35

Current Transformers and their Applications

Introduction, Specifications — Burden — Accuracy — Magnetization curve — Secondary current ratings — Class of accuracy — Polarity — Open circuited secondary — CT's for protection — Effect of transients — CT's for circulating current protection — Procedure of calculating the error — Types of construction — Testing of CT — Selection of CT's for Protective Relaying — Transient Performance of CT's.

35.1. INTRODUCTION

Protective relays in a.c. power systems are connected in the secondary circuits of current transformers and potential transformers. The design and use of these transformers is quite different from that of well known power transformers. In current transformers, primary current is not controlled by condition of the secondary circuit. Hence primary current is a dominant factor in the operation of current transformers. Current transformers must be further classified into two groups :

1. Protective current transformers used in association with relays, trip coils, pilot wires etc.
2. Measuring current transformers—used in conjunction with ammeter, wattmeter etc.

As a rule, the ratio error is very important in protective current transformers, and phase angle error may be less important.

Voltage transformer is used for transforming voltage from one value to another (generally lower) value.

Both current transformers and voltage transformers come under the little 'Instrument Transformers.'

As the relay time has reduced to the order of a few milli-seconds is modern protective relays, the transient behaviour of current transformers and voltage transformers need more attention. In order to prevent saturation of current transformer cores during sub-transient currents, larger cores and air gaps are introduced in CT's for fast protective relays.

The Standard Specifications given by IEC and BIS cover several aspects about current transformers such as requirements, specification, testing, application, terms and definitions etc. These should be referred.

The major criterion of selection of the current transformer is the ratio at maximum load current through primary and secondary. In other words, the current transformer secondary current at maximum load should not exceed the continuous current rating of the applied relay. This is particularly applicable to phase type relays where load current flows through the relays. This criterion applies indirectly to the ground relays even though they do not receive load current because they are generally connected to the same set of current transformers as the phase relays. Since the ratio has been set on the basis of load current for the phase relays, this ratio would then apply to the ground relay. Thus, the current transformer ratio should be selected to provide around 5 amperes secondary for the maximum load current. Some relays can carry up to 10 amperes and the ratio can be selected accordingly. Where delta-connected CT's are used, the $\sqrt{3}$ factor should not be overlooked.

35.2. TERMS AND DEFINITIONS

(*a*) **Instrument transformer.** The transformers which are used in conjunction with measuring instruments, protective relays and control circuits. Instrument transformers include measuring and protective current transformers and voltage transformers.

(*b*) **Current transformer.** Instrument transformers used in conjunction with ammeters, overcurrent relays, etc. Current transformers step down current from high value too a low value. Their current ratio is substantially constant for given range of primary current and phase angle error is within specified limits. The VA rating of current transformers is small as compared with that of a power transformer.

(*c*) **Rated Primary Current.** The value of primary current on which the performance of the current transformer is specified by the manufacture [Ref. Sec. 35.9 (*a*)]

The maximum permissible temperature-rise of a current transformer carrying its rated continuous thermal current is given in Sec. 35.9. Unless otherwise specified, the rated continuous thermal current is equal to the rated primary current. It should therefore, be noted that normally current transformers have no continuous overcurrent rating. When selecting a current transformer, therefore, the rated primary current should be so chosen as to make it suitable for all but the momentary overcurrent that will occur in service. Where intermittent overcurrents are frequent and severe, the manufacturer should be consulted as to a suitable current rating.

Rated primary current is assigned after conducting heat run test. (Ref. Sec. 10.12.2).

(*d*) **Rated short time Current (primary).** It is defined as r.m.s. value of a.c. component of current which the CT can carry for rated time without damage due to thermal or electrodynamic stresses.

The heating effect depends on the average r.m.s. value of the primary current and its duration of flow through the current transformer, whereas the mechanical stresses due to the electromagnetic forces set up in a current transformer depend on the peak value of the rated dynamic current. The rated dynamic current being in turn dependent on the rated short-time thermal current, it is desirable that purchasers should inform the manufacture regarding the magnitude and duration of the short-time thermal current to be withstood.

The short-time current is associated with time, (Rated duration of short-current) which may be 0.25, 0.5, 1, 2.0 or 3 seconds.

The short-time current rating is proved by conducting short-time current tests (Ref. Sec. 11.6).

(*e*) **Rated Secondary Current.** The value of secondary current market on the rating Plate. [Ref. Sec. 35.9 (*a*)]

(*f*) **Rated Transformation Ratio.** The ratio of the rated primary current to rated secondary current.

(*g*) **Actual Transformation Ratio.** The ratio of the actual primary current to the actual secondary current.

(*h*) **Exciting Current.** The r.m.s. value of current taken by the secondary winding of a CT when sinusoidal voltage of rated frequency is applied to secondary, with primary winding open circuited.

(*i*) **Rated Saturation Factor.** The ratio of rated primary saturation, current to rated primary current.

(*j*) **Rated Primary Saturation Current.** The maximum value of primary current at which the required accuracy is maintained.

(*k*) **Overcurrent factor.** The ratio of Rated Short-time current to rated primary current.

(*l*) **Burden.** The value of load connected across the secondary of CT, expressed in VA or ohms at rated secondary current.

(*m*) **Rated Burden.** The burden assigned by manufacture at which the CT performs with specified accuracy.

(*n*) **Current Error or Ratio Error.** The percentage error in the magnitude of the secondary current is defined in terms of Current Error.

$$\% \text{ Current Error} = \left(\frac{k_n I_s - I_p}{I_p}\right) \times 100$$

k_n = Rated transformation ratio

I_s = Actual secondary current for I_p

I_p = Actual primary current.

(*o*) **Phase angle error.** The phase angle between primary current vector and the reversed secondary current vector.

(*p*) **Rated accuracy limit primary current.** The highest value of primary current assigned by the manufacture of CT, upto which the limits of composite errors are complied with.

(*q*) **Composite Error.** The r.m.s. value of the difference ($k_n\, i_s - i_p$) integrated over one cycle under steady condition, given by

$$\text{Composite error} = \frac{100}{I_p}\sqrt{\frac{1}{T}\int_0^T (k_n\, i_s - i_p)^2\, dt}$$

where k_n = Rated transformation ratio

I_p = Primary current, r.m.s.

i_p = Primary current, instantaneous

i_s = Secondary current, instantaneous

T = Time of one cycle, in sec.

35.3. ACCURACY CLASS

The class assigned to the current transformer with the specified limits of ratio error and phase angle error.

For relaying purpose the ratio-error becomes important. Generally the load on the secondary side of CT is at such a high lagging power factor that the secondary current is almost in phase opposition with the magnetising currents and, therefore, phase angle error is negligible. Ratio error is very significant because the currents are high during short-circuit conditions.

Ratio Error is expressed as

$$\% \text{ R.E. at } I_p = \left(\frac{K_n\, I_s - I_p}{I_p}\right) \times 100$$

where % R.E. = %ratio error

I_p = r.m.s. value of current in primary.

