White Paper

Relay Work Group

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Relaying Current Transformer Application

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Introduction

This paper was prepared by the WECC Relay Work Group for utility engineers who apply current transformers for Protection Systems. It is meant to be a ready reference, particularly among WECC members who are trying to solve a mutual protection problem or operation. It is also suitable as a tutorial for engineers entering the protection field.

Current Transformer Characteristics

Core Construction and Accuracy Classes

Although many current transformer designs exist for various purposes, the basic types of core construction can be grouped into two categories, toroidal or wound.

The bushing-, window-, or bar-type current transformers are of the toroidal core construction. The primary winding is the main conductor passing through the center of the core. The secondary winding is uniformly distributed around the toroidal core. Essentially, all the flux that links the primary conductor also links the secondary winding. The leakage flux, and thus the leakage reactance, is negligible. This is a common construction for HV and EHV current transformers.

Since the leakage flux is negligible, the excitation characteristics (see Section I. B. Exciting Current) can be used directly to determine performance. Current transformers of this type have an accuracy class designation of “C” per ANSI C57.13, indicating that the ratio correction at any current can be calculated adequately if the burden, secondary winding resistance, and excitation characteristics are known. The C- or K-classification applies to all tap sections of the current transformer winding, but the accuracy class (i.e, C400, C800, etc.) applies only to the full winding. The previous ANSI classification (L) applied only to the full winding. Tap sections of current transformers with an L classification may not be uniformly distributed.

K-class current transformers are identical to C-class devices except that K-class current transformers shall have a knee-point voltage at least 70 percent of the secondary terminal voltage rating. The secondary terminal voltage rating is the voltage that the transformer will deliver to a standard burden at 20 times normal secondary current (i.e., 100 amps for a five-amp nominal CT) without exceeding 10 percent ratio error.

The presence of leakage flux has a significant effect on current transformer performance. When this flux is appreciable[1], it is not possible to calculate ratio correction. Current transformers of this type have an accuracy class designation of 'T,' indicating that ratio correction must be determined by Test.

Wound-type current transformers, T-type classification, are usually constructed with more than one primary turn and undistributed windings. Because of the physical space required for insulation and bracing of the primary winding, and fringing effects of non-uniformly distributed windings, flux is present; which does not link both primary and secondary windings. Figure 1 is included to clearly illustrate the effect but does not reflect usual construction practice. An auxiliary current transformer is an example of a wound-type current transformer.

Exciting Current

In an ideal current transformer, the primary ampere-turns are equal to the secondary ampere-turns. However, every core material requires some energy to produce the magnetic flux that induces the secondary voltage necessary to deliver the secondary current. In an actual current transformer, the secondary ampere-turns are equal to the primary ampere-turns minus the exciting ampere-turns. For a C- or K-class, or a toroidal-core-constructed current transformer, the simplified equivalent circuit is shown in Figure 2. Figure 3, extracted from ANSI C57.13, shows the typical excitation curves for a multi-ratio C- or K-class current transformer. The maximum tolerance of excitation values above and below the knee is also specified. These curves define the relationship of the secondary exciting current (Ie) to the secondary voltage (Ee). The unsaturated slope is determined by the magnetic core material. The saturated region is the air-core reactance.

When the current transformer core is unsaturated, the error due to exciting current is normally negligible. When the voltage is above the knee of the excitation curve, the current transformer is said to be operating in its saturated region where the exciting current is no longer negligible. Therefore, the ratio error of the current transformer becomes much greater beyond the knee.

For T-class current transformers, the leakage flux can be appreciable. The exciting flux should be considered, along with the leakage flux, in determining current transformer accuracy. Although a test should be done, Figure 4—also extracted from ANSI C57.13—shows typical overcurrent ratio curves for a T-class current transformer.

[1] As stated in ANSI C57.13, an appreciable effect is defined as one percent difference between the actual ratio correction and the ratio correction calculated.

Remanence

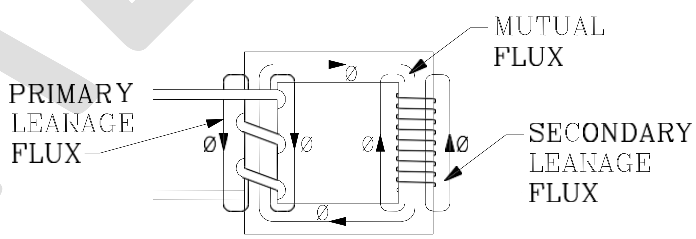
Remanent flux can be set up in the core of a current transformer under operating or test conditions. During operating conditions, remanent flux can be left in the core when the primary current is interrupted while the flux density in the core of the transformer is high. This may occur when clearing fault current. Testing, such as resistance or continuity measurements, may also leave remanence.

The remanent flux in the core depends on many factors. The most important ones are the magnitude of primary current, the impedance of the secondary circuit, and the amplitude and time constant of any offset transient. Since the impedance of the secondary circuit is generally fixed, the magnitude of remanent flux is governed by the magnitude of the symmetrical component of the primary current and the magnitude of the offset transient prior to the primary current interruption. Maximum remanent flux can be obtained under conditions whereby the primary current is interrupted while the transformer is in a saturated state.

When the current transformer is next energized, the flux changes required will start from the remanent value. If the required change is in the direction to add to the remanent flux, a large part of the cycle may find the current transformer saturated. When this occurs, much of the primary current is required for excitation and secondary output is significantly reduced and distorted on alternate half cycles. This phenomenon is illustrated in Figure 5and Figure 6. The performance of both C- and T-class transformers is influenced by this remanence or residual magnetism. Relay action could be slow or even incorrect.

The remanence can be corrected by de-magnetizing the current transformer. This is accomplished by applying a suitable variable alternating voltage to the secondary, with initial magnitude sufficient to force the flux density above the saturation point, and then decreasing the applied voltage slowly and continuously to zero. If there is any reason to suspect that a current transformer has been subjected recently to heavy currents, possibly involving a large DC component, it should be demagnetized before being used for any test requiring accurate current measurement.

Figure 1: Leakage Flux Associated with T-Class Current Transformers



Thermal Ratings

Current transformer continuous ratings can be increased beyond nominal by use of a continuous thermal current rating factor. This factor is defined in ANSI/IEEE C57.13-1993(R2003) as:

The number by which the rated primary current of a current transformer is multiplied to obtain the maximum primary current that can be carried continuously without exceeding the limiting temperature rise from 30°C average ambient air temperature. The RF of tapped secondary or multi-ratio transformers applies to the highest ratio, unless otherwise stated. (When current transformers are incorporated internally as parts of larger transformers or power circuit breakers, they shall meet allowable average winding and hot spot temperatures under the specific conditions and requirements of the larger apparatus.)

Note: Standard rating factors are 1.0, 1.33, 1.5, 2.0, 3.0, and 4.0.

As an application example, a power circuit breaker with a 1600-amp continuous rating could use 1200/5 (maximum ratio) current transformers with a thermal rating factor of 1.33. In this way, the current transformer could continuously carry 1600-amps primary and would therefore not limit the breaker capability.

Auxiliary current transformer thermal ratings do not conform to this standard and are handled differently among manufacturers.

Figure 2: Simplified Equivalent Circuit of CT on Secondary N Turn Base

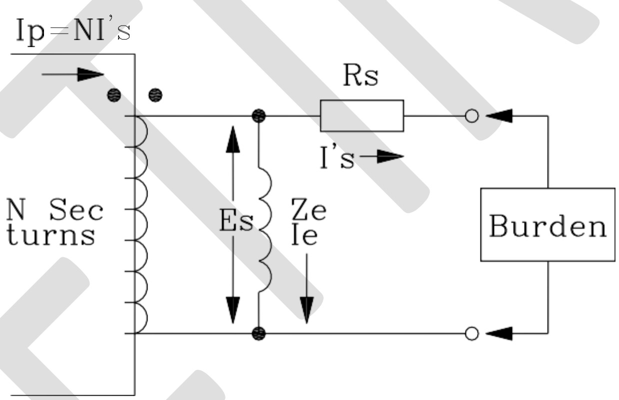


Figure 3: Typical Excitation Curves for Multi-Ratio C- Or K-Class Current Transformers with Non-Gapped Cores

