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Current Transformer Performance during Transient Conditions and the Development of a Current Transformer Selection Criterion for Protection Applications

W.D.A.S. Wijayapala, J. Karunanayake and R.R.T.W.M.R.A.I. Madawala

Abstract: One of the most crucial requirements for the correct functioning of power system protection equipment is the optimum selection of current transformers (CTs). Therefore, when selecting CTs, the protection engineer has to pay attention to steady state performance as well as transient performance of current transformers. The transient performance of current transformers varies with both system parameters and current transformer parameters. System parameters vary with the fault level and with the inductance to resistance ratio (L/R) at the fault location. In the power system of Sri Lanka, these parameters rapidly vary due to network developments. Thus, the type of the protection relay selected, the type of the protection function and the arrangement of the switchgear have a huge influence on current transformer selection. This paper discusses the development of a current transformer selection criterion for protection applications based on the transient performance of the transformers.

In addition to analyzing the current transformer transient performance, PSCAD software has been used in this study to simulate current transformer performance during fault conditions with a case study done to validate the developed selection criterion.

Keywords: Current transformer, Transient factor, Primary time constant, Secondary time constant

1. Introduction

Background

Current transformers (CTs) play a vital role in the protection and measuring functions of a power system. The correct selection of current transformers will lead to the proper operation of protection and measuring equipment. The magnetic saturation of the current transformer core creates undesirable problems in protection devices and therefore a current transformer has to be designed to activate protection devices within the first few cycles of a fault, without letting its core to get saturated.

During fault conditions, the DC component of the fault current is responsible for the saturation of current transformer cores[1]. The L/R ratio of the system (at the fault location) and the L/R ratio of the secondary loop, determine the magnitude and the decaying time of the DC component of the CT secondary current[2]. When the hardware of a transmission system is changed, the L/R ratio changes and adding up more generators to the power system will increase the fault currents. These factors have considerable impacts on the performance of the existing CTs in their protection functions.

CT errors due to saturation or mismatch have an adverse impact on protection functions and hence on the system stability. The saturation may be avoided by selecting an oversized CT, which however will be at an increased cost. Generation and transmission expansion is a continuing process and therefore the duties CTs have to perform will become more and more demanding. Thus the utilities need proper selection criteria when procuring new CTs as well as when replacing existing CTs.

Objective

The conventional electromagnetic relays take nearly more than 6 cycles for the operation of their instantaneous protection functions.

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During this 6 cycle delay, the dc component of the fault current decays from the sub transient time zone to transient time zone and this helps to minimize the effects of transient currents on the operation of protection relays. Old bulk oil circuit breakers take nearly 15 cycles for a tripping operation. Such delayed clearing times do not require detailed studies on the behavior of current transformers during the first few cycles of a fault. As a result, attention was constantly focused those days on the CT's steady state performance.

Power system expansions and interconnections have been continuing at a very rapid rate globally along with large additions of generation capacity. To maintain system stability under these scenarios, fault clearing times have to be made much lower and numerical relays and fast acting circuit breakers have been developed for this purpose. The advent of numerical relays and high speed circuit breakers has achieved lower fault clearing times as desired, but questions have arisen on the capability of current transformers in feeding relevant information to the relays, as these CTs have been selected based on their steady state performance.

In respect of instantaneous protection functions (differential and distance), a numerical relay operation takes place during the sub transient period. Therefore, protection engineers and CT manufacturers have focused their attention on the satisfactory transient performance of CTs. IEC has also published its standards on the transient performance of CTs.

The main objectives of this study are:

a. to study current transformer performance under transient conditions and its impact on protection functions
b. to revisit the present selection criteria and develop a generalized current transformer selection criteria based on system parameters and current transformer parameters for different protection functions

2. Analysis of Current Transformer Performance under Transient Conditions

2.1 Parameters that govern CT performance under transient conditions.

a. Fault level or fault current at the particular location
b. Primary time constant (T_P)
c. Secondary time constant (T_s)
d. Burden of CT secondary
e. Remanence flux of the CT core
f. Number of secondary turns and the cross sectional area

2.2 Fault Inception Angle and Fault Loop Impedance

The magnitude of the DC component of the fault current varies with the fault inception angle and the power factor of fault impedance. The total fault current at any instant is defined by the equation:

$$i_p = \frac{V\sqrt{2}}{Z}\left\{\sin(\omega t + \alpha - \emptyset) - \sin(\alpha - \emptyset)\, e^{-\frac{t}{\tau_p}}\right\} \quad .....(1)$$

where

i_p = Instantaneous value of fault current

$\frac{V\sqrt{2}}{Z}$ = I_P, Peak Fault current

α = Angle of fault inception

Ø = Phase angle of the fault impedance

The magnitude of the DC component ($\sin(\alpha - \emptyset e{-}t\tau p$) varies with the angle $\alpha{-}\emptyset$ and will be a maximum when $(\alpha - \emptyset) = \mp 90^0$. In the case of transmission lines, typical values of $\emptyset$ lie around 90° as fault impedances are highly inductive. As can be seen, the DC component of the fault current is a function of the fault inception angle and the fault loop impedance. This indicates that if the fault inception angle equals to zero or near zero, the DC component will also take its maximum value. However, the fault inception angle will vary and cannot be predicted. Hence, CT sizing is carried out for the worst case or by assuming that the DC component is at its maximum. Equation (2) gives the instantaneous fault current with a zero inception angle and a pure inductive fault loop impedance or when$(\alpha - \emptyset) = -90^0$.

$$i_p = I_p\left[e^{-\frac{Rt}{L}} - cos\omega t\right] \quad .....(2)$$

2.3 Fault Current Variation with the Primary Time Constant (T_P)

The Primary Time constant (T_P) is defined as the L/R ratio of the fault location and it determines the decaying time of the DC component of the fault current. A very high primary time constant will lead to very high decaying times of the DC component of the fault current (Figure 1).

