CHAPTER 1

INTRODUCTION

1.1 Introduction

Current transformer is an instrument transformer in which the secondary current, in normal conditions of use, is substantially proportional to the primary current. It differs in phase by an angle which is approximately zero for an appropriate direction of the connections (IEC 60044-1) (TNBE, 2003).

Another definition of current transformer is generally regarded as a device, which reproduces a primary current at a reduced level or simply transducers or sensors for measurement. A measuring current transformer is normally designed to operate over a range of current up to a specific rated value, which usually corresponds to the circuit‘s normal rating, and has specified errors at that value. In contrast, a protection current transformer also performs the same function but is required to operate over a range of current far greater than the circuit rating.

Being frequently subjected to conditions greatly exceeding those used within a normal measuring current transformer, under such condition, the flux density corresponds to advanced saturation and the response during this initial transient period of short-circuit current is important (Mustafar Kamal Hamzah, 2005).

The detailed knowledge of the operation of a current transformer may be required in order to predict the performance of the protection. Current transformers for protection must have two important qualities:

- Produces the secondary current at sufficiently lower level so that smaller sized cables can be used to carry the current to control panel and relays.
- Provides an insulating barrier to other equipments such as relay, which are normally small signal devices which is insulated to a normal 600V operation (Mustafar Kamal Hamzah, 2005).

Besides, the swapped polarity or Transformation Error which results from external faults could endanger the stability of the protected object. A uniform dimension and design of the CTs should therefore always be strived for. This is particularly true if the protection does not contain any specific additional stabilization against CT saturation (Gerhard Ziegler, 2005).

1.2 Main CT function

The main functions of CT are:

- To transform the high current values in primary system to values which are suitable or compatible for direct connection to measuring instruments, meters , protection relays/devices and other similar apparatus.
- To isolate, insulate or galvanic ally separation of primary high voltage system from the accessible part of the secondary systems.
- To provide the possibility of monitoring large currents at high voltage system with low range equipment.
- To reproduce an accurate scaled down replica of input quantity.
- To provide the possibility in order to standardize the relays and instrument to rated current, i.e. secondary rating: 1A or 5A.

1.3 Research Objective

The Objectives of this dissertation are:

- To model and simulate the current transformer calculation by using GUI MATLAB
- To study the characteristic of the CT IEC 60044-6, magnetizing curves and over dimensioning factor characteristic
- To describe the calculation of the actual accuracy limit factor (ALF) for the protection type (P) current transformer (CT).

1.4 Methodology

The approach used here is study the performance of Current transformer and use the CT calculation produced by the manufacturer. The comparisons between the performance of the CT and the standard of CT calculation from Siemens have to be done based on the given method. There are 2 main factors of the CT application which are Accuracy limit factor (ALF) and the knee point Voltage to investigate the requirement of CT application. It is to prove that the corresponding rated accuracy limit factor and rated accuracy limit current must show a better improvement compared to the manufacturer's manual relay. Also we need to demonstrate the over dimensioning factor for internal fault which can be determined from the graph which has been produced and shown in chapter 4. (Fault inception Anglel and Transient Over-Dimensioning factor KTF)

The list of methodology have been listed as follows:

i. To investigate the performance of CT at PMU Perling substation.
ii. To understand the function and application of CT.
iii. To understand and to forecast the performance of CT requirement.
iv. To understand the connection of current transformer in protection system.
v. To implement a selected numerical value required by protection Model into GUI MATLAB.
vi. To analyze the internal fault which is applied for differential and transformer protection.
vii. To analyze all the information from the journals regarding the specification of CT.

1.5 Outline of Dissertation

This dissertation consists of five chapters and focusing to investigate the performance of current transformer under the Accuracy limit factor required to be based on CTs data and the current transformer saturation under knee point voltage.

a. Chapter 1 – Introduction

   Chapter 1 discussese more on literature review about CT Application and functions of CT. It also describe CT application for the protection system.

b. Chapter 2- Literature Review

   This chapter is a study about the general background of CT and structure of performance of CT. The main important point discussed here is the definition and the purpose of CT.

c. Chapter 3- Software Development

   This software will illustrate the development and work flow of the program to determine the CT calculation of the protection relay which needs to be studied. Furthermore, there is implementation of the software development model and the input parameters.

d. Chapter 4- Result and Discussion

   In this chapter, the performance of the CT is investigated based on the simulation output.

e. Chapter 5 – Conclusions and Discussions

Chapter 5 contains the conclusion from the simulation results and future development of this project.

CHAPTER 2

LITERATURE REVIEW

2.1 Application

The current transformer is used for the following applications;

- Protection
- Control and Instrumentation
- Revenue Metering

2.2 Fundamentals of Current Transformer

Current transformers as the name implies are used to transform high currents used by a large customer to lower levels that can safely be measured by a standard watt-hour meter.