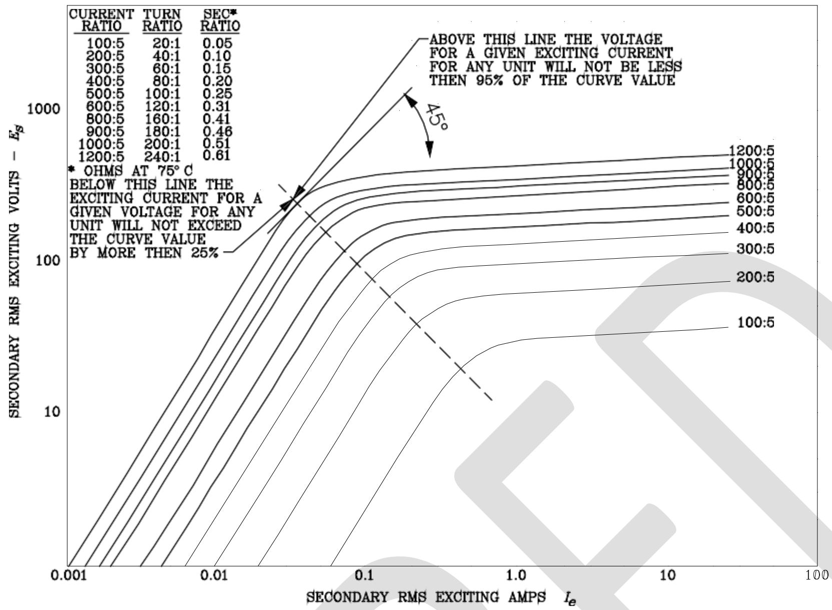


Figure 4: Typical Overcurrent Ratio Curves for T-Class CTs

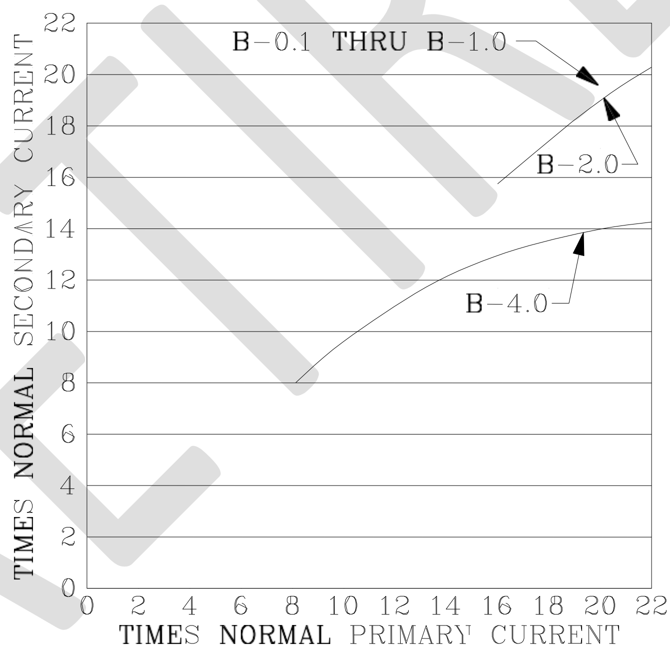


Figure 5: Normal Hysteresis Curve

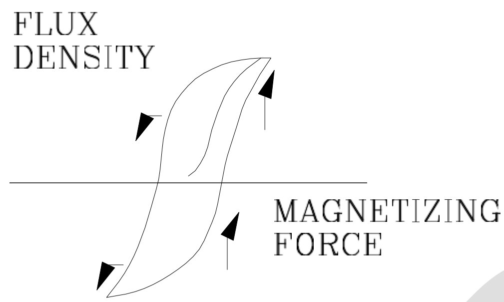
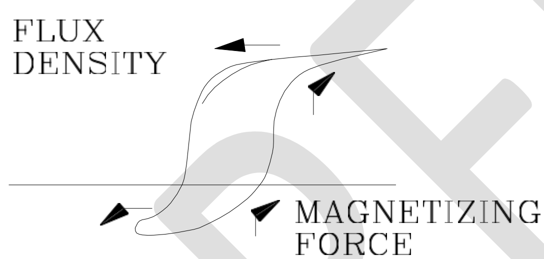


Figure 6: Hysteresis Curve with Remanence



Current Transformer Burden

General

The performance of a current transformer used in a Protection System is largely dependent on the total burden or impedance in the secondary circuit of the current transformer. The current transformer core flux density (and thus the amount of saturation) is directly proportional to the voltage that the current transformer or secondary must produce. So for a given amount of secondary current, the larger the burden impedance becomes, the greater is the tendency of the current transformer to saturate.

Ideally, protective relay systems would ignore current transformer saturation. However, as that is usually not possible it is best that the relay engineer minimizes current transformer burden impedance. Manufacturers' publications give the burdens of individual relays, meters, and other equipment. Adding the resistance of interconnecting leads and internal resistance of the current transformer gives the total current transformer burden. In modern microprocessor relays with very small burdens, the total relay burden is often dominated by the lead impedance or internal CT impedance.

Sufficient accuracy results when series burden impedances are added arithmetically. The results will be slightly pessimistic, indicating slightly greater than actual CT ratio inaccuracy. However, if a given application is so borderline that vector addition of impedance is necessary to prove that the CTs will be suitable, such an application should be avoided.

The current transformer burden impedance of most electromechanical relays decreases as the secondary current increases because of saturation in the magnetic circuits of the devices. Therefore, a given burden may apply only for a particular value of current. If a publication does not clearly state for what value of current the burden applies, this information should be requested.

At high saturation, the burden impedance approaches its DC resistance. This effect is exploited in high-impedance bus differential relays. Neglecting the reduction in impedance with saturation provides a quick conservative analysis, but an accurate calculation may be necessary if the initial calculation indicates marginal performance.

Effect of CT Connections

The interconnection of two or more current transformers supplying a common burden influences the burden seen by each individual current transformer.

When current transformer primaries and secondaries are connected in series, the burden on each individual transformer is decreased in proportion to the number of current transformers in use.

When current transformers are connected in parallel, the effect is to increase the burden on each individual transformer. The amount of increase is dependent on the number of transformers and the distribution of current between the transformers. This is the case in breaker-and-a-half, ring, and double bus arrangements.

In three-phase current transformer connections, the burden on an individual current transformer can vary with the type of connection (wye or delta) and the type of fault on the system (one- or two-line-to-ground or multi-phase). These topics will be discussed further in Section V.D.

Effect of Auxiliary CTs

Beware of attempts to "step-up" current from the main CT to the relay with the use of an auxiliary CT. The auxiliary CT may be adequate, but the main CT will see the burden impedance multiplied by the auxiliary ratio squared.

Estimates of CT Transient Performance

The primary fault current in the power system is symmetrical only after the transients of the predominantly RL circuit have decayed to zero. Considering the worst case conditions of switching angle and power factor that produce the highest offset, the fault current is of the form:

$$I(t) = I' \; [\cos(\omega t) - e^{-(R_1/L_1)t}]$$

Where:

I' = the peak value of the symmetrical wave
R_1 = the resistance of the entire primary circuit
L_1 = the inductance of the entire primary circuit

A time response plot is shown in Figure 7.

The exponential portion of this wave is a high-peak, non-directional or DC component, and is normally responsible for saturation of CTs when it is present. This is because the DC component causes the flux in the CT core to exceed the saturation level very easily. The expected flux and its effect on CT performance are illustrated in Figures 8, 9, and 10.

In most applications, the saturation of the CT by the AC component is avoided by properly selecting the turns ratio, burden, and CT accuracy class. As long as the product of expected secondary current and burden impedance does not exceed the saturation or knee-point voltage of the CT, then the CT performance will be satisfactory for the AC component. Figure 11 defines saturation voltage on a typical CT secondary excitation curve.

If saturation is to be avoided on the DC component as well as the AC component, then very severe requirements are imposed on the CT that many times are impractical or impossible to satisfy. The available voltage must be times the voltage required for the AC component. In the worst case this requirement may not be attainable.

The possibility of saturation should be known and avoided, if possible, by design and operation of the CT/relay combination.

The IEEE Power Systems Relaying Committee produced a report on transient performance of current transformers in 1977 titled Transient Response of Current Transformers. Publication 76 CH1130-4 PWR contains very useful discussion and curves from which the time to saturation can be estimated. In this section we present a method that permits direct calculation of the time to saturation.

Certain system, CT, and relay parameters must be determined before the curves or equations can be used. These are as follows:

Ks = Saturation factor

This is the ratio of the saturation voltage (Figure 11) to the voltage determined by the product of the expected symmetrical secondary current and the total secondary burden impedance. For bushing CTs with negligible leakage reactance:

$$K_S = \frac{V_X}{\left[\left(\frac{I_1}{N_2}\right) * R_2\right]}$$

Where:

V_X = saturation voltage of CT
I_1 = symmetrical primary current
N_2 = secondary turns of CT
R_2 = total secondary burden of CT

This factor is a measure of the margin that exists between the available voltage and the voltage necessary to reproduce the maximum symmetrical primary current in the secondary burden circuit.

T1 = primary system time constant

This time constant influences the core flux-time relationships and is the primary determinant of the time it takes the core flux to reach saturation.

$$T_1 = \frac{X_1}{R_1\omega} \text{ seconds}$$

Where X_1 = reactance of the primary system to the point of fault

$$\omega L_1 = X_1$$

R_1 = resistance of the primary system to the point of fault

$$\omega = 377\,\Omega \text{ at 60 Hz}$$

T2 = Current transformer secondary time constant

This time constant also influences the core flux-time relationship and is most important in determining the time for the flux to return to and below saturation level as the DC component decays.

$$T_2 = \frac{(L_2 + M_2)}{R_2} \text{ seconds}$$

Where:

L_2 = burden inductance if any
M_2 = CT inductance
R_2 = resistance of total secondary burden circuit (relay + leads + CT winding)

In most cases the burden inductance is negligible and the CT inductance is the equivalent exciting inductance, determined from the secondary excitation curve at the point of maximum permeability. For a true hysteretic B/H magnetization curve, maximum permeability is the point where the slope of the B/H curve for the un-magnetized (no remanence) material is greatest. This point is usually taken as the point where a straight line from the origin is tangent to the B/H curve.

For an approximation of this point on a CT saturation curve, see Figure 11.

$$T_2 = V_e / (I_e R_2 \omega)$$

With the parameters T1, T2, and KS, the curves in the IEEE report can be used to determine the time to saturation of the CT.

As an alternative, using equations derived from the results of the IEEE report and from other references, the time to saturation and the time to exit from saturation can be calculated.

These give results in close agreement with the curves in the IEEE report.

t_S = time to saturation in seconds

$$t_S = -T_1 \left[\ln\left(1 - \frac{K_s - 1}{T_1 \omega} \right) \right]$$

t_e = time to exit from saturation in seconds

$$t_e = T_1 \ln\left(\frac{\omega T_2}{K_S} \right)$$

Another useful equation can be developed by solving the first equation for Ks thus:

$$K_S = \omega \left(\frac{1 - e^{\frac{-t_S}{T_1}}}{1/T_1} \right) + 1$$

If we now assume ts goes to infinity (that is, saturation does not occur) then we can determine the value for Ks required to accommodate the symmetrical and DC components without saturation.

then $K_S = \omega T_1 + 1$

Combining this equation with the definition of Ks in section A:

$$K_S = V_k / (I_1 R_2 / N_2) = \omega T_1 + 1$$

and solving for Vk

$$V_k = (I_1 R_2 / N_2)(\omega T_1 + 1)$$

This equation for Vk indicates that if saturation is to be avoided when the DC component is present, then Vk (the knee-point voltage) must be times the steady state voltage requirement. This may be quite high and impossible to provide.

