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Solutions to Consider in Current Transformer Selection for APR1400 Nuclear Power Plant Medium Voltage Switchgears

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Abstract: This paper discusses a preferable solution to mitigate the CT (current transformer) saturation problem, and at same time, reduce the accuracy errors when considering the selection of CTs for installation on the medium voltage switchgear of a nuclear power plant. This consideration is important for both measurement and protection functions of the digital protective relays. This is a study to ascertain the best options for a suitable solution to prevent CT saturation in relations to its protective capabilities during short circuit fault without compromising the CT accuracy class during normal operation of the system, while ensuring its conformity to the design requirement is within limit. The advantages of current transformers have proven not only to be reliable and safe, but also are of easy handling, reduction of the cost and components on the MV (medium voltage) switchgear. The purpose of this research is to identify best approach to resolve the existing problems in the current protection system. With the view of LPCT (low power current transformer) which has been newly constructed by few manufacturers to provide good protection and a wide range of measuring function without errors, some other solutions will be considered in this research.

Key words: CT, CT saturation, accuracy class, metering CT, protection CT, MV switchgear, short circuit fault current, knee voltage.

1. Introduction

CTs (Current transformers) are used for current metering and protection in high voltage network systems. They transform the high current on the high voltage side into low current (1 or 5 A) adequate to be processed in measuring and protection instruments (secondary equipment, such as relays and recorders).

The current transformer also isolates the measuring instruments from the high voltage of the monitored circuit. Current transformers are commonly used for metering and protection in the electrical power industry. Current transformers are selected based on the ability to conduct full load current continuously, and to be able to withstand over-currents and fault currents of short duration within their specified (ANSI C57.13 Requirements for Instrument Transformers IT) relay accuracy classification, while producing a secondary current proportional to the primary current, but of a smaller magnitude (generally 0-5 A range).

The selection of current transformers must be carried out carefully to ensure that the protection, instrumentation and measuring systems do function correctly. The relaying CT should not saturate at maximum fault currents.

The CT saturation problem occurs due to high short circuit fault current and the secondary voltage becomes non-proportional to magnetizing current, which gives errors in protection.

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The high ratio CT may mitigate the saturation errors in a high faulty current condition. However the high rating CTs are physically large, and hence, optimizing CT design to meet the technical performance required (while keeping the costs and size within limit) needs a fine engineering balance.

In this study, the existing criteria for CT will be reviewed in Section 2 to understand the expected performance of the device (CT) in the consideration of a design change, including its normal practice will be discussed in line with the accuracy errors and saturation conditions. In Section 3, the challenges of the current design will be examined in view of the accuracy and saturation problems. Then, in Section 4, the proposed solutions will be briefly highlighted to compare with the current solution to this problem (introduction of low power current transformer LPCT). In Section 5 the methodology will be conducted by interpreting and analyzing the technical and manufacturers' data to ascertain the exact performance of the device (CT). Then discussions based on other findings relating to this investigation and the result obtained will be included in Section 6. Then, in Section 7, a conclusive decision will be drawn from the observation of this study to know if this issue requires further study in the future.

1.1 Objective

This paper elaborates the selection methods of CT for medium voltage switchgears in nuclear power plants, while the main objective is to prevent CT saturation for relaying and reducing CT error for metering.

2. General Criteria for CT Selection

According to the general criteria for CT selection, the rated primary current (I_{pn}) of CT will always be greater than or equal to the service current. The rated thermal short-circuit current (I_{th}) is usually the short-circuit current of the installation and its duration is usually assumed to be 1 sec. All CTs must be able to resist the rated short-circuit current in the primary winding both thermally and dynamically until the malfunction induces shutdown. The secondary circuits of a CT must be suitable for the constraints related to its application for metering or protection purposes [1]. In general, secondary current rating (I_{sn}) of the CT for use in a local situation is 5 A and for use in a remote situation is 1 A.

