OPERATIONAL FEATURES AND OPTIMISATION OF CURRENT TRANSFORMERS

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Introduction

Current transformers (CTs) are used to transform large primary currents to a small secondary current suitable for instrumentation and protective relay systems. The ratio of the windings determines the relation between the primary and secondary currents. CTs utilises the magnetising intensity/ magnetic field strength of a primary conductor carrying alternate current (AC) on secondary winding(s) having many turns, by electromagnetic induction. The primary having one or few turns passed through a toroidal core wound with many turns as secondary. This method enables an interfacing solution between high current line and low current secondary circuits having measuring instruments/ protective relays in the electrical control systems. The essential components are:

1. Primary conductor/ winding which is connected in series with the circuit where the current is to be transformed.
2. Magnetic core for secondary winding.
3. Secondary winding(s) which receive energy from the primary circuit by induction and to the sec ondary terminals which are connected to the measuring instruments or relays. The devices connected to secondary constitute the **Burden** on the CT.

Burden may be treated as a fourth essential component of any CT in view of its influence on various performances, size and economical design.

National / International standards specify various definitions, service conditions, ratings, constructional features, performance requirements, classification of tests and test methods/ procedures applicable for the CT. Apart from the standard stipulations, it requires sufficient knowledge to the purchaser for evolving specification considering the real need. If not, the manufacturer will reach a situation to deviate the requirements in the tender stage itself. For which, a thorough study is essential at purchaser side while evolving the specification.

This paper outlines the operational features including design parameters and optimisation requirements of CTs aiming at standardisation in High voltage systems to meet the requirements of utilities to certain extend. This is feasible as the protective devices and schemes available in electrical control circuits are almost standard with varied performance settings. Specification errors/ stringent requirements will always lead to oversize and increased cost to the equipment.

OPERATIONAL FEATURES

General Equivalent Circuit

The equivalent circuit of various types of CTs and accuracy classes remains the same as shown below, but the design parameters will differ.

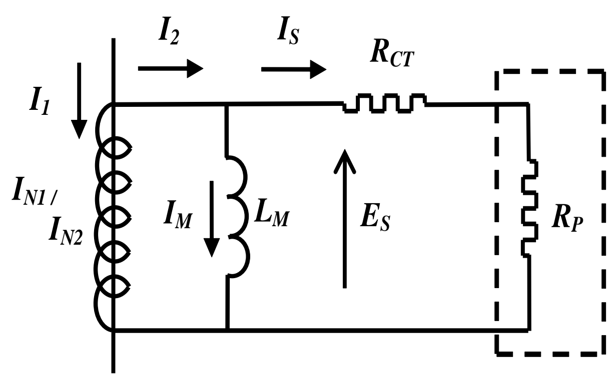

Fig.:1. General Equivalent Circuit of CT

I_{N1}/I_{N2} = Current ratio (primary to secondary)
I_1 = Primary current.
I_2 = Secondary current corresponds to ideal CT
I_S = Effective secondary current (rated current)

$$I_M = \frac{H \times L}{N_S}$$

(I_M is CT magnetisation current or excitation current, H is magnetising intensity AT/m, L is mean length of magnetic circuit and N_S is number of turns in secondary winding)

$$L_M = \frac{\pi \times \sqrt{2} \times f \times B_M \times A \times N_S{}^2}{H \times L}$$

(L_M is CT shunt impedance/equivalent excitation impedance: saturable)

Roughly, $I_2 = I_1 \times \frac{I_{N2}}{I_{N1}}$

Precisely, $\vec{I_2} = \vec{I_M} + \vec{I_S}$

R_{CT}= Secondary winding resistance

R_P= Secondary impedance (metering/ protection relay / other device including connection cable resistance R_L)

$E_S = I_M \times L_M$ or

$E_S = I_S \times (R_{CT} + R_P)$ or

$E_S = \pi \times \sqrt{2} \times B_M \times A \times N_S$, for preliminary design

(B_M is peak flux density and A is cross sectional area of secondary core,)

Output Currents

The secondary current can be 1 or 5A against primary current up to typically 2400 A, due to manufacturing hurdles and size limitations. In high current applications typically for 5000A, it is a standard practice to use a cascaded arrangement of 5000/20A main CT + 20/5A or 20/1A interposing auxiliary CT. In earlier days, in electromagnetic instruments and relays, 5A secondary was essential to activate the magnetic needles/ latches. With the advent of modern instruments and protective relays having relatively low burden, 1A secondary is enough for its working. Moreover, the burden in the control cables being I^2 R, 1A output from a CT reduces the cable burden 25 times lower that of 5A secondary. Thus with 1A secondary, the size and cost have been reduced considerably followed by low resistance of secondary winding R_{CT} and that of lead wires/cables R_L.