Figure 7: Primary Current Waves

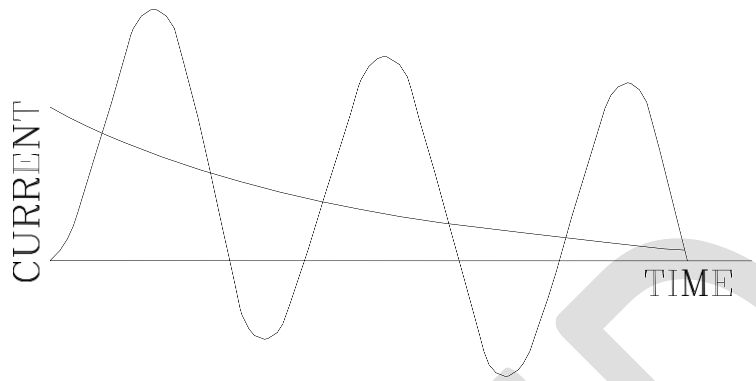


Figure 8: Rise of Flux in the Core of a Current Transformer

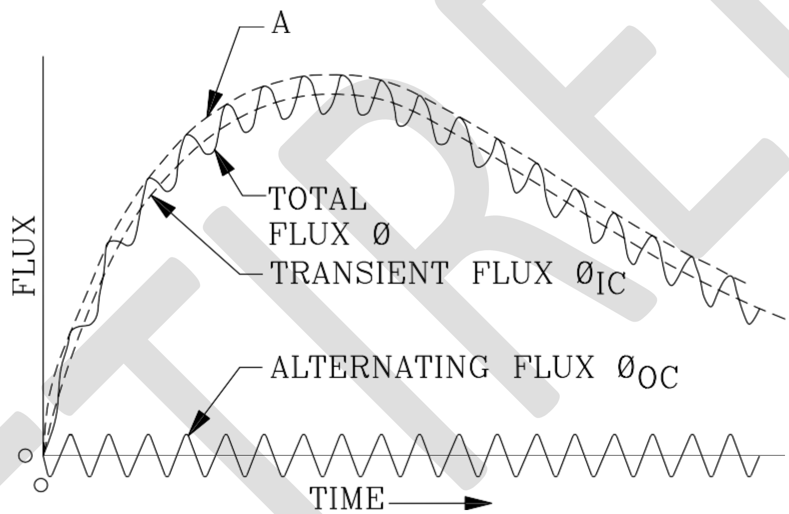


Figure 9: Distortion in Secondary Current Due To Saturation

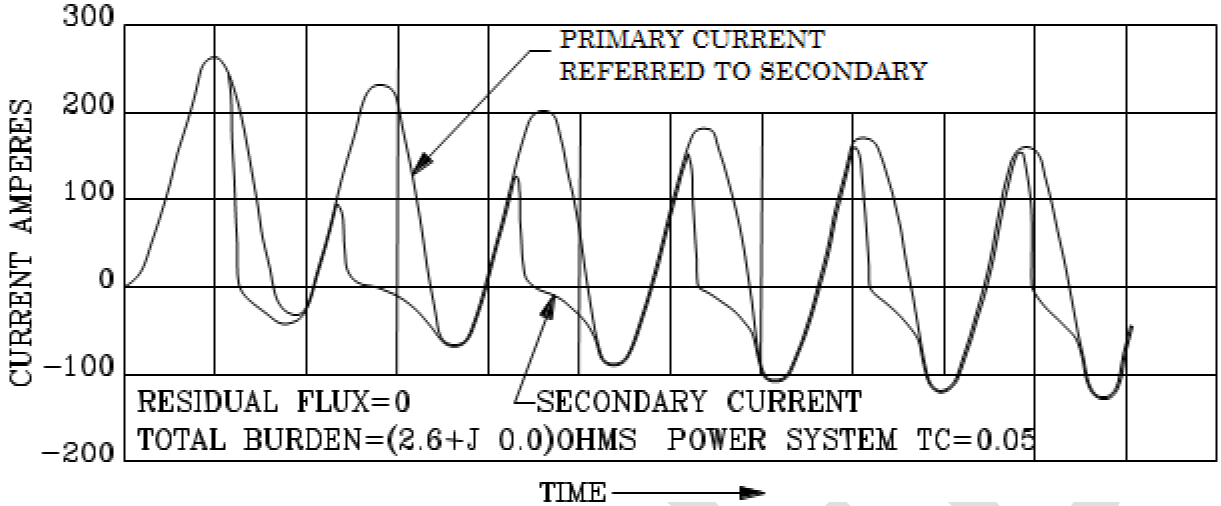


Figure 10: Distortion in Secondary Current Due To Saturation

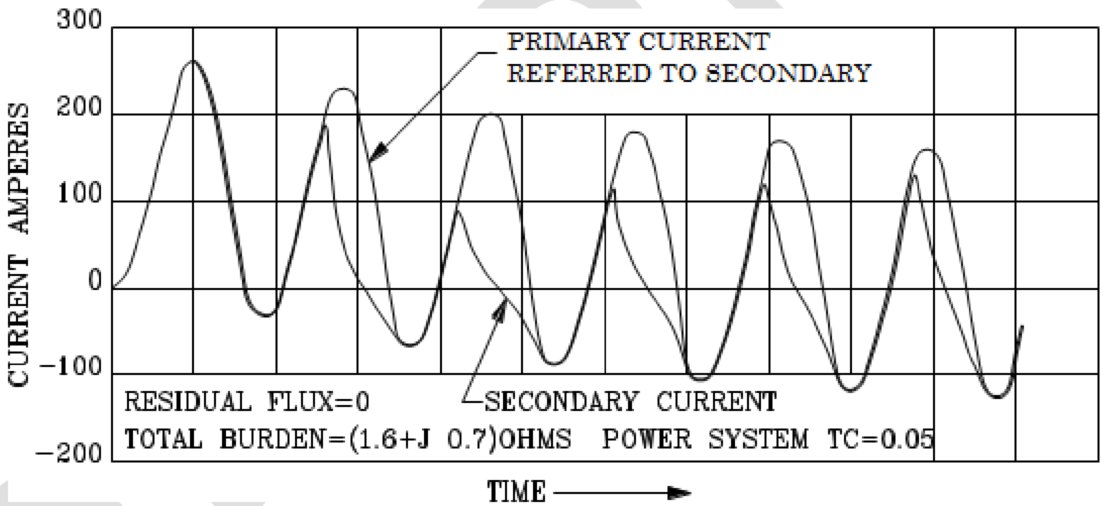
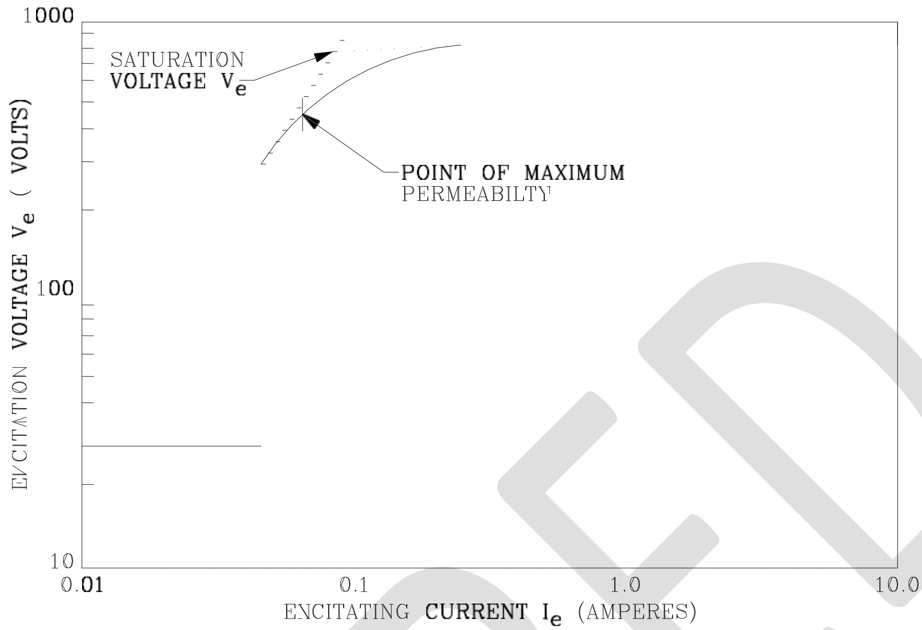


Figure 11: Secondary Excitation Curve 230-kV Current Transformer



Ratio: 1200-5 Amperes
Frequency: 60 Hz

Performance Requirements of Current Transformers for Relaying Purposes

Distribution Feeders, Phase and Ground Overcurrent

Current transformers that operate the time overcurrent relays used for feeder protection will typically provide satisfactory protection if they meet or exceed the applicable ANSI standard. For switch gear voltage classes 8.25 through 43.8-kV (where most distribution circuits lie), the accuracy classes are given by the National Electrical Manufacturers Association (NEMA) as follows: [1]

Multi-Ratio Current Transformers	Accuracy Voltage Classes
600:5	C100
1200:5	C200
2000:5, 3000:5	C400
4000:5, 5000:5	C800

The current transformer primary ratio normally corresponds to the continuous current rating of the circuit breaker (800 and 1600 amp power circuit breakers (PCB) use 1200 and 2000 amp current transformers).

The CT ratio is usually chosen so that approximately five amperes flow in the secondary phase relays for full load in the primary. Where five amp meters are used in relay circuits, a higher ratio may be chosen to permit overload readings on the feeder circuit. Also, the higher ratio may be necessary or desirable to minimize the secondary current during fault conditions.

Since overcurrent relays have a wide range of taps, the actual CT ratio is usually not critical. However, using higher ratio may limit the primary sensitivity.

In installations where very high fault currents are available, care should be exercised not to exceed the short time (one second) rating of devices connected to the secondary. Another possible problem with high fault currents is severe saturation of the CT core, resulting in very high voltage peaks or spikes. If the CT burden is high and the primary current is many times the CT's continuous rating, it is possible to develop voltage spikes of sufficient magnitude to damage CT insulation or switch gear secondary wiring. [2]

When the secondary current is highly distorted, the induction disk element of an overcurrent relay will deviate from the published time curve. [3]

The presence of the DC component of an offset wave not only causes saturation of the CT but also must be considered when setting hinged armature instantaneous trip attachments.

Determining CT performance requires the excitation curve, the impedance of the secondary connected devices and secondary wiring, and the resistances of the secondary CT turns. The impedance of the meters and relays will vary with the amount of current because their magnetic circuits saturate at high currents. Neglecting this saturation will yield optimistic results when checking thermal conditions but pessimistic results for accuracy calculations.

At very high currents, (20 times normal), most secondary burdens become so saturated they are predominantly resistive. On multi-grounded four-wire distribution circuits, the ground relay setting is usually kept at a relatively high value due to the unbalanced load current flowing in the neutral. Where sensitive ground relay settings are desired, care must be exercised to assure that the high burden introduced because a very sensitive residual relay does not drive a poor quality current transformer into saturation. Also, as shown in the calculation section, the impedance of the ground relay affects the distribution of secondary current and affects the primary sensitivity of the ground relaying.

Differentially-Connected CTs for Buses, Transformers, and Generators

Differentially-connected current transformers for equipment protection produce the most severe test of current transformer performance. This is because sensitivity and speed of operation of the relay is very important.

In most relay schemes where current transformers are differentially connected, the most important consideration is that the excitation characteristics of all current transformers are well matched. This does not always ensure proper operation but it allows much easier and dependable calculation of performance.

The primary current flow on each of the current transformers that are paralleled and/or differentially connected can be vastly different and thereby the performance calculation is very difficult. Modern bus protection can be subdivided into three main categories:

- High-Impedance Differentially-Connected Bus Protection Relays
- Low-Impedance Differentially-Connected Bus Protection Relays
- Medium-High-Impedance Percentage-Restraint Differential Relays

High-Impedance Differentially-Connected Bus Protection Relays

Since their introduction in the mid-1950s, high-impedance relays have dominated the bus protection practices in the U.S. When properly applied, they are dependable and secure.