T_P makes a high impact on the flux development in a CT core and plays a vital role in CT sizing. The flux development in a closed core application is given in Figure 3.

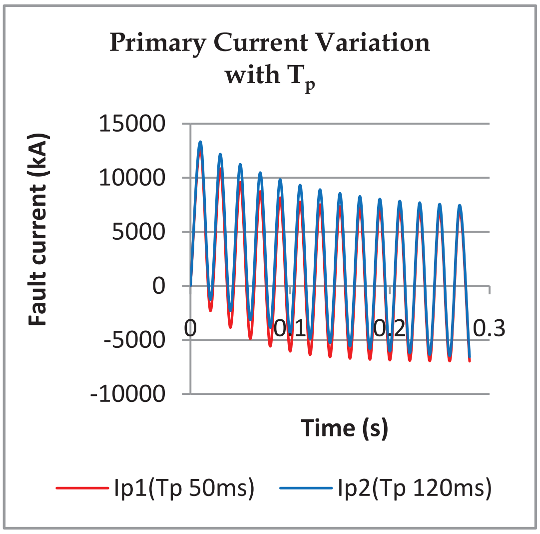

Figure 1 - Primary Current Variation with Tp

2.4 CT Flux Requirement under Transient Conditions

Consider the equivalent circuit shown in Figure 2.

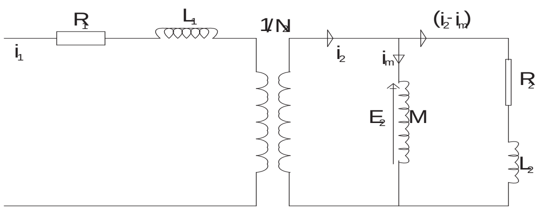

Figure 2 - Equivalent Circuit of a CT

where

R_1 = Primary resistance of CT

R_2 = Total secondary resistance

M = Magnetic inductance

L_1 = Primary leakage inductance of CT

L_2 = Secondary leakage inductance

Then based on the following assumptions:

1. CT is ring type with N_1=1, and turns ratio of $1/N_2$.
2. Fault current wave form is fully offset (i.e.fault inception angle= 0° and fault impedance fully inductive).

$$i_1 = I_1\left[e^{-\frac{t}{T1}} - cos\omega t\right] \quad \ldots\ldots (3)$$

$$i_2 = \frac{1}{N2} I_1\left[e^{-\frac{Rt}{L}} - cos\omega t\right] \quad \ldots\ldots (4)$$

From fundamentals, the secondary induced e.m.f. E_2 will be given by

$$E_2 = N_2 \frac{d\emptyset}{dt} \quad \ldots\ldots (5)$$

and for the circuit in Figure 3;

$$E_2 = (i_2 - i_M)R_2 + L_2\frac{d(i_2 - i_M)}{dt} \quad \ldots\ldots (6)$$

$$i_M = \frac{N_2}{M}\emptyset \quad \ldots\ldots (7)$$

where M is a constant.

From Equations 5 and 6

$$N_2\frac{d\emptyset}{dt} = i_2R_2 - \frac{N_2R_2\emptyset}{M} + \frac{L_2di_2}{dt} - \frac{L_2N_2}{M}\frac{d\emptyset}{dt} \quad \ldots\ldots (8)$$

and rearranging Equation 8,

$$\frac{d\emptyset}{dt}\left(N_2 + \frac{L_2N_2}{M}\right) + \frac{N_2R_2\emptyset}{M} = i_2R_2 + \frac{L_2di_2}{dt} \quad \ldots\ldots (9)$$

From the above equations, the solution for Ø is obtained as (applicable $for\ \ t > 8.3ms$)

$$\emptyset = \frac{I_1R_2}{N_2 2\omega}\left(\frac{T_1T_2\omega}{(T_2-T_1)}\left(e^{\frac{-t}{T2}} - e^{\frac{-t}{T1}}\right) - \frac{1}{\cos\theta}\sin(\omega t + \theta)\right) \quad \ldots\ldots (10)$$

where $\theta = \tan^{-1}\frac{L_2\omega}{R_2}$, $T_2 = \frac{L_2+M}{R_2}$, $T_1 = \frac{L_1}{R_1}$

Thus the core flux is a function of the time, primary current, turns ratio, primary time constant, secondary time constant and the burden. Figure 3 shows the flux development in a CT core having a 1000ms secondary time constant (T_S)[1] and for primary time constants(T_P) of 140ms, 120ms and 60ms.

Figure 4 shows core flux variation with the secondary time constant and the DC current component of the primary current. The "Flux 3" curve in Figure 4 corresponds to a 300ms secondary time constant (T_2) and this low time constant causes a rapid decaying of core flux with the DC current component. This characteristic is used to minimize the flux component which is increasing due to DC primary current. Gapped cores are used to reduce the secondary time constant.