Accuracy

Current Ratio error

Accuracy of current transformation is considerably dependant on primary current to secondary current ratio (I_{N1}/ I_{N2}), Core material/ its optimum size and burden connected. The CT being a current source, when the secondary is connected with a burden, a lion share of primary ampere-turns (AT) is transformed to secondary leaving a very small portion I_M for the secondary core excitation; refer Fig.1 - general equivalent circuit. i.e. core excitation (magnetisation) current I_M through impedance L_M. Thus the reduction in transformation causes the current ratio error in a CT. Reference may be made to relevant standards for limits of error at various currents and burden.

Phase Displacement

Phase displacement between primary & secondary currents to a low level is caused due to leakage reactance and capacitance in the secondary winding and also with the nature of burden connected. It will be negligibly small in the case of a CT having few primary turns and many turns provided on toroidal secondary core. The phase displacement error if any will lead to large errors, in combination measurement of real power, power factor etc. in conjunction with a Voltage transformer. Refer relevant standards for error limits.

Open Circuit Voltage (E_k)

CT is normally connected to a burden; the voltage across the secondary terminals will be in the order of volts corresponding to the secondary current and burden resistance R_P . If the secondary is open circuited while current flowing on primary, the secondary voltage will rise dangerously to a high value. This is due to the fact that all the primary ampere-turns (AT) have become exciting ampere-turns and saturation of the core occurs. Hence, no CTs are allowed in service with its secondary open (keep the secondary shorted when not in use). This effect will be more in a 5A CT as the core size is comparatively high.

Excitation Characteristic (E_k vs I_m)

The excitation characteristic (Voltage vs Current) is obtained by applying AC voltage on secondary and measuring corresponding current taken for various voltage levels until saturation is reached; the primary circuit being open circuited. For practical purposes, it can be treated that these voltages and currents are same as that E_S & I_M occurring on CT when a current is flowing on the primary. This is again related to the Flux density B *Tesla* vs Magnetic field strength $H\ AT/_m$ of the core material. The resulting curve has three regions viz. initial non saturated, intermediate (linear) and final saturated regions; in turn L_M varies non-linearly and saturate finally. This is the practical and indirect way of separating the magnetising/ exciting current (of core) from primary current.

Rated Knee point e.m.f. (E_k)

The minimum sinusoidal e.m.f. (r.m.s.) at rated power frequency when applied to the secondary terminals of the transformer, all other terminals (primary) being open-circuited, which when increased by 10% causes the r.m.s. exciting current to increase by not more than 50%. The actual knee point e.m.f. will be ≥ the rated knee point e.m.f in exceptional cases.

Burden of CT ($I_S{}^2 R_P$)

Burden has an important role in all CTs while considering its accuracy, size and cost. The CT secondary circuit impedance in relation with a power factor is called the burden and expressed precisely in its resistance and reactance. There is a practice to express the burden in terms of volt-amperes and power factor also, the volt-amperes being the apparent power consumed in the burden impedance at rated secondary current. For example a burden of 5 Ω impedance may be expressed as 5 VA at 1A ($I_S{}^2 R_P$). The total burden on the CT is the individual burden of meters/ relays in the secondary together with the resistance of the interconnecting cables. The CT burden impedance may decrease while increasing the secondary current, because of saturation in the magnetic circuits of instruments/ relays connected to it. Hence, a given burden may apply only for a particular value of secondary current. In the application side, this has to be confirmed either by conducting separate tests or referring the impedance data for over currents in the device operation manual. However, modern trend is low burden with resistive component alone for the instruments/relays involved.

Basic Classification

Basic classification of the CTs is by its application as Metering class and Protection class. Both CTs have transformation errors; which under normal load condition is considered for metering class and under abnormal (fault) condition is considered for protection class. In view of metering and various types of protection devices a CT has to accommodate 3 to 5 different secondary cores. The design parameters are follows.

Metering Class

With the increased demand of energy and in view of correct billing, utilities have to measure current in precise accuracy 0.2 class, over a wide range: 5 to 120 % of rated primary current as against 0.5 or 1.0 class in limited range 50 to 120 % earlier.

Measurement/ metering class cores are designed with cross section area so as to saturate normally at 5 times the rated current, aiming at safe guarding the instruments during fault conditions. Thus, it is rated with an Instrument security factor F_S (indication of multiples of rated current at which core saturates). F_S is directly related to rated burden. Thus the operation of metering core is far below the saturation region of core.