I_s = r.m.s. value of current in secondary.

$$K_n = \text{Nominal ratio} = \frac{\text{Rated primary current}}{\text{Rated secondary current}}$$

In general the percentage ratio error increases with increase in primary current. Refer table 35.1, to get an idea of permissible error.

Table 35.1. Limits of Error [Ref. Sec. 35.9 (*d*)]

Accuracy class	*Current Error at Rated Primary current*	*Phase Displacement at Rated Current*	*Composite Error Rated Accuracy Limit Primary Current*
	Per cent	Minutes	Per cent
5 P	± 1	± 60	5
10 P	± 3	—	10
15 P	± 5	—	15

The current transformers are marked as follows [*e.g.*, 30/5 P 10] where, first number : output in VA (*i.e.* 30),

Second number : accuracy class (*i.e.* 5 P).

Last number : composite error (*i.e.*, 10).

The class of accuracy required for protective current transformer depends upon the particular application. These aspects are discussed below :

For Instantaneous Overcurrent Relays and Trip Coils, class 15 P protective current transformers are generally sufficiently accurate. Rated accuracy limit factor of 5 should be enough. However, when the instantaneous overcurrent relays are set to operate for high values of overcurrents, say 6 to 16 times of rated primary currents, the accuracy limit factor should have atleast the value of the setting used.

The current transformers for high set overcurrent relay may be allotted higher rated primary current thereby reducing the required accuracy limit factor.

For IDMT relays class 10 P current transformer is preferred for system networks discrimination is obtained by graded time lag. Where close discrimination is not desired, class 15 P may be preferred.

For residually connected Inverse and Definite Minimum Time Earth fault relays, the choice of accuracy class of CT depends on characteristic and arrangement of protective system. Where phase fault stability and accurate time grading is not required, class 10 P and 15 P current transformers may be used. The product of rated burden and rated accuracy limit factor should approach 150, provided earth fault relay setting is not less than 20 per cent of rated secondary current of associated CT class 5 P CT's are preferred where accurate time grading and stability are desired.

35.4. BURDEN ON CT

Impedance of secondary circuit expressed in ohms and power factor. It can be expressed as apparent power and rated secondary current at specified power factor. This power factor is not the power factor of the secondary load.

The circuit connected to the secondary winding is termed as 'burden' of the current transformer. If the term 'load' is used, it refers to the primary current magnitude. Burden is expressed preferably in terms of impedance of the circuit connected to the secondary and its resistance and reactance. The British method is to specify the burden on the CT in volt-amperes at rated secondary current at specified power factor.

Thus we may express the burden in the following two forms, *e.g., 0.5 ohm impedance or 12.5 volt-amperes at 5 amperes. Let rated burden be P* volt-amperes at rated secondary current I_s, amperes. Then, the ohmic impedance of the burden Z_b can be calculated as follows :

$$Z_b = \frac{P}{I_s^2} \text{ ohms}$$

If burden power factor is cos ϕ, P = *VA* Burden

$$R_b = Z_b \cos\phi \text{ ohms}$$

$$X_b = \sqrt{Z_b^2 - R_b^2} \text{ ohms.}$$

Example 35.1. *Calculate the VA output required for a C.T. of 5 A rated secondary current when burden consists of relay requiring 10 VA at 5 A plus loop lead resistance 0.1 ohm. Suggest choice of CT.*

Solution.

Volt ampere required to compensate loop lead resistance

$$= I^2 R = 5^2 \times 0.1 = 2.5 \text{ VA}$$

Relay requires 10 VA

Hence total VA output required

$$= 10 + 2.5 = 12.5$$

Hence a CT of rating 15 VA and secondary current 5 A may be used.

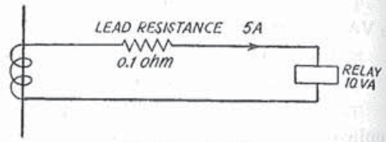


Fig. Example 35.1.

The burden on a protective current transformer comprises the individual burdens of associated relays, trip coils, connecting leads etc. The total burden is calculated by addition of component burdens as explained in Example 35.1. When individual burdens are expressed in the ohmic value the burdens are converted into VA burdens at rated secondary current. When VA burdens are referred to certain base VA, they should be converted to a common base VA.

Although usual practice is to add the component burdens arithmatically it is more accurate to add resistances and reactances separately, and then calculate impedance.

The impedance of relay coil changes with current setting Impedance decreases with increase in current above rated current.

When the relay is set to operate at current different from the rated secondary current of CT, the effective burden of the relay is calculated as follows :

$$P_e = P_r \left(\frac{I_s}{I}\right)^2$$

where, P_e = effective VA burden caused by the relay.

$P_r = V_b$ burden of relay at its current setting.

I_s = rated secondary current of CT.

I_r = current setting of relay.

The following aspects should be noted :

— Impedance of relays, coil, etc., changes with current setting.

— Impedance of relays, trip coils, etc., decreases with increase in current beyond current setting.

— Impedance of electromechanical relay depends upon the position armature.

The values of power consumption of relays, trip coil etc., are given by their manufacturer.

After calculating the total burden on the CT is described above, the CT of suitable burden should be selected.

It is uneconomical to select a CT having a VA output which is very much in excess of the burden. The CT becomes unduly large.

When the nearest standard VA rating is slightly less than the calculated burden, the former may be adopted after consulting the manufacturer.

Example 35.2. *The rated secondary current of a current transformer is 5 A.*

The plug setting of a relay is 2.5 A. The power consumption of the relay at the 2.5 A plug setting is 2 VA. Calculate the effective VA burden on the current transformer.

Solution.

$$P_e = P_r \left(\frac{I_s}{I_r}\right)^2$$

where P_r = VA burden of relay at given setting.

P_e = Effective VA burden on the CT.

I_s = Rated secondary current of CT.

I_r = Current setting of the relay.

In the given problem, P_e is to be determined

$$P_e = P_r \left(\frac{I_s}{I_r}\right)^2 = 2\left(\frac{5}{2.5}\right)^2 = 2 \times 4 = 8 \text{ VA.} \quad \textbf{Ans.}$$

The choice of rated VA output of CT should be nearest to that computed as above. Too much margin between calculated and selected values makes the choice either uneconomical or inadequate. Nearest standard VA rating should be selected. CT manufacturer may be consulted.

35.5. VECTOR DIAGRAM OF CT

Symbols : (Ref. Fig. 35.2)

K_n = normal ratio, $\dfrac{\text{Rated primary current}}{\text{Rated secondary current}}$

K_T = turns ratio, $\dfrac{\text{Secondary turns}}{\text{Primary turns}}$

K_C = actual current ratio, $\dfrac{\text{Actual primary current}}{\text{Actual secondary current}}$

I_P = primary current

I_S = secondary current

I_0 = exciting current

I_m = magnetizing component of I_0, in phase with ϕ, responsible for setting flux ϕ

I_e = component of I_o, in quadrature with ϕ, responsible to cater for eddy current and hysteresis loss in core

ϕ = main core flux

α = angle between I_o and ϕ

γ = angle of burden

β = phase angle between primary current and reversed secondary current.