2.1 Normal Practice of Existing Design

For practical purposes, the continuous CT primary rating selected for motor branch circuits is that standard CT rating between 1.4 and 1.8 times the calculated full load current. For example, considering the smallest load in the medium voltage switchgear is 1,500 hp and the rated current is 49 A, with a 50/5 A and 75/5 A ratio CTs have a low accuracy class, a 100/5 A CT ratio will be preferred as the minimum rating for protection applications. Take note that there is no exception to present ANSI standards (Table 6 of ANSI C37.20), which require 100/5 A CTs as a minimum CT when the available momentary short circuit current equals 60,000 A. Transformer primary overcurrent protection is normally set in the 200-300 percent of the transformer current rating, and a standard switchgear CT equal to twice the full load current (assuming only one fan stage) would appear to be adequate, because most relaying CTs can continuously carry at least 1.33 times its primary rating ($1.33 \times 2.0 = 2.66$). However, a CT rating equal to three times the transformer primary current rating would be more conservative and preferred, bushing CTs on a transformer high voltage winding (such as on the Reserve Transformer) may be multi-ratio, in which case the correct ratio may be determined during the preliminary coordination study. Power transformer secondary sides are generally protected in the 125-200 percent range, with a CT equal to the next CT primary rating standard. For example, a 1,500 kVA load center transformer has a secondary current rating of 1,803 A [5]. The bus, cable, and CT may each be rated 2,000 A continuous, and the bus supply breaker relay or trip device would be set to operate at approximately 2,400 A, at a voltage level of 480 V. These settings should automatically set the protective device characteristic below the I^2t (below the knee voltage level) limit of the transformer; however, the transformer limits should be checked in each case.

3. Challenges of the Existing CT Design

A low-ratio CT can be applied for protective relaying of small loads fed from switchgear and MCC (motor controllers center) of relatively high short-circuit capacity. Assume the worst-case scenario of 60 kA available fault current from bus feeding a small motor load of normal current below 50 A, in theory, CTs rated as low as 50:5 and relay class C10 may be applied for protection purposes. Realizing that 60 kA of fault current is 1,080 times the rated current of the 50:5 CT; the magnitude of the problem is evident. Protection class CTs are designed to work in the linear range, with minimal errors and minimal waveform distortion, only up to 20 times the rated nominal current with the burden as defined by the relay class (saturation voltage) of the CT per IEEE Std. C57.13 [5].

3.1 CT Accuracy Problem

The conventional practice, over many years, has been to set the secondary current just under 5 A for the maximum load. This was because instruments were often on the same circuit and had 5 A movements. Following this practice, select the CT ratio of 100:5 (CT ratio = 20). This gives a maximum continuous secondary current when the load is 90 A, of secondary current (I_s) [2].

$$I_s = 90/20 = 4.5\ \text{A} \qquad (1)$$

The rated primary current (I_{pr}) of a 13.8 kV MV switchgear feeders in APR 1400 is ranged from about 30 to 450 A. That means the accuracy class can be C20 to C200 according to Table 1, if a motor load of 13.8 kV switchgear is 1,500 hp and rated current is 49 A, a 50:5 CT or 75:5 CT is applicable in terms of CT ratio. In addition, the CT rated thermal short-circuit current (I_{th}) shall be no less than the rated short-circuit current in the primary winding.

3.2 CT Saturation Problems

When analyzing the operation principle that leads to the saturation condition of the current transformer, there is a need to effectively understand the principle behind its operation especially under a short circuit fault condition. In Fig. 1, it shows the equivalent circuit of a current transformer with load impedance and details of parameter in CT [8]. Basic working principle of the CT is same as the traditional transformer so no more difference in CT equivalent circuit as compare to traditional transformer. As shown in Fig. 1 the CT secondary voltage V_S should not be saturated and the exciting current should be low for better protection & measurement. When the voltage developed across the CT burden is low, the excitation current will be low. This will reduce the distortion of the waveform of the secondary current to an appreciable

Table 1 CT accuracy voltage available in medium-voltage switchgear [ANSI C37.20].