Current transformers or CT's are designed so that the service conductors going to the customer service entrance run through the center of the CT. The secondary winding terminals have reduced current and are connected to standard protection equipment. In this manner, only a portion of the electricity used by the customer is actually protected.

CT's have their current reduction ratio given on their nameplate. A CT with a current reduction ratio of 400:5 would reduce the current by a ratio of 400 divided by 5 or 80 times. For every 400 amps going to the customer, 5 amps would go to the protection or relay equipment. The Relay now only measures 1/80th of the amount of electricity actually used by the customer. In order to bill the customer for their actual usage, the meter reading must be multiplied by the CT ratio of 80. This value is called the account or meter multiplier and will be found on all customers accounts with CT protection.

2.2.1 Current Transformers Physical Behavior

In order to understand the standards and background of the physical behavior of the current transformer it must be shortly mentioned at first. The most important is the fact that a CT due to its physics always tries to draw such a secondary current *Is* through its secondary circuit that equalizes the magnetic flux Ψp or induction *Bp* excited by the primary current *Ip* (Figure 2.1). It means that each current transformer is forced to introduce such a secondary current *Is* so that the secondary magnetic flux Ψ *s*. linked with it equalizes at every point of time the primary flux Ψp (J. Jaeger, 2008).

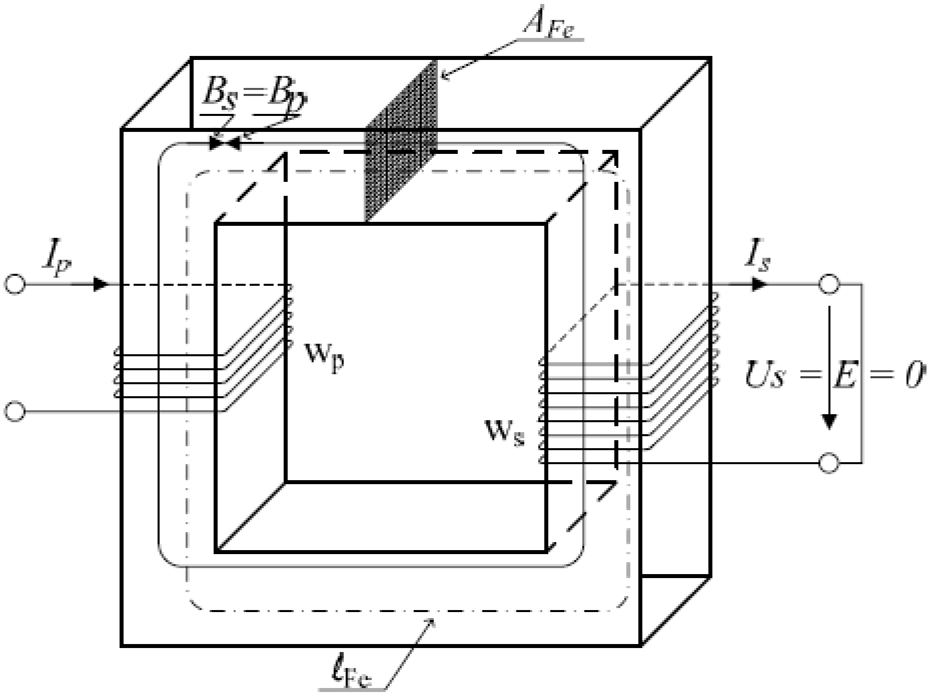

Figure 2.1 Simplified Equivalent of an Ideal CT

The primary core flux for sinusoidal quantities is given by equation 2.1:

$$\Phi_p = w_p \cdot \mu_0 \cdot \mu_r \cdot \frac{I_p}{\ell_{Fe}} \cdot A_{Fe} \tag{2.1}$$

And the secondary core flux by equation 2.2 respectively:

$$\Phi_s = w_s \cdot \mu_0 \cdot \mu_r \cdot \frac{I_s}{\ell_{Fe}} \cdot A_{Fe} \tag{2.2}$$