At normal operation, $E_S = I_S \times (R_{CT} + R_P)$

At fault condition,

Protection Class

Protection devices viz. Relays & Recorders connected to the secondary are intended for sensing the abnormality of the primary current mainly the fault conditions. It requires high capability of current transformation during fault conditions rather than the current transformation accuracy in a metering class. The current transferred thus allow protection relays to measure and disconnect the fault. Typical protection classes are 5P, 10P and PS.

5P & 10P Classes

These are normally used with over current protection schemes by allowing larger errors than the measuring class. Its high saturation voltage is decided by a factor called Accuracy Limit Factor *ALF*, which means an over current as a multiple of the rated primary current up to which the rated accuracy is ensured for a burden (rated) connected to the secondary. The burden on the secondary influences the *ALF*, thus it can be defined as the ratio between voltage at over current and voltage at rated current across the burden for practical purpose (actual definition is ratio between rated accuracy limit primary current & rated primary current). 5P means 1% current at rated current & 5% composite error at fault limit current.10P means 3% current error & 10% composite error at fault limit current.

At normal operation,

At fault condition,

Composite Error is the Current Error at accuracy limit current by taking account of harmonics in the secondary current caused by non-linear magnetic characteristics, especially at higher flux densities.

PS or Special Purpose Class (PX as per IEC 60044-1)

CT under this class is normally used with unit protection schemes (balanced protection) where the required characteristics of CTs can not conveniently expressed in terms used for 5P/ 10P class.

The knee point voltage, exciting current(s), limited turns ratio error and secondary winding resistance are so dependent on the protective gears involved. CTs of this class are suitable for protective schemes requiring close balance of the secondary currents from different phases or circuits. Such CTs should be so designed that balance is maintained within the protective system, i.e. stability of the protection must be assured, whether in transient or steady state, up to the maximum through-fault current which can be passed in service through their primary windings.

At normal operation, $E_S = I_S \times (R_{CT} + R_P)$

At fault condition,

$$E_K = K_X \times I_S \times (R_{CT} + R_P)$$

K_X is the dimensioning factor as a multiple of rated secondary current at fault conditions.

Optimisation Requirements

CTs in the HV systems: 145/245/420 kV require bulk insulation to isolate the secondary from the primary turn/ loop. Owing to the size of primary insulation the secondary windings have inner diameter limitations as compared with LV CTs of same ratings. Various parameters essential for optimisation of CTs in such systems are given below.

Short Time Current *(STC)*

Overestimation of STC can lead to feasibility problems and high cost especially in multi ratio CTs. Adequate requirement will reduce the cost and size of the CTs.

Primary Reconnection & Secondary Tapping

As in LV CTs, too many ratios can not be assigned in a single CT as the increased number of primary turns will reduce the short time current withstand capability. However, multi ratio requirements are essential in view of its varied usage and economy as below:

Ratio arrived in a relation 4:2:1 or 2:1; e.g. 800-400-200/1A or 800-400/1A by allowing primary-reconnection is an economic choice. There will not be secondary taps which ensures same burden, accuracy, and FS/ ALF for all ratios. These ratios are normally adopted in 145kV systems, STC: 20 to 31.5 kA.

Too many ratios like 1200-800-600-400-300-150/1A will not be optimum as it requires both primary reconnection and secondary tapping. Burden capability, accuracy and FS/ALF will be different in set of ratios 1200-600/1, 800-400/1& 300-150/1A. Similar ratios were adopted both in 145 and 245kV systems earlier, STC: 25 to 31.5 kA.

Ratios like 1600-800/1 & 2000-1000-500/1A are not permitting a primary reconnection in 245 and 420kV systems in view of STC: ≥ 40 kA. In such cases, the out put requirement must be carefully arrived/ standardised optimum.

Reasonable Ampere-turn AT for all Classes

The error increases as the inverse proportion to the square of *AT*. In order get stable error for various currents, reasonable *AT* has to be adopted. This is achieved by providing turns in the primary as far as possible by primary reconnection.

Low Burden and Reasonable ALF in 5P or 10P Class

In over current protection, 5P or 10P class, rated burden has to be assigned considering the resistance of wiring leads together with that of the protection device in the system. Usage of actual burden lower than the rated value will increase *ALF* by another factor K_S as below.

$$K_S \approx ALF \times \frac{I_S^2 \times (R_B + R_{CT})}{I_S^2 \times (R_N + R_{CT})}$$

Where, R_N is the actual burden impedance.