CT ratio	Min. accuracy class	Normal accuracy class	Accuracy can be provided
50:5	C10	C10	C20
75:5	C10	C10	C20
100:5	C10	C10	C20
150:5	C20	C20	C50
200:5	C20	C20	C50
300:5	C20	C50	C100
400:5	C50	C50	C100
600:5	C50	C100	C200
800:5	C50	C100	C200

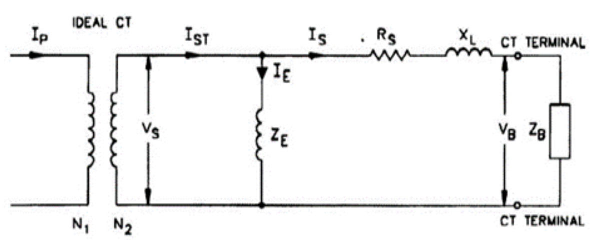


Fig. 1 Equivalent circuit diagram current transformer.

extent. As the voltage across the CT secondary winding increases because either the current or the burden is increased, the magnetic flux in the CT core will also increase. Eventually the CT will operate in the region where there is a disproportionate increase in exciting current. The CT core is entering the magnetically saturated region; the operation beyond this point (when the excitation current $I_e \geq$ knee voltage V_k) will result in an increasing metering error and a distorted secondary current waveform will be formed [3].

where,

V_s: Secondary excitation voltage;

V_B: CT terminal voltage across external burden;

I_{pr}: Primary current;

Z_E: Exciting impedance;

I_{sr}: Secondary current;

R_s: Secondary resistance;

I_s: Secondary load current;

X_L: Leakage reactance (negligible in class C CTs);

I_e: Exciting current;

N_2: N_1 CTs turn ratio;

Z_B: Burden impedance (secondary devices and loads).

In other words, at the saturated region where the CT protection capability is compromise, it may lead to current overload on the burden, which the output voltage (V_s) may be too small for accurate measurement (occurrence of accuracy error).

For example, the burden of C20 CT is 0.2 Ω and accuracy voltage is 20 V (Table 2). If the short circuit current of the bus is 40 kA then the voltage developed on the 50:5 CT secondary terminal is:

$$I_s = 40\text{ kA} / 10 = 4{,}000\text{ A} \tag{2}$$

$$V_{ef} = 4{,}000\text{ A} \times 0.2\ \Omega = 800\text{ V} \tag{3}$$

where, I_s is the secondary current of current transformer and V_{ef} (effective voltage) is the voltage developed on the secondary of the current transformer.

As a result, it will make CT saturation and errors. Instead, select 300:5 CT of which accuracy voltage is 100 V then developed voltage is:

$$I_s = 40\text{ kA} / 60 = 666.7\text{ A} \tag{4}$$

$$V_{ef} = 666.7\text{ A} \times 0.2\ \Omega = 133.3\text{ V} \tag{5}$$

Primary current (I_s) is close to accuracy voltage 100 V. Therefore, no lower than C100 accuracy class CT should be used in the 13.8 kV switchgear circuits. In this case, a CT ratio of 300:5 or higher for relaying CT should be preferable. Table 2 shows the international standard (ANSI C57) for the manufacturing and installation purpose.

On the other hand, the rated primary current for metering should not exceed the service current by a factor greater than 1.5, so that the operator can read the analog meter accurately [6]. However, in the above case the primary current rating (I_{pi}) of the 300:5 CT is more than 6 times of 49 A rated current (I_n). At full load, the analog ampere meter will indicate only 16.3% of full scale. The relaying CT must perform with acceptable accuracy at (high) fault values of current, whereas a metering CT must perform well in the lower current range.

4. Proposed Solutions to CT Saturation and Accuracy Class Errors

There have been some attempts to resolve the saturation problem when carrying out relaying action and the accuracy errors during measurement. In this analysis we will be considering four approaches to resolve these challenges, which are listed below.

- Parallel CTs for small loads;
- High ratio Standard CT for digital relays;
- Interposing CT for isolation and current balancing;
- LPCT (low power current transformer).

Table 2 Standard CT burden [ANSI C57.13, Table 9].