[1] in CT sizing,1000ms can be considered as infinite

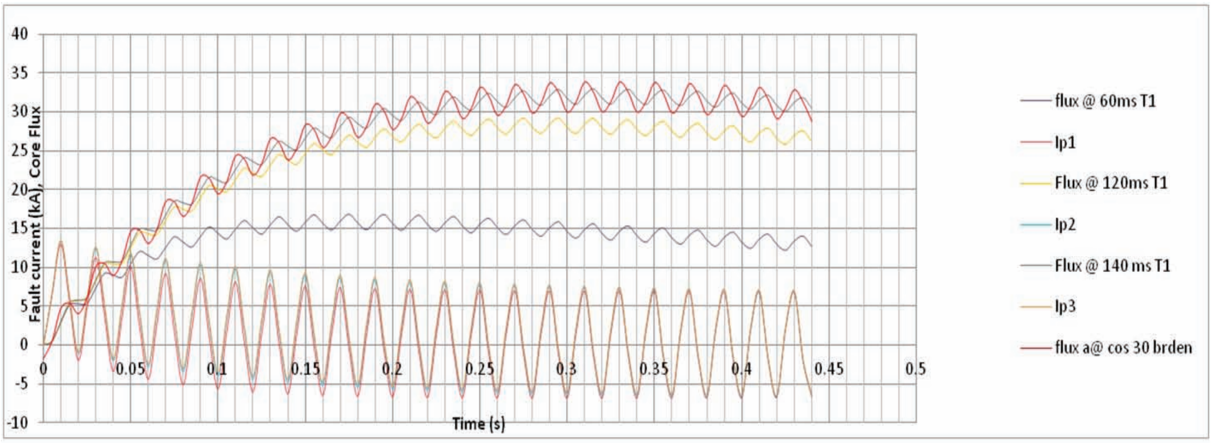

Figure 3 - Development of CT Core Flux with different TPs and a constant TS (= 1000ms)

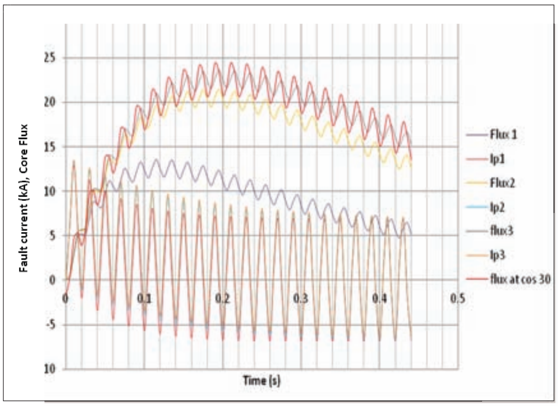

Figure 4 - Variation of Core Flux with T_2

Inductance in the burden has an effect on the peak flux developed in the CT core. The burden in electro-magnetic type protection relays is predominantly inductive. Yet, modern numerical relays have negligible inductance. The variation of peak flux in the CT core and burden inductance is shown in Figure 5.

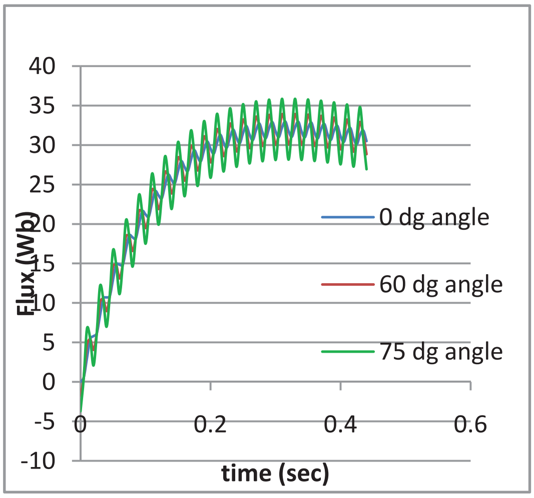

Figure 5 - Variation of core flux with secondary burden phase angle

2.5 CT Flux Requirement under Transient Conditions with a Fully Resistive Burden

In this case, $\cos\theta = 1, \theta = 0$

$$\emptyset = \frac{I_1 R_2}{N_2 2\omega}\left(\frac{T_1 T_2 \omega}{(T_2 - T_1)}\left(e^{\frac{-t}{T_2}} - e^{\frac{-t}{T_1}}\right) - \sin(\omega t + \theta)\right)$$

…… (11)

3. Dimensioning of Current Transformers

Protection current transformers must be capable of accurate performance under both steady state and transient state conditions. The dc component contained in the fault current during the transient period makes the flux in the CT core to increase and it thus the core has to have sufficient cross section to avoid its saturation. Optimum CT sizing, usually called CT dimensioning, will avoid over or under sizing. CT dimensioning calculations are based on the transient factor (K_{tf}) and the transient dimensioning factor (K_{td}). Network, CT and relay parameters are needed for dimensioning calculations.

3.1 Transient Factor (K_{tf})

The ratio of the theoretical total linked flux to the peak instantaneous value of the ac component of the flux when a current transformer is subjected to a specified single energization with secondary loop time constant (T_S) remaining at a constant value throughout the energization is referred to as the transient factor (**K_{tf}**) [4].

$$K_{tf} = \left(\frac{T_1 T_2 \omega}{(T_2 - T_1)}\left(e^{\frac{-t}{T_2}} - e^{\frac{-t}{T_1}}\right) - \sin(\omega t \theta)\right) \text{……. (12)}$$

3.2 Transient Dimensioning Factor (K_{td})

The Transient Dimensioning Factor is introduced to indicate the transient dimensioning necessary to ensure that the current transformer will be able to meet the specified performance requirements including the requirements necessary under the specified duty cycle. It defines the dimensioning necessary to ensure that the CT will be able to meet the performance requirements because of the increase of secondary linked flux resulting from the dc component of the primary short circuit current. K_{td} is derived from K_{tf} and it is a function of time which depends on selected protection relay parameters; and network and CT parameters. In the case of protection relay based K_{td} calculation, the relevant time value is given by the protection relay manufacturer. This defined value for the time is termed as the required 'saturation free time (T_{al})' for the proper operation of the protection function and is determined during relay type tests. The theoretical quantification of K_{td} is categorized into three time zones[1].