With

$$\Phi = B \cdot A_{Fe} \tag{2.3}$$

Where B is magnetic flux density, A_{Fe} is the core cross-sectional area, ℓ_{Fe} is the mean length of magnetic path and wp, ws are the number of primary and secondary windings, respectively. For ideal conditions, as shown in Figure 2.1, where winding resistance and leakage flux were totally neglected, one can write the equation for the core flux as:

$$\Phi_p - \Phi_s = \Phi_m = 0 \; or : \Phi_p / \Phi_s = 1 \tag{2.4}$$

Considering the relation in equation 2.4 and using equation 2.1 and equation 2.2 one can write the following relation:

$$\frac{I_p}{I_s} = \frac{w_s}{w_p} \tag{2.5}$$

This describes the law of Ampere-turn balance and is the basics of the whole CT performance (Gerhard Ziegler, 2005). That means that no magnetizing flux Φ*m* is present inside an ideal CT core, or, in other words, ideal working-conditions for a CT are given when its core is fully balanced and no magnetic flux is present. In reality, there are no ideal conditions as described above. There exists always some secondary burden as resistance or impedance, e.g. at least the inner secondary winding burden, which causes a voltage drop in the secondary circuit. Thereby, the total linked flux (coil flux) relevant in the secondary circuit is

$$\Psi_{m,s} = w_s \cdot \Phi_m = w_s \cdot B_m \cdot A_{Fe} \tag{2.6}$$

where the inner induced voltage on the secondary CT side equals to:

$$U_m = \frac{d\Psi_{m,s}}{dt} \propto \frac{dB_m}{dt} \tag{2.7}$$

The magnetizing curve measured from the secondary side in steady-state conditions usually with RMS – values describes the non-linear magnetic characteristic (equation 2.8) of the iron core on the shunt inductance *L* (J. Jaeger, 2008).

$$U_m = f(I_m) \tag{2.8}$$

Practically, the current transformer during its duty of ‘core-balancing’ by drawing the secondary current through the secondary circuit always has to overcome a couple of ‘burden’. In other words it is forced to magnetize itself (i.e. the magnetizing flux in the core Φ*m*≠0) to produce such a voltage (on the inductance *L*) that draws the secondary ampere-turns current which equalizes the ampere-turns of primary current. Such ‘burden’ for the CT is internal impedance of the secondary winding and the total impedance that is connected to its secondary clamps (i.e. wire and instrument burden). Thereby, the higher the burden or the higher the primary current, the higher voltage must be induced to allow the secondary current flow. In practice the construction of the CT for a simple design is close to the one presented in Figure 2, where the primary conductor is symmetrically wound through the iron core. On this iron core there are windings wounded symmetrically over the core that builds secondary winding of such CT-core. As a the comparison to the simplified CT equivalent in Figure 2.1 the length of magnetic path ℓ_{Fe} and the core cross-sectional area A_{Fe} are shown in Figure 2.2, correspondingly. The inductance of such CT can be described as

$$L = \cdot \mu_0 \cdot \mu_r(H) \cdot {w_s}^2 \frac{A_{Fe}}{\ell_{Fe}} \tag{2.9}$$

Where μ_0 is the absolute permeability = $4\pi \,.10^{-7}$ H/m and μ_r is the relative permeability of the material used. In case of iron, μ_r is a non-linear function of the magnetic field H and varies usually between 1000 and 50000 (J. Jaeger, 2008).