The basic setting for the pick-up of a high-impedance relay is made so that the relay will not operate for a nearby external fault if the CT on the faulted circuit is completely saturated, while the remaining CTs are not saturated at all. The resulting voltage, developed by the good CTs, must force current through the impedance of the saturated CT and leads without exceeding the voltage pickup setting of the relay, plus the safety factor. This calculation is only valid if all CTs are wound on toroidal cores and have their windings completely distributed around their cores.

The secondary wiring resistance, including the CT secondary winding, is critical in determining the relay pickup setting. Obviously a CT with an unusually high winding resistance will limit the sensitivity of the relay protection for the whole bus.

If one or more CTs have an overall ratio that differs from the rest of the CTs on the bus, there is a temptation to merely connect the common ratios in parallel. On external faults, the high burden of the relay will result in the design voltage across the CT tap used. However, by auto-transformer action, a higher voltage will appear across the full CT winding. This higher voltage may exceed the capability of the circuit insulation.

Several possible solutions for the problem where the overall ratios differ are shown below:

(The reader is cautioned that most of these solutions (except Solution #1) are complex in their application. Refer to the General Electric publication titled, "Bus Differential Protection, GET-6455" [13] for special curves and formulae needed to make the proper settings.)

Solution #1

The best solution is to make all CT ratios the same by retrofitting the offending breakers with slip-on CTs of the proper ratio.

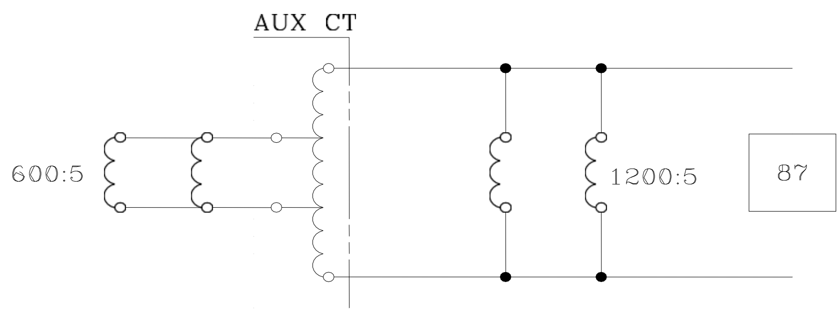
Solution #2

The relays most commonly used have four thyrite or varistor non-linear voltage-dependent resistor disks connected in series, and then in parallel with the relay. These resistors limit the voltage that appears across the CT circuits for the first cycle (or until the auxiliary relay has shorted the CT leads). Since the amount of voltage that can appear is a function of the total relay current and the resistance of the voltage-dependent resistor, reducing the amount of resistance will limit the peak voltage. Using two disks in series instead of the usual four will cut the peak voltage in half.

However, the energy dissipated in each disk is a function of the current through the disk and the voltage drop across it so it is usually necessary to add a series pair of two disks in parallel with the first pair to handle the extra energy.

Since the instantaneous or high-current tripping relay is in series with the voltage-dependent resistor disk, its pickup increases dramatically. A typical change in pickup setting might be from 3A to 50A.

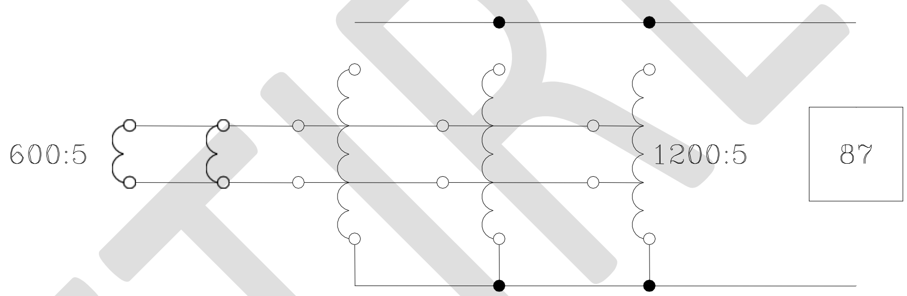
Solution #3



This approach is to match the higher CT ratio and the lower one with a special auxiliary CT. This auxiliary CT must have distributed windings on a toroidal core (a bushing CT). (Never try to use an ordinary auxiliary CT in a current or voltage bus differential circuit.)

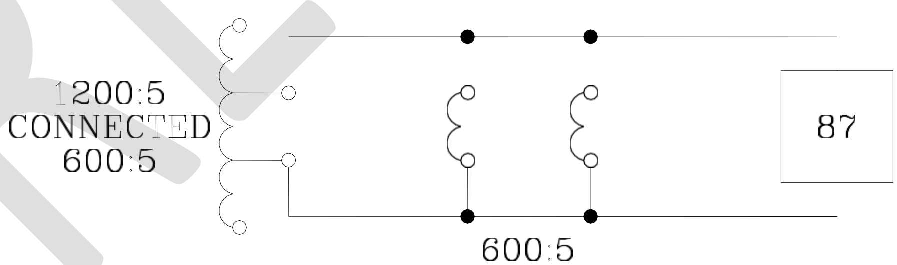
A variation of this method is to use one of the higher ratio CTs on one of the PCBs for double duty (auxiliary CT and bus differential CT). The disadvantage of this scheme is that when the PCB with the higher ratio is removed from service, the bus protection must be removed from service.

Solution #4



This solution eliminates the concern about removing the critical matching CT from service, but the difficulty of determining the CT secondary current distribution in the CT connections of the 1200:5 CTs—which is required to calculate a proper relay setting—limits its application.

Solution #5



This solution presents a hazard to equipment and personnel because of the high voltage that may be generated. It requires the calculation of the voltage developed by highest ratio CT when connected as described above. The peak voltage developed must be less than the circuit insulation rating (1500 volts root-mean square (rms)) by an appropriate safety factor, and the tapped voltage must be enough to satisfy the relay manufacturer's setting instruction. Extra thyristors or varistors may be required in the relay, or across the unused portion of the CT(s).

Low Impedance Differentially-Connected Bus Protection Relays

Overcurrent relays have long been connected in bus differential circuits with varying degrees of success. A few general rules for their application are:

1. Use the highest available CT ratios. Note: the maximum through-fault current should not exceed 20 times the CT rating. [2]
2. Never use an ordinary auxiliary CT. If an auxiliary CT must be used, use a toroidal type (bushing CT) with a distributed winding.
3. Never use an overcurrent differentially-connected relay near a generating station or where high X/R ratios exist since the time constant at these locations will produce very severe CT saturation problems.
4. Never use plunger-type or hinged-armature instantaneous relays without time delay in this type of circuit unless they are set very high. They operate too fast and operate equally well on DC. However, they may be useful when used in conjunction with induction disk overcurrent relays. If the instantaneous unit is set for the same pickup as the time unit with the contacts connected in series, by dropping out faster it prevents the time unit from false tripping by coasting closed after the error current is gone. This assumes that the drop out of the instantaneous device has not been extended by the DC component of an offset wave.
5. Never use on buses that have more than three or four sources of fault current. The current transformer on the faulted line will probably saturate so severely that the error current will cause the relay to trip for through-faults.
6. A stabilizing resistor can be very useful in improving the security of an overcurrent relay in a differential circuit (see example in calculation section [2], [6]).

Medium-High-Impedance Percentage Restraint-Differential Relay

This relay was introduced in the U.S. about 1970. It violates most of the application rules (previously noted) for other bus differential relays in that it does not require current transformers with similar characteristics or even the same ratio. The relay uses rectifying diodes to sum the total of the secondary currents for use as restraint. The differential current that flows is matched against this restraint and used to operate a 1-to-two millisecond tripping relay. The relay is designed to respond to the output of the current transformers before they saturate and to reject false information after saturation. Thus, the relay does not require matched CT characteristics or ratios, low-leakage reactances, or low-secondary circuit resistance. The high limits of maximum internal or external fault currents, and the high sensitivity for internal faults even with an extreme number of sources to the bus, make this relay easy to apply.

However it is troublesome and expensive to bring the secondaries of all of the PCB CTs into the relay house instead of paralleling them in the field. Since the relay operates on one ampere, auxiliary CTs are usually required for all of the CTs. This is also expensive and consumes much space.

Transformer Differential Relaying

Current transformers used for transformer differential relaying are subject to several factors that are not ordinarily present with other forms of differential protection. The following are application principles pertaining to electromechanical relays, with comments appropriate to microprocessor relays incorporated.

1. Because of the current transformation by the power bank, the CT ratios may be different to compensate for the different primary currents. While many CT taps and relay taps are available, they seldom make a perfect match. This results in error current in the relay. If the transformer has a load tap changer, this error will change with the tap position.
2. Since the power circuit breakers on the high and low side of the power transformer are seldom of the same voltage class, the CTs associated with them have different characteristics and often different accuracy classes.
3. The power transformer has a 30-degree phase shift if it is connected wye-delta or delta-wye. This requires the CT to be connected delta-wye (or wye-delta) to shift the secondary currents into phase so that they may be compared in the relay.
4. A power transformer connected delta-grounded wye becomes a source of zero sequence currents for external faults on the wye side, so these currents must be eliminated from the relay secondary circuits.
5. When a power transformer is energized, magnetic in-rush currents appear in the primary circuit. These currents are often many times the full-load rating and are seen by the relay as internal faults.

As with other forms of differential protection, transformers were originally protected with ordinary overcurrent relays connected differentially. They had to be made quite slow and insensitive to overcome the problems mentioned above. Modern relays use percentage restraint to take care of the first three problems noted above, and harmonic restraint or harmonic blocking for the in-rush current problems.

Internal Faults

Faults that occur within the protected zone of the differential relay will often result in very severe saturation of at least some of the CTs. This is of little consequence unless the high harmonic content of the CT secondary current blocks the operation of the differential relay.

A saturated CT produces a highly distorted current. Second and third harmonics predominate initially, and each may be greater than the fundamental. Eventually the even harmonics will disappear. The odd harmonics persist as long as the CT remains saturated. For these reasons, a high-set instantaneous unit should be included in the differential circuit of harmonic-restrained relays that will trip in spite of any harmonics.