1st Time Zone ($0 \leq T_{al} \leq T_{al1}$)

$$T_{al\ 1} = \frac{\pi+\varphi}{\omega} \quad \text{......... (13)}$$

where

$$\varphi = \tan^{-1} \omega T_p$$

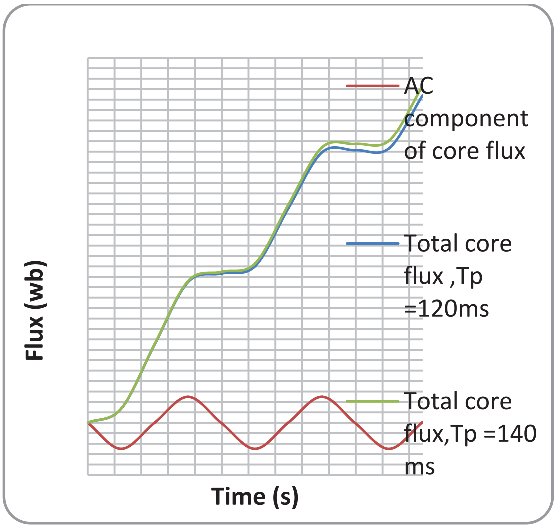

Figure 6 - AC Flux Component and Total Flux Development of the CT Core.

Figure 6 shows the total flux development and ac flux development of the CT core in the first few cycles. Figure 6 shows the flux development in the first few cycles and the flux relationship of K_{td} is given below:

$$K_{td} = F1/F2 \quad \text{.......(14)}$$

where F1 is the secondary linked flux due to the actual transient current (AC+DC) and F2 is the secondary linked peak flux of only the AC component.

In the first half cycle, the sinusoidal component dominates the K_{td} sizing. In the CEB transmission system, the maximum T_p is around 140ms and using Equation (13) [2].

$$T_{al\ 1} = \frac{\frac{22}{7} + \tan^{-1}\left(2 \times \frac{22}{7} \times 50 \times 0.14\right)}{2 \times \frac{22}{7} \times 50}$$

$$T_{al\ 1} = 10.6ms$$

Thus, $T_{al\ 1}$ just exceeds half a cycle. T_{al} requested by modern numerical relays is in this time range and due to this reason K_{td} required for satisfactory relay performance becomes a very low value.

2nd Time Zone ($T_{al1} \leq T_{al} \leq T_{al\ @\ B\ max}$)

$T_{al\ @\ Bmax}$ is defined as the time taken for core flux to reach its maximum. In this time zone, K_{td} can be quantified by Equation (15) [2].

$$K_{td} = \left(\frac{T_1 T_2 \omega}{(T_2 - T_1)}\left(e^{\frac{-T_{al}}{T_2}} - e^{\frac{-T_{al}}{T_1}}\right) + 1\right) \quad \text{...(15)}$$

In the case of electromagnetic relays and static protection relays, the defined saturation free time lies in this second time zone.

3rd Time Zone ($T_{al} \geq T_{al\ @\ B\ max}$)

During the period beyond $T_{al\ @\ Bmax}$, core flux begins to decay. The mathematical expression for the maximum flux in the CT core is given by Equation (16) and the time taken to reach the maximum flux ($T_{al@\ B}$ max) is given by Equation (18) [2].

$$\frac{B}{B_{ac}} K_{ft} = \left(\frac{T_1 T_2 \omega}{(T_2 - T_1)}\left(e^{\frac{-t}{T_2}} - e^{\frac{-t}{T_1}}\right) + 1\right) \quad \text{..... (16)}$$

$$\frac{B_{max}}{B_{ac}} = K_{td\,(max)} = 1 + \omega T_2 \left[\frac{T_1}{T_2}\right]^{\frac{T_2}{(T_2 - T_1)}} \quad \text{...... (17)}$$

$$T_{al\ @B\ max} = \frac{T_N T_S}{T_S - T_N} l_n \frac{T_S}{T_N} \quad \text{..... (18)}$$

This time zone is more important in CT sizing for maximum possible core flux or highest saturation free time. In the case of static and electromagnetic relays used in differential protection applications, due to sizing requirements of through fault conditions, a CT must provide a saturation free current input to the protection relay during the entire fault period. Therefore, $T_{al\ @B\ max}$ must be considered in CT sizing for differential protection with electro-magnetic and static relays (relays without saturation detection.)

If the critical fault clearing times are available for unprotected zones by differential protection and if this critical clearing time is less than $T_{al\ @\ B\ max}$, then this critical clearing time can be used as T_{al} in the K_{td} calculation. In general, this K_{td} value is less than the value of $K_{td\ (max)}$ calculated by Equation (17). The K_{td} calculated in this manner can be considered as the optimum.

