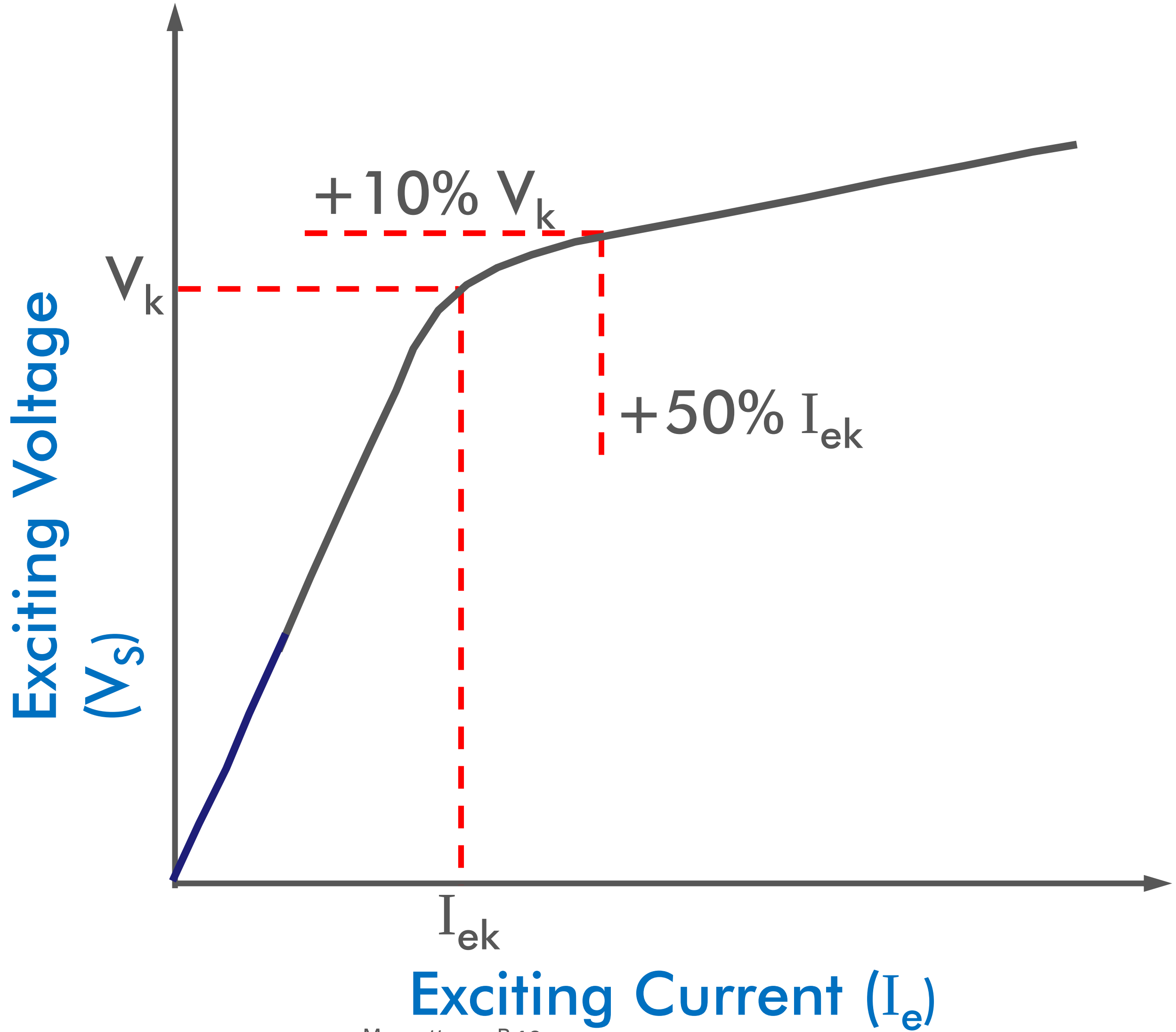
$$V_k = \frac{(4.44 \times 1.6 \times 20 \times 50 \times 400)}{10^4} = 284 \text{ Volts}$$

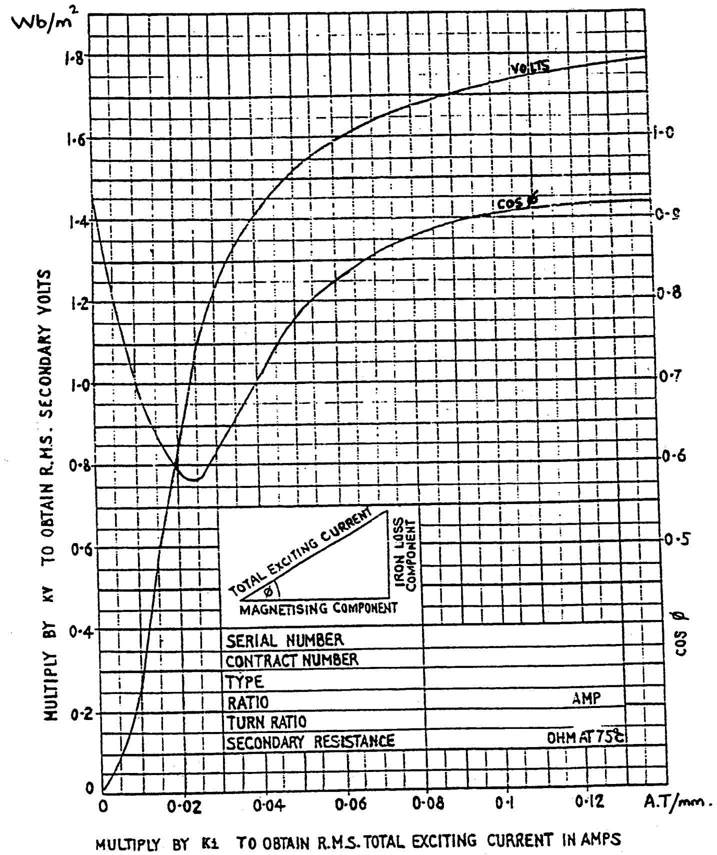
Therefore Maximum Burden $= 284/100$
$= 2.84$ Ohms.

Hence Maximum CONNECTED burden :

$2.84 - 0.31 = 2.53$ Ohms

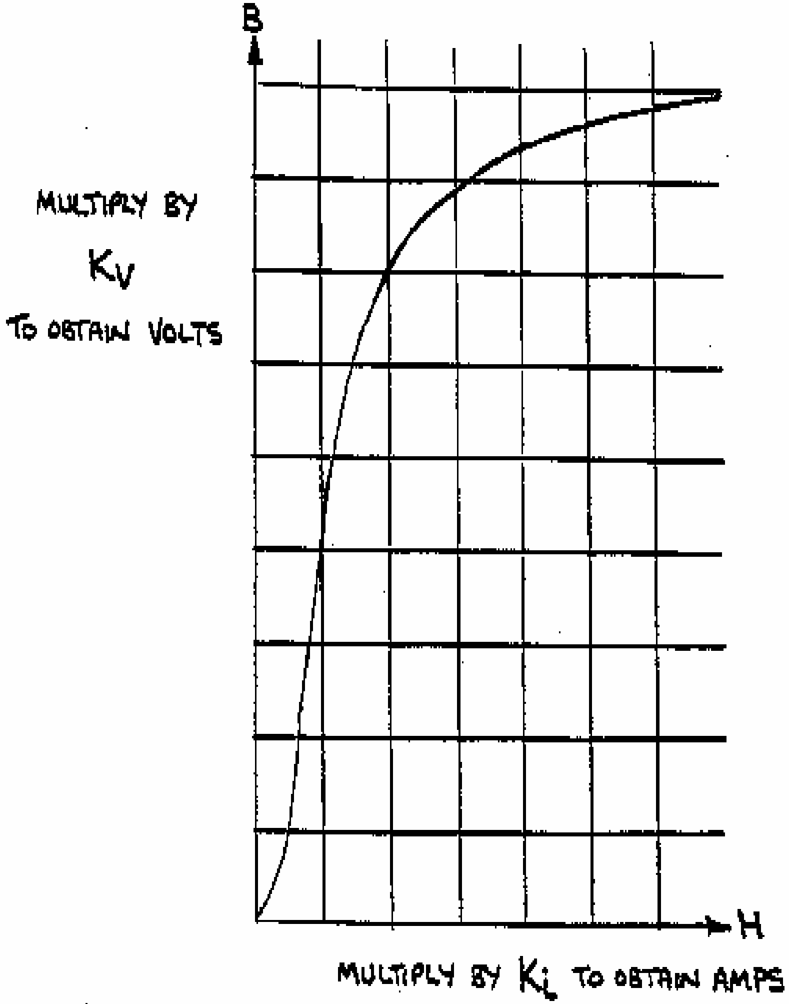
Knee-Point Voltage Definition





50 HZ.

ESTIMATED MAGNETISATION CURVE FOR CURRENT TRANSFORMER	DRAWN	EMG.
	DATE	
	APPROVED	



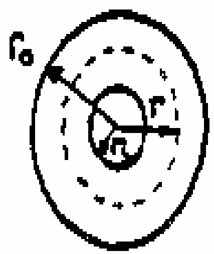
$K_V \times B$ = VOLTS (E)

$K_i \times H$ = AMPS

UNITS: $K_V = \frac{E}{B} = 4.44\,NfA$ ($m^2 \times$ TURNS)

$K_i = \frac{I_e}{H} = \frac{L}{N}$ (m/TURNS)

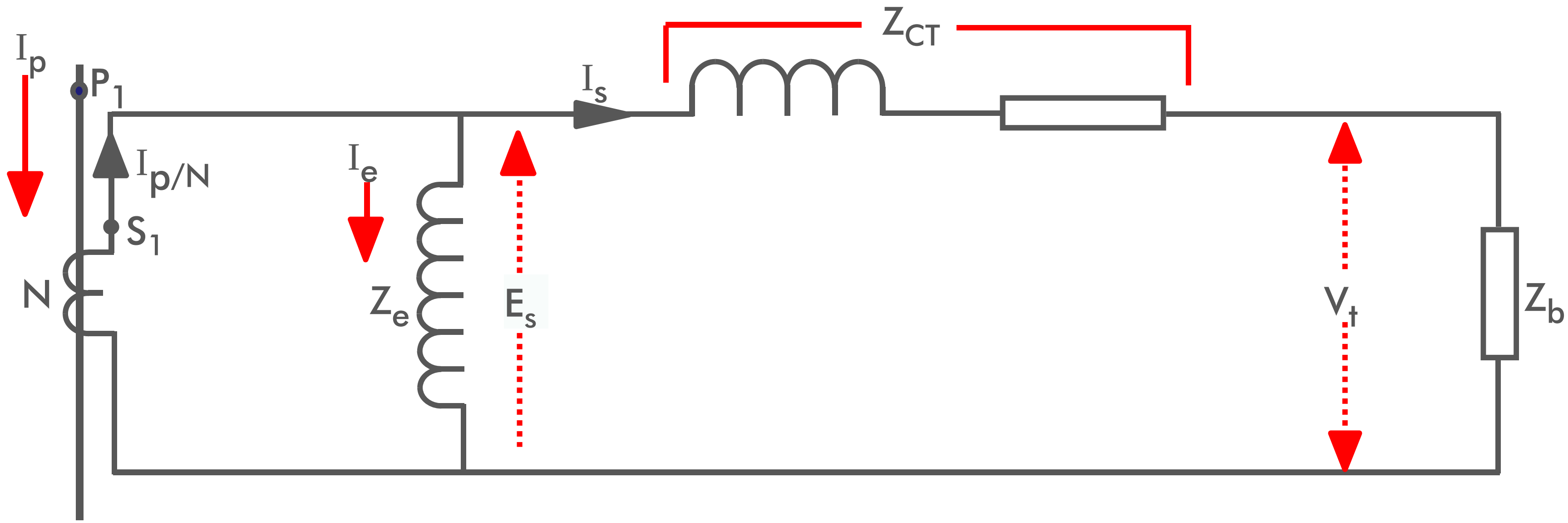
NOTE: L = MEAN MAGNETIC PATH



MEAN MAGNETIC PATH = $2\pi r$

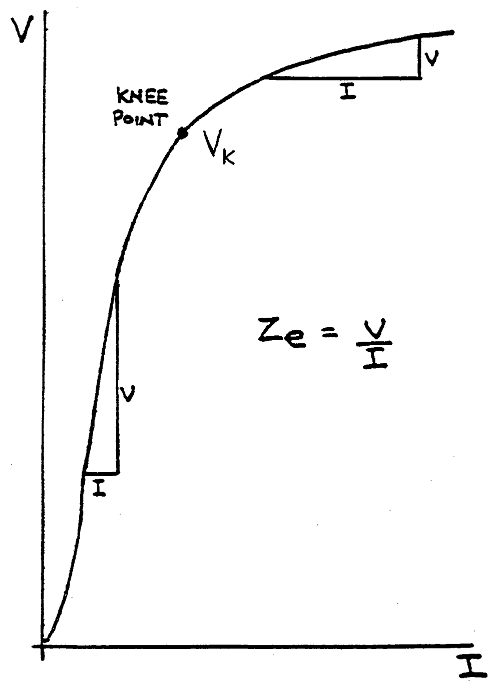
$$r = \frac{r_o - r_i}{2} + r_i$$

C.T. Equivalent Circuit



I_p	=	Primary rating of C.T.	I_e	=	Secondary excitation current
N	=	C.T. ratio	I_s	=	Secondary current
Z_b	=	Burden of relays in ohms (r+jx)	E_s	=	Secondary excitation voltage
Z_{CT}	=	C.T. secondary winding impedance in ohms (r+jx)	V_t	=	Secondary terminal voltage across the C.T. terminals
Z_e	=	Secondary excitation impedance in ohms (r+jx)			

Z_e IS SLOPE OF MAG. CHARACTERISTIC



ABOVE KNEE POINT Z_e EFFECTIVELY COLLAPSES

THUS, REDUCED CURRENT OUTPUT FROM C.T.