External Faults

If only one PCB — therefore, one CT — is used at each voltage level, the through-fault current is limited by the power transformer impedance and all of the secondary current flows through the restraint windings of the differential relay. If two PCBs are used at one voltage level — such as with a ring bus, breaker-and-a-half, or double-bus-double-breaker — the short circuit current is not limited by the power transformer impedance when it flows through these PCBs. If the CTs are merely paralleled, they can saturate unequally and produce error currents that may cause an incorrect operation. If a ring bus or breaker-and-a-half scheme is involved, the chance of this type of through-fault occurring is high enough that each CT should be connected to its own restraint winding. If the PCBs are part of a double-bus-scheme, the chances of this through-current flowing are remote.

Two PCBs with paralleled CTs also may present problems with security for through-faults on the low side of the transformer because the error current of the existing CTs is doubled.

Current transformers connected in delta also may cause problems with security for through-faults because the current transformer must circulate current through two relays and lead burdens for some faults (see sample problem).

Directional Overcurrent and Distance

The general requirements of minimizing the burden placed on current transformer secondaries apply to directional overcurrent and distance relays as well. Using adequate CT secondary lead conductor sizes, using higher CT ratios, higher overcurrent relay taps when possible (since the relay burden is inversely proportional to relay tap squared), and taking care in paralleling several CT polarizing sources for use with directional elements [1], [5] are just a few examples of the areas of concern when applying these relays. Even when these precautions are taken, relay circuits may be exposed to transient (AC and DC) and harmonic current waveforms caused by CT saturation effects. The effects on the different types of relays will depend upon the specific relay design used.

Directional Elements

The directional elements used in relays often use a "polarizing" voltage or current source to establish a reference phasor relationship between the "operating" (monitored power system) secondary current and the polarizing source value. This phasor relationship establishes an operating torque (in an electromechanical design) or digital signal (in a microprocessor design) for faults in the protected zone.

CT saturation can cause phase shifts and harmonics in the operating current source that are different from what may be generated in the polarizing voltage or current source. For example, induction-cup electromechanical relays tend to be frequency dependent; operating torque is created only for like-frequency operating and polarizing waveforms (e.g., the fundamental frequency waveforms' phase angles are compared). [2] Therefore, the relative phase shift between the compared waveforms may lessen the operating torque for faults in the protected zone. Under extreme cases, phase shifts may even cause false operation for faults in the reverse direction.

As in electromechanical relays, microprocessor relay designs also may use a polarizing source in addition to an operating current. Some designs incorporate waveform zero-crossing points for phase reference and may be susceptible to phase shifts caused by CT saturation effect. Some microprocessor relays may be higher speed (less than 0.5 cycles operating time) and lower burden than their electromechanical counterparts. Therefore, depending upon the CT's time to saturation (see Section III - "Estimates of CT Transient Performance") microprocessor relays may be less likely than electromechanical relays to operate (or not operate) incorrectly, because the microprocessor relays may have completed their measurements prior to CT saturation. Many microprocessor designs filter the input waveforms and consequently are frequency-dependent, as well.

Overcurrent Elements

The common electromechanical induction disk designs used for time-overcurrent (TOC) characteristics measure the rms operating current. Under CT saturation conditions, the actual rms value of the relay current will be less than under non-saturated CT conditions. Therefore, the TOC relay element will take longer to operate than desired. Loss of relay coordination may result from this delay, especially with the applications using more inverse time-overcurrent characteristic relays. Time-overcurrent relays typically are not very susceptible to DC offsets since DC offsets usually have died out within the delay period of the relay. Instantaneous overcurrent units (IOC) can be very sensitive to DC offsets. The DC offsets may cause high-level transient spikes in the relay current that could cause the IOC element to trip for fault current levels below its set point. Additionally, for CT distortion of fault currents near the instantaneous pickup setting, the instantaneous relay may have an undesirable trip delay (e.g., additional 20-25 ms or more).

Microprocessor relay designs using analog or digital techniques (such as microprocessor based) will typically filter the input current waveform to eliminate DC offsets, harmonics, etc. This may alleviate some of the problems relating to the instantaneous elements. However, the time-delay elements' operating times may experience the same type of unpredictability, lower sensitivity, and extra delay times as experienced with the electromechanical designs.

Distance Relays

In general, the reach of distance relays will be affected by CT saturation. This is true whether the relay design is an electromechanical design using rms current measurement, or a microprocessor design referencing peak instantaneous or rms current levels or various combinations of waveform values for measurement. The distance relay will be desensitized for faults near the end of its zone because the relay will sense the fault as being further away than it actually is, based on the reduced currents produced from the CT secondary circuits. Short line and particularly zone 1 instantaneous-relay applications with a fault value near the relay operating decision point should be considered carefully if CT saturation is possible. A guideline referred to by G.D. Rockefeller from Consolidated Edison Co. of New York is: "To avoid delayed tripping for faults near the zone 1 decision point, time to CT saturation should exceed 1.5 cycles." Microprocessor relays with their high-speed operation and low burden may be preferred in these applications, depending on the individual situations and systems involved.

The directional characteristics of distance relays are generally adequate and selective for reverse direction faults even with phase shifts in the current waveform measurement. However, close-in, high-magnitude faults in the reverse direction may result in false tripping by directional relays. This may occur if the reference stabilizing voltage as measured by the relay is below a design minimum value in the presence of zero-crossing phase shift error in the current waveform caused by saturated CTs. Electromechanical relays using induction units produce an operating torque based on the product of an integrated full cycle of voltage and the fundamental current waveform. This reduces the possibility of distortion-related false tripping.

In summary, current transformer saturation effects should be considered when applying directional overcurrent and distance relays. For relay directional elements, CT saturation may cause false directional interpretation created by phase shifts between the relative measurement points on the distorted current and undistorted voltage waveforms (or possibly distorted voltage waveforms if Coupling Capacitor Voltage Transformers are used). Unpredictable or added time delay and lower sensitivity may be experienced with overcurrent elements. Inaccurate distance measurements, maximum torque angle characteristic changes, and other factors, may lead to false operations in directional overcurrent and distance relays. The best way to avoid these potential problems is to take precautionary steps through minimizing CT secondary burden, by using larger conductor sizes in CT leads, and using lower burden relays when possible, combined with using adequate accuracy class CTs. The transient response characteristics of the CTs should be considered (e.g., time to saturation) when deciding on electromechanical or microprocessor relay applications. With proper planning measures and consideration of these factors, correct relay operation should result under the great majority of fault conditions.

EHV Transmission Line Systems

The effects on these relay systems due to CT saturation can be serious because of their operating speed, the configuration of current transformer sources, and the need for exactly the same performance at each terminal of the relaying systems.

The relay operating speed is typically eight-to-25 milliseconds. In many cases these may have operated, before any saturation effects take place. On an external fault, although saturation is less likely, the system will be dependent upon correct CT operation throughout the fault period.

Most phase comparison systems are designed to accept significant phase angle errors without undue effects. A more likely source of problems is distortion of the magnitude of phase quantities producing incorrect components on which proper operation depends; primarily internal faults.

Directional comparison systems will have performance problems similar to stand-alone directional instantaneous elements. One difference is that instead of just one or two CTs affecting the devices' performance the CTs at both ends are involved so there may be as few as two or as many as six CTs involved.

The configuration of CTs is an important consideration in the operation of these schemes since the primary currents in each CT and each CT's history determines what information is supplied to the relay. This exposes the relay system to possible problems from any of the connected CTs. In many cases, the EHV system was designed for short circuit duty that has not and may not ever be experienced. This means that it may be many years into the life of the EHV system before trouble is experienced with CT saturation. However, the mismatched CTs may produce problems long before the problems of saturation are evident.

Examples of Calculations

Ratio and Phase-Angle Error of CT

The Ratio Correction Factor (RCF) is the factor by which the marked ratio must be multiplied to obtain the true ratio. The true ratio equals the marked ratio times the ratio correction factor.

$$RCF = \frac{\text{true ratio}}{\text{marked ratio}}$$

Where:

true ratio = the ratio of rms primary current to the rms secondary current,

marked ratio = the ratio of the rated primary current to the rated secondary current as given on the nameplate.

The phase-angle of a CT is designated by the Greek letter . The Phase-Angle Correction Factor (PACF) is the factor by which the reading of a watt meter, operated from the secondary of a CT must be multiplied to correct for the effect of phase displacement of current due to the measuring apparatus. It is the ratio of the true power factor to the measured power factor.

$$PACF = \cos\theta \,|\cos(\theta - \beta)$$

Where:

θ = angle of lag of load current behind load voltage

$\cos\theta$ = power factor = cosine of the angle between the voltage and current

The factor by which the reading of a watt meter or the registration of a watt hour meter must be multiplied to correct for the effect of ratio error and phase angle is the Transformer Correction Factor (TCF).

$$TCF = RCF \times PACF$$

<u>Example 1:</u>

If a CT has a phase angle error = +15' and is used for measuring a load where the power factor is 0.500 lagging, determine its phase angle correction factor, PACF.

1. The primary current lags the line voltage by an angle whose cosine equals the power factor.

$$\cos^{-1}(0.500) = 60° = \theta$$

or

$$\cos\theta = \cos 60° = 0.500$$

2. The secondary current leads the primary current by 15'. Therefore, the secondary current actually lags the primary voltage by .

$$\theta = 60° = 59°60'$$

$$(\theta - \beta) = 59°60' - 0°15' = 59°45'$$

Thus, $\cos(\theta - \beta) = \cos(59°45') = 0.5038$

$$PACF = \frac{\cos\theta}{\cos(\theta - \beta)} = \frac{0.500}{0.5038} = 0.9925$$

If the CT has an RCF of 1.0020, what is the TCF at the same power factor?

$$TCF = RCF \times PACF$$
$$= 1.0020 \times 0.9925$$
$$= 0.9945$$

<u>Example 2:</u>

Calculation of the ratio of relaying CT. Consider a bushing CT with the following characteristics:

$$\text{ratio} = 600\,|5$$
$$\text{relaying classififcation} = \text{C100}$$
$$\text{CT secondary resistance} = 0.298\,\Omega$$

1. The rating of C100 means that the ratio is to be calculated on the basis of 100 volts at the secondary terminals with 100 amps flowing through the burden, which in turn means a burden of B-1. Referring to Table 1 for a B-1 burden:

$$\text{R} = 0.5\,\Omega = \text{resistance}$$
$$\text{L} = 2.3\,\text{mH} = \text{inductance}$$

2. The inductive reactance, X_L, is then calculated:

$$X_L = 2\pi fL$$
$$= 2 \times 3.14 \times 60 \times (2.3 \times 10^{-3}\,H)$$
$$= 0.866\Omega$$

Where f = frequency in Hz

3. To obtain the induced or excitation voltage, the resistance of the secondary winding must be added to the impedance, Z, of the burden.

$$Z = \sqrt{R^2 + X^2}$$

$$Z = \sqrt{(0.298 + 0.5)^2 + (0.866)^2}$$

$$= 1.18\Omega$$

The induced voltage is therefore:

$$E_{SE} = (100\ amps) \times (1.18\ \Omega) = 118V$$

Referring to Figure 12, the excitation curve for this transformer indicates that an excitation current, Ie, of 0.15 amps is required to produce this voltage.