4. Current Transformer Selection

Oversized CTs may facilitate accurate protection operations, but such selections cannot be economically justified. Once the optimum selection of CTs is done at the planning stage, the protection system will operate satisfactorily, but power system parameters will keep on changing with system expansions. Hence, all transmission and distribution system operators are required to study and analyze each and every protection relay operation and determine the causes of mal-operations if any.

4.1 CT Selection Criteria

CT selection criteria largely depend on the following main parameters:

1) CT class
2) Core construction
3) CT capacity

CT Class

CT class selection depends on the following parameters:

a) Protection function
b) Type of protection relay
c) Required limit of unit or system stability

Protection Functions

The protection function determines the required delay for the relay operation. Differential protection needs high speed operation or even operation without a delay. First zone operation of distance also needs high speed fault detection. In this research, it has been identified that the categorization of instantaneous or non-delayed tripping functions are more appropriate for CT class selection.

The decaying time of the DC component and the fault detection time of the protection function are the major factors that influence CT class selection. With this information, the maximum CT error that can be permitted within the time duration starting from the fault inception to the time that the instant relay makes its decision to operate has to be worked out.

Differential Protection

The following are the key features of differential protection that need to be considered in the determination of CT requirements:

a. No time delays are involved as the operation is instantaneous. Hence, the relay is required to do its fault detection within the first few cycles of the fault, which is within the transient period.
b. Protection is based on the circulating current principle. Hence at any instant, secondary currents from two or more CTs are evaluated to make the tripping decision.
c. To accomplish (b), the protection relay will need real time secondary currents with errors at levels lower than the stipulated levels to determine primary circuit current differences.
d. Biased curve setting is used to mitigate CT errors. This curve setting is used to mitigate effects which originate from CT and network mismatches for through faults. In case of transformer differential protection, the transformer magnetizing current component dominates to some extent. The tripping value of the differential current of the protection relay is set to follow the biased curve.

In the case of in-zone faults, the protection relay operation has been categorized as instantaneous operation. However, the relay takes time to detect the fault and make the tripping decision. This delay time depends on the type of relay and numerical relays are very fast in this process. Static and electro-magnetic relays take more time than numerical relays. The fastest numerical relay takes nearly 25ms for in zone faults and this lies in the sub transient time zone. According to network parameters of Sri Lanka and magnetic characteristics of CTs, saturation starts after ½ cycle and remains until around 400ms and numerical relays and static relays make their tripping decisions within this time period (sub transient and transient period). Hence, transient class CTs are more suitable for in zone fault detection of static and numerical relays.

In case of through faults, the protection relay can take full fault period and this time zone may be sub transient to steady state and CT should correctly perform in this time zone.

If the protection scheme guarantees protection relay operation within the first ½ cycle for in-zone faults and if the protection system also guarantees a critical fault clearing time less than ½ cycle for through faults, the use of class P CTs can be accepted.

Distance Protection
To maintain system stability, faulty sections of a power system must be isolated from the healthy system within the critical clearing load angle and critical clearing time. Thus, the relay has to operate fast. In a distance relay's first zone, operation is instantaneous and the relay operates within the transient period. When secondary current distortions are present due to inaccurate transformation by CTs, the fault location as measured by the relay can differ from the actual location. For a first zone fault close to the boundary between the first zone and the second zone, secondary current distortions may make the relay to see it as a second zone fault and hence will result in delayed tripping. If this delay exceeds the critical clearing time of this particular location it will cause system instability.

In the power system of Sri Lanka, the maximum primary time constant (T_P) is around 140ms. In a closed core CT construction, the DC current component will take more than 300ms to decay and the maximum saturation may occur in the second cycle. The grading time (delay time) in distance schemes is 250-300ms. This implies that the 2nd zone operation also may take place before the complete decay of the DC transient component. Therefore, the transient class is the preferred option for distance protection. As discussed above, 1st and 2nd zone operations of differential relays lie within the 10ms to 400ms region and the exact operation time varies with the type of the relay and therefore, the relay selection has a considerable influence on the CT class selection.

Selection of CT Classes - Different Types of Protection Relays
In distance/differential protection, the type of protection relay plays a vital role in the CT class selection. There are three types of distance relays in use in the power system of Sri Lanka. These are:

a. Electromagnetic (electro-mechanical) relays
b. Static relays
c. Digital relays
d. Numerical relays

CT Core Selection
CT core selection is based on the following:

a. Type of CT installation
b. The Value of acceptable K_{td} for any given protection relay
c. Cost of CT

Type of CT Installation
The CT size is not a major issue in outdoor type CT installations where generally sufficient space is available for switchgear installation. This environment allows for the use of CTs with large cross sections, such as closed core CTs in which remanence flux mitigation will take place.

In the case of indoor substations (Gas Insulated Substations (GIS)), the installation space becomes an important parameter. In GIS, CTs are encapsulated with the circuit breaker and isolator units. Therefore, smaller size CTs are more suitable for GIS. Gapped core CTs have relatively low cross sections. Class TPZ CTs have approximately only 60% of the cross section of closed core CTs and 40% of that of class PR and class TPX cores.

The Value of Acceptable K_{td} for a Given Protection Relay
Alow K_{td} means a low cross section for a CT. If a protection relay can operate accurately with lower K_{td}, then a closed core CT in which accurate DC component transformation is possible can be selected.