At the same time, if a CT having R_{CT} low as compared with another CT having the same rated burden also will increase the *ALF*.

Low Burden for Precise Metering Class

Precise 0.2 class accuracy limits have to be complied for 5 to 120 % rated primary current. This is achieved by assigning the operation of the CT almost in the linear portion of excitation characteristic. In turn, the burden capability became low while comparing with a 0.5 class intended for 20 to 120% current range.

Modern measuring instruments together with 4mm^2 connecting cables have burden is only in the order of 10VA. Normally, CT is designed aiming at minimum error at 80 ~ 90 % of the rated current or typically 75% of the rated burden. It can be made optimum by assigning rated burden as 1.5 times the actual burden; worked out to 15VA (normally). More precise 0.2S class is with

5 VA; the accuracy limits have to be complied for 1 to 120% rated primary current.

Usage of actual burden lower than the rated value will increase FS by another factor as in the case of ALF in protection class.

$$K_S \approx F_S \times \frac{I_S^{\,2} \times (R_P + R_{CT})}{I_S^{\,2} \times (R_N + R_{CT})}$$

Reasonable Knee Point Voltage, E_K for PS Class

CT winding resistance R_{CT} and Burden R_P (including resistance of connection cables R_L) must be limited to minimum as far as possible for reasonable E_k.

Characteristic Voltages related to various Classes

Considering a particular grade of CRGO core material, the characteristic voltages: $E_k < E_{5P} < E_{10P} / E_{FS}$. Flux density (Tesla) generally adopted for these voltages are typically: 1.45 for E_K, 1.56 for E_{5P}, 1.90 for E_{10P} & E_{FS}. CTs are designed for optimum by selecting the flux density as above. In a given CT. By knowing one of these voltages, the others can be found from the relation below.

$$\frac{E_K}{E_{5P}} = \frac{1.45}{1.56} ; \frac{E_K}{E_{10P}} = \frac{1.45}{1.90} ; \frac{E_{5:P}}{E_{10P}} = \frac{1.56}{1.90} \text{ etc.}$$

Secondary Toroidal Core

The core on which the secondary winding plays a significant part on the performance of a CT. Cold rolled grain oriented (CRGO) steel strips are used for making secondary toroidal core (strips wound spirally by eliminating joints to form ring shape). Nickel alloyed steel is used in exceptional cases for metering. The core material determines the price and accuracy of metering class.

Excitation Current I_M (Magnetisation Current) at $E_K/2$

Generally preferred excitation current (as per relay manufacturers) is 30 mA at $E_K/2$. At a particular induced e.m.f E_S in secondary, I_M is directly proportional to corresponding electromagnetic field strength H $AT/_m$ and mean diameter of the secondary core; and inversely proportional to the number of secondary turns. In low current CTs (e.g. 75/1 or 150/1), aiming at reasonable E_K and low I_M, over-rating of primary current is a usual practice by limiting the R_{CT}.

Redefinition of One type to Other

A CT available with certain class can be redefined into different classes by knowing the Secondary winding resistance and Secondary excitation characteristic.

Given, 1A sec. CT, 30VA, 5P10, its $R_{CT} = 5\ \Omega$

5P to 5P with changed VA & ALF

E_{5P}= 10 x 1^2 x (5+ (30/1^2)) =350V

For other lower outputs:

15 VA; E_S = 350V = *ALF* x 1^2 x (5+ (15/1^2)), or *ALF*=17.5

10 VA; E_S = 350V = *ALF* x 1^2 x (5+ (10/1^2)), or *ALF*=23.3

5P to 10P with changed VA & ALF on the above CT

Take $\frac{E_{5P}}{E_{10P}} = \frac{1.56}{1.90}$

E_{10P}= (1.90/1.56) x 350 = 426 *V*

For higher output:
40 VA; Es = 426V = ALF x 1^2 x (5+ (40/1^2)), or ALF = 9.4
For lower output;
20 VA; Es = 426V = ALF x 1^2 x (5+ (20/1^2)), or ALF = 17.0

5P10 to PS (E_K, R_{CT})

For, E_K of the given CT, take $\frac{E_K}{E_{5P}} = \frac{1.45}{1.56}$

or E_K = (1.45/1.56) x 350 = 325V,

R_{CT} is already given, 5 Ω

Confirm I_M corresponding to 325V from the excitation characteristic.