Since this excitation current is shown as the equivalent secondary current, it should be compared to the burden secondary current of 100 amps.

The ratio of exciting current to burden current is,

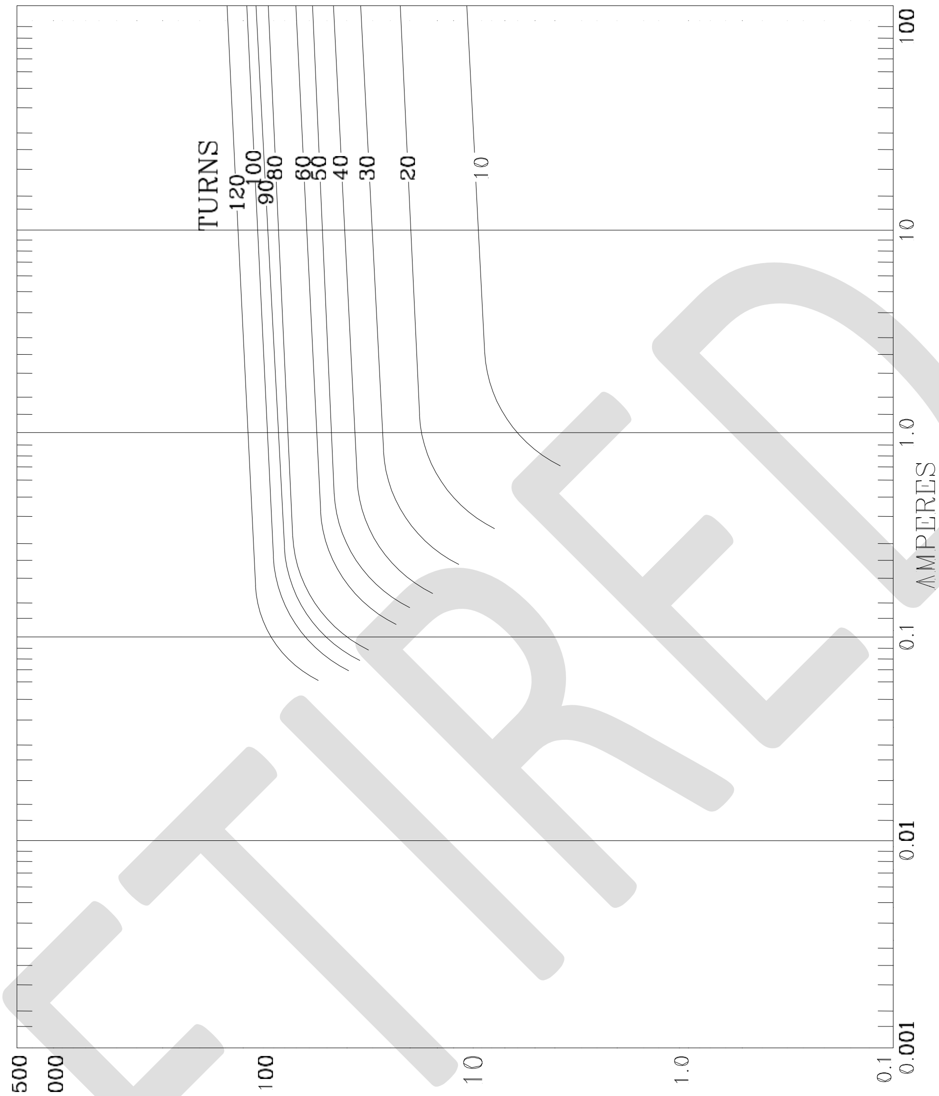
$$0.15 | 100 = 0.0015$$

Therefore the Ratio Correction Factor (RCF) is 1.0015.

Table 1: Standard Burdens for Current Transformers with Five-Amp Secondaries

Burden Designation	Resistance (Ω)	Inductance (mH)	Impedance (Ω)	Volt Amperes (at 5A)	Power Factor
Metering Burdens					
B-0.1	0.09	0.116	0.1	2.5	0.9
B-0.2	0.18	0.232	0.2	5.0	0.9
B-0.5	0.45	0.580	0.5	12.5	0.9
B-0.9	0.81	1.04	0.9	22.5	0.9
B-1.8	1.62	2.08	1.8	45.0	0.9
Relaying Burdens					
B-1	0.5	2.3	1.0	25	0.5
B-2	1.0	4.6	2.0	50	0.5
B-4	2.0	9.2	4.0	100	0.5
B-8	4.0	18.4	8.0	200	0.5

Figure 12: Excitation Curves for Multi-Ratio Bushing CT with ANSI Classification of C100



Estimation of Current Transformer Performance

A current transformer's performance is measured by its ability to reproduce the primary current in terms of the secondary; in particular, by the highest secondary voltage the transformer can produce without saturation. CT performance can be estimated by:

- The CT excitation curves.
- The ANSI transformer relaying accuracy classes.

These methods require determining the secondary voltage that must be generated.

$$V_S = I_L \left(Z_L + Z_{LEAD} + Z_B \right)$$

Where:

V_S = The rms symmetrical secondary induced voltage

I_L = The maximum secondary current in amps

This can be estimated by dividing the known maximum fault current by the selected CT ratio.

Z_L = The secondary winding impedance

Z_{LEAD} = The connecting lead burden

Z_B = The connected external impedance

1. Excitation Curve Method

   The excitation curve of Figure 10 can be used to determine the excitation current required by the CT for a particular turn's ratio, primary current, and secondary burden parameters.

   Procedures:

a. determine nominal secondary current from primary current and desired turns ratio: $I_L = I_P \,|I_N$
b. determine required secondary voltage from $V_S = I_L(Z_L + Z_{LEAD} + Z_B)$
c. determine secondary excitation current from Figure 12
d. determine approximate burden current by arithmetic subtraction of excitation current from nominal secondary current

Example 1:

Given a CT with excitation characteristics as shown in Figure 12:

1. A burden of relays and instruments of 0.15 Ω - instruments and overcurrent relays with a burden of 0.3 Ω on Tap 5.
2. Secondary lead resistance including CT winding of 0.15 Ω.

   For simplicity, these impedances are assumed to be at the same angle.

   $(Z_L + Z_{LEAD} + Z_B)$ = 0.15 + 0.15 + 0.3 = 0.6 Ω.
3. The primary fault current expected is 12,000 amperes.

   The desired CT ratio is 400:5, or 80:1.
4. Then IL = 12,000/80 = 150 amps

   VS = 150 (0.6) = 90V

   from Figure 11, Ie = 18.0 amp

5. Then 150 - 18 = 132 amps of burden current, for an effective ratio of 12,000/132 = 455:5.

   This means the performance is not within the intended accuracy of a 10C100

   (see Section C).

6. If a 500:5 or 100:1 ratio is selected, then:

   IL = 12,000/100 = 120 amps

   VS = 120 (.6) = 72V

   Ie = 0.105 amps from Figure 12

7. Burden current = 120 - 0.1 = 119.9 for an effective ratio of 12,000/119.9 = 500.4:5; is well within the intended accuracy.

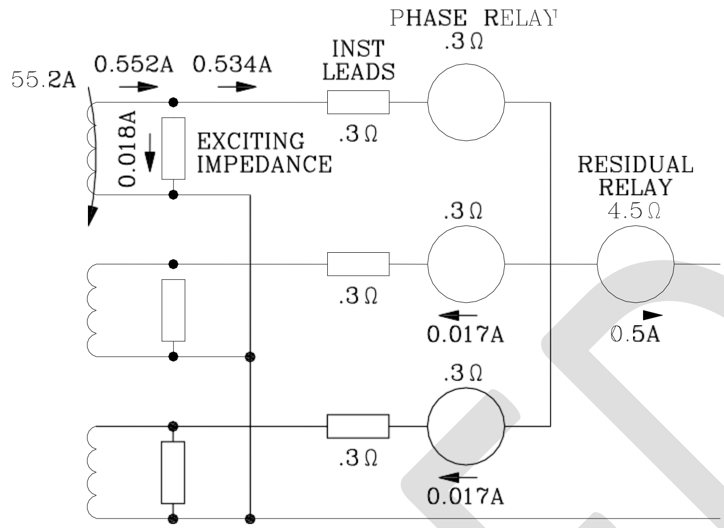
Example 2:

1. With the results of Example 1, determine the primary operating current for a residual relay of burden 4.5 ohms on Tap 0.5.
2. See the sketch of Figure 13.
3. At pickup, there will be 2.25 volts across the residual relay, (0.5A x 4.5). This voltage also appears across the CT on the un-faulted phases. From Figure 10, each of these CTs will require 0.017A exciting current.
4. The current from the CT on the faulted phase supplies

   0.5 + 0.017 +0 .017 or 0.534 amps, as shown in Figure 11.

5. These 0.534 amps develop 2.57V across the secondary of the CT on the faulted phase. This requires an additional 0.018 amps of exciting current.
6. The total secondary current supplied by the CT on the faulted phase is then 0.5 + 0.017 + 0.017 + 0.018 = 0.552 amps.

Figure 13: Secondary Current Distribution At Pick up of Residual Relay



7. If the CT ratio is 100:1, then the primary current must be 55.2A at pick up of the residual relay.

ANSI CT Relaying Accuracy Classes

The American National Standards Institute (ANSI) Relaying Accuracy Class is described by two symbols - letter designation and voltage rating that define the capability of the transformer. The letter designation code is as follows:

C - The transformer ratio can be calculated (as for the earlier lOL-type transformers).

T - The transformer ratio must be determined by test (similar to the earlier 10H-type transformers).

The secondary terminal voltage rating is the voltage that the transformer will deliver to a standard burden at 20-times normal secondary current, without exceeding 10-percent ratio correction. Furthermore, the ratio correction must be limited to 10 percent at any current from 1-to-20 times the rated secondary current at the standard burden. For example, relay accuracy class C100 means that the ratio can be calculated and that the ratio correction will not exceed 10 percent at any current from 1-to-20 times the rated secondary current with a standard 1.0 burden (1.0 times 5A times 20 times the rated secondary current, equaling 100V).

ANSI accuracy class ratings apply only to the full winding. Where there is a tapped secondary, a proportionately lower voltage rating exists on the taps.