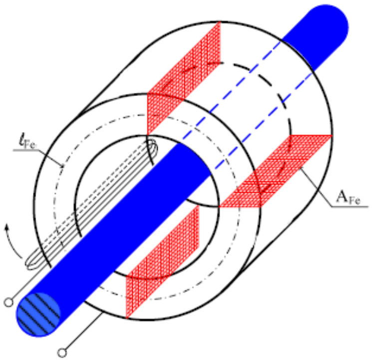

Figure 2.2 Typical Design CT within GIS switchgear

2.2.2 Current Transformer equivalent Circuits

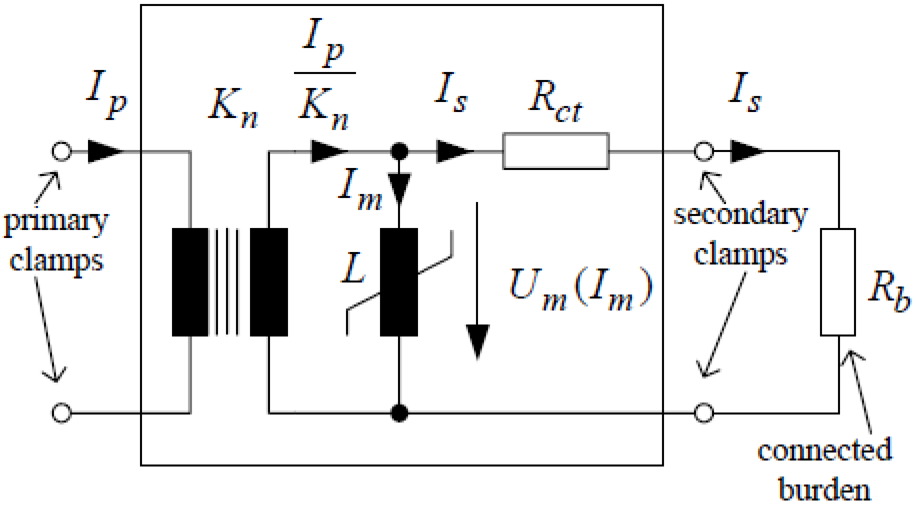

Figure 2.3 Simplified Equivalent Circuit of a CT

At this stage, for simplicity, the influence of leakage inductance as well as the inductance of the secondary wires and the inductance of the input burden of the instrument/relay are neglected. The first assumption cannot be made if for example the distance between primary winding and core is high and the primary winding has unsymmetrical layout with respect to the core or there exists close proximity to return or neighboring conductors. For almost all practical purposes the performance of CT can be described by its simplified equivalent circuit shown in Figure 2.3.

The current ratio Kn of the CT is the ratio of primary Ipn and secondary Isn nominal currents: Kn = Ipn /Isn. This is illustrated in Figure 2.3 by the ideal transformer. The nonlinear magnetic characteristic of the iron core is described by the shunt inductance L on the electrical side. The typical magnetizing curve Um i.e Vs (Im i.e Is) of this shunt inductance L is shown in Chapter 3, Figure 3.8. Before the secondary current reaches the

CT, the secondary clamps and the connected burden is passed to the internal resistance Rct. (so called: “internal CT burden”) (J. Jaeger, 2008).

2.2.3 Dimensioning of the Current transformer

The required operating accuracy limit factor may be derived with the following equation:

$$ALF' = (I_F/I_N).K_{TF}.K_{Rem} \qquad (2.10)$$

The corresponding rated accuracy limit factor is then:

$$ALF = (R_{CT} + R_B/R_{CT} + R_N).\ ALF' = (P_i + P_B/P_i + P_N).ALF' \qquad (2.11)$$

The ratio I_F/I_N must consider the maximum fault current that can arise. Often, the rated short circuit of the plant is used in this context.

K_{TF} is the over dimensioning factor that considers the single sided magnetizing effect of the CT core due to the DC component in the fault current. (Gerhard Ziegler, 2005)

K_{Rem} is the over dimensioning factor that considers the remanence. It is calculated using the remanence factor K_r:

$$K_{Rem} = 1/\ (1 - K_r) \qquad (2.12)$$

2.2.3.1 Over dimensioning factor K_{TF}

In most cases it is of primary importance to for define of the CT dimensions. Initially the common CTs with closed iron cores, 5P or 10P are considered. For these, the transient response is defined with class TPX. The CT secondary time constant TS= $Lm/\Sigma R_2$ in the cases is always large in comparison to the system time constant TN. Usually TS is several seconds long, while TH in the system only assumes a value above 100ms in exceptional cases (Gerhard Ziegler, 2005).

Equation 2.13 shows the simplified equation where $T_S >> T_N$:

$$K_{TF} = B_{Max} / B = 1+\omega.T_N \tag{2.13}$$

To achieve saturation free transformation of the fully off-set fault current for the entire duration of the fault, the CT must have a dimension calculated with the transient over dimensioning factor:

$$K_{TF} = B_{Max} / B = 1+\omega.T_N = 1 + X_N/R_N = 1 + (X_S + X_L/R_S + R_L) \tag{2.14}$$

In the equation 2.14, T_S is the DC time constant of the affected fault loop calculated with the values of the source impedance ($X_S.R_S$) and the line impedance ($X_L.X_L$).

The X/R ratio of the fault impedance close to generators and transformers and at the EHV level in general is very large so that large over dimensioning factor of $K_{TF} = 30$ (at T_N=100ms) and more may appear (Gerhard Ziegler, 2005).

CTs with such large dimensioning usually cannot be implemented due to larger costs involved. With encapsulated switchgear (e.g. GIS) where the CT must be fitted inside the encapsulation, space constrains prohibits such large CTs.

If, instead of saturation-free transformation for the total duration of the fault current, saturation is permitted after a particular time the dimension of the CT may be reduced.

The minimum time to saturation must satisfy various criteria:

- With internal faults, a minimum saturation free time (a minimum non-distorted data window) is required to comply with the measurement process inside the protection. With distance protection this can assume a value 25ms especially if an exact fault location is required. Differential protection on the other hand can manage with shorter times of, for example 5ms.
- During external faults protection stability is ensured if the CT transforms the through flowing fault current until the fault is switched off. In these cases the relevant time is made up of the operating time of the protection and the circuit breaker. At the EHV level this equates to a time of approximately 100ms.

For protection devices that contain a saturation detector, the differential protection can cope with shorter times as the CT must only transform until the saturation is detected. In the case of, for example, the busbar protection 7SS52 a time of 3ms is already sufficient (Gerhard Ziegler, 2005).