Secondary voltage	Standard burden	Imped. (Ω)	Power factor
10	B-0.1	0.1	0.9
20	B-0.2	0.2	0.9
50	B-0.5	0.5	0.9
100	B-1	1.0	0.5
200	B-2	2.0	0.5
400	B-4	4.0	0.5
800	B-8	8.0	0.5

4.1 Parallel CTs for Small Loads

In Fig. 2 the load current is 83.7 A and 150/5 CT is appropriate in terms of CT ratio. However, 150/5 C50 CT will develop the secondary voltage at maximum fault current 40 kA.

$$I_s = 40 \text{ kA} / 30 = 1{,}333 \text{ A} \tag{6}$$

$$V_{ef} = 1{,}333 \text{ A} \times 0.5\ \Omega = 666.7 \text{ V} \tag{7}$$

However, if applying parallel CT as shown in Fig. 2, the secondary voltage of 300/5 C100 CT at maximum fault current 40 kA is:

$$I_s = 40 \text{ kA} / 60 = 666.7 \text{ A} \tag{8}$$

$$V_{ef} = 666.7 \text{ A} \times 0.5\ \Omega = 333.3 \text{ V} \tag{9}$$

It is possible to increase CT accuracy voltage from 50 V to 100 V without reducing relay input current.

The parallel CT connection is already adopted in the nuclear power plant technology. This parallel CT will not compromise the accuracy for metering and mitigate saturation problem at short circuit fault current.

4.2 High Ratio Standard CT for Digital Relays

Recently in a nuclear power plant project, a standard ratio CT was used for small load feeders. All CTs of which ratio is equal or less than 400:5 in the conventional design were replaced by 400:5 CT with the integrated digital relays. By doing so, saturation problem in low ratio CT was mitigated.

The higher CT ratio the higher saturation voltage, just as it is shown in Fig. 3, the characteristic curve below depicts the excitation current and its proportionality to the secondary voltage. Since in high CT ratio, CTs are recommended for high fault current circuit [4].

Alternatively, the high ratio CT as shown in Fig. 4 may compromise the metering accuracy at the low current range. If the rating of a load is smaller than 1,000 kVA at 13.8 kV, the full load current is lower than 10% of 400/5 CT. In that case, the manufacturer does not guarantee current meter error. To resolve the problem an interposing CT is also proposed to rectify this problem. Fig. 4 presents a secondary current superimposed on the ratio current. The primary current is 200 times the CT rating (10 kA). It shows the relation between the secondary current, and peak value of the ratio current of CT (10-75 kA range), in which the blue curve shows the secondary current when the output ratio is too small to withstand short circuit fault, while the red curve is the expected ratio

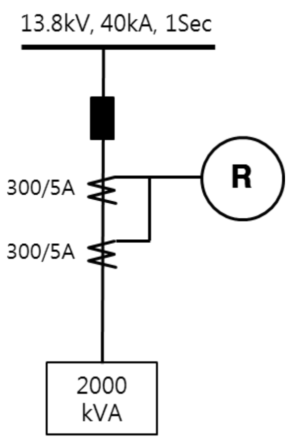


Fig. 2 Parallel CT connection for small size load feeder.

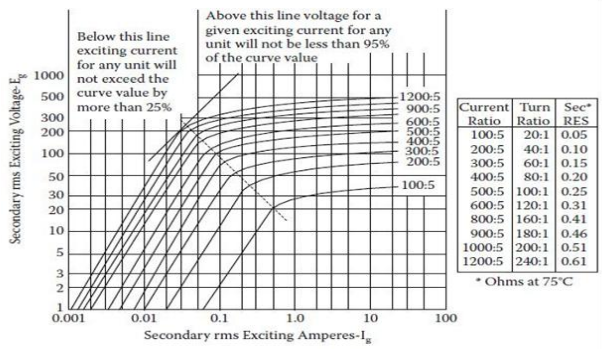


Fig. 3 Typical excitation curves for multi-ratio C or K class current transformers with non-gapped cores.