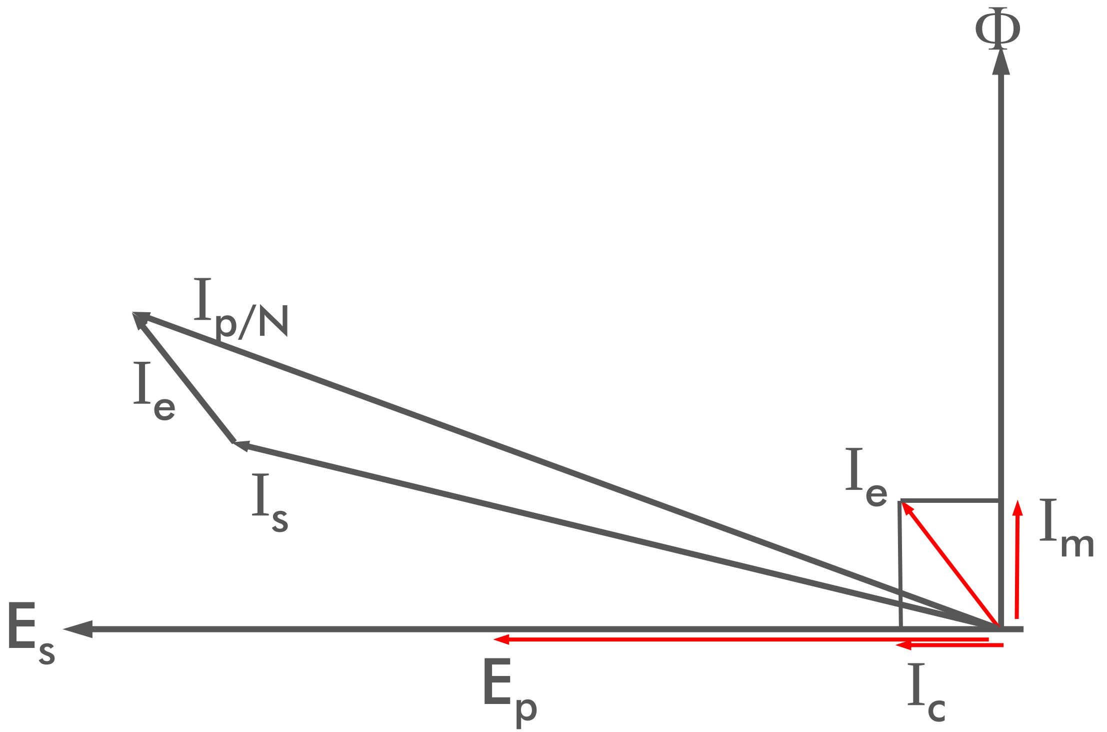
Low Reactance Design

Resistance & leakage reactance must be kept as low as possible

With evenly distributed winding the leakage reactance is very low and usually ignored.

Thus $Z_{CT} \simeq R_{CT}$

Phasor Diagram



E_p = Primary voltage

E_s = Secondary voltage

Φ = Flux

I_c = Iron losses (hysteresis & eddy currents)