The Transient over dimensioning factor for time limited saturation free transformation K_{TF}' is calculated with equation 2.15, if the increase of flux is limited the time t_M:

$$K_{TF} = 1 + (\omega.\ T_N.T_S/T_N\text{-}T_S).\ (e^{-tM/TN} - e^{\ tM/TS}) \tag{2.15}$$

For the closed iron CT cores, where $T_S >> T_N$, the equation can be simplified as follows:

$$K_{TF} = 1 + \omega.T_N\ .e^{\ -tM/TN} \tag{2.16}$$

The required CT dimension may be substantially reduced if the saturation free time t_M is much smaller than the system time constant. In the example at hand a reduction of K_{TF}=16 to K_{TF}'=7 is achieved.

In the equation 2.15 and 2.16 the AC component of the flux is assumed to have a peak value equal to 1. This is a good approximation when the current flow takes place for a long time as the dc flux in this case determines the transient over dimensioning factor and large values for K_{TF} or K_{TF}' are obtained (Gerhard Ziegler, 2005).

If the time to saturation however is short, the AC flux has the same order of magnitude as the DC flux and may even be larger if very short saturation free time less than 5 ms are considered. Under these conditions the sinusoidal course of the AC flux components must be considered. i.e. the complete equation for the course of flux must the applied. The corresponding over dimensioning factor K_{TF}' is then calculated with the following equation 2.17:

$$K_{TF}(t_M, T_N) = \omega.T_N.\ \mathrm{Cos}\ \theta(t_M, T_N)\ (1\text{-}\ e^{-\ tM\ /\ TN}) + \mathrm{Sin}\theta(\ t_M, T_N) - \mathrm{Sin}(\omega.t_M + \theta(\ t_M, T_N))] \tag{2.17}$$

Hence θ is the angle of fault inception that results in the maximum K_{TF}" –factor depending on the required saturation free time t_M and the applicable dc time constant T_S of the fault current.

$$\theta(t_M, T_N) = \text{acos}[\ 1 / \sqrt{}\ [\ 1 + (\ 1\text{-Cos}(\omega.t_M)/\ \omega.T_N\ (1\text{-}\ e^{-\ tM\ /\ TN}) - \text{Sin}\ (\omega.t_M)]^2] \qquad (2.18)$$

The angle θ is calculated with equation 2.18 for the practical case when the time constant $T_N \geq 10$ms. With time constant < 10ms it must be checked in each case if the angle θ, that corresponding to the negative value of the square root does not result in a larger K_{TF}" factor (see Figure 4.4) (Gerhard Ziegler, 2005).

2.2.3.2 Over dimensioning factor for remanence K_{Rem}

The remanence may be as much as 80% (K_r=0.8) in closed iron core CTs. Consequently only 20% flux increases up to saturation would remain (see Figure.3.8) and the CT dimension would have to be increased by the remanence over dimensioning factor K_{Rem} = 1 / (1-Kr) = 5 (Gerhard Ziegler, 2005).

2.2.4 Choosing CTs According to protection and Application

Knowing the properties of CTs, their possibilities and their limits is useful only when they are associated with a specific protection relay whose characteristic and scope of action regarding the monitored current range are known.

The protection relays installed on an electrical network are defined in the protection plan. This plan specifies the position and setting of the selected protections. It also defines the position of the CTs, Their ratio and, more rarely, their power, accuracy and ALF. In point of fact, complete specification of CTs also requires knowledge of:

- The protection input impedance
- The wiring impedance

- The protection operating thresholds (normally taken into account in the protection co-ordination study),

Today most protections are of the digital technology kind and are highly accurate. Ct accuracy is thus a decisive factor. The type of protection also affects the required CT accuracy:

- An Over current protection takes only the current value into account
- A differential protection compares two currents
- An earth fault protection treats the sum of the three phase currents(P. Fonti, Schneider Electric, 2000)

2.2.5 Characterizing Current Transformer

To associate the current transformer for protection, a number of characteristics need to be considered, among others;

i. Short Time Factor – when a current transformer is used in a power system it may be subjected to fault current very much larger than it s primary rating and , therefore it must be able to withstand the effects of this current for the time for which it is likely to persist.

ii. Accuracy limit factor – when a current transformer is used to energize a protection relay it must maintain its characteristic ration up to some multiple of its rated current. This multiple is known as the “Accuracy limit factor”.

iii. Specification of Current Transformer – A method of specifying current transformers for protection purpose is detailed in BS 3938. In this specification they are defined in terms of rated burden, accuracy class and accuracy limit. Amongst typical values of rated burden are; 2.5, 5, 7.5,10,15 and 30VA. Two accuracy typical classes are quoted 5P and 10P, which gives a composite error at rated accuracy limit of 5% and 10% respectively. Standard accuracy limit factors are defined in the range of; 5,10,15,20 and 30 (Mustafar Kamal Hamzah, 2005).