The primary winding of current transformer has a few turns and low impedance. The primary is connected in series with main circuit. The current in main circuit flows through primary. *The primary current does not depend on the secondary current.* The voltage drop in primary winding of current transformer is negligibly low due to its low impedance.

The secondary of current transformer is connected to a low impedance burden such as relay coil, ammeter current coil. In absence of such a coil, the secondary is kept short circuited. Secondary is not left open for reason discussed later.

Ref. Fig. 35.2. The primary current I_p produces magnetic flux ϕ in the core which induces e.m.f. E_s in secondary. E_s is at 90° behind flux ϕ.

Secondary voltage V_s is given by,

$$V_s = E_s - I_s (Z_s + Z_b) \qquad \text{...(1)}$$

where V_s = Secondary voltage

Z_s = Secondary impedance

Z_b = Burden.

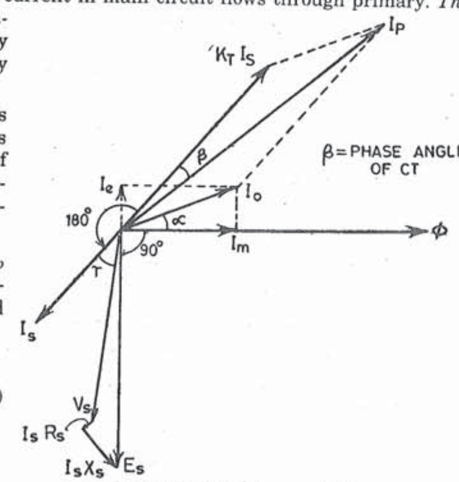


Fig. 35.2. Vector Diagram of VT.

The primary current I_p is given by,

$$I_p = I_o + K_T I_s \quad \text{...(2)}$$

where, I_o is exciting current required for setting magnetic flux ϕ in the core and to cater for iron losses in core. From Eq. (2), it can be seen that, for ideal transformer,

$$\frac{I_p}{I_s} = K_T \text{ ... if } I_o = 0.$$

However, exciting current I_0 introduces the error and

$$\frac{I_p}{I_s} \neq K_T$$

This error is called current ratio error.

Secondly, ideal transformer the secondary current vector when reversed should be in phase with primary current vector. However, from vector diagram it can be seen that, due to exciting current I_o, the reversed secondary current vector leads primary current vector by angle β. This angle is called phase angle error of CT and is expressed in degrees and minutes.

Let us see what happens with increase in burden Z_b.

The secondary e.m.f. E_s is given by equation :

$$E_s \propto f K_n \cdot A \cdot B \quad \text{...(3)}$$

where f = Frequency ; K_n = Turns ratio

A = Area of core ; B = Flux density in core

$$E_s = V_s + I_s (Z_s + Z_b) \quad \text{...(1)}$$

For zero burden *i.e.* short circuited secondary, secondary current I_s (determined by I_s/K_T) produces less drop and E_s is nearly equal to V_s in magnitude and phase. The flux density B is determined by Eq. (3).

If the impedance of the burden increases, the second term on right-hand side of Eq. (1) increase. Thereby *Es* increases. To increase this e.m.f. the flux in core increases as indicated in Eq. (3). Thus, higher impedance of burden leads to more flux in core and, therefore, increased exciting currents and increased error.

If secondary is open left circuited (by mistake), the secondary current is reduce to zero. The secondary voltage V_s becomes equal to induced e.m.f. $E_s \cdot E_s$ increase significantly as turns ratio K_n is high and flux density B increases due to absence of any reverse flux. From the above analysis, following conclusions can be drawn :

1. The exciting current I_o introduces ratio error and phase error in CT's. The phase angle error is caused mainly by magnetizing component I_m of I_c and ratio error by exciting component I_s. (Phase angle error is important in directional relays).

2. The exciting current I_o depends upon primary ampere-turns ; magnetic properties of core material, reluctance of core cross-section and length of core.

For good design of CT, the reluctance of core should be low. For this the core should be of smaller lengths and increased cross-sectional area. The material of core should be of high permeability, low loss, small retentivity, high saturation limit.

3. The burden on the CT secondary (Z_b) should be within specified limits. Higher burden results in higher ratio error.

4. Open circuited CT secondary results in very high secondary voltage and saturation of core, and possibly permanent damage to CT.

35.6. MAGNETISATION CURVE OF CT

Fig. 35.3 shows the excitation characteristic curve of a typical oriented electrical steel. The excitation curve may be sub-divided into four main regions— (*i*) from origin to ankle point (*ii*) from ankle point to knee (*iii*) knee region (*iv*) saturation region. Knee point is defined as where a 10% increase in flux density causes 50% increase in exciting ampere-turns. Protective current transformer generally operates over-working range of flux density extending from the angle point to the knee-region or above, while the measuring current transformer has the flux density in the region of ankle-point only.

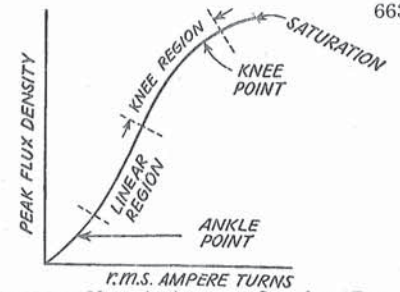


Fig. 35.3. (*a*) Magnetisation curve—Secondary AT *vs.* peak flux density.

Prior to saturation, the flux density in core is proportional to ampere-turns. On reaching saturation, magnetising inductance becomes low and the total primary current is utilized in exciting the core alone and, therefore, the secondary output of CT disappears. The saturation continues till the primary transient current is reduced below saturation level. On entry in saturation zone, the CT behaves as open circuited.

It is difficult to avoid saturation during short circuit condition. The **effect of saturation**, is the reduced output, hence reduced speed of over-current relays. In differential relays, the saturation disturbs the balance and the stability of protection is affected.

Current transformer saturation curve is generally plotted in secondary volts *vs.* exciting current measured in secondary. For the required magnitude of secondary voltage, the degree of saturation can be seen from the curve and is also indicated by magnitude of exciting current to produce this voltage [Fig. 35.1 (*b*)].

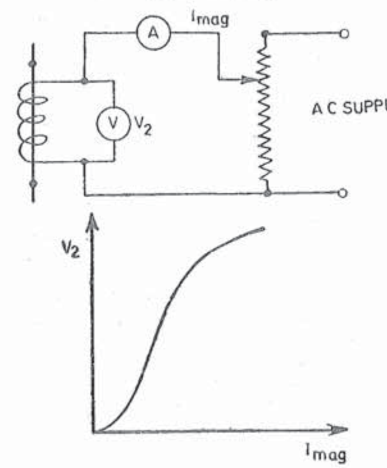


Fig. 35.3. (*b*) Experiment for Magnetization Characteristic of CT.