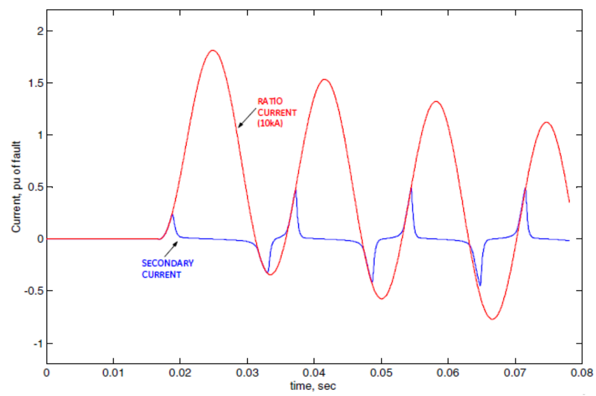


Fig. 4 CT secondary current when short circuit fault occurs in the primary circuit.

current of the CT output during short circuit fault [10]. The figure illustrates the severity of the problem. The secondary is as low as 5%-8% of the expected current, which shows pulses shorter than 1 ms when the fault current is approximately up to 75 kA.

4.3 Interposing CT for Isolation and Current Balancing

The method of avoiding surge voltage produced by high fault current, if a shared CT should be used, is to connect a metering-class interposing CT after the protection circuit and use that to feed the metering circuit [5]. In Fig. 5, an additional CT (interposing CT) is installed before the meter to ensure its accurate reading of the secondary current with a ratio of about 0.625/5 A. If the high ratio is selected for the main CT against a low load current, interposing CTs may be used across the main CT to reduce the ratio effectively and satisfactorily cater to the rated current requirement of the burden [6].

The CTs are interposed between the main CT and the burden (load) so that the secondary current of the main CT is adjusted as required by the burden. Interposing CTs are equipped with a ratio that can be selected by the user to achieve the balance required [5]. It can reduce metering error in the low current range. Interposing CT may be considered for small loads in the medium voltage switchgears at the same time with a review of CT saturation problem.

4.4 LPCT (Low Power Current Transformer)

The LPCT operates on the proven instrument transformer principle that is based on the specific matching to an internal shunt resistor [3]. This principle is exceptionally non-sensitive to external stray fields. The secondary current produces a voltage across the internal shunt resistor that is directly proportional to the primary current. This voltage is the output signal of the LPCT. The shunt itself is designed to withstand short circuit currents without any change of its resistance value. LPCTs operate linearly and saturation-free up to the short circuit currents. They are compatible with the modern microprocessor controlled relays (digital relays) and other secondary equipment. It can be used at medium- and high-voltage applications to replace the conventional CTs for measurement and protection purposes. Low power CTs can easily fit into the existing switchgear and will remain valuable in the future designs. The LPCT technology has not been applied to any nuclear power plant facility until date, it has more advantages in resolving the problems common (CT saturation and accuracy errors) to the existing system (CTs). Fig. 6 shows, the secondary winding of the low power current transformers being short-circuited with a shunt resistor. The shunt resistor becomes part of the secondary winding. Therefore, the output signal of this device is the voltage across the shunt resistor [10]. This output voltage is directly proportional to the primary current, which can be expressed as:

$$U_s = R_{sh} \times N_1 / N_2 \times I_{pr} \tag{10}$$

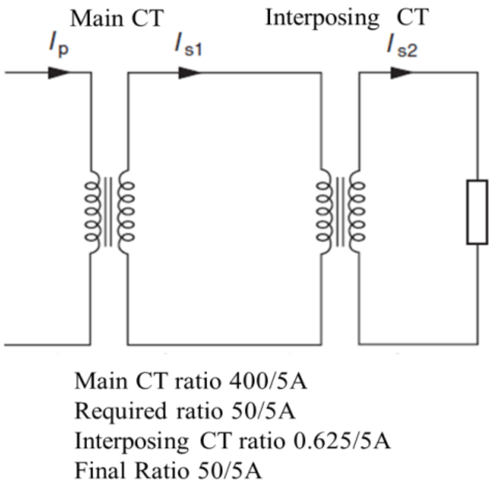


Fig. 5 Interposing CT for meter in a relay and meter shared CT.