Example:

The maximum calculated fault current for a particular line is 12,000 amps. The current transformer is rated at 1200:5 and is to be used on the 800:5 tap. Its relaying accuracy class is C200 (full-rated winding); secondary resistance is 0.2 ohm. The total secondary circuit burden is 2.4 ohm at 60-percent power factor. Excluding the effects of residual magnetism and DC offset, will the error exceed 10 percent? If so, what corrective action can be taken to reduce the error to 10 percent or less?

The current transformer secondary winding resistance may be ignored because the C200 relaying accuracy class designation indicates that the current transformer can support 200 volts plus the voltage drop caused by secondary resistance at 20-times rated current, for 50 percent power-factor burden. The CT secondary voltage drop may be ignored then, if the secondary current does not exceed 100 amps.

$N = 800/5 = 160$

$I_L = 12{,}000A/160 = 75$ amps

The permissible burden is given by:

$Z_B = (N_P\ V_{CL})/100$

Where:

Z_B = permissible burden on the current transformer
N_P = turns in use divided by total turns
V_{CL} = current transformer voltage class
N_P = 800/1200 = 0.667 (proportion of total turns in use)

Thus, ZB = 0.667 (200)/100 = 1.334 Ω

Since the circuit burden, 2.4 ohms, is greater than the calculated permissible burden, 1.334, the error will be in excess of 10 percent at all currents from five to 100 amps. Consequently, it is necessary to reduce the burden, use a higher current transformer ratio, or use a current transformer with a higher-voltage class.

Effect of Current Transformer Connections on Burden

Whenever two or more current transformers have their secondary circuits interconnected, the effect is to alter the secondary burden on each transformer. The way in which the burden is affected is dependent on the particular connection.

Various types of connections are described in the following discussion.

Series Connection:

When current transformers are connected with their secondaries in series, the general effect is to decrease the burden on each individual transformer. This statement assumes that the secondary currents are nominally in phase and of equal magnitude.

If N transformers with identical excitation characteristics are connected in series and are supplying current to a burden Z, then the burden on each transformer equals Z/N.

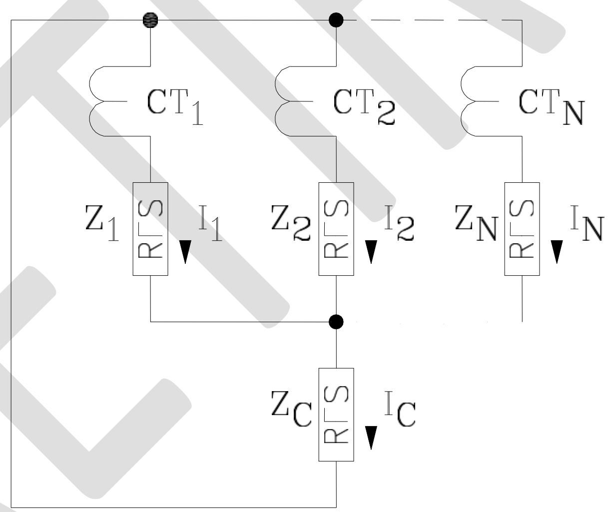
Parallel Connection:

When two or more current transformers are connected in parallel, the general effect is to increase the burden on each individual transformer. The amount of increase is dependent on the type of connection, the number of transformers, and the distribution of current between transformers.

When low ratios are required, standard CTs may not be available to supply the required burden. It is sometimes possible to apply two standard higher-ratio CTs that have a higher relaying-accuracy-classification voltage (with the primaries connected in series and the secondaries connected in parallel) to supply this burden. The desired overall low ratio is achieved with a substantially improved accuracy. In paralleling the secondary circuits of CTs, the secondary winding shall be paralleled at the relay to keep the common burden as low as possible. The effective burden on each transformer should not exceed its rated burden.

The following diagrams show some of the more common ways in which current transformers are interconnected. General equations are given for the burden on a typical current transformer. In applying these equations, it should be noted that all impedances in series, including lead resistance, have been lumped into one value to simplify the equations.

Parallel Connection



General case: $$Z_{CT_1} = Z_1 + Z_C\left[\frac{I_1 + I_2 + \ldots . I_N}{I_1}\right]$$

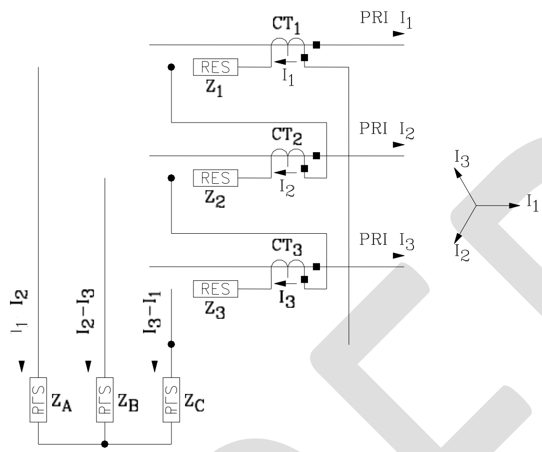
Special cases:

1. Two CTs in parallel, equal contributions from each CT: $I_1 = I_2$:

$$Z_{CT_1} = Z_1 + 2Z_C$$

2. Two CTs, unequal contributions: $I_2 | I_1 = K$; $Z_{CT_1} = Z_1 + Z_C(1+K)$

Delta Connection



General case: $Z_{CT_1} = Z_1 + Z_A\left[1 - \frac{I_2}{I_1}\right] + Z_C\left[1 - \frac{I_3}{I_1}\right]$

Special cases:

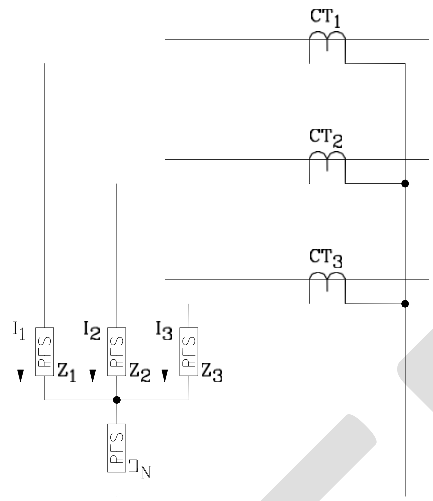
1. Symmetrical burdens:

$$Z_A = Z_B = Z_C = Z_L \qquad Z_{CT_1} = Z_1 + 2Z_L - Z_L\left[\frac{I_2 + I_3}{I_1}\right]$$

2. Symmetrical burdens and balanced three-phase currents:

$$Z_{CT_1} = Z_1 + 3Z_L$$

Wye Connection


CT1
CT2
CT3
I1
I2
I3
Z1
Z2
Z3
ZN

General case: $Z_{CT_1} = Z_1 + Z_N\left[\frac{I_1 + I_2 + I_3}{I_1}\right]$

Special cases:

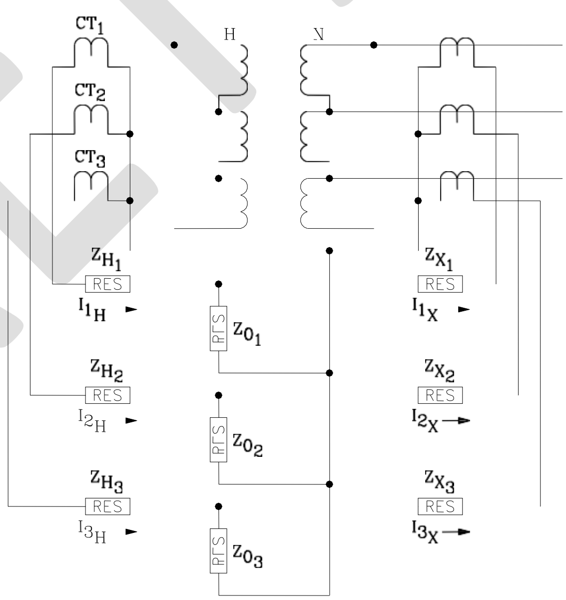
1. Three-phase fault: $Z_{CT_1} = Z_1$
2. Phase-phase fault (1-2): $Z_{CT_1} = Z_1$
3. Line-ground fault: $Z_{CT_1} = Z_1 + Z_N$
4. Two-line-ground (1-2-G): $Z_{CT_1} = Z_1 + Z_N\left[\frac{I_1 + I_2}{I_1}\right]$

Transformer Differential Connection

When used for transformer differential relaying, current transformers can be connected in several different ways, depending on the type of transformer being protected. As a general rule, relay misoperation due to high burden is a problem only for external faults where false tripping may occur if one current transformer saturates.

Wye-Wye CT Connection

(delta-delta transformer or if CT connection compensation available in relay)



General case: $Z_{CT} = Z_H + Z_0\left[1 - \frac{I_{1X}}{I}\right]$

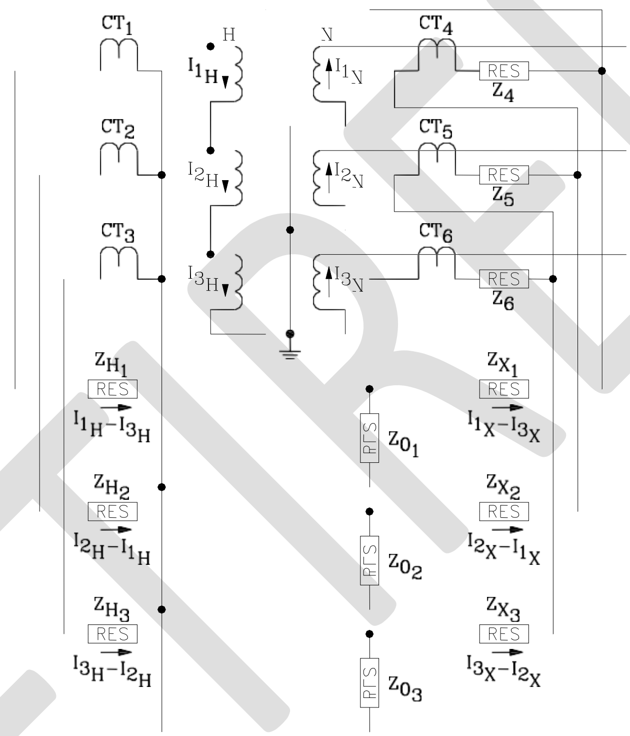
$$1 \quad 1 \quad 1 \left\lfloor \quad 1_H \quad \right\rfloor$$

Special cases:

External fault with ideally matched CT ratios: $Z_{CT_1} = Z_{H_1}$

Internal fault with equal per-unit contributions from each side of the transformer:
$Z_{CT_1} = Z_{H_1} + 2Z_{0_1}$