For any transformer, the a.c. performance can be determined by this formula

$$E_s = 4.44\, fNA \cdot B_{max.} \text{ volts}$$
$$= I_s (Z_b + Z_s + Z_l) \text{ volts.}$$

where, E_s = r.m.s. secondary induced voltage, volts

N = Number of secondary turns

f = frequency

A = Cross sectional area of core, m^2

$B_{max.}$ = maximum flux density Tesla, (1 T = 1 Wb/m^2)

Z_b = external burden

Z_s = secondary burden

Z_l = connecting lead burden.

while calculating CT performance, E_s is determined. I_s is calculated from known fault current and choice of CT ratio. I_s multiplied by total burden gives E_s.

Saturation is checked as follows :

Example 35.3. *A 2000/5 Ampere, silicon steel CT has 28.45 cm² cross-section and secondary resistance is 0.31 ohm. The maximum primary current for CT is 40,000 amp. at 50 Hz. Relay burden including secondary leads is 2 ohms. Will the core saturate ?*

Solution. Primary current = 40,000 A Ratio $N = 400$

$$\text{Secondary current} = I_s = \frac{40{,}000}{400} = 100 \text{ Amp.}$$

$$E_s = 100\,(2 + 0.31) = 231$$

$$E_s = 4.44\, fNA\, B_{max}$$

$$= 4.44 \times 50 \times 400 \times 28.45 \times 10^{-4} \times B_{max}$$

$$231 = 252.63 \times B_{max}$$

$$B_{max} = 0.914 \text{ Wb, peak} = 0.7 \text{ Wb, rms}$$

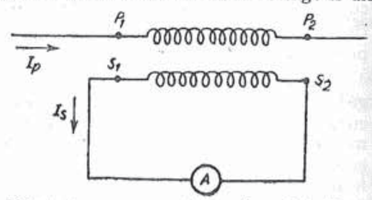
From *B-H* curve material, the saturation for this flux density is checked.

35.7. OPEN CIRCUITED SECONDARY OF CT

An important aspect in CT operation is, the voltage appearing across open circuited secondary. Normal voltage across secondary of a 15 VA CT with current of 5A, secondary voltage is 15/5 = 3V.

However, if by mistake, secondary is open circuited, the voltage across the secondary rises to a high value. The peak value may reach some kilovolts. Open circuiting of secondaries results in zero secondary current, hence reduced back e.m.f. The working flux ϕ increases and core gets saturated. The secondary e.m.f. increases due to increased flux.

The primary gets overheated and the core also gets overheated. Voltages are induced in the secondary by electro-magnetic induction. The peak value of the secondary voltage on open circuit may be several times the r.m.s. value since the core is saturated and waveform of voltage is distorted. This may cause danger to personnel working on secondary side. Therefore, when primary current is flowing, secondary should never be disconnected. In bus zone protection, a non-linear resistor may connected across secondary to limit the peak voltage to safe value.



If instantaneous current flows from P_1 to P_2 as marked by the arrow, the instantaneous current will flow from S_1 to S_2 through ammeter as shown by arrow I_s.

Fig. 35.4. (*a*) Polarity of a CT.

35.8. POLARITY OF CT AND CONNECTIONS

Polarity gives the relative instantaneous directions of currents in the primary and secondary leads. According to B.S. 3938 the polarity of CT is marked.

P_1 and P_2 : Primary Terminals

S_1 and S_2 : Secondary Terminals

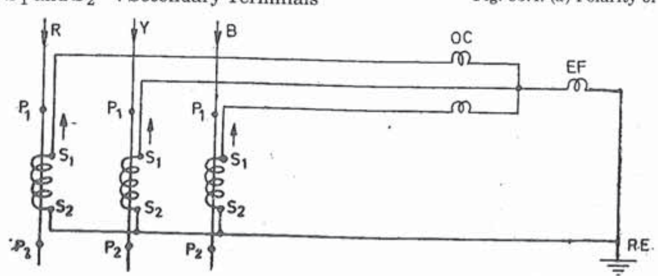


Fig. 35.4. (*b*) Polarity of CT, for OC and EF protection.

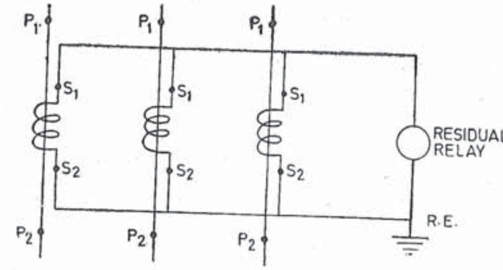


Fig. 35.4. (*c*) Polarity of CT for EF protection, by residual relay.

Reference Earth (R.E.)

The star point of secondary star is usually earthed for getting stable neutral for protection, measurement and control circuits. The earthing is at only one point as shown in Fig. 35.4 (*b*) and (*c*).

Separate CTs are provided for protection, current measurement, watt-hour meter, VAr meter, control circuits. CTs may be separately mounted in outdoor yards or in bushing-turrets or in metalclad switchgear.

35.9. SELECTION OF CURRENT TRANSFORMERS OF PROTECTION RATINGS

(*a*) **The rated primary current** should be selected from standard values. The value should be so chosen that it is suitable for all normal currents and permissible overload currents in the primary circuit.

Current transformer operating a high-set instantaneous overcurrent relay may be selected for higher rated primary current thereby the required accuracy limit may be reduced.

Referring values of rated primary currents : 0.5 — 1 — 2.5 — 5 — 10 — 12.5 — 15 — 20 — 25 — 30 — 40 — 50 — 60 — 75 — 100 — 125 — 150 — 200 — 250 — 300 — 400 — 500 — 600 — 750 — 800 — 1000 — 1250 — 3000 — 4000 —5000 —6000 — 7500 — 10000 Amperes.

Reference values of rated secondary currents :

1 — 2 — 5 Amperes.

Reference values of Rated output :

2.5 — 5 — 7.5 — 10 — 15 — 30 VA and above.

(*b*) **Rated short time current and its duration,** example : 750 A for 0.5 sec., 525A for 1 sec., 300 A for 3 sec.

(*c*) **Rated output,** the choice depends on connected load. It is desirable to select rated output near the calculated total burden but not less than the same. Considerable excess rated output will make the choice of CT uneconomical.

(*d*) **Accuracy class,** for protection purposes :

(*i*) *Instantaneous overcurrent relays* : Class 15 P.

(*ii*) *IDMT relays* : Class 10 P where discrimination is important. Class 15 P where discrimination is not important.

(*iii*) Where phase fault stability and accurate time grading is not required : Class 10 P, 15 P.

(*iv*) Where accuracy, phase fault stability and accurate time grading is desired : Class 5 P.

(Refer : "Application guide for current transformer" IS : 4201. Revised Reprint 1973).

(*e*) **Insulation level.** The insulation level should be coordination with other system apparatus. Standard levels are given IS : 2705 Part I —1964. The following aspects need consideration :

— Highest system voltage
— System of earthing
— Degree of exposure to overvoltage.