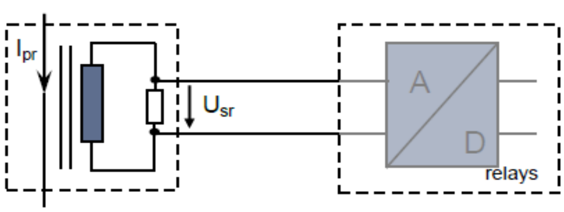


Fig. 6 Current measurement with low power current transformer.

In this case, the burden of the LPCT is the shunt resistor and the internal burden of the resistance of the secondary winding. This very low burden will change the accuracy performance of the CT when compared to the conventional CTs [10].

5. Characteristics of LPCT

Fig. 7 clearly shows how LPCT ranges from 50 A to 5,000 A of the rated primary current, and with secondary voltage as low as 0.01 to about 100 V, while the primary current ranges from 50 A to 10,000 A.

5.1 Technical Data of Low Power CT

The followings are the technical data of the LPCT:

- Rated primary current:
  I_{pr}: 50 A up to 5,000 A
- Secondary voltage:
  U_{sr}: 22.5 mV to 2.25 V
- Rated short-time thermal current:
  Up to 63 kA/3 s
- Accuracy:
  Class 0.2, 0.5 or 1.0 and simultaneously class 5P up to 63 kA
- Burden: ≥ 20 kΩ [7].
- System freq.: 50 Hz, 60 Hz [9].

In Fig. 7, the curve shows linearity in the primary current and the secondary winding voltage ranging from:

Primary current (I_{pr}) = 10,000 A =>

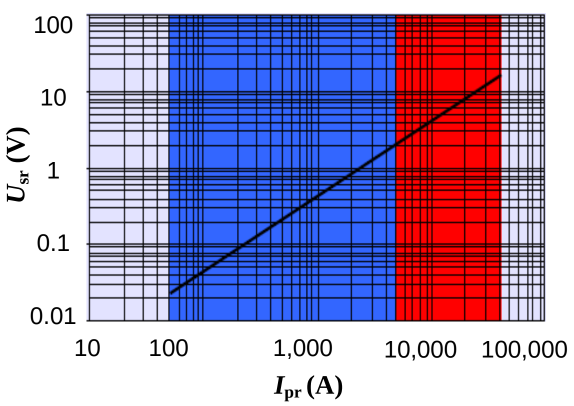


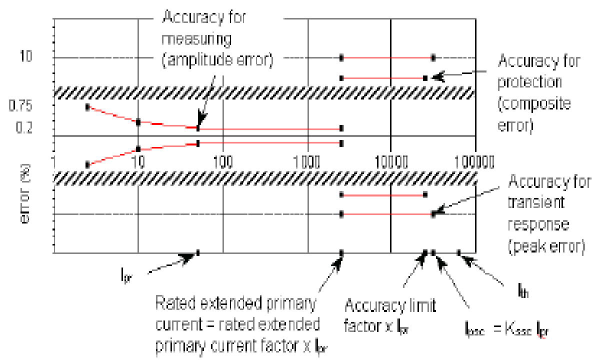
Fig. 7 CT performance characteristics curve.

Secondary voltage U_{sr} = 0.450 V. When the range of linearity is much larger, a high accuracy can be achieved in a big range of primary current. In addition, the size of the core can be much smaller which reduces the costs and the weight [9].

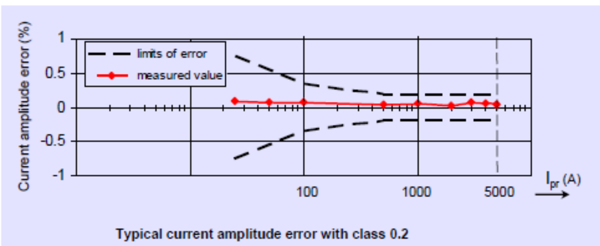
This CT has proven to have no saturation problem and a high accuracy class of the secondary voltage value that can be measured. It can fulfil the CT requirement. These low power current transformers are also defined in the IEC standard 60044-8 [2].