I_m = Magnetising current

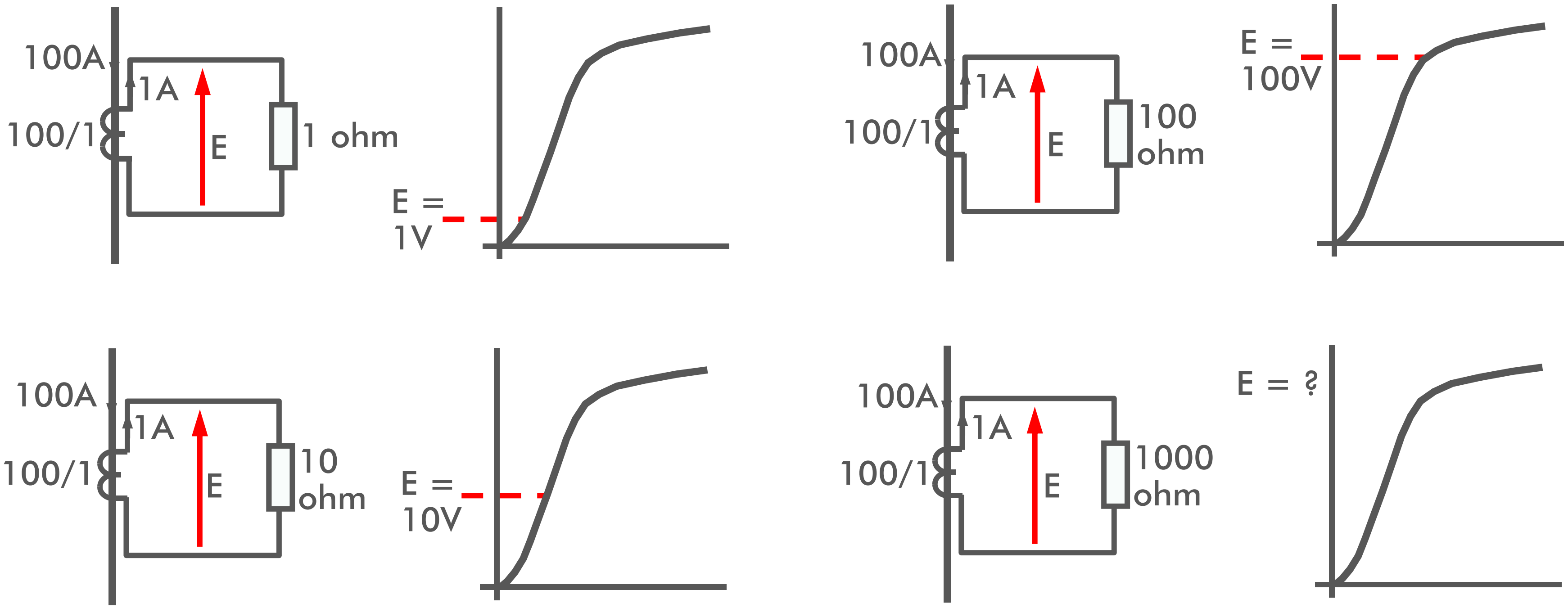
I_e = Excitation current

I_p = Primary current

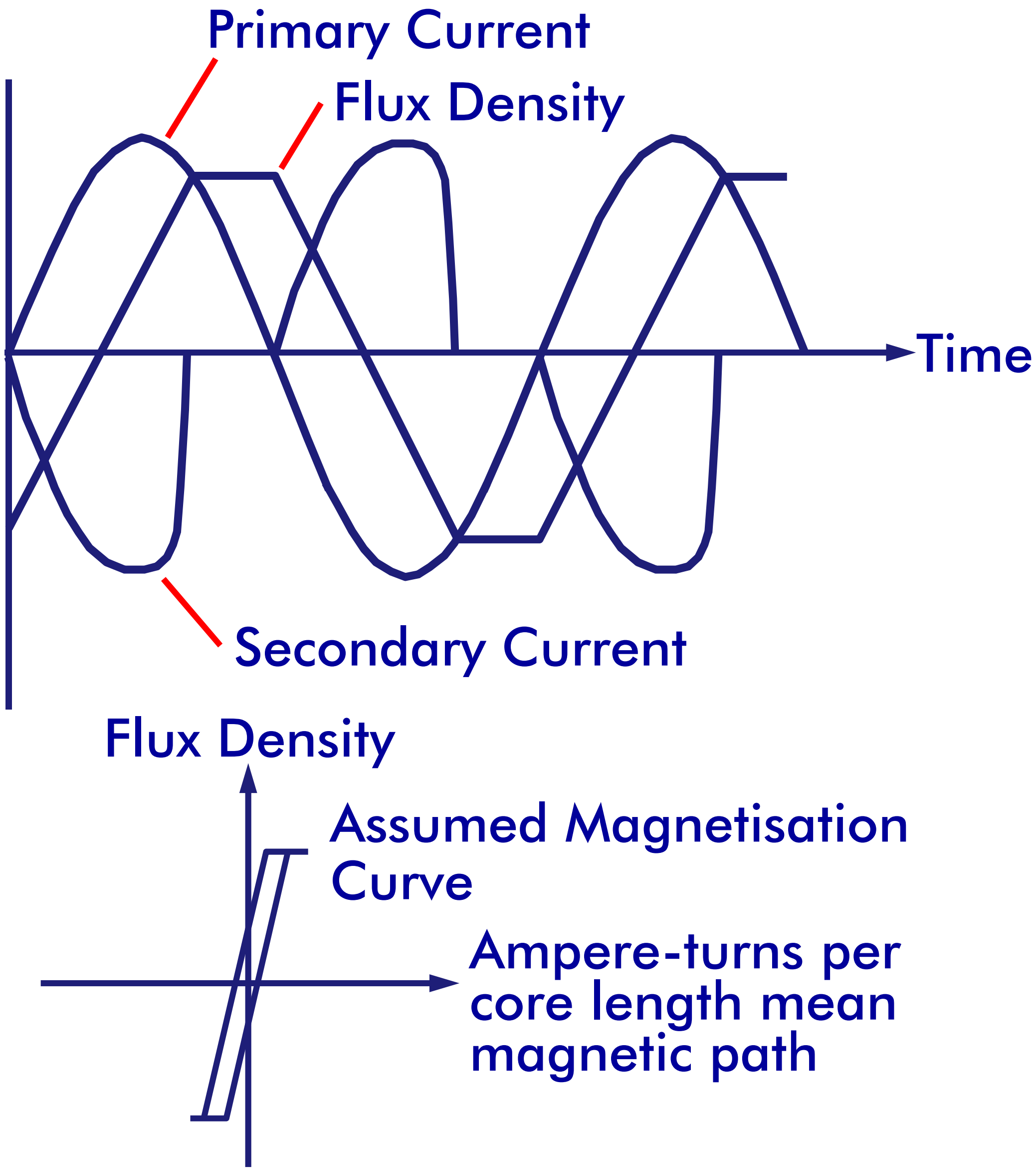
I_s = Secondary current

Saturation

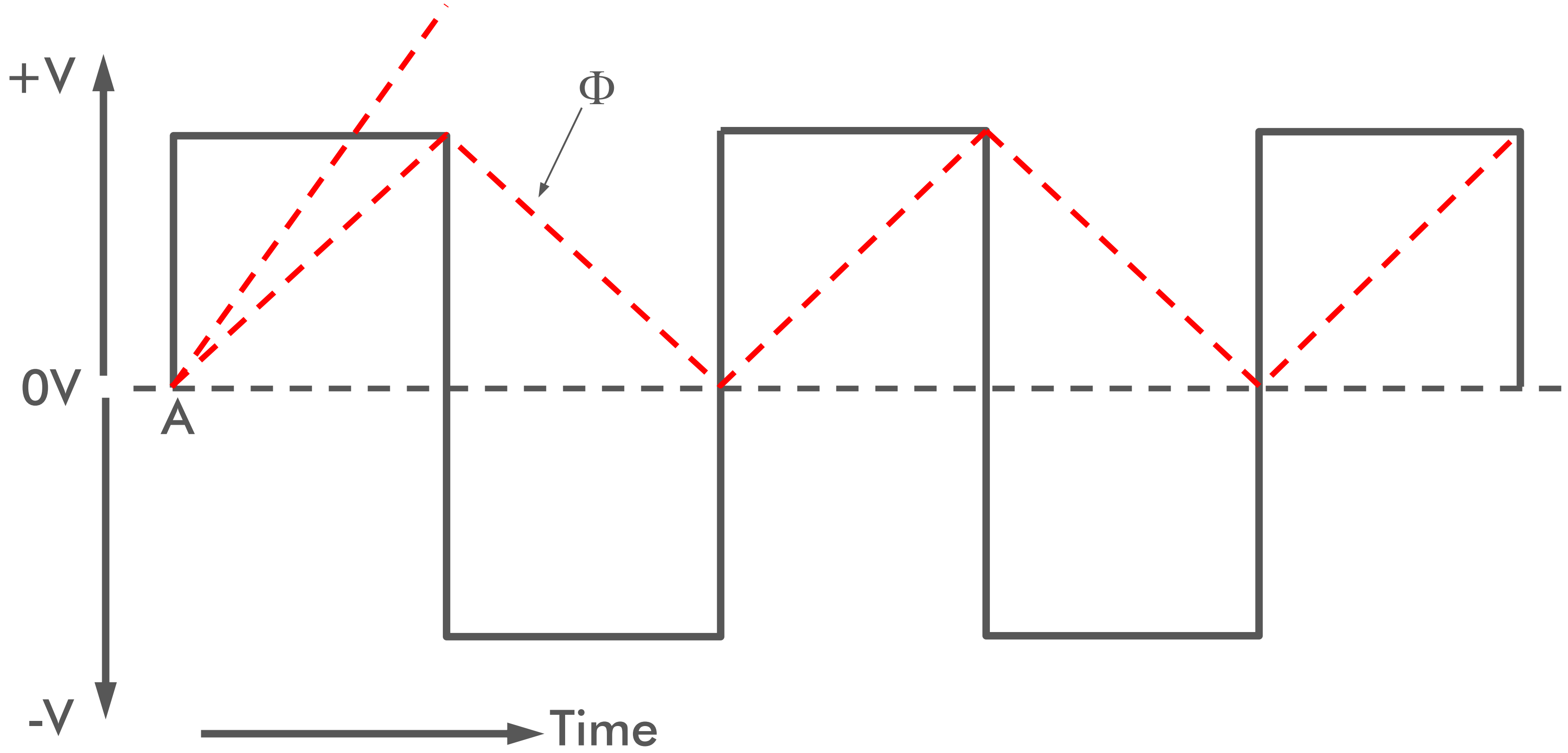
Steady State Saturation (1)



Steady State Saturation (2)

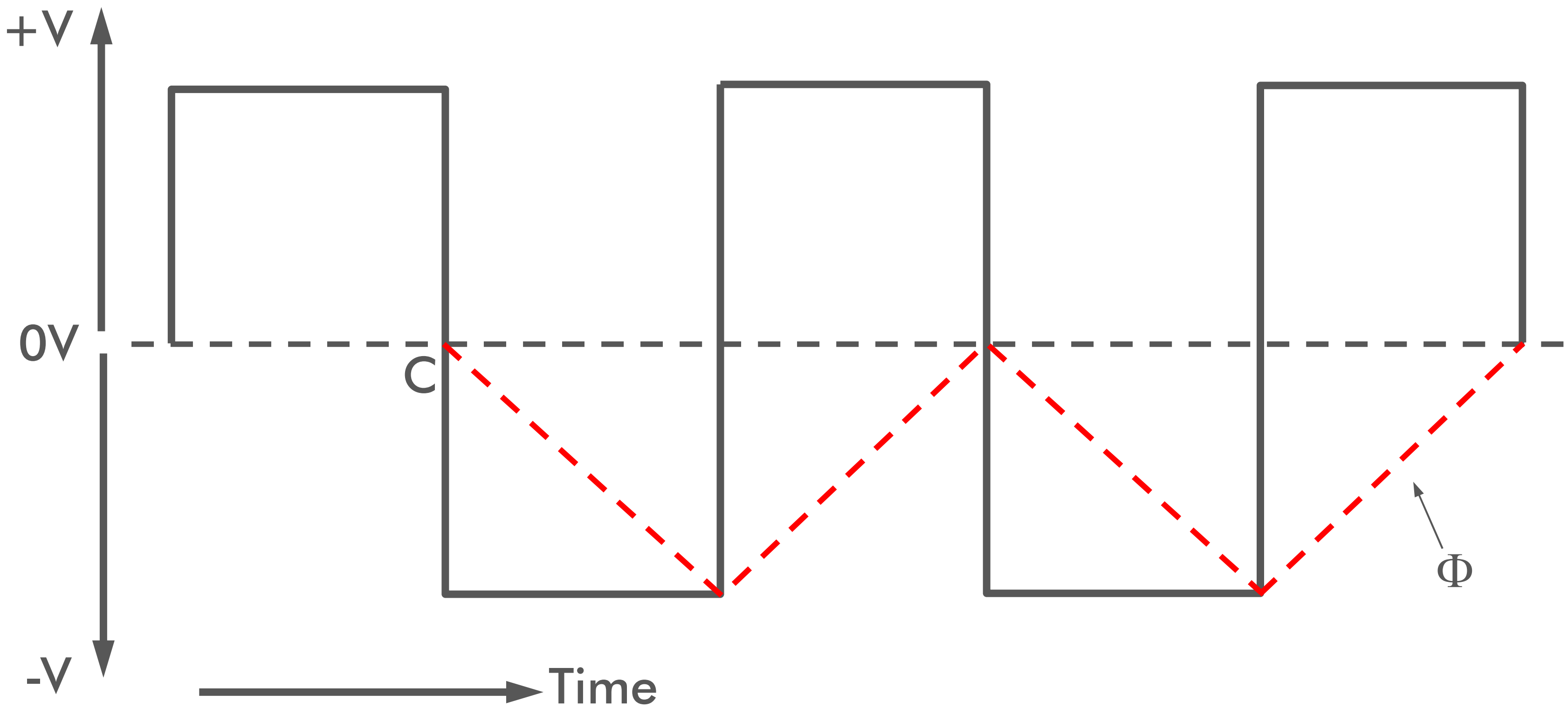


Steady State Saturation (3)



Assume :- Zero residual flux
Switch on at point A

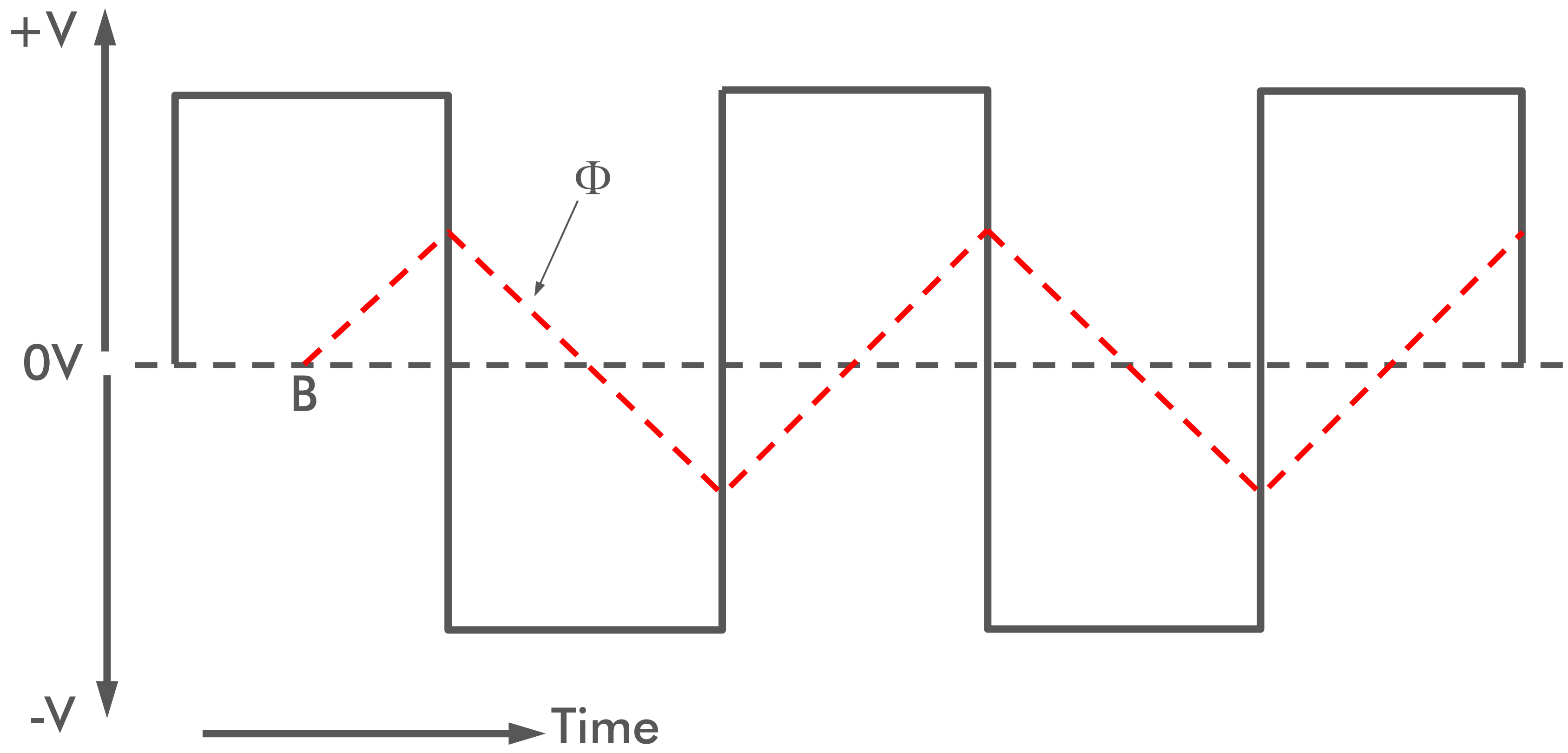
Steady State Saturation (4)



Assume :- Zero residual flux

Switch on at point C

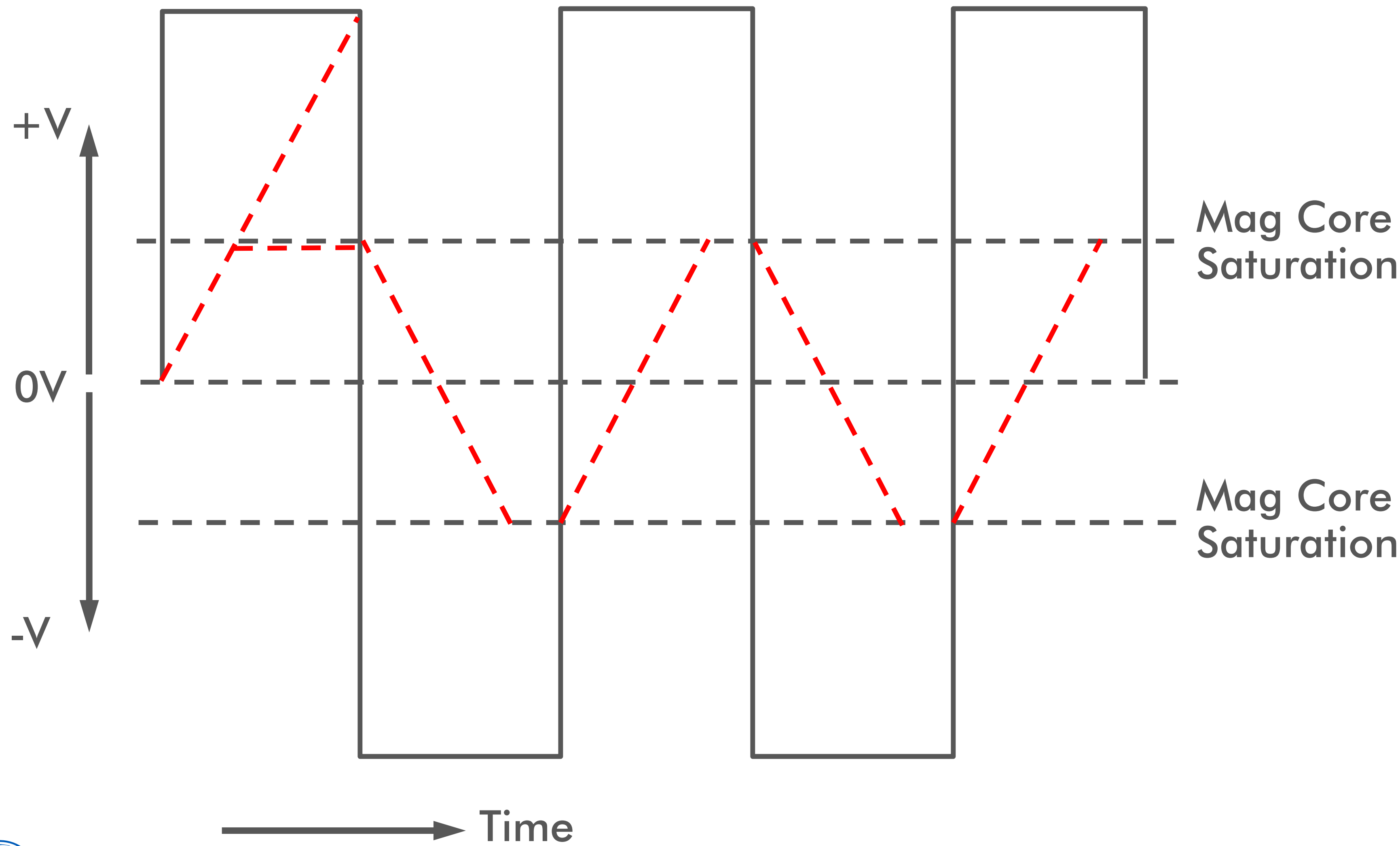
Steady State Saturation (5)