The quality of current transformers required generally varies with the type of relay application, better quality transformers are desirable. These tend to reduce application problems, provide less hazards in operation is that rally promote better relaying. The most critical application is that of the differential schemes where the performance of all the current transformers should match. In such schemes the relay performance is a function of the accuracy of reproduction not only at load currents, but also at all fault currents.

Some differences can be taken care of in the relays. In general, for transmission line protection, the performance of the current transformer is not as critical. They should reproduce reasonably faithfully for faults near the remote terminal or at a balance point where co-ordination or measurement is being made. For the heavy close in faults, the current transformer may saturate, but in that case, the magnitude of fault current, usually is not as important. For example, an induction overcurrent relay would be operating on the part of the curve for a heavy close in fault. Therefore, it becomes relatively unimportant whether the current transformer current is accurate as the timing is essentially the same. The same is true for instantaneous of distance type relaying operating for a heavy internal fault well inside the cut-off or balance point. In all cases the current transformer should provide sufficient current during saturation to operate the relay positively.

35.10.1. CT'S FOR CIRCULATING CURRENT DIFFERENTIAL PROTECTION

In earlier chapters, the principle of circulating current, differential protection was given. Let us briefly study the requirements of CT's. For through faults (External faults or faults beyond the protected zones) the relay should not operate. The relay should be "stable" during steady state and transient state for through faults.

Let I_p = rated primary current.

I_s = rated secondary current.

I_a = nominal relay setting.

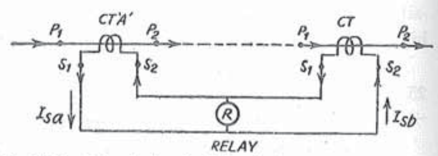
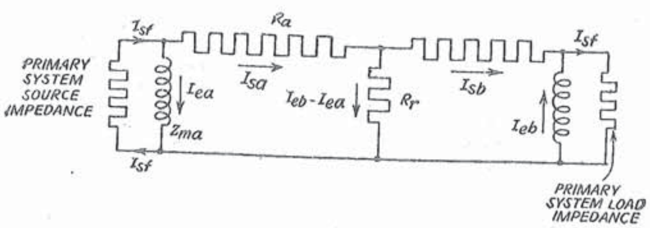


Fig. 35.5. (*a*) Basic circuit of circulating current protection.



R_a = resistance of secondary of CT '*A*'. Plus resistance of pilot leads
R_b = resistance of secondary of CT '*B*'. Plus resistance of pilot leads
I_{tf} = secondary current for through fault
Z_{ma}, Z_{mb} = excitation impedance of CT's.

Fig. 35.5. (*b*) Equivalent circuit when R_p is small.

$$= \frac{XI_s}{100}$$

where X = percentage setting of relay

n = number of times rated primary current upto which stability is desired.

$\left.\begin{matrix} I_{sh} \\ I_{sa} \end{matrix}\right\}$ = actual secondary current during through fault condition

R_a = resistance of secondary of CT '*A*' plus pilots.

R_b = same for CT '*B*'

$E_a = I_{sa} R_a + R_r (I_{sa} - I_{sb})$

$E_b = I_{sb} R_b + R_r (I_{sb} - I_{sa})$

neglecting relay resistance R_r

$$E_a = I_{sa} R_a$$

and
$$E_b = I_{sb} R_b$$

From excitation curve Fig. 35.6 corresponding excitation currents I_{ea} and I_{eb}, are determined

$$\frac{nI_p}{K_t} = I_{sa} + I_{ea} = I_{ea} + I_{sb}$$

where K_r = turns ratio so that current

tending to operate relay I_{so} is given by

$$I_{ro} = I_{sa} - I_{sb}$$

$$= \left(\frac{nI_p}{K_t} - I_{ea}\right) - \left(\frac{nI_p}{K_t} - I_{eb}\right) = I_{eb} - I_{ea}$$

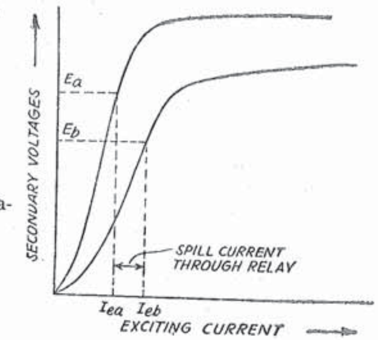


Fig. 35.6. Magnetisation curves of CTs in Fig. 35.5.

where I_{ro} is the current which tries to operate the relay.

Let I_r be the pick-up current, then for $I_{ro} > I_r$ relay operates and $I_{ro} < I_r$ relay does operate

$\boxed{\text{Hence for stability } I_{eb} - I_{ea} < I_r}$

For time relays such as induction type, the transient response is not important because of the slow operation of the relay.

Procedure of calculating ratio error. The procedure is explained here by taking an example.

Example 35.4. Data. *Current transformer of nominal rated 50/5 A.*

Secondary winding resistance 0.1 ohm. Burden connected to secondary ;

0.4 ohms at primary current 1000 A and saturation factor 20.

Excitation curve as in Fig. 35.7. To calculate ratio error of the CT.

Solution. Secondary circuit impedance is the sum of (burden + secondary impedance), *i.e.* 0.1 + 0.4 = 0.5 ohm. Draw an impedance line *AXY* having slope of 0.5 ohm.

Primary current 1000 A, secondary current (nominal) $\frac{1000}{10}$ = 100 A. Point *A* corresponds to

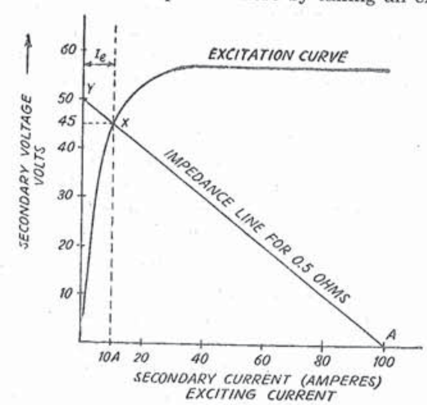


Fig. 35.7. CT excitation curve with impedance line.

secondary current 100 Amperes, primary current $100 \times \frac{5}{50} = 10$ A.

Excitation current I_e is given by the intersection of impedance line AY with excitation curve. From the graph $I_e = 10$ A, secondary induced e.m.f. = 45 V.

Assuming that exciting current oppose each other, we get secondary current value equal to

$$100 - 10 = 90 \text{ A.}$$

$$\% \text{ R.E.} = \left(\frac{K_n I_s - I_p}{I_p}\right) \times 100$$

$$\%\text{R.E. at } 1000 \text{ A} = \frac{(10 \times 90 - 1000)}{1000} = -10\%.$$

In differential protection, the balance between secondary currents from different phase circuits should be maintained within close tolerance. Hence ratio error should be limited during through faults on all the phases. The CT's should be designed and selected such that the stability is not lost during transient and subtransient state of through unbalanced fault. The CT cores get saturated due to d.c. component of short-circuit current super imposed on a.c. component. To avoid this tendency, the CT's selected for differential protection should have such normal current rating that I_{sh}/I_p is not very high, where I_{sh} is maximum through fault current in primary and I_p is rated primary current. In other works, the turns ratio K_n should be sufficiently high. (I_p high)

The difficulties arising due to CT saturation and unbalance is solved by Biased Differential Relays or High Impedance Differential Relays.