2.2.6 Unit protection Scheme

These employ the use of principles of Merz-Price or current residue balance as a method of fault detection. This technique is normally being used in the protection design of expensive equipment. The system only detects and removes faults occurring within the zone it protects. If fault occurs on incoming supply as well as outgoing supply, the protection system will not respond. They are generally used for transformer protection schemes and other expensive equipments. The principle of operation can be illustrated using Figure 2.4.

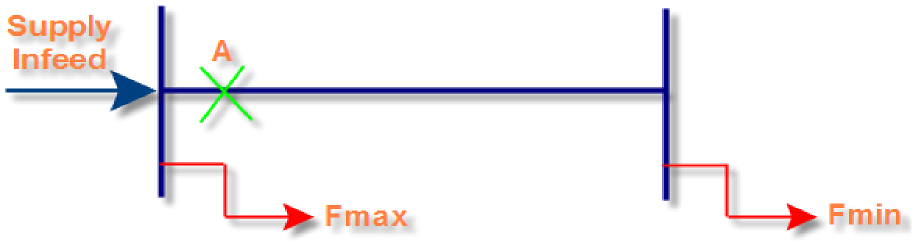

Figure 2.4 Different Fault level

Case 1: From Figure 2.5, which represents normal operation, where $I_1=I_2$. A balance current will be detected at the relay and hence the system will not respond.

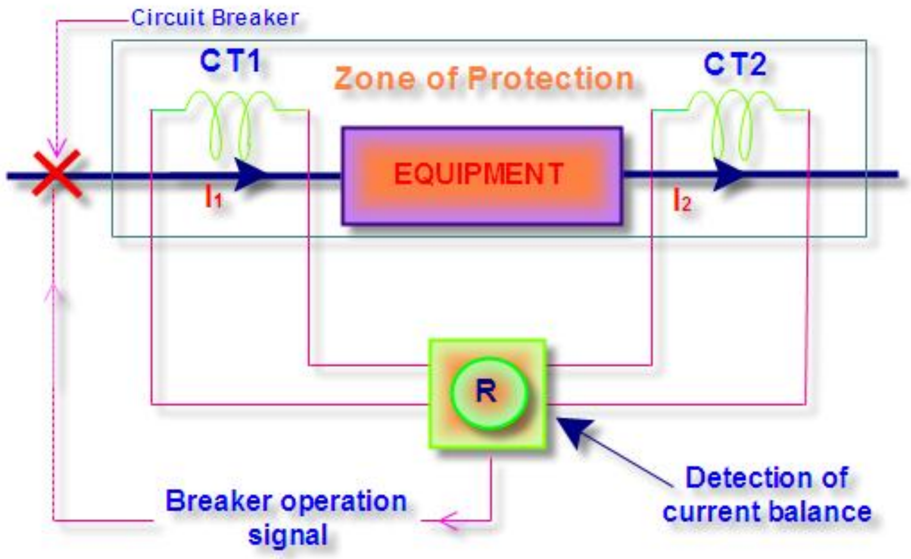

Figure 2.5 Unit Protection scheme.

Case 2: A fault I_F occurring before the breaker as shown in Figure 2.6: again by inspection I_1=I_2, a balance current will be detected at the relay and hence the system will also not respond.

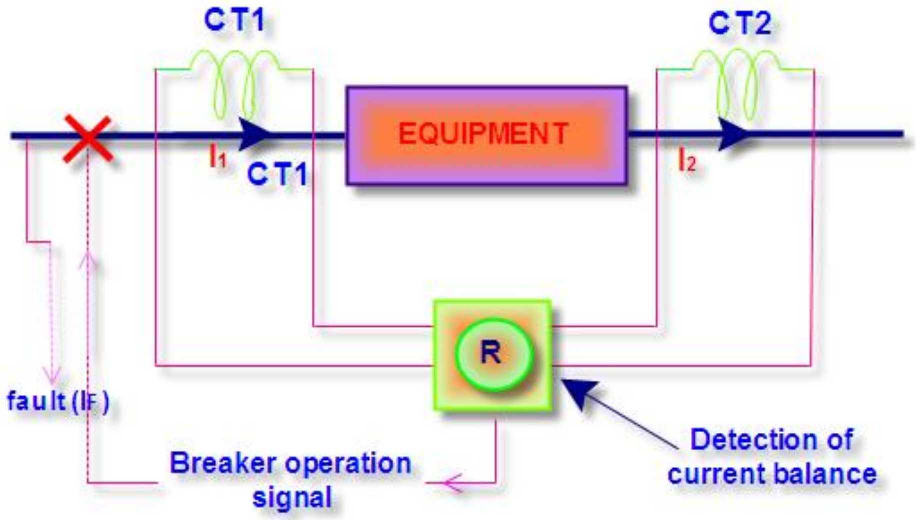

Figure 2.6 Unit protection Scheme (Before Zone)

Case 3: A fault I_F occurring after the equipment and beyond the outgoing sensor CT2 as shown in Figure 2.7; again by inspection $I_1=I_2$, a balance current will be detected at the relay and hence the system will not respond. Although fault current I_F will pass through the equipment but the system will not respond since it will detect that the current passing through between CT1 and CT2 are equal in magnitude. Another means has to be designed in order to address the fault current that is passing through.