PS (E_K, R_{CT}) to 10P

Take $\frac{E_K}{E_{10P}} = \frac{1.45}{1.90}$

E_{10P}= (1.90/1.45) x 325 = *426V*
(VA/ ALF: 40/ 9.4 or 20/ 17.0 as above)

Metering Class

As in 5P to 5P with changed VA, metering VA can be changed (reduced), by retaining the same accuracy. Increased operation range is an advantage in such cases; but the FS will be increased and a shunt reactor is required across the secondary so as to safeguard the instrument during over currents. eg.20VA/ 0.2 redefined as 10VA/ 0.2, ext.150%.

Last minute changes on various requirements, after awarding the order will make troubles to both purchaser and manufacturer. Redefinition as above will help in resolving such situations to certain extend.

Review of standard CTs in the National grid.

In the 400/220 kV interconnection system, standardised CTs are rendering service for more than 2 decades. These multi ratio CTs do not permit primary reconnection in view of high STC. It has 5 secondary cores; one metering and four PS class as detailed below.

420kV CT with STC 40kA, 1s

Core 1&2: 2000-1000/1, PS, 2000-1000 V, 10-5.0 Ω, 30-60 mA at E_K

Core 3: 2000-1000-500/1, 20VA, 0.2

Core 4&5: 2000-1000-500/1, PS, 4000-2000-1000V, 10.0-5.0-2.5 Ω, 30-60-120 mA at E_K

245kV CT with STC 40kA, 1s

Core 1,2,4 &5: 1600-800/1, PS, 1600-800 V, 8.0-4.0 Ω, 25-50 mA at E_K

Core 3: 1600-800/1, 20VA, 0.2

Though these CTs are standardised, there is further scope for redefinition/ optimisation.

- Metering cores of both 420 & 245kV CTs have been redefined from 40VA/ 0.5 to 20VA/ 0.2 in the mean time of their service and further scope is 15VA.
- Assuming same protective devices at secondary, core 1&2 of 420kV CT can be redefined in line with core 1&2 of 245kV CT. i.e. 1600-800V, 8.0-4.0 Ω in place of 2000-1000 V, 10.0-5.0 Ω.
- If feasible, the core 4&5 of 420kV CT also can be redefined to 3200-1600-800 V, 8.0-4.0-2.0 Ω in place of 4000-2000-1000 V, 10.0-5.0-2.5Ω.
- The secondary protective devices being same, 30-60 mA at E_k can be adopted in 245 kV CT in place of 25-50 mA.
- All the PS class cores can be redefined for 5P class 20/ 30VA, but ALF will be > 20 always.
- As these CTs do not permit primary interconnection, the core area is decided based on lowest ratio. If redefinition as above is feasible on these standard CTs, it would lead to further optimisatiion.

Requirements affecting Optimum Design

Manufacturer will reach a situation to deviate the requirements in the tender stage, if the CTs have been specified without real requirements and set parameters in its application. Requirements contrary to the following points will increase the size and cost of the equipment.

- Primary reconnection is a must in low current multi ratio CTs aiming at sufficient AT, to meet accuracy requirements and to reduce the size.
- Avoid too many ratios in a CT with precise requirements.
- Avoid wide gap between ratios for metering and protection in the same low current CT; eg. 200/1 metering and 1200/1 PS.(over-rating of primary current for PS class aiming at low I_M).
- Do not expect precise metering / 5P/ IM < 30mA at EK/ 2 for CTs mounted on Bushings where current is < 500A
- Specify realistic burden/ E_K for protection class.
- Metering burden higher than 15/ 20 VA will not ensure precise class 0.2
- Do not try to add a 6th core for the above standard 420/245 kV CTs aiming at a 5P class, as it can be managed with redefining the existing PS.

High voltage CTs require bulk insulation for the primary, which can be made optimum by grading of electrical stress in the insulation structure. In order to preserve the high quality of insulation achieved during manufacture, the equipment has to be sealed hermitically by giving sufficient nitrogen cushion at top expansion chamber. Interruption to the sealing has to be avoided as far as possible. The insulation withstand voltages for the CT applicable to various systems have been standardised as per relevant standards. The photograph shows a standard 245kV CT undergoing High voltage withstand or Dielectric tests in a Laboratory.

Fig.: 2. 245kV CT under High voltage tests

Conclusion

Standardised requirements have been evolved only in 420/ 245 kV interconnection systems in the country. There are varieties of specification in 145 & 245kV. With the advent of new generation instrumentation/ protection systems, the secondary parameters are assumed same for a particular range of primary currents. 5P/10P can be redefined to PS and vice versa with a unified specification. Thus there is scope for standardisation and there by optimisation in 145/ 245kV to a larger extend. For such attempts, STC withstand is also to be taken in to account.

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