35.10.2. CT's for Overcurrent Phase Fault Protection

While selecting CT's for overcurrent phase fault protection by IDMT relays, it should be ensured that CT's are so selected that they do not saturate upto at least 20 times current setting of relay. This is achieved by selecting CT of low burden and by selecting CT ratio of appropriate high value. High ratio CT will have high rated primary current and would saturate at higher value of short-circuit current.

For graded time lag overcurrent protection, it is practice to employ high ratio CT's in some location and low ratio CT's on other locations.

The low ratio CT's are likely to get saturated for fault currents and high ratio CT's are not.

Saturation of CT core gives rise so predominent third harmonic current in secondary current. The effect of this harmonic on induction disc relays is to increase the time of operation. Thus during fault conditions, the relay connected to low ratio CT's are likely to take more operating time than to high ratio CT's. Hence discrimination based on graded time lag is not satisfactorily achieved.

35.11. CT'S FOR OTHER PROTECTION SYSTEMS ; CT'S FOR DISTANCE PROTECTION

The current coil of distance relay is connected to CT. Here also the saturation of CT due to fault current causes reduced CT output, hence the operating time of a distance relay is considerably increased. The transient saturation factor (X/R ratio) of the source side should be considered. The CT should be selected such that the saturation is avoided during fault conditions.

CT's for Directional Relays

Phase angle errors are particularly important for CT's used for Directional Relays. The CT's should not saturated for maximum through fault current.

35.12. TYPE OF CONSTRUCTION CT'S

I. Ring type CT or Window type CT. This is the simplest type of CT. The core has three **types of** popular **shapes (1)** rectangular (2) oval (3) ring shape.

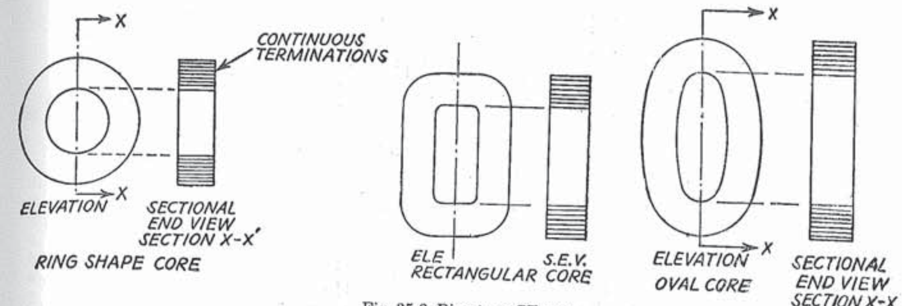
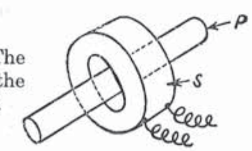
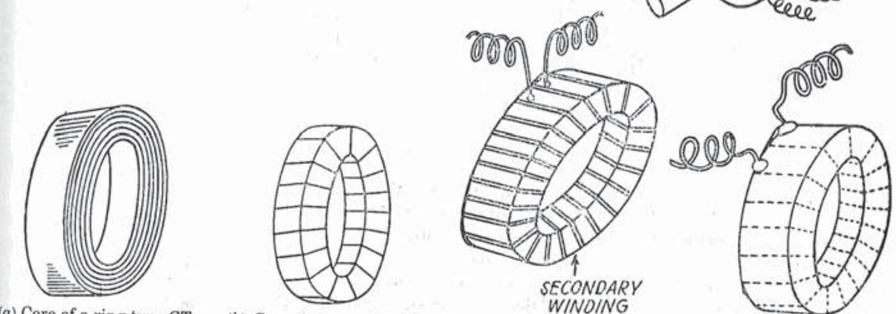


Fig. 35.8. Ring type CT core.



Bar primary current transformer schematic diagram.
P = Primary bar
S = Secondary as in (d)

The core is of a Nickel-Iron Alloy, or grain oriented sheet steel. The core is continuously wound type. Before applying secondary winding, the core is insulated by means of end collars and circumferential wraps.



(*a*) Core of a ring type CT, Core made of Nickel-iron alloy or oriented electrical steel continuous wound.

(*b*) Core is tapped with insulating type.

(*c*) Secondary winding conductor wound on the tape core by means of hand-winding or toroidal winding machine.

(*d*) Exterior taping is then completed with circumferential insulating wraps.

Fig. 35.9. Development of a ring type CT in sequence *a-b-c-d*.

Recently, the continuously wound cores are available in encapsulated form. Synthetic resins are used as encapsulating material. The material is applied by fluidised beds or electrostatic spraying. The secondary winding conductor is then wound on the insulated core [Fig. 35.9 (*c*)] in the form of toroidal winding by hand winding or toroidal winding machine.

The secondary winding is then completely wrapped by external tape with or without exterior ring ends and circumferential insulating wraps. [Fig. 35.9 (*d*)].

35.13. CORE SHAPES FOR MULTITURN WOUND PRIMARY TYPE CT

Cores are either hot rolled silicon-steel stampings or spirally wound strips of cold rolled grain oriented nickel-iron alloy.

Wound primary CT's have primary and secondary windings arranged concentrically. The latter winding is generally the inner one since resistance of this winding should be minimum.

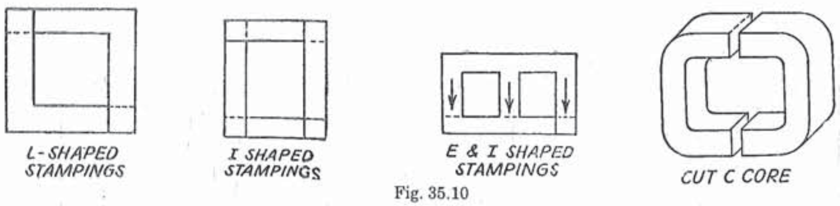


Fig. 35.10

35.14. CURRENT TRANSFORMER FOR HIGH VOLTAGE INSTALLATIONS

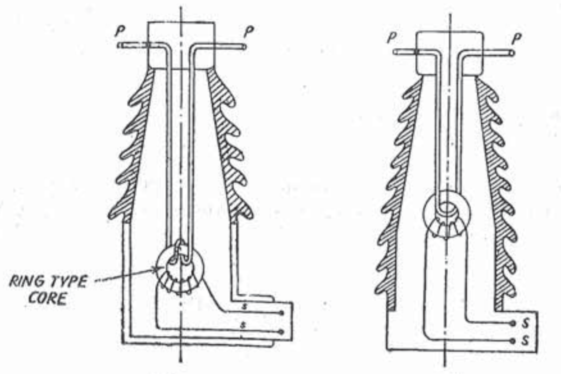
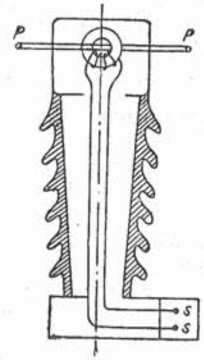


Fig. 35.11. Outdoor High Voltage CT.