5. Conclusions

The final conclusion of this research is the development of a CT selection criterion for protection applications. The developed selection criterion is mainly focused on two streams. Network and CT parameter based CT selection can be generalized to protection applications irrespective of the type of the protection relay. In this case, CT selection is carried out in the first stage and the protection relay selection is lined up after the CT selection. The second stream of CT selection criterion is based on the selected protection relay and on the parameters which are given by the relay manufacturer. This second stream highly depends on the literature provided by the relay manufacturer. Therefore, adequate CT selection guidelines are a must for correct CT selection. The proposed CT selection process as an outcome of this research is shown in Figure 7 and Figure 8 and a simple computer program can use the given algorithm and facilitate a fast selection process.

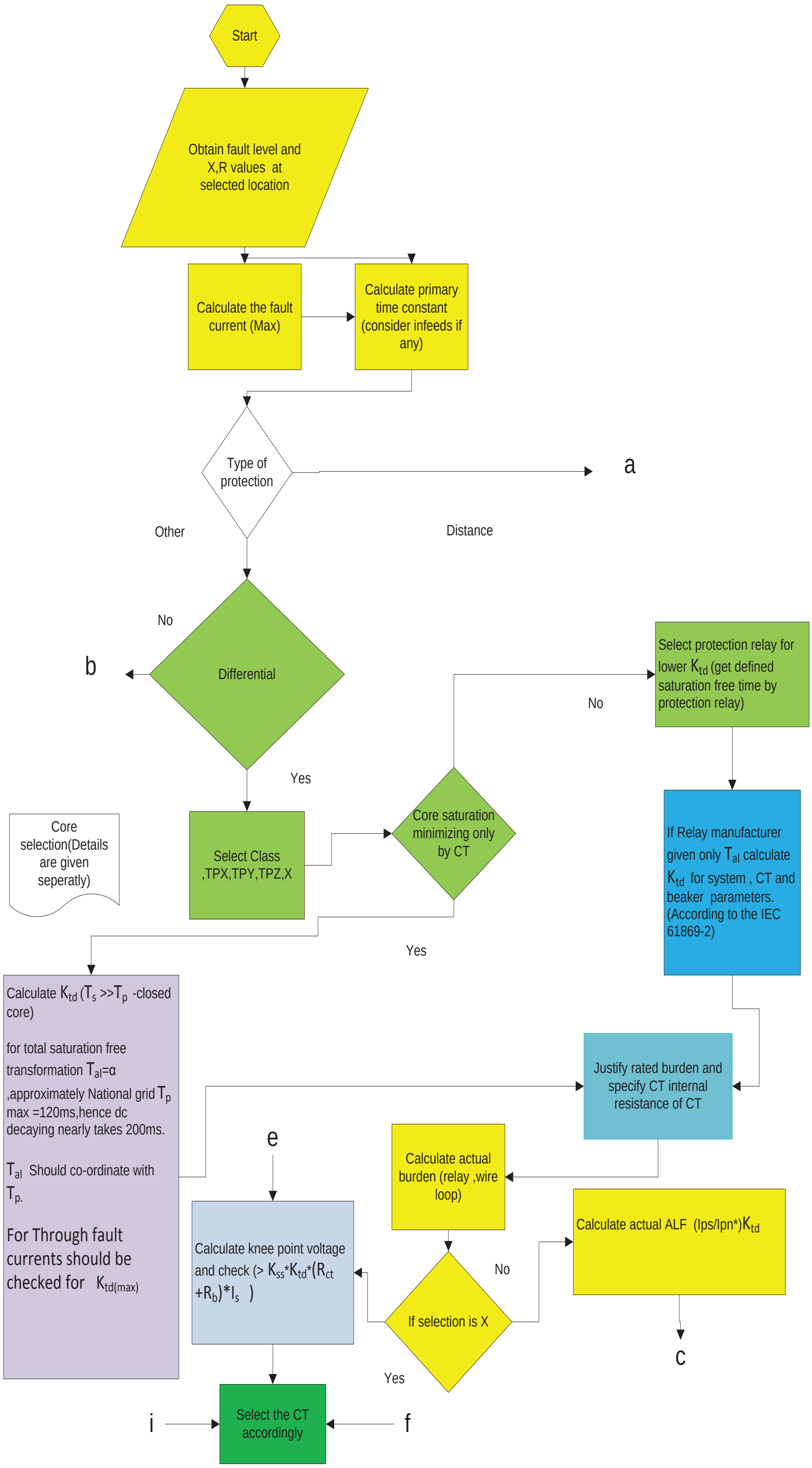

Figure 7 - Network and CT Parameters based CT Selection Criteria (continued on next page)