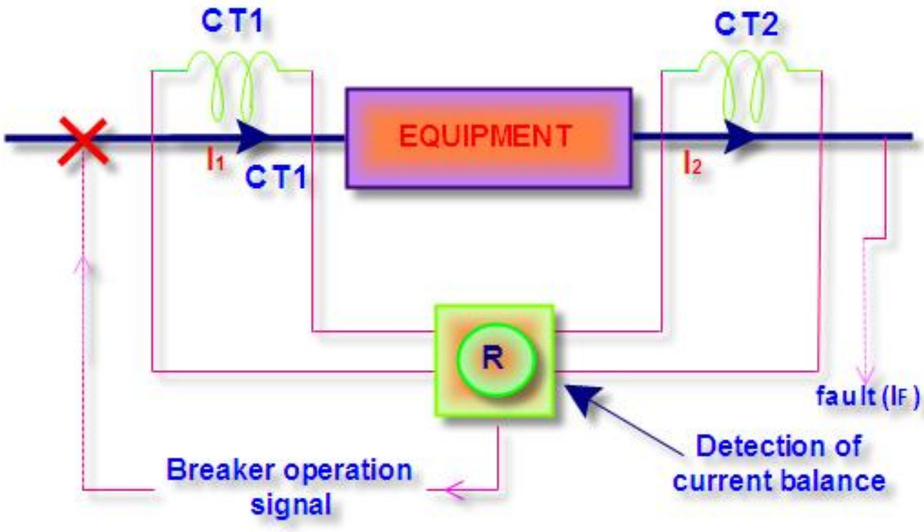

Figure 2.7 Unit protection Scheme (After Zone)

Case 4: A fault I_F which occurs inside the zone of protection. This could either be as shown in Figure 2.8 (Before Zone) and Figure 2.9 (After Zone). In both cases we could deduce this relationship;

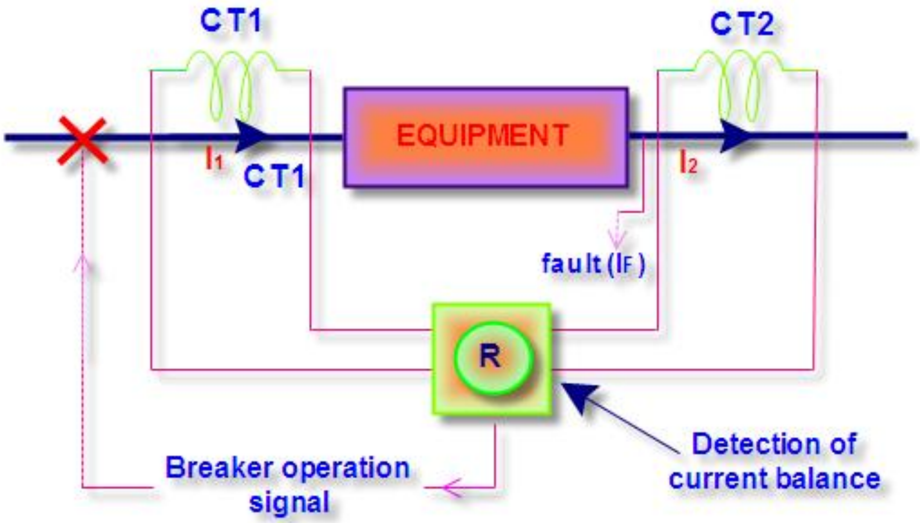

Figure 2.8 Unit protection scheme (Before Zone)

Hence I_1 will never be the same in magnitude when compared with I_2, a balance current will always be detected at the relay. Under these circumstances; by suitable setting on the relay the system will respond and send a signal to initiate the breaker opening and interrupt the supply (Mustafar Kamal Hamzah, 2005).