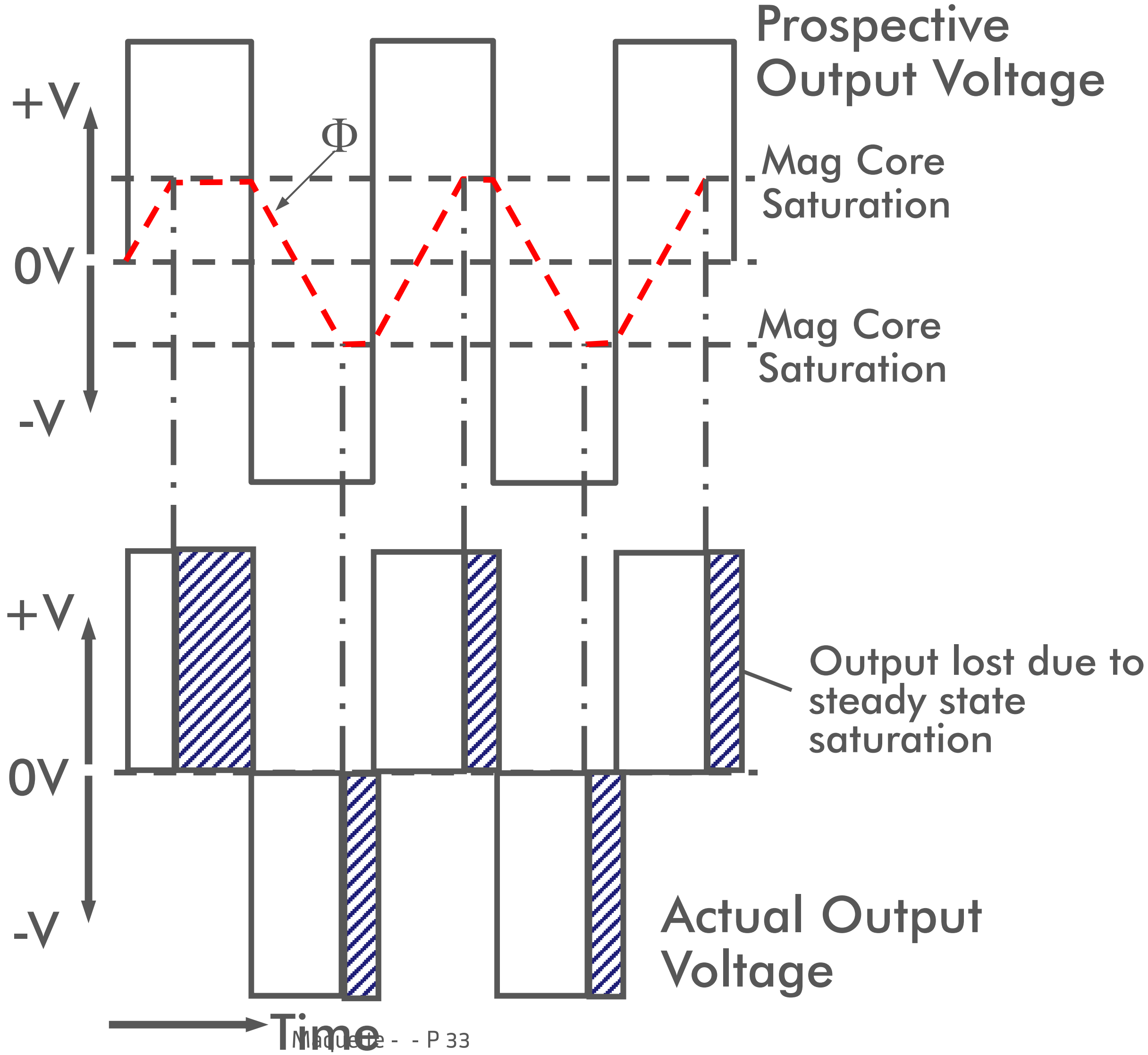
Assume :- Zero residual flux

Switch on at point B

Steady State Saturation (6)

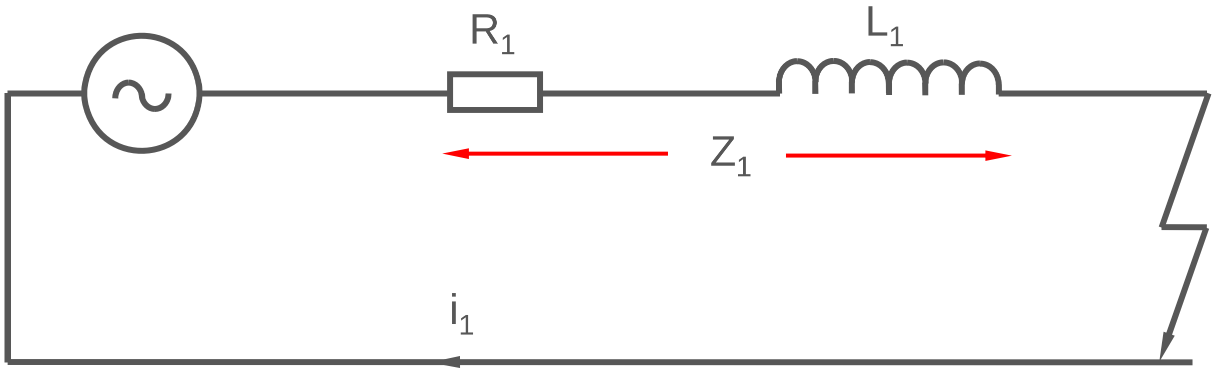


Steady State Saturation (7)



Transient Saturation

$$v = V_M \sin(wt + \sigma)$$



$$v = V_M \sin(wt + \sigma)$$

$$i_1 = +\frac{V_M}{Z_1}\sin(wt + \sigma - \varnothing) = \frac{V_M}{Z_1}\sin(\sigma - \varnothing).e^{-R_1 t / L_1}$$

$$= +\hat{I}_1 \sin(wt + \sigma - \varnothing) - \hat{I}_1 \sin(\sigma - \varnothing).e^{-R_1 t / L_1}$$

= STEADY STATE + TRANSIENT

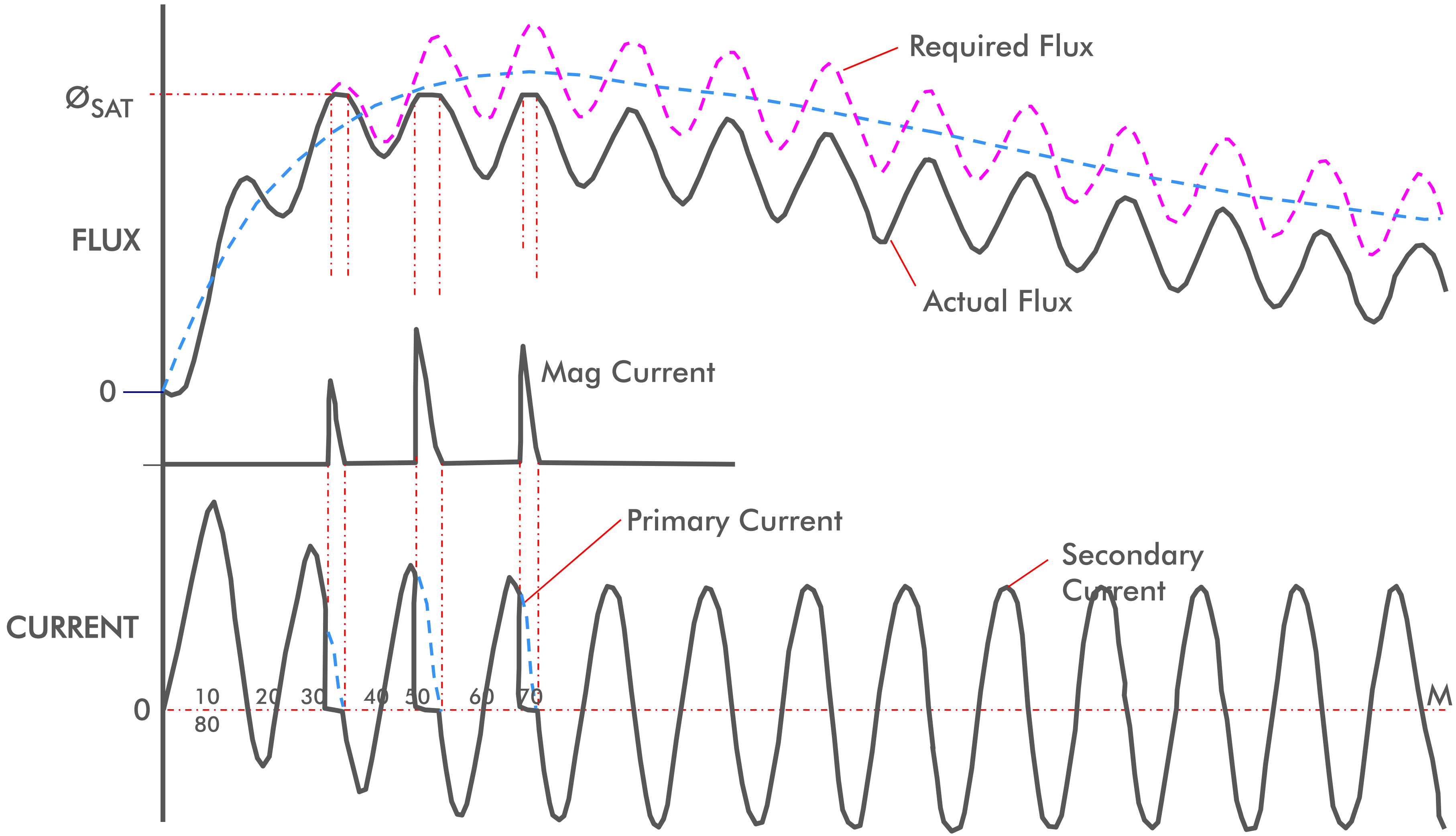
where :-

$$Z_1 = \sqrt{R_1^{\,2} + w^2 L_1^{\,2}}$$

$$\varnothing = \tan^{-1}\frac{wL_1}{R_1}$$

$$\hat{I}_1 = \frac{V_M}{Z_1}$$

Transient Saturation : Resistive Burden



CT Types

Current Transformer Function

Two basic groups of C.T.