Separately mounted post-type CT's are suitable for out door service. They are usually installed in the outdoor switch yard. The primary conductor is at high voltage with respect to earth. Hence it is insulated by means of an insulator column filled with dielectric oil. The secondary of CT is just like the ring type CT described earlier.

Dielectric oil is used as an insulating medium. Alternatively SF_6 gas at a pressure of 2 to 3 atmospheres is now being used,

Bushing mounted CTs. Several CTs are conveniently mounted in turrets of power transformers. The primary conductor passes through the center-line. CT cores encircle the primary conductor several cores are provided. Suitable turns ratios are provided for each CT.



(c)

Fig. 35.11. Typical arrangement in out-door HV CT. (Secondary is wound on bushing type insulated core. Primary is mounted in insulator bushing insulation around primary not shown.)

35.15. INTERMEDIATE CT

Application

Intermediate current transformers are used ; when the secondary current of a main current transformer is not the same as that for which the devices connected to it are designed to operate ; where two circuits have to be insulated from one another (insulating transformers) ; for

summation or where the current vectors have to be displaced. They are, therefore, used for feeding :

— protective devices
— control systems
— measuring systems
— relays in general

In order to satisfy the various requirements, intermediate c.t. of standard design are available in five sizes. The choice is governed in particular by the rated output, the accuracy class and the internal consumption.

1. Primary terminal
2. Secondary terminal box
3. Secondary terminal base
4. Primary coil
5. Primary coil insulation
6. Internal shield
7. External shield
8. Secondary coil
9. Core (circular)
10. Expansion chamber cover
11. Expansion chamber
12. Oil level gauge
13. Porcelain
14. Cover
15. Tank
16. Sealed opening (upper)
17. Sealed opening (lower)
18. Rating plate
19. Pressure relief valve
20. Ground terminal
21. High-voltage lead
22. Secondary terminal board

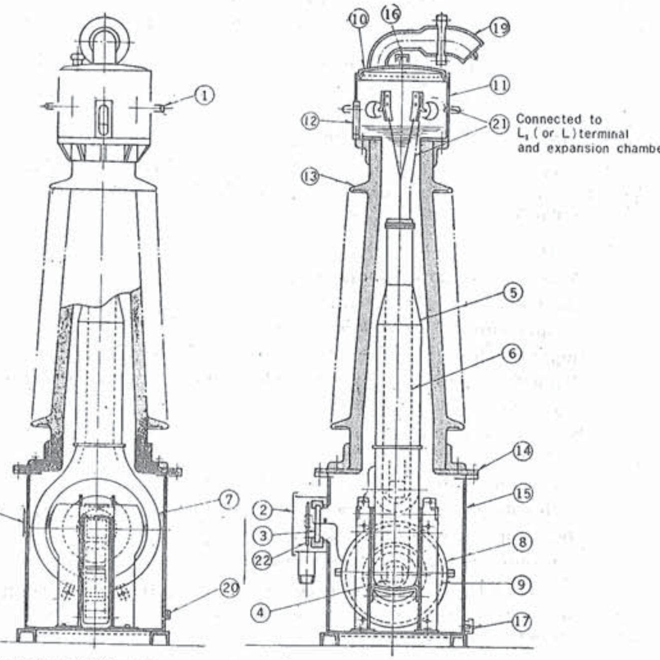


Fig. 35.12. Construction of HV outdoor current transformer shown in Fig. 35.11 (*a*).

Design

The standard open-type design has vacuum-impregnated windings and a double-loop core consisting of a pair of high-grade C-cores (small air gap = low magnetizing current = small current error).

The core and coils are held in two vertical frames attached to which is the terminal block with protective wire clip (the terminals may be in one or two rows). Also fixed to the frame is the earthing screw, this being at one side so that if the transformers are connected in threes, a continuous earth connection is assumed. Due to their vertical construction the transformers occupy little floor space, which results in a very compact arrangement, especially when they are grouped in threes, which is the most frequent form.

As special design, the transformers can be supplied, with the same fixing holes, potted in resin. In this case the cores and coils are moulded in a metal casing.

Co-ordination of main intermediate CT

When intermediate CT are used it is always important to check whether the rated output of the main CT is large enough to cater for the requirements of the intermediate CT (rated output plus internal consumption). Since the output of a CT is always shown as the rated output, *i.e.* its output at rated current, the individual output figures (leads, internal consumption of the intermediate CT burden) must always be referred to the secondary current rating of the main CT. This is always important if the ratio of the intermediate CT applies under definite working conditions and is not referred to the rated current of the main CT. Conversion of the outputs in accordance with the rated data of the main CT must then take into account the squares of the currents, *i.e.* the sum of the total consumption of the intermediate CT has to be multiplied by the factor :

$$\left(\frac{\text{Secondary current rating of the main CT}}{\text{Rated primary current of the intermediate CT}}\right)^2$$

35.16. TESTING OF CT'S (BRIEF)

Tests on CT's can be classified as Type Tests and Routine Tests. Type tests are conducted on one or first few CT's of each type, to confirm the design and ratings. Routine tests are conducted on each CT before despatch.

Type Tests

— Verification of terminal markings and polarities.
— Short time current test. (Ref. Sec. 11.6).
— Temperature rise test. (Ref. Sec. 10.12.2).
— Impulse voltage test (for outdoor CT's) (Ref. Sec. 13.11).
— Power frequency voltage withstand test on primary. (Ref. Sec. 10.2.6, 12.10)
— Over-voltage interturn test, etc.
— Error Measurement.

Routine Tests

— Verification of terminal markings and polarities.
— High voltage power frequency voltage withstand test on secondary.
— Over-voltage interturn tests.
— Determination of errors and accuracy class.

Furthermore, tests are performed on protective systems by injecting current in primary. Thereby the correctness of polarity connections and stability of protection is ascertained. Some tests on CT's are briefly described below :

(1) **Error Measurements.** The error measurements are carried out in two different methods namely

1. Direct method.
2. Comparison method.

In direct method, two ammeters are used. One is connected to measure the primary current, the other to measure secondary current, as shown in Fig. 35.13.

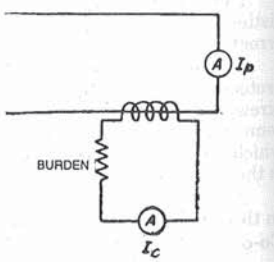


Fig. 35.13. Direct testing of CT.

In comparison method a sub-standard CT is taken, whose error is known. The CT under test is compared with the sub-standard CT. There are several methods based on comparison principle. These are not given here.

Specially designed test equipment is available for testing CT's.