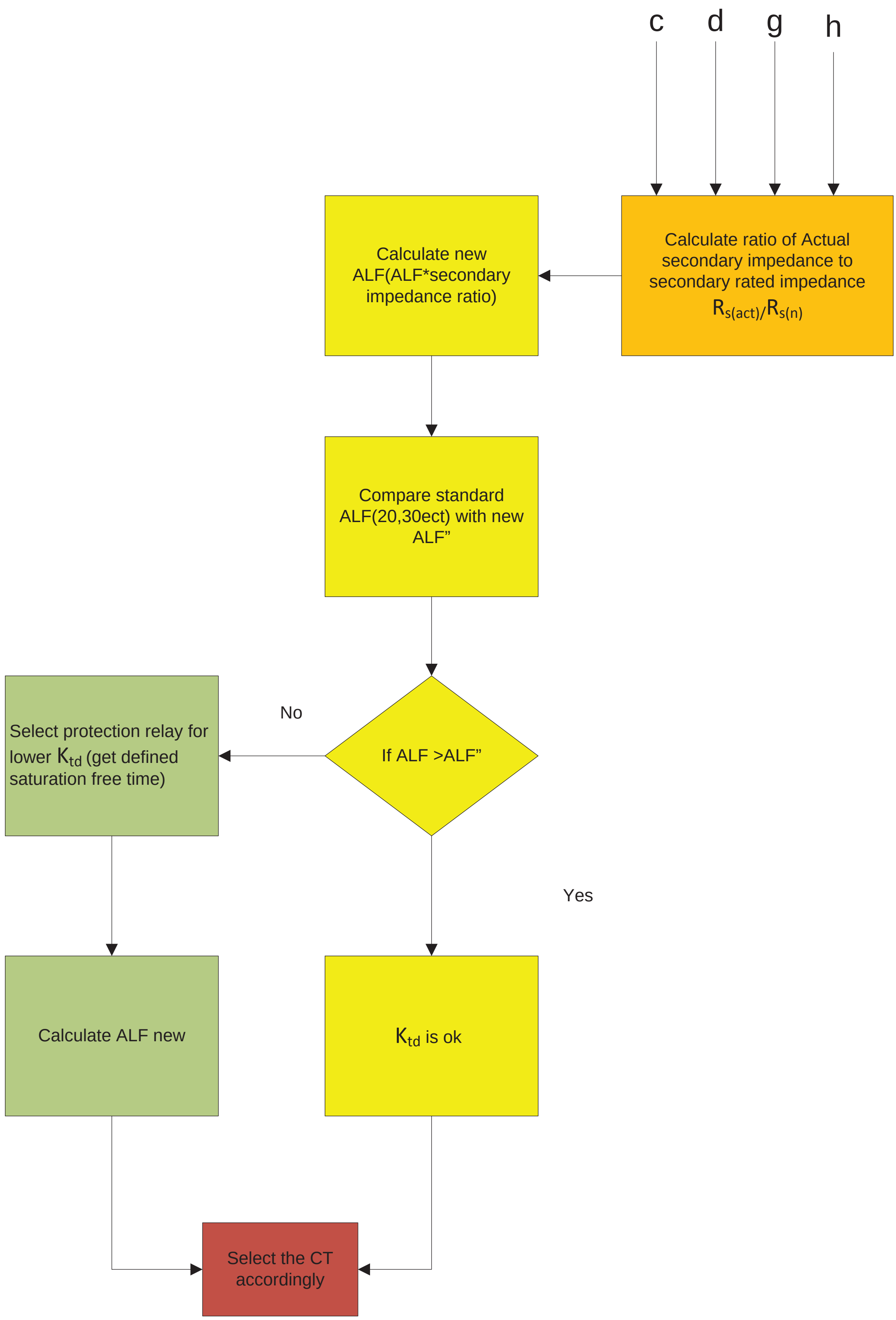

Figure 7 - Network and CT Parameters based CT Selection Criteria **(continued on next page)**

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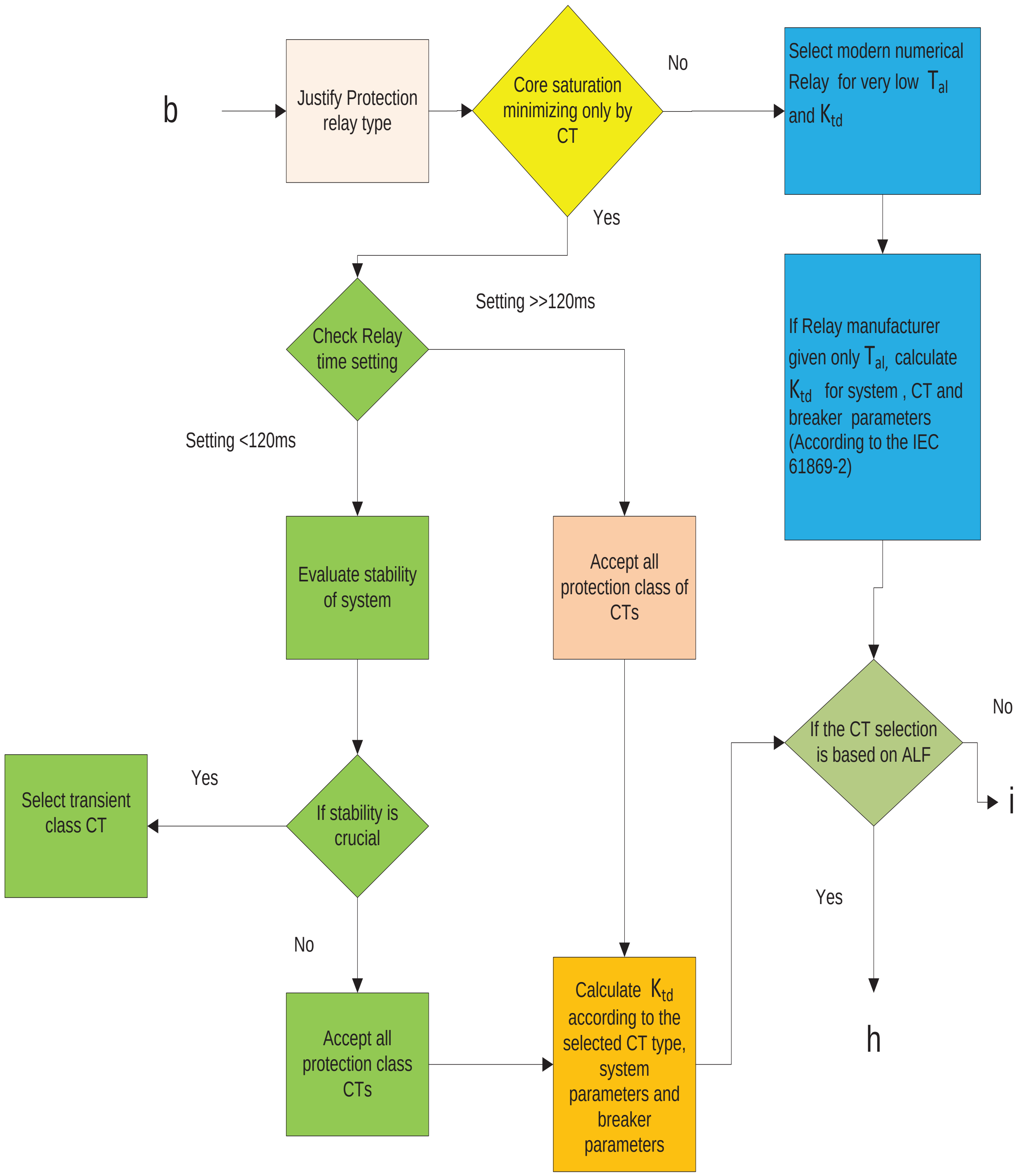