Measurement C.T.s

- Limits well defined

Protection C.T.s

- Operation over wide range of currents

Note : They have DIFFERENT characteristics

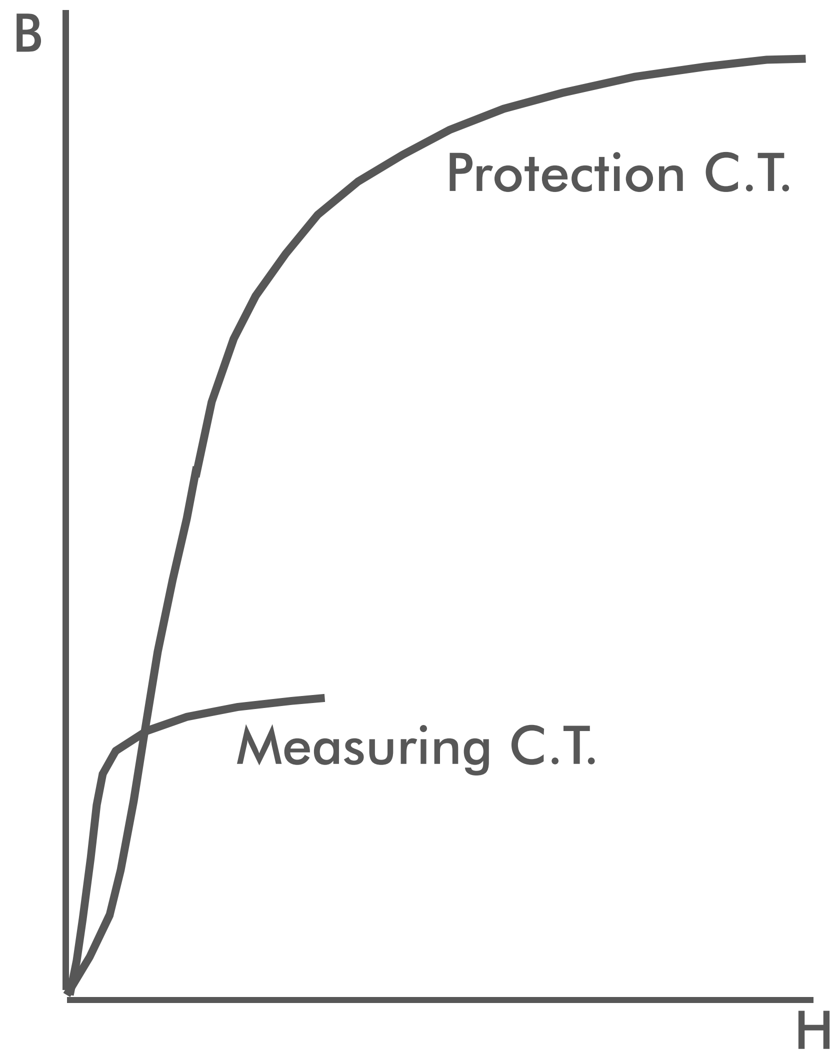
Measuring C.T.s

Measuring C.T.s

- Require good accuracy up to approx 120% rated current.
- Require low saturation level to protect instruments, thus use nickel iron alloy core with low exciting current and knee point at low flux density.

Protection C.T.s

- Accuracy not as important as above.
- Require accuracy up to many times rated current, thus use grain orientated silicon steel with high saturation flux density.



Current Transformer Ratings

Current Transformer Ratings (1)

Rated Burden

- Value of burden upon which accuracy claims are based
- Usually expressed in VA
- Preferred values :-

2.5, 5, 7.5, 10, 15, 30 VA

Continuous Rated Current

- Usually rated primary current

Short Time Rated Current

- Usually specified for 0.5, 1, 2 or 3 secs
- No harmful effects
- Usually specified with the secondary shorted

Rated Secondary Current

- Commonly 1, 2 or 5 Amps

Current Transformer Ratings (2)

Rated Dynamic Current

Ratio of :-

I_{PEAK} : I_{RATED}

(I_{PEAK} = Maximum current C.T. can withstand without suffering any damage).

Accuracy Limit Factor - A.L.F.

(or Saturation Factor)

Ratio of :-

$I_{PRIMARY}$: I_{RATED}

up to which the C.T. rated accuracy is maintained.

e.g. 200 / 1A C.T. with an A.L.F. = 5 will maintain its accuracy for $I_{PRIMARY} < 5 \times 200 = 1000$ Amps

Current Transformer Ratings (3)

Composite Error

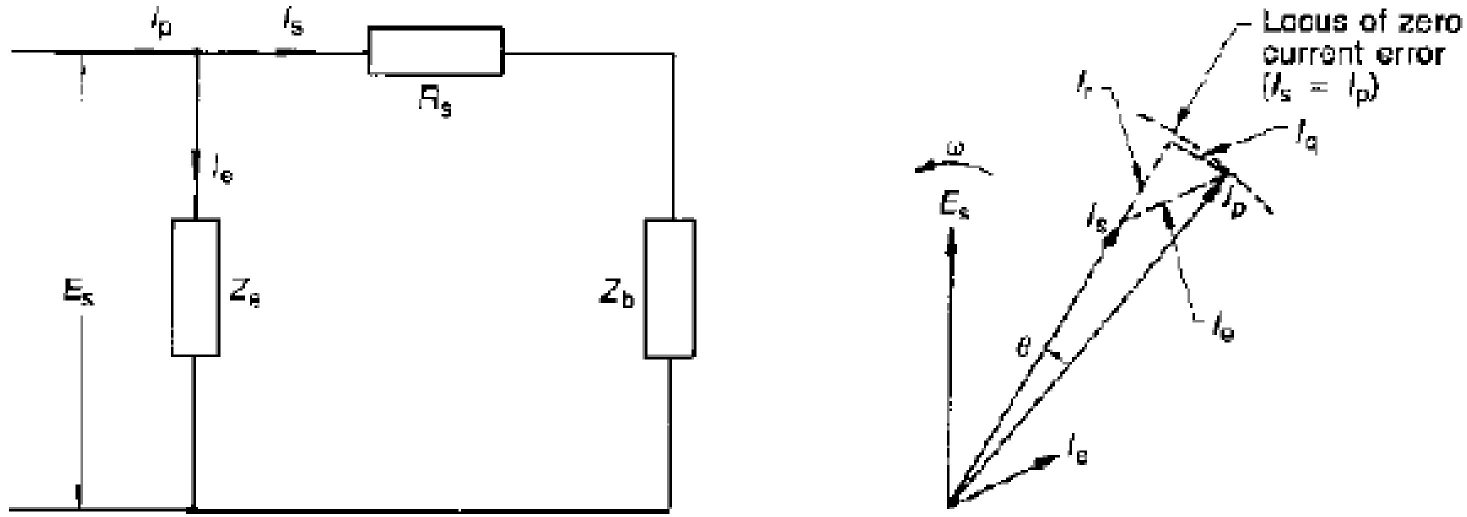


Fig. J1. EQUIVALENT CIRCUIT AND PHASOR DIAGRAM FOR A CT HAVING TOTAL ELECTROMAGNETIC COUPLING BETWEEN WINDINGS, ZERO INSULATION LEAKAGE CURRENTS, LINEAR Z_e, AND 1/1 TURNS RATIO

The following equations are applicable to this case:

$$E_s = I_s (R_s + Z_b) \quad \text{(Eq.1)}$$

$$I_e = I_p - I_s \quad \text{(Eq.2)}$$

Current Transformer Ratings (4)

Composite Error (IEC 60044-1)

RMS value of the difference between ideal and actual currents in the CT secondary

Includes ratio error, phase error, harmonics

Class	Current error at rated primary current (%)	Phase displacement at rated current (minutes)	Composite error at rated accuracy limit primary current (%)
5P	+/-1	+/-60	5
10P	+/-3		10
Standard accuracy limit factors are 5, 10, 15, 20, and 30			

Table 6.5: Protection CT error limits for classes 5P and 10P

Choice of Ratio

Primary Rating

$I_P \geq$ normal current in the circuit

if thermal (continuous) rating is not to be exceeded.

Secondary Rating

Usually 1 or 5 Amps (0.5 and 2 Amp are also used).

If secondary wiring route length is greater than 30 metres - 1 Amp secondaries are preferable.

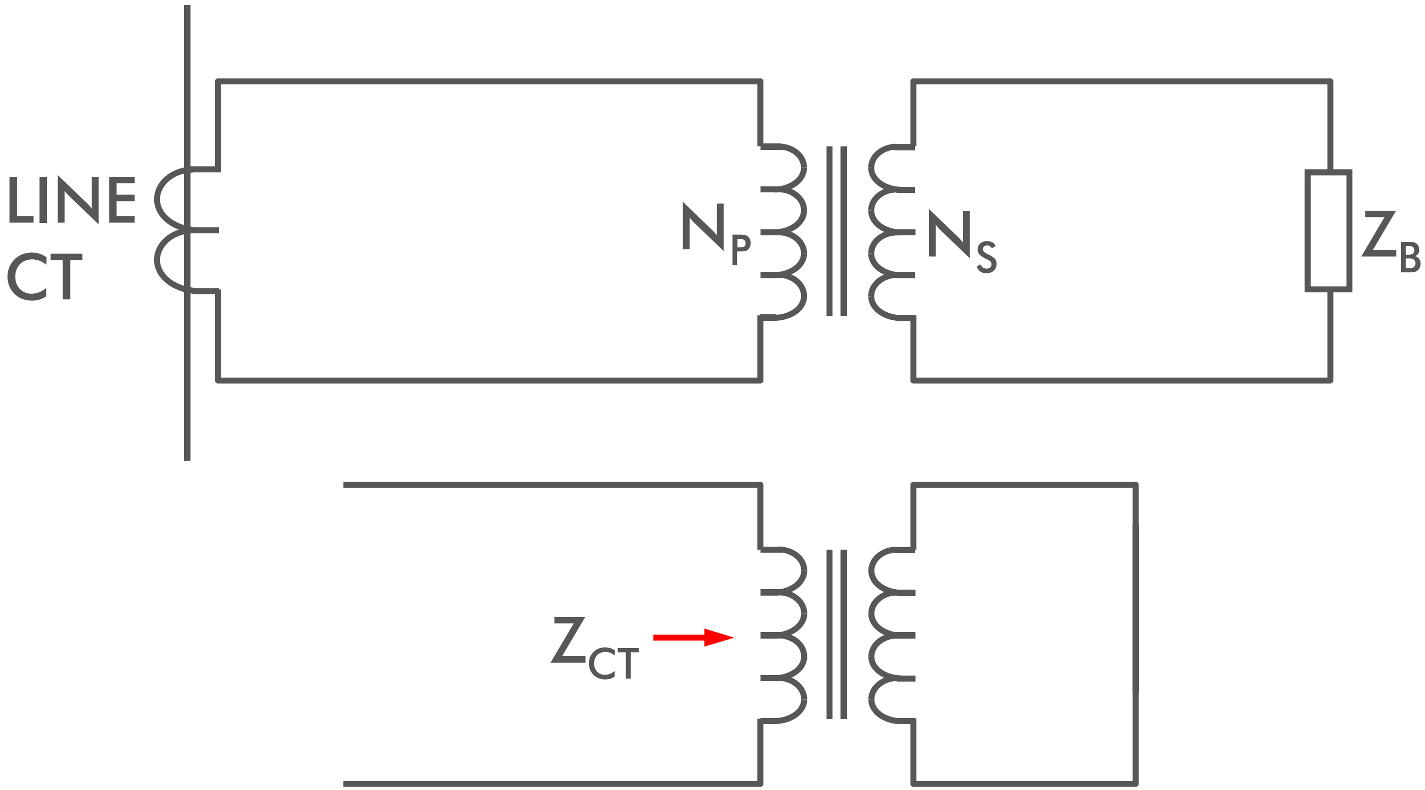
A practical maximum ratio is 3000 / 1.

If larger primary ratings are required (e.g. for large generators), can use 20 Amp secondary together with interposing C.T.

e.g. 5000 / 20 - 20 / 1

Interposing CT

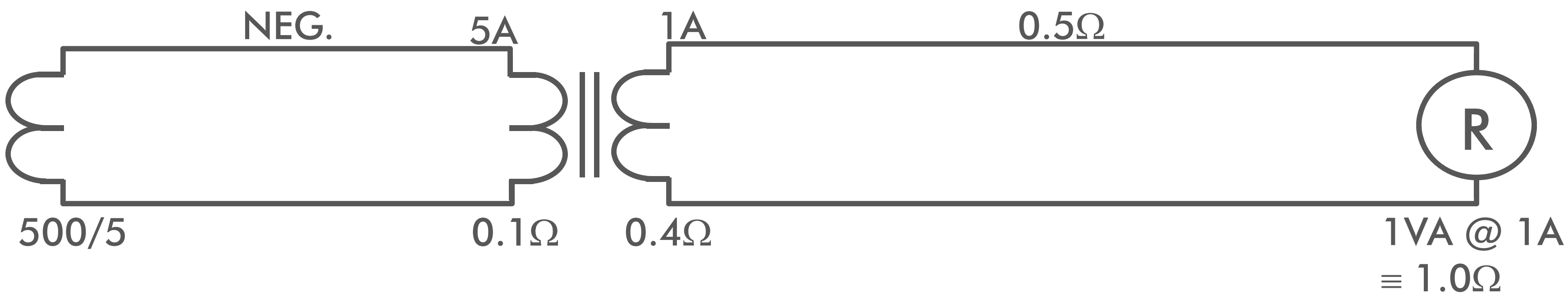
Interposing CT



Burden presented to line CT

$$= Z_{CT} + Z_B \times \frac{N_P^2}{N_S^2}$$

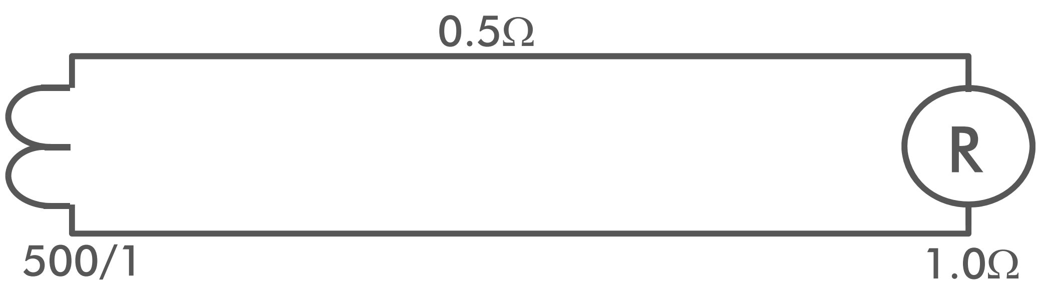
Example: Interposing CT



'Seen' by main ct :- $0.1 + \frac{(1)^2}{(5)^2}(2 \times 0.5 + 0.4 + 1) = 0.196\Omega$

Burden on main ct :- $I^2{}_R = 25 \times 0.196 = 4.9VA$

Burden on a main ct of required ratio :-



Total connected burden $= 2 \times 0.5 + 1 = 2\Omega$

Connected VA $= I^2{}_R = 2$

$\therefore$ The I/P ct consumption was about 3VA.