Wye-Delta Connection



General case:

$$Z_{CT_1} = Z_{H_1} + Z_{0_1} + Z_{0_1}\left[\frac{I_{3X} - I_{1X}}{I_{1H} - I_{3H}}\right]$$

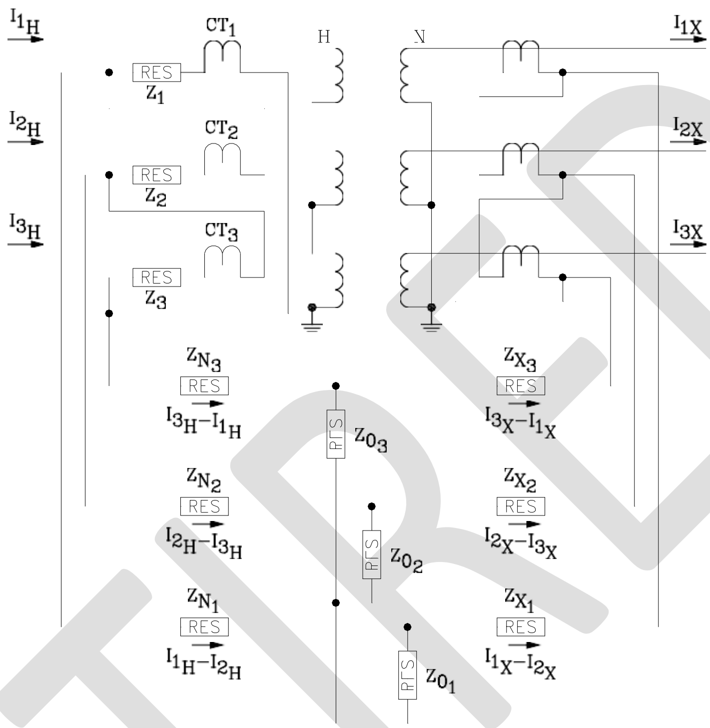
$$Z_{CT_4} = Z_4 + Z_{X_1} + Z_{0_1} + Z_{0_2} + Z_{X_2} - Z_{X_1}\left[\frac{I_{3X}}{I_X}\right] - Z_{0_1}\left[\frac{I_{1H} - I_{3H} + I_{3X}}{I_{1X}}\right] + Z_{0_2}\left[\frac{I_{2H} - I_{1H} - I_{2X}}{I_{1X}}\right] - Z_{X_2}\left[\frac{I_{2X}}{I_{1X}}\right]$$

Special cases – assuming matched CTs and symmetrical burdens:

1. External three-phase fault: $Z_{CT_1} = Z_{H_1}$ $Z_{CT_4} = Z_4 + 3Z_{X_1}$

2. Internal three-phase fault with equal per-unit contributions from each side of the transformer: $Z_{CT_1} = Z_{H_1} + 2Z_{0_1}$ $Z_{CT_4} = Z_4 + 3Z_{X_1} + 6Z_{0_1}$

Delta-Delta CT Connection (Wye-Wye Transformer)



<u>General case:</u>

$$Z_{CT_1} = Z_1 + Z_{H_1} + Z_{H_3} + Z_{0_1} + Z_{0_3} - \frac{I_{2_H}}{I_{1_H}}\left[Z_{H_1} + Z_{0_1}\right]$$

$$-\frac{I_{3_H}}{I_{1_H}}\left[Z_{H_3} - Z_{0_3}\right] - \frac{I_{1_X}}{I_{1_H}}\left[Z_{0_1} + Z_{0_3}\right] + \frac{I_{2_X}}{I_{1_H}} Z_{0_1} + \frac{I_{3_X}}{I_{1_H}} Z_{0_3}$$

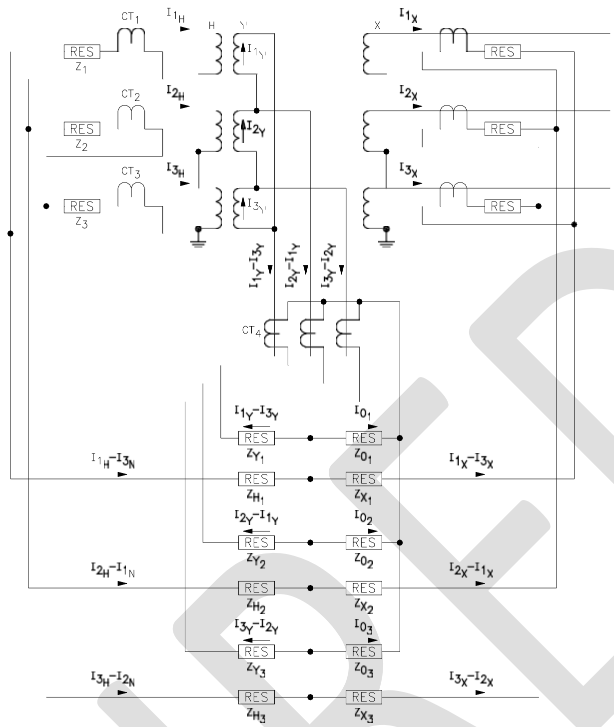
<u>Special cases – assuming matched CTs and symmetrical burdens:</u>

1. External line-ground fault on phase 1: $Z_{CT_1} = Z_1 + 2Z_{H_1}$

2. External three-phase or line-to-line (1-2) fault: $Z_{CT_1} = Z_1 + 3Z_{H_1}$

3. Internal line-to-ground on phase 1 with equal per-unit contributions from each side of the transformer: $Z_{CT_1} = Z_1 + 2Z_{H_1} + 4Z_{0_1}$

Wye-Delta-Wye Connection



General case:

$$Z_{CT_1} = Z_1 + Z_{H_1} + Z_{H_2} + \frac{1}{I_{1_H}}\left[I_{0_1} Z_{0_1} - I_{3_H} Z_{H_1} - I_{0_2} Z_{0_2} - I_{2_H} Z_{H_2}\right]$$

$$Z_{CT_4} = Z_{Y_1} + \frac{Z_{0^1}}{\left(I_{3_Y} - I_{1_Y}\right)}\left[I_{1_H} - I_{3_H} + I_{3_X} - I_{1_X} + I_{3_Y} - I_{1_Y}\right]$$

Special case:

1. External three-phase fault with symmetrical burden and ideally matched CTs:

$$Z_{CT_1} = Z_1 + Z_{H_1}$$

$$Z_{CT_4} = Z_{Y_1}$$

Estimates of Transient Performance

Example

CT turns = N_2 = 240

CT saturation voltage = V_X = 850 volts

CT primary current = I_1 = 15,000 amps

CT sec. burden = R_2 = 1 Ω

Primary system X_1/R_1 = 15

$$\text{Then } Ks = \frac{Vx}{I_1R_2 | N_2} = \frac{850}{15{,}000 | 240} = 13.6$$

$$\text{or } V_X = \frac{I_1R_2(\omega T_1 + 1)}{N_2} = \frac{15{,}000}{240}(1)\left(\frac{377(15)}{377} + 1\right)$$

$$= 1{,}000 \text{ volts}$$

Comparing the calculated VX - (1000) with the available VX - (850) means we can expect some saturation under fully offset conditions.

The time to reach saturation is given by t_S:

$$t_S = -T_1\left[\ln\left(1 - \frac{K_s - 1}{T_1\omega}\right)\right]$$

$$T_1 = X_1 | R_1\omega = 15(1|377) = 0.04$$

$$\text{Then } t_S = -0.04\ln\left(1 - \frac{(1|0.04)(13.6 - 1)}{377}\right)$$

= .0722 seconds

= 4.33 cycles

Note that the time to saturation is sensitive to the primary-system time constant and the saturation factor K_S. If the offset is less than full, then K_S is greater and the time to saturation is long or saturation may not occur.

The X/R ratio determines the possible DC offset and the system time constant; therefore, K_S can be increased from the value calculated to that corresponding to the X/R ratio.

In this case the X/R ratio is 15 and from the following table:

X/R	I'/I
2	1.18
4	1.38
7	1.52
10	1.54

20	1.68
50	1.73
100	1.75

The offset could be 1.64/1.75 or .94 per unit of the maximum possible.

$$Then\ K_S = 13.6\ |0.94 = 14.47\ and$$

$t_S = 0.0845$ seconds instead of 0.0722 seconds

The time to leave saturation is given by:

$$t_e = T_1 \times \ln\left(\omega T_2\ |K_S\right)$$

$$T_2 = 2.0 \sec$$

$$K_S = 13.6$$

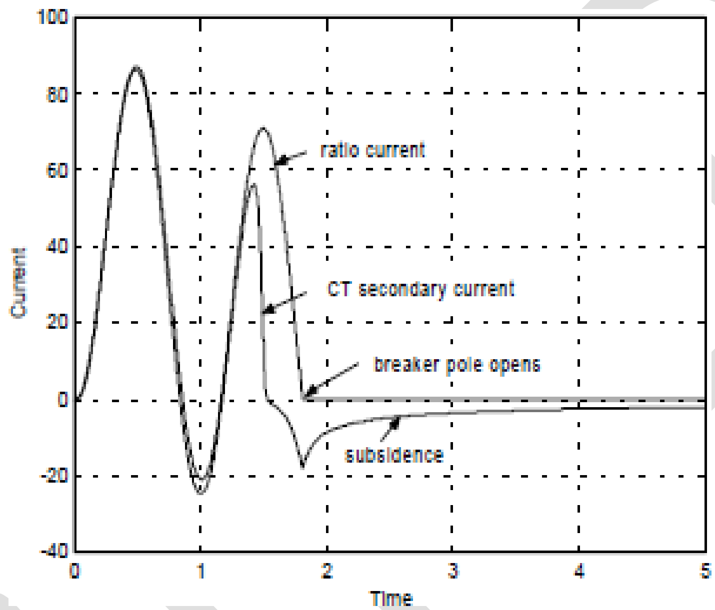
$$t_e = 0.04 \ln\left(377(2)\ |13.6\right) = 0.161 \sec$$

$$= 9.66\ cycles$$

Subsidence Current

When the breaker interrupts the primary fault current (i.e., breaker poles open) the CT secondary output does not immediately go to zero current. Trapped magnetic energy in the CT exciting branch produces a unipolar decaying current with a fairly long time constant. Figure 14 indicates the unipolar decaying secondary current that still flows through the CT burden. [17]

Figure 14: (17)



Subsidence current may be of particular concern in breaker failure applications. Some modern relays have unique logic meant to deal with this phenomenon.

It should be considered that, if air gaps are employed in CTs to reduce remanence, subsidence current will persist longer after fault clearing than for solid core devices. [14]

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Approved By

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