Figure 7 - Network and CT Parameters based CT Selection Criteria (end of the diagram)

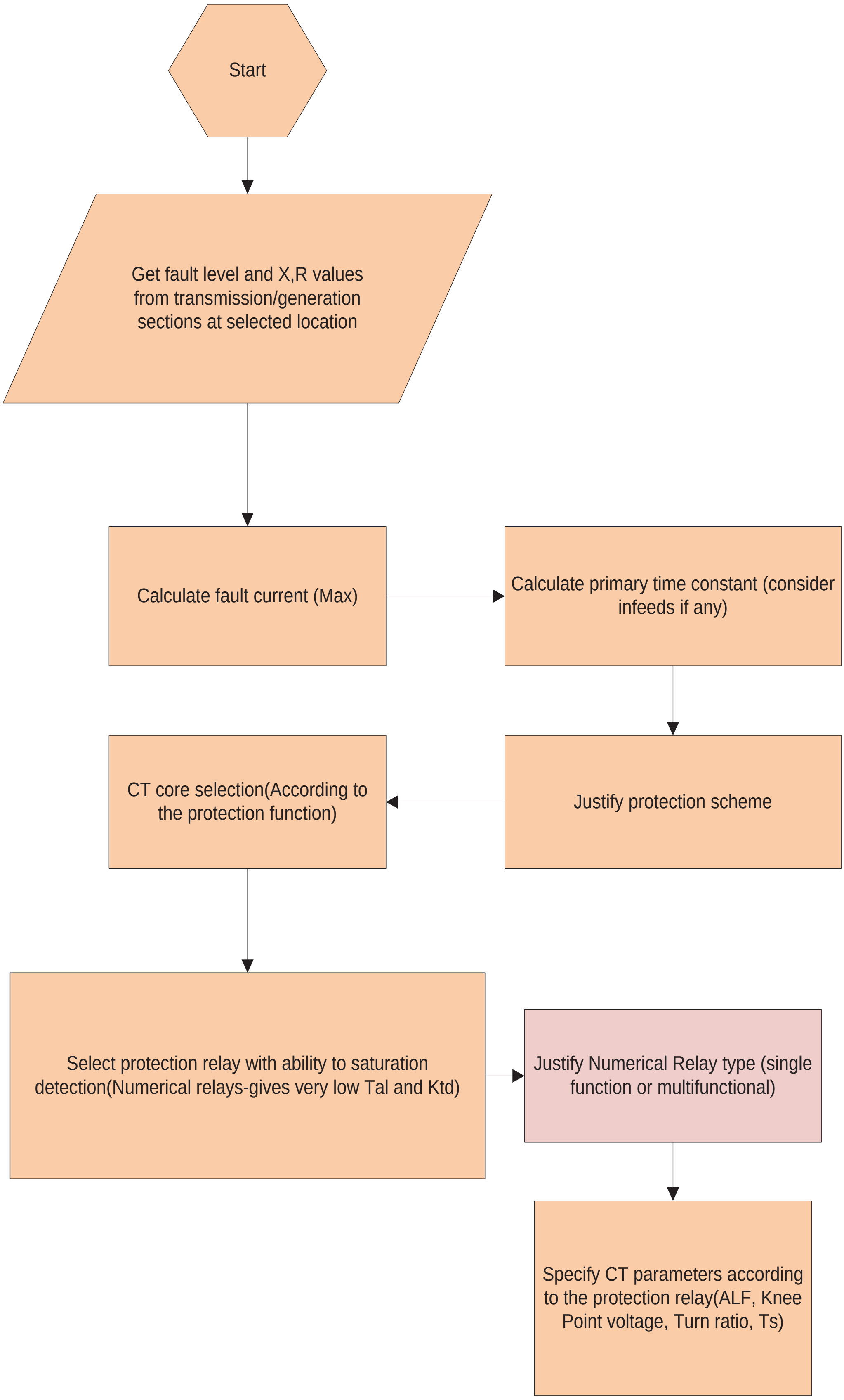

Figure 8 - Relay based CT Selection Criteria

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