Current Transformer Designation

Current Transformer Designation AS 1675

Class "P" (General Purpose Protection CT)

Specified in terms of :-

i) Class (5P or 10P)
ii) Secondary reference voltage
iii) Accuracy limit factor (A.L.F.)

Example :-

10P 150 F15

BS approximation of above CT

10VA 10P 15 1A CT

50VA 10P 15 5A CT

$V_{SR} \cdot I_N = VA \times ALF$

Current Transformer Designation AS 1675

3.4 CLASS P CTs.

3.4.1 Designation. A Class P CT shall be designated as follows:

EXAMPLE: **AS 1675—1986: 10P 150 F15**

(a) Number of this standard

(b) Date (year of publication) of this standard

(c) Rated composite error (see Note) at accuracy limit current, in percent

(d) Class

(Optional space)

(e) Rated secondary reference voltage

(Optional space)

(f) Letter 'F' for factor

(g) Rated accuracy limit factor

NOTE: The rated composite error was formerly referred to as 'declared'.

Current Transformer Designation

BS3938 Classes :- 5P, 10P. 'X'

Designation (Classes 5P, 10P)

(Rated VA) (Class) (ALF)

Multiple of rated current (I_N) up to which declared accuracy will be maintained with rated burden connected.

5P or 10P.

Value of burden in VA on which accuracy claims are based.

(Preferred values :- 2.5, 5, 7.5, 10, 15, 30 VA)

Z_B = rated burden in ohms

$$= \frac{\text{Rated VA}}{I_N^2}$$

Current Transformer Designation

Class "X"

Specified in terms of :-

i) Rated Primary Current

ii) Turns Ratio (max. error = 0.25%)

iii) Knee Point Voltage

iv) Mag Current (at specified voltage)

v) Secondary Resistance (at 75°C)

Current Transformer Designation

Class "P" **IEC**

Specified in terms of :-

i) Rated burden
ii) Class (5P or 10P)
iii) Accuracy limit factor (A.L.F.)

Example :-

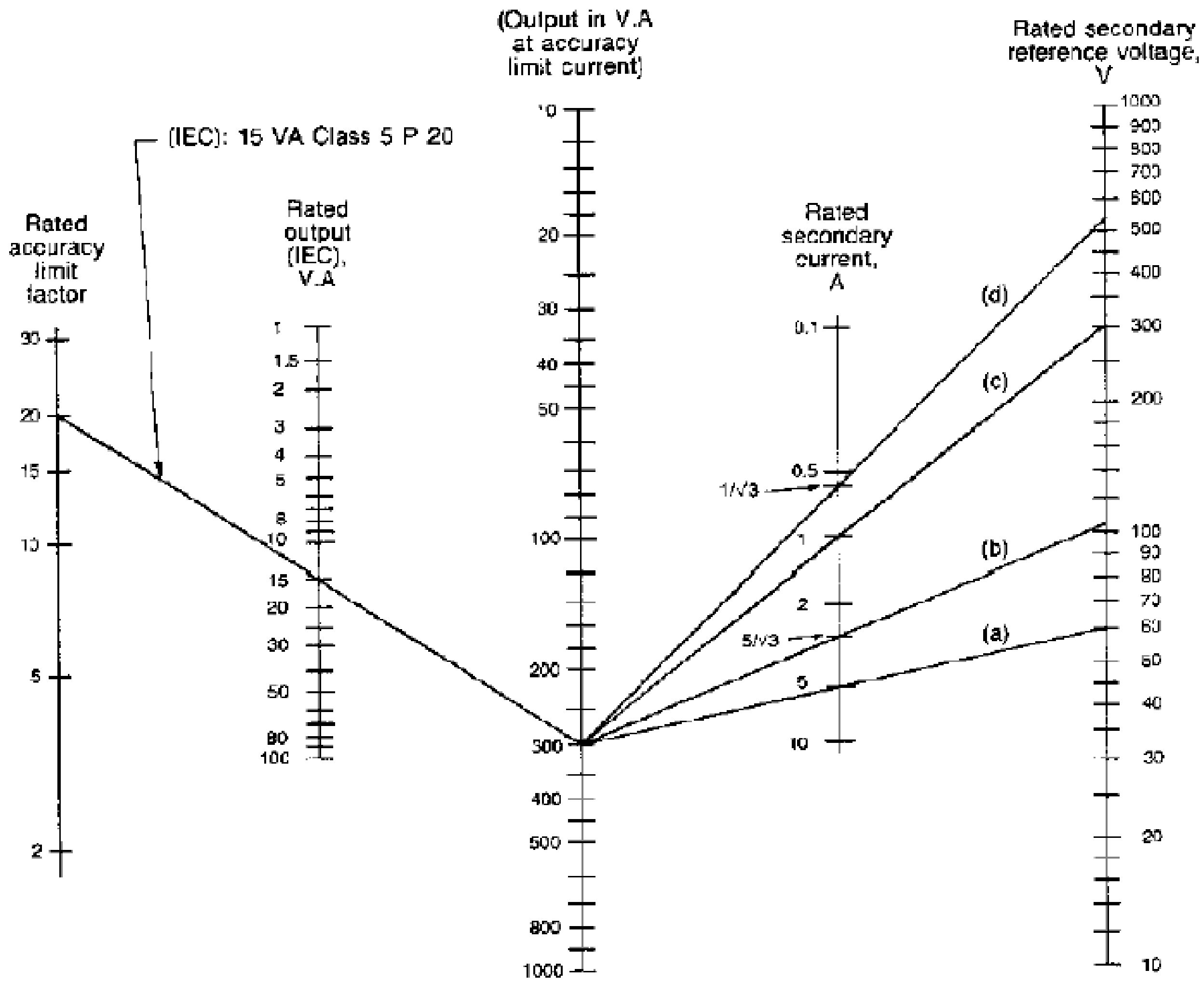
15 VA 10P 20

To convert VA and A.L.F. into useful volts

$$V_K \approx \frac{VA \times ALF}{I_N}$$

Current Transformer Designation

Conversion Nomogram



Current Transformer Designation

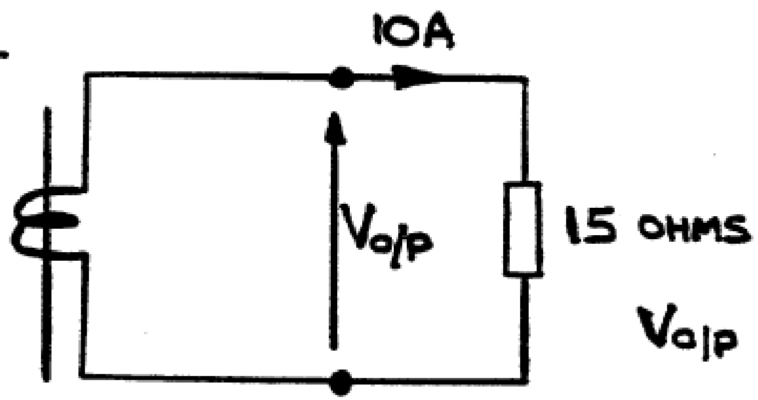
WHAT DOES C.T. CLASSIFICATION TELL US ?

CONSIDER 15VA 5P 10 (1 AMP SECONDARY)

$$\text{RATED BURDEN} = \frac{\text{RATED VA}}{(\text{RATED CURRENT})^2} = \frac{15}{1^2} = 15 \text{ OHMS}$$

MAX CURRENT (WITH 5% ACCURACY) = 10 × 1 = 10 AMPS

THUS :-



$V_{o/p}$ = 150 VOLTS

=> CT can deliver 150 V across the burden

Current Transformer Designation

What if burden connected is less than rated ?

The effective ALF increases proportionately

The CT can drive upto 30 times rated current through this reduced burden.

$$150\ \mathrm{V} = 30\mathrm{A} \times 5\ \Omega$$

$$ALF' = ALF \times (R_{CT} + R_{Bo}) / (R_{CT} + R_{B})$$

Where

R_{CT} : **CT Secondary Resistance**
R_{Bo} : **Rated burden**
R_{B} : **Connected burden**

Current Transformer Designation AS 1675

3.4.6 Current error. When a Class P CT is energized at rated primary current with a burden not exceeding 0.04 Ω, the current error shall not exceed the following:

(a) For rated primary currents ≤ 100 A . . . 2 percent.

(b) For rated primary currents > 100 A . . . 1 percent.

Current Transformer Designation AS 1675

Class “PL” (Special Purpose Protection CT)

Special purpose low reactance CT’s, (Class X in IEC)

Specified in terms of :-

i) Maximum magnetising current at kneepoint voltage
ii) Kneepoint voltage
iii) Maximum secondary winding resistance in ohms

Example:-

0.05 PL 950 R3

Current Transformer Designation

- Turns Compensation
  - Reduce N_2 (secondary turns) by a few turns
  - I_2 is correspondingly higher, compensates for I_e

- What happens with Class X ?
  - Max. turns ratio error is 0.25%
  - Consider 500/1 CTs, 15 kA fault level
  - With 5% setting, operating current is 50mA + Imag
  - CT1 : 500 turns, Isec = 30A
  - CT2 : 501 turns, Isec = 29.94A

=> Relay might maloperate

Current Transformer Designation

IEC 60044-6 Class TPS

- Closed iron core, low leakage reactance
- Corresponds to BS 3938 Class X
- For differential protection applications

IEC 60044-6 Class TPX

- Closed iron core, no limits on remanence
- Similar to Class P (IEC), but with transient performance spec
- For line protection applications

Current Transformer Designation

IEC 60044-6 Class TPY

- Air gapped core, remanence < 10%
- Otherwise identical to Class TPX

IEC 60044-6 Class TPZ

- CT with linear core, negligible remanence

CT Class	Ratio Error @ rated I	Angle Error @ rated I	Peak instantaneous error at accuracy limit
TPX	± 0.5%	±30 min	< 10%
TPY	± 1.0%	±60 min	< 10%
TPZ	± 1.0%	±180 min	< 10% (AC only)

Choice of Current Transformer

- **Instantaneous Overcurrent Relays**
  - Class P Specification
  - A.L.F. = 5 usually sufficient
  - For high settings (5 - 15 times C.T rating)
    A.L.F. = relay setting

- **IDMT Overcurrent Relays**
  - Generally Class 10P
  - Class 5P where grading is critical

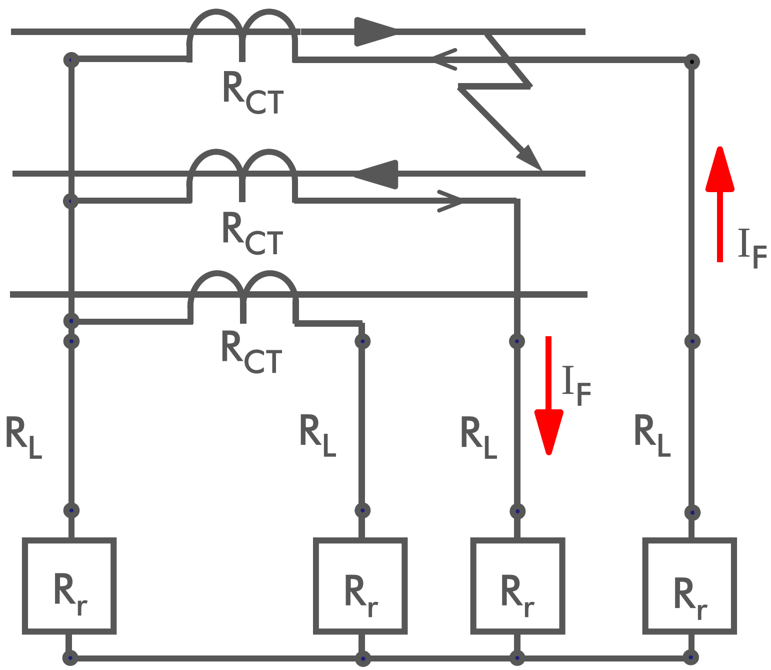
Note : A.L.F. X V.A < 150

- **Differential Protection**
  - Class X Specification
  - Protection relies on balanced C.T output