(2) **Turns Ratio Tests.** The usual method is to measure magnitudes of primary and secondary currents near rated secondary current with a low value of secondary burden.

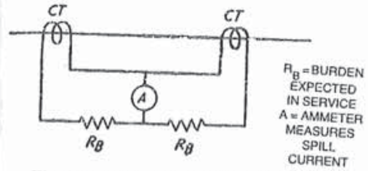


Fig. 35.13. Testing for differential protection.

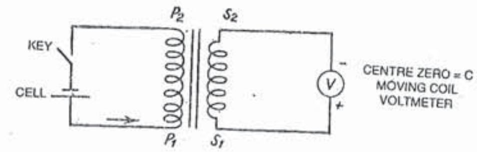


Fig. 35.14. Polarity test.

3. **Exciting Currents.** Exciting current is measured for several secondary e.m.fs. This is accomplished by applying appropriate voltage to the secondary winding, measuring the current taken by secondary winding, the primary and other windings being open circuited.

4. **Current transformers for balanced differential protective schemes.** The CT's are connected in the test circuit. The spill current is measured for through faults.

5. **Polarity Test.** If at any instant, current is entering the primary from P_1 the current should leave secondary from terminal marked S_1. A set-up shown in the figure can show whether the polarity markings are correct or not. When the key is pressed, current enters the primary through terminal P_1, the voltmeter connected as shown, should read positive.

6. **Insulation Tests.** These are conducted according to B.S. 3938 (1965). Specified power frequency voltages are applied to primary for one minute. Impulse tests are conducted on high voltage current transformers.

For secondary circuit test, voltage of 2 kV, 50 Hz is applied for one minute between secondary terminals and ground.

7. **Overvoltage Interturn Test.** In this test the secondary winding is open circuited. Rated frequency, rated primary current is flowed through primary for about one minute. The secondary winding is then checked to see if the insulation has passed the test.

35.17. TRANSIENT BEHAVIOUR OF CT'S

The measuring times of protective relays of today are reduced to the transient state. Hence full attention must be paid to the transient behaviour of the instrument transformers for protective relays.

In current transformers of conventional design saturation of the cores within a few milliseconds is possible due to d.c. components of the short circuit current, during which their secondary current is fully distorted. In order to prevent this, the current transformer cores must be greatly enlarged or air-gaps should be introduced in cores.

The necessary increase is impractical with an iron core of CT's, whereas the use of air gaps limits the physical dimensions to reasonable values.

The short circuit current has d.c. component and a.c. component (Ch. 3). The extreme case is that of a fully displaced short circuit current with ohmic load on secondary side. Primary current can be represented by the equation :

$$i_1 = \bar{i}_2 (\cos \omega t - e^{-t/T})$$

where i_1 = primary current, max. value
T = time constant of system
t = instantaneous value of primary current.

The d.c. component $\bar{i}_1 e^{-t/T}$ causes d.c. magnetic flux density $B_{d.c.}$ the a.c. component $i_1 \cos \omega t$ causes magnetic flux density $B_{a.v.}$

$$\frac{B_{d.c.}}{B_{a.c.}} = \frac{\omega}{\frac{1}{T} - \frac{1}{Tw}} \cdot (e^{-t/Tw} - e^{-t/T})$$

where $T \neq Tw$

and $$\frac{B_{d.c.}}{b_{a.c.}} = \omega \cdot te^{-t/T}$$

where $T = Tw$

Tw being time constant of instrument transformer formed by inductance of main CT and total burden. Taking *T* as 50 ms and several values of *Tw* between 1000 and 2000 ms it is observed that d.c. component causes very high flux densities during transient period. This again is superimposed on a.c. component.

The conventional CT core saturates during transient condition. The result being, high speed relays are delayed in operation (Ref. Sec. 55.10.2).

Choosing the appropriate current transformer design is determined by the protective system requirement. Where the operation of the protective system is not affected by saturation phenomena of the current transformers as, for instance, with plain overcurrent relays, one may keep using the conventional type of current transformers. Where, however, a saturation-free current transformation is important for a correct and rapid working of the system protection, the dimensions of the current transformer core must be greatly increased. The appropriate factors of core section increase for such cases lead, however, to unreasonable core sizes with iron-enclosed cores and high-power systems. Therefore, for such cases cores with air gaps, have been developed. In providing such air gaps the current transformer time constant, *T*, is reduced since the current main flux density is diminished. Generally, the flux caused by the D.C. component assumes smaller values, if the current transformer time constant is reduced. The maximum flux density value is, only half if the current transformer time constant *Tw* is reduced from 2000 ms to 100 ms. Hence the core section dimensions can be 1 limited to values which are still realizable. This is especially true with cores having air gaps are residual flux is practically zero and thus each phenomenon begins again with a flux equal to practically zero. The current transformer time constants can be chosen as small as the resulting increase in phase error allows. A phase error of 1% corresponds for instance, to a current transformer time constant of 250 ms, 3% approximately to 100 ms and 5% to about 60 ms : such values may still be admissible in several systems.

The linear core provides a completely new solution to a wide range of protective systems permitting saturation free transformation of transient phenomena with D.C. components of great time constants.*

SUMMARY

Protective transformers include current transformers and voltage transformers. The relays are connected in the secondary circuit of protective transformers. The standard secondary voltage of CT's is either 5 A or 1 A. The standard secondary voltage of voltage transformers is 110 V between phases and 63.5 V between phase and neutral.

The construction of CT follows a general pattern in which the primary has a few turns or a bar which is insulated from earth by means of a poreclain. The secondary is wound on a circular core. The primary passes through the orifice of the core.

The 'burden' of protective transformer is specified in volt amperes at rated secondary current at specified power factor.

The accuracy of protective transformer is specified by classification based on limits of ratio error and phase error.

* Ref. : "Transient Behaviour of Current and Voltage Transformers" Dr. Ing. Rudof Zahorka Courtesy, ASEA, Sweden.

QUESTIONS

1. Describe the construction of current transformers with the help of neat sketches. Sketch the sectional elevation of a current transformer to be used for high voltage circuit, say 110 kV.
2. What is 'Burden' of a CT ? How is it specified ?

   Calculate VA output required from a CT of 5 A rated secondary current when the burden consists of relay requiring 10 VA at 5 A plus loop lead resistance of 0.9 ohms.
3. State the specification to be mentioned while selecting a CT.
4. Why the secondary of a CT should not be open circuited ?
5. State the specifications to be mentioned while selecting a potential transformer.
6. Discuss the problem of transient behaviour of the CT's associated with high speed protective relaying.
7. Write short notes on any two :
   - — testing of CT
   - — summation transformer
   - — intermediate CT
   - — selection of PT for protective relaying
   - — selection of CT for differential protection
   - — selection of CT for bus-zone differential protection.
8. Illustrate CT connections for overcurrent protection and earth-fault protection. Indicate polarities clearly.
9. Explain the behaviour of CT's under transient fault condition. What is the effect of CT saturation on.
   - — overcurrent protection
   - — impedance protection