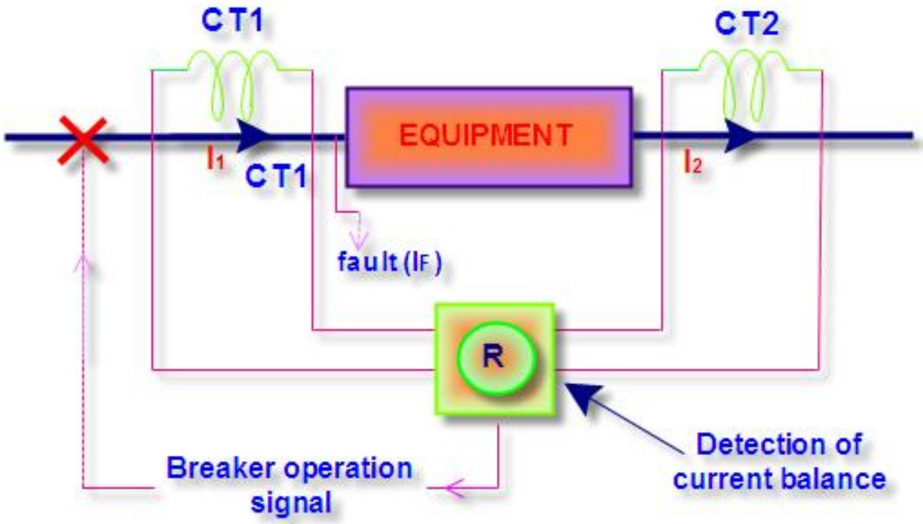

Figure 2.9 Unit protection scheme (After Zone)

2.2.7 Ferromagnetic Transformer

Current transformers are used to supply information to the protective relays and/or current, power and energy metering “instruments”. For this purpose they must supply a secondary current proportional to the primary current flowing through them and must be adapted to network characteristics: voltage, frequency and current. They are defined by their ratio, power and accuracy class. Their class (accuracy as a function of CT load and of Over current) is chosen according to the application.

- A “protection” CT must saturate sufficiently high to allow a relatively accurate measurement of the fault current by the protection whose operating threshold can be very high. Current transformers are thus expected to have an Accuracy Limit Factor (ALF) that is usually fairly high. Note that the associated “relay” must be able to withstand high over currents.
- An “instrument” CT requires good accuracy around the nominal current value. The metering instruments do not need to withstand currents as high as the protection relays. This is why the “instrument” CTs, unlike the “protection” CTs, have the lowest possible Safety Factor (SF) in order to protect these instruments through earlier saturation.
- Some CTs have secondary windings dedicated to protection and metering. These “instrument” and “protection” CTs are governed by standard IEC 60044-1 (in France NF C 42-502). The matching of CTs with protection relays calls for a thorough knowledge of CTs. The following section gives a few reminders of CTs corresponding to this use (Paola FONTI, 2000).

2.2.8 Non-magnetic Transformers

The output signal, delivered by the non-magnetic transformers (also known as ROGOWSKI coils) is a voltage proportional to the derivative of the primary current.

(Lenz law: $e = -n\frac{d\phi}{dt}$)

They do not saturate and their response is linear. Consequently, they can be used over wide current ranges: the only limitation is the dynamics and the linearity of the input circuit of the associated protection. The technology of the protection, control and monitoring units connected to these nonmagnetic transformers is of the digital microprocessor type. This technology is able to process signals of very low amplitude. For a given non-magnetic transformer, in view of the linearity of the output signal, the nominal primary current is replaced by a wide range, for example 30 to 300 A. In addition to the advantage of linearity, the use of non-magnetic CTs reduces:

- cricks of error when choosing primary current at the design stage of the installation,
- The number of models to be managed. It also minimizes the delivery times.

Today these transformers are seldom used. A standard (IEC 60044-8) should define them. Schneider Electric has been using these transformers (see Figure 2.10) in association with the Sepam protection, control, monitoring and metering units since 1986. To specify them, all that has to be done is indicate:

- The CT insulation level, defined just as for a traditional CT.

- The rated thermal short-circuit current and the dynamic current set according to the same rules as for the CTs (Paola FONTI, 2000).
- The utilization range (rated primary current and the thermal current) (Paola FONTI, 2000).

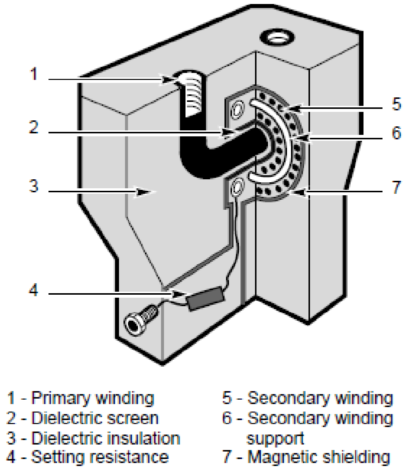

Figure 2.10 Cross section of a non-magnetic transformer used in MV