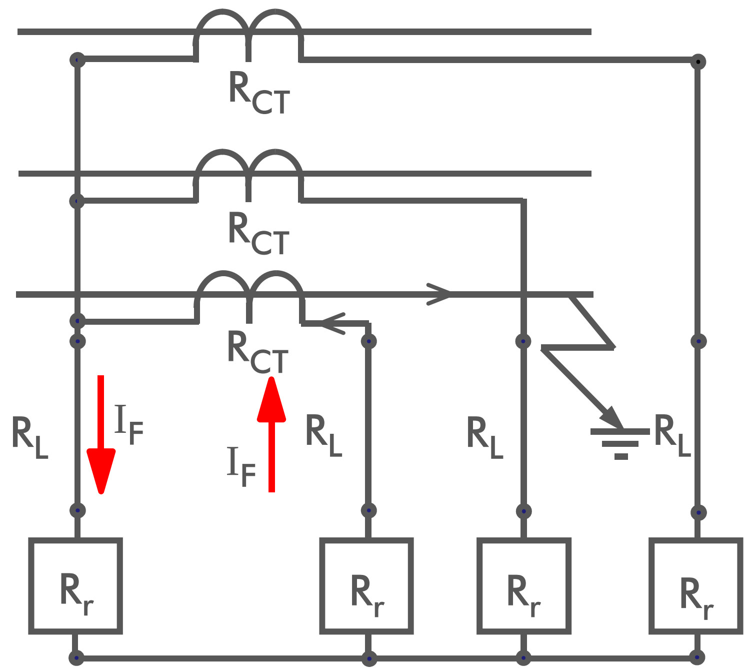
CT Selection Example

Burden on Current Transformers

1. <u>Overcurrent</u> : $R_{CT} + R_L + R_r$



2. <u>Earth</u> : $R_{CT} + 2R_L + 2R_r$



Overcurrent Relay V_{SR} Check

Assume values :

$I_{f\,max}$	=	7226 A	R_{CT}	=	0.26 Ω
C.T	=	1000 / 5 A	R_r	=	0.02 Ω
		7.5 VA 10P 20	R_L	=	0.15 Ω

Check to see if CT is large enough :

$I_{f\,max} = 7226/1000 = 7.226 < ALF$

Required output voltage $= V_S = I_F\,(R_r + R_L)$

$$= \frac{7226 \times 5}{1000}(0.02 + 0.15) = 36.13 \times 0.43 = 6.14 \text{ Volts}$$

Current transformer V_{SR} approximates to :-

$$V_{SR} = \frac{VA}{I_n} \times ALF$$

$$= \frac{7.5}{5} \times 20 = 30 \text{ Volts}$$

$V_{SR} > V_S$ therefore C.T V_K is adequate

Earth Fault Relay V_{SR} Check

Assume values : As per overcurrent.

<u>Note</u> For earth fault applications require to be able to pass 10 x relay setting.

Check to see if V_{SR} is large enough : $V_{SR} = 30$ Volts

Total load connected $= 2R_L + 2R_r$

$= 2 \times 0.15 + 2 \times 0.02$

$\therefore$ Maximum secondary current

$= \frac{30}{0.6} = 88.2A$

Typical earth fault setting $= 30\% \ I_N$

$= 1.5A$

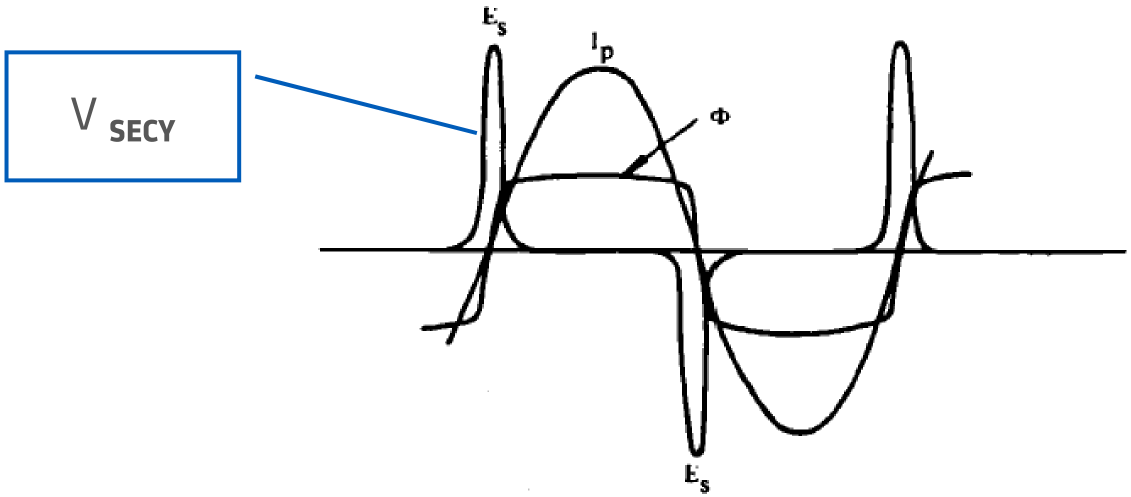
Therefore <u>C.T can provide > 58 x setting</u>

C.T V_K is adequate

Open Circuited Secondary Winding

Secondary must never be left O/C with primary energised !!
If left open with primary winding effective

V_{SECY} = High
= Danger
= Possible insulation breakdown

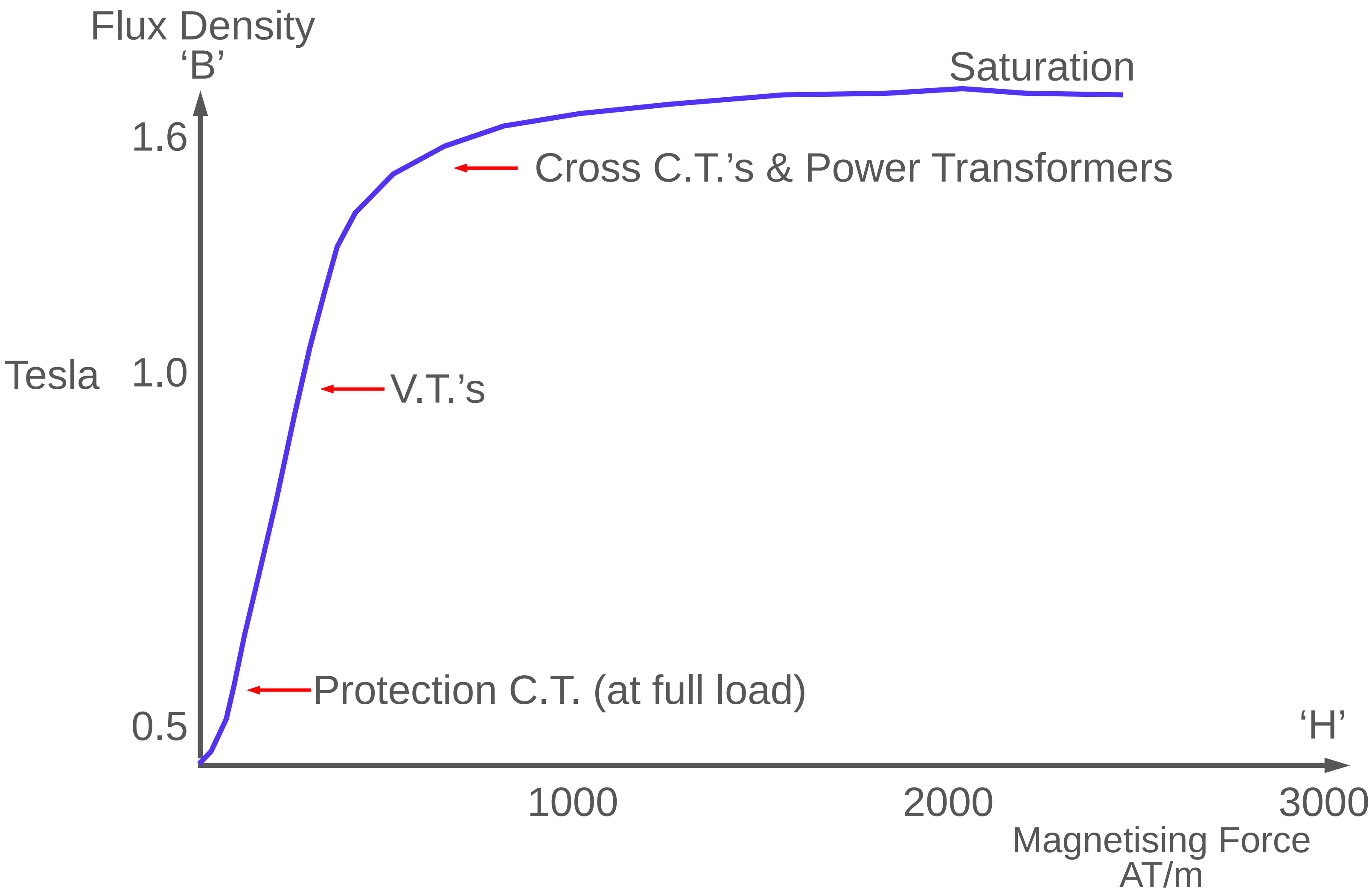


Voltage Transformers

Voltage Transformers

- Provides isolation from high voltages
- Must operate in the linear region to prevent accuracy problems - Do not over specify VT
- Must be capable of driving the burden, specified by relay manufacturer
- Protection class VT will suffice

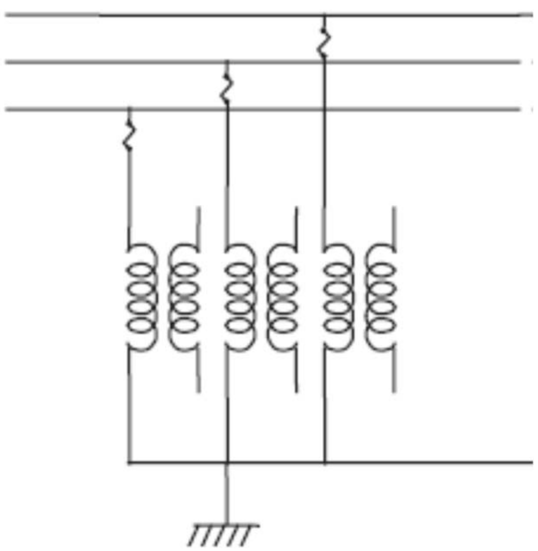
Typical Working Points on a B-H Curve



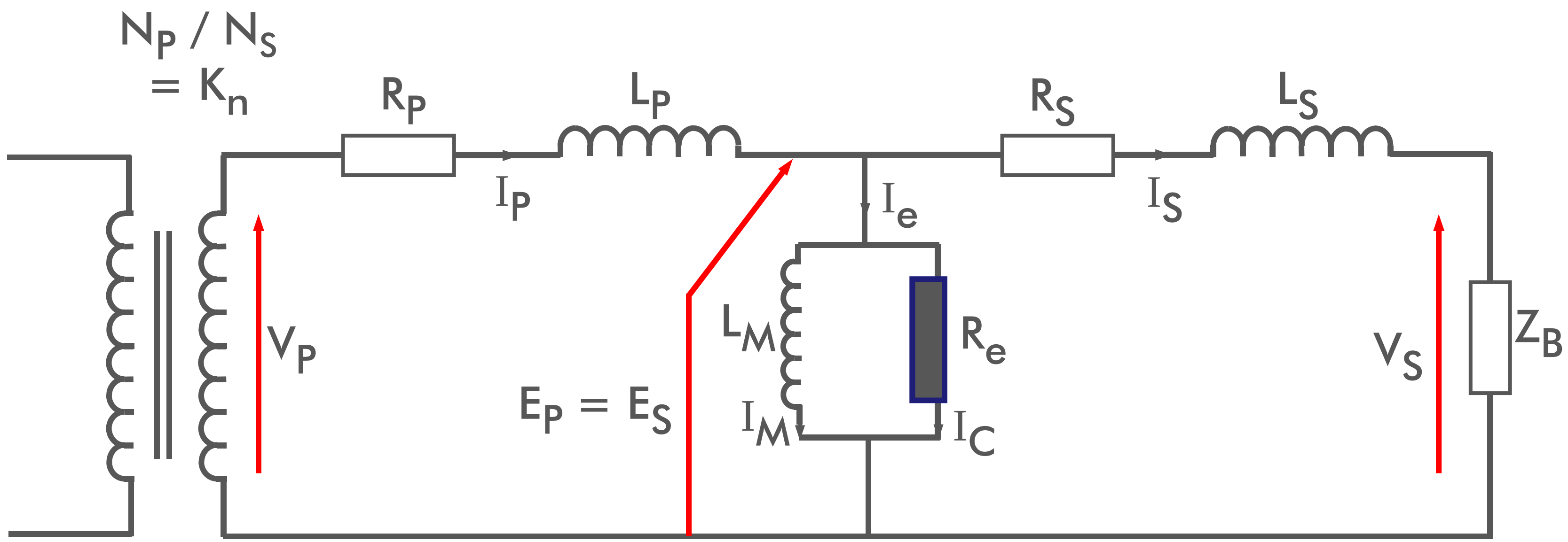
Types of Voltage Transformers

Two main basic types are available:

- Electromagnetic VT`s
    - Similar to a power transformer
    - May not be economical above 132kV
- Capacitor VT`s (CVT)
    - Used at high voltages
    - Main difference is that CVT has a capacitor potential divider on the front end.

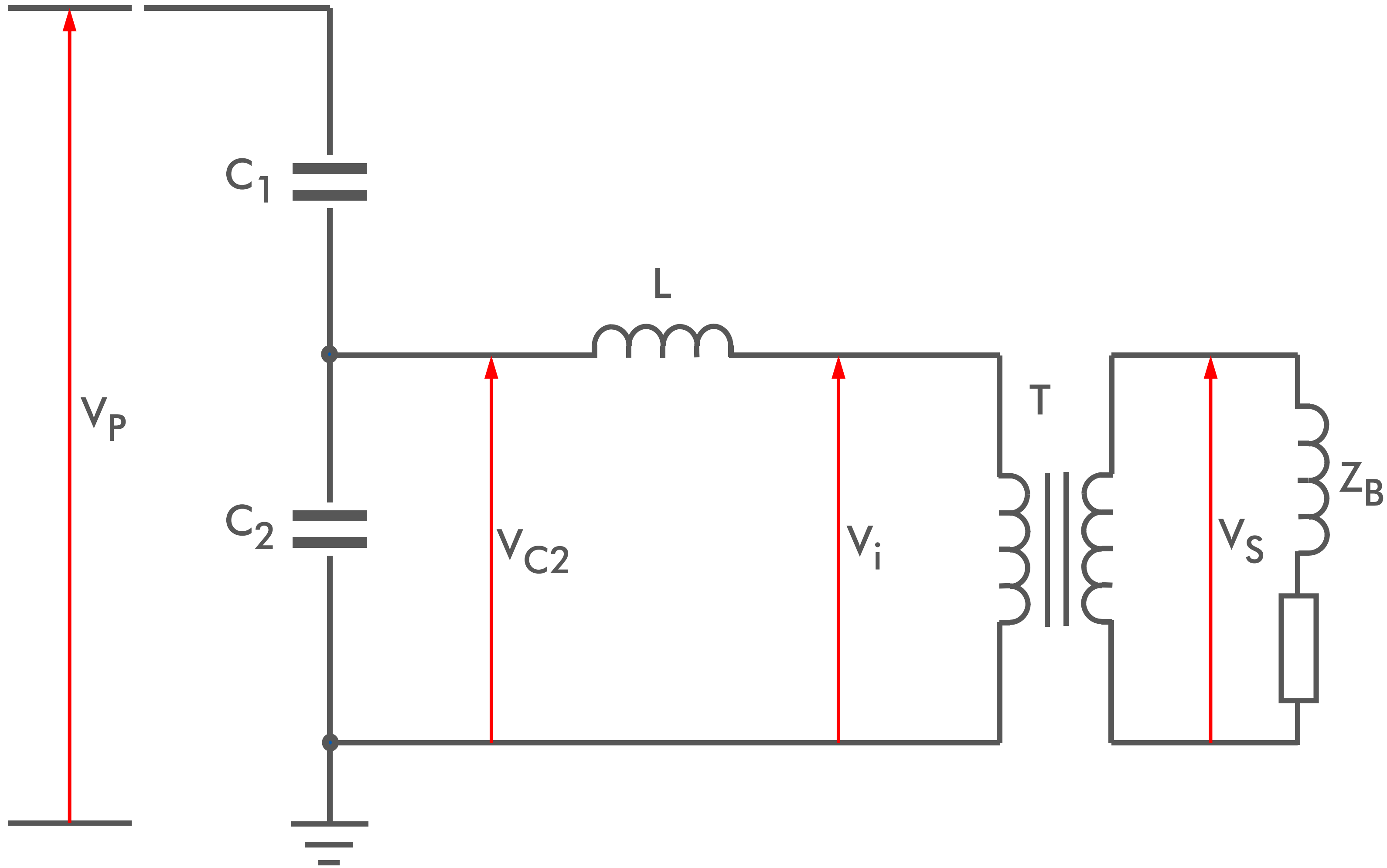


Electromagnetic Voltage Transformer

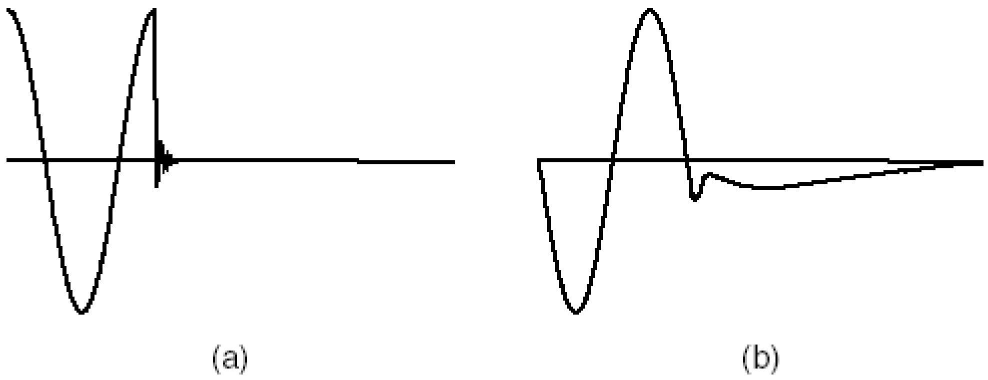


$$\text{Voltage Error} = (K_n V_s - V_p) / V_p$$

Basic Circuit of a Capacitor V.T.



Capacitor VT Transient Response



Capacitor VT response – typical - for ‘ zero voltage’ faults

- Fault at voltage max
- Fault at voltage zero

Need to be considered in distance protection design

Ferro-resonance

- The exciting impedance of auxiliary transformer T and the capacitance of the potential divider form a resonant circuit.
- May oscillate at a sub normal frequency. Resonant frequency close to one-third value of system frequency
- Manifests itself as a rise in output voltage, r.m.s. value being 25 to 50 per cent above normal value
- Use resistive burden to dampen the effect

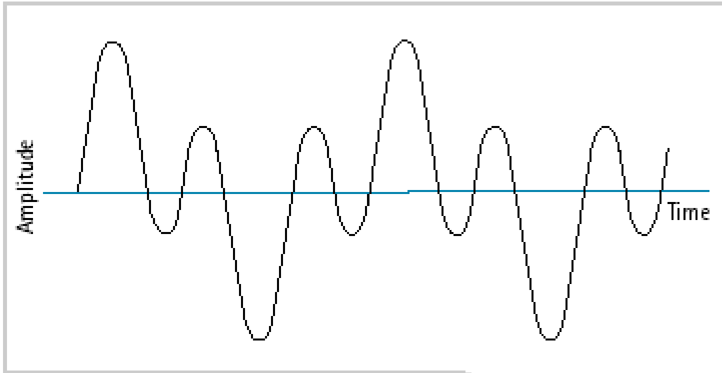


Figure 6.8: Typical secondary voltage waveform with third sub-harmonic oscillation.

VT Earthing

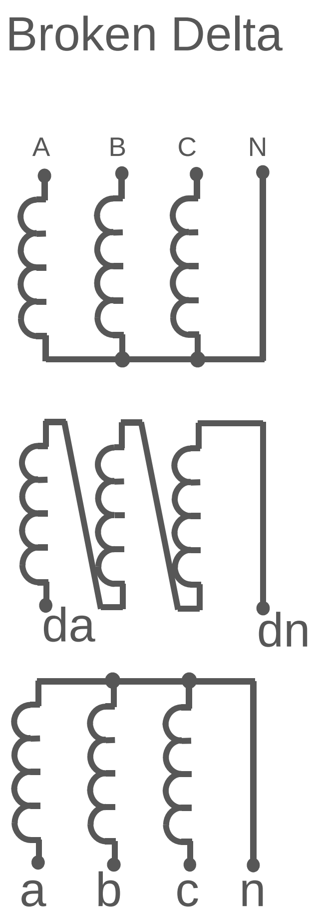
- **Primary Earthing**
  - Earth at neutral point
  - Required for phase-ground measurement at relay

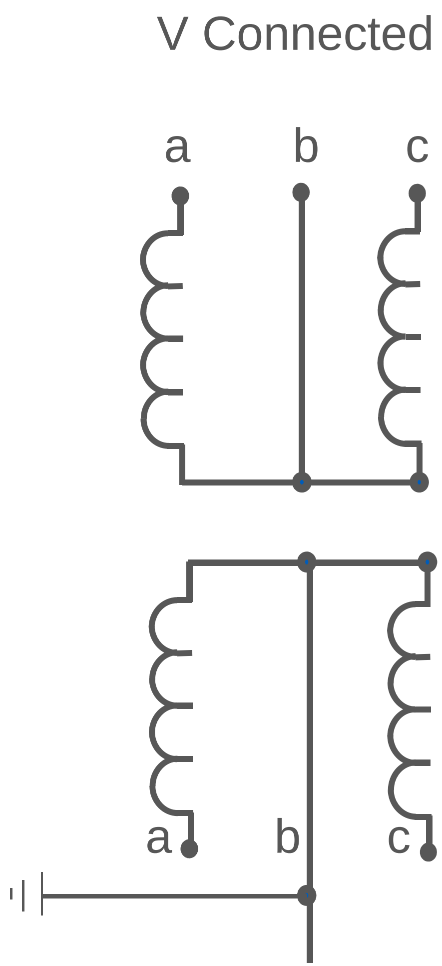
- **Secondary Earthing**
  - Required for safety
  - Earth at neutral point
  - When no neutral available - earth yellow phase (VERY COMMON)
  - No relevance for protection operation

VT Construction

- 5 Limb
  - Used when zero sequence measurement is required (primary must also be earthed)
- Three Single Phase
  - Used when zero sequence measurement is required (primary must also be earthed)
- 3 Limb
  - Used where no zero sequence measurement is required
- V Connected (Open Delta)
  - No yellow phase
  - Cost effective
  - Two phase-phase voltages
  - No ground fault measurement

VT Connections





VT Construction - Residual

- Used to detect earthfault
- Useful where current operated protection cannot be used
- Connect all secondary windings in series
- Sometimes referred to as `Broken Delta`
- Residual Voltage is 3 times zero sequence voltage
- VT must be 5 Limb or 3 single phase units
- Primary winding must be earthed

Voltage Factors Vf

- Vf is the upper limit of operating voltage.
- Important for correct relay operation.
- Earthfaults cause displacement of system neutral, particularly in the case of unearthed or impedance earthed systems.

Voltage factor V_f	Time rating	Primary winding connection/system earthing conditions
1.2	continuous	Between lines in any network. Between transformer star point and earth in any network
1.2	continuous	Between line and earth in an effectively earthed network
1.5	30 s	
1.2	continuous	Between line and earth in a non-effectively earthed neutral system with automatic earth fault tripping
1.9	30 s	
1.2	continuous	Between line and earth in an isolated neutral system without automatic earth fault tripping, or in a resonant earthed system without automatic earth fault tripping
1.9	8 hours	

Table 6.3: Voltage transformers: Permissible duration of maximum voltage

Protection of VT's

- H.R.C. Fuses on primary side
- Fuses may not have sufficient interrupting capability
- Use MCB