In Figs. 8a and 8b, the curve shows rated primary current of the LPCT that ranges from approximately 50 A (minimum rated current) to 5,000 A (maximum rated current). According to the figure, 10 to 50 A would have a low range measuring issue, and the 50 to 1,000 A would have high accuracy of about 1%, while 1,000 A to 100,000 A can provide protection up to 3% [7].

LPCT can fulfill the requirements for protection cores (e.g. 5P according to IEC 60044-8, 2002) up to the short circuit current [10]. It can also provide protection at a short circuit of 63 kA below 3%.



(a)



(b)

Fig. 8 (a) Accuracy limits of multi CT accuracy performance curve (IEC standard 60044-8); (b) Accuracy limits of multi CT accuracy performance curve (IEC standard 60044-8).

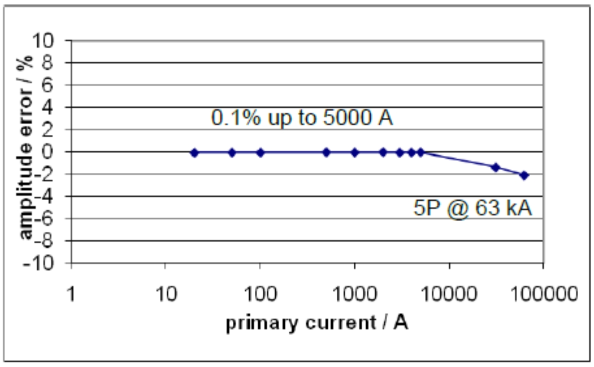


Fig. 9 Low power CT accuracy performance curve of about 0.2 accuracy class.

It also shows the measured accuracy of this device.

The bigger the primary current, the smaller the accuracy errors becomes for qualitative metering as shown in Fig. 9.

5.2 Benefit of LPCT

Listed below are the benefits of low power CTs:

- Only one core is required for all measurement and protection requirements, e.g class 0.2 or 0.5 5p, in accordance with IEC 60044-6.
- Reduced inventory: one low power current transformer covers current from 50 A to 5,000 A.
- Linear and saturation free up to short time current.
- Insensitive to burden: accurate for a total burden ≥ 20 kΩ, making it possible for several relays and meters to be connected in parallel to the LPCT current transformer without affecting accuracy.
- Connecting cable (double shielded twisted pair) and connector are parts of the LPCT and a very low voltage amplitude error and phase displacement (ideal for earth-fault protection) [7].

6. Discussions and Conclusions

Comparing the various solutions proposed earlier, we could see that during short circuit fault, the high ratio CT does not saturate but errors in metering do exist during normal operation especially in small load current. For the interposing relays, no saturation but small errors are still present in measurement, additional CT is required. In the case of the parallel CTs (double CTs), it has no saturation, and no decline in the accuracy class, but in this case, CT price is doubled and it would occupy more space. However, the CT does not saturate and the accuracy class is not reduced. The LPCT can also pick up a wide range of incoming current from 50 A to 5,000 A, with accuracy class as low as for example 0.2 (metering) to 5P (protection), it is guaranteed to be free from saturation and errors in accuracy measurement [10].

Among the proposed CT solutions to mitigate errors in accuracy class and to prevent CT saturation due to short circuit fault occurrence and during normal operation due to its ability to withstand short circuit fault without any change of its resistance value, thereby, preventing saturation without reducing the metering accuracy class, this helps to keep the secondary voltage within control for the relay to pick-up fault. However, it is a new technology not yet implemented on the medium voltage switchgear in nuclear power plant; perhaps, it would be helpful to consider this technology because it is already tested on medium and high voltage systems by some other engineers in the industry. As described in the introduction, the main objective of this paper is to explore the CT selection methods for the design of medium voltage switchgears in nuclear power plants. In comparison with the conventional CTs, low power current transformers show some crucial advantages. The main advantages are the wide linearity, the wide measuring range, the small size, and the low weight. This further leads to less effort in configuration, installation, and reduces the huge number of current transformers required in the electric power system.

The application of this new technology allows designing switchgear with optimized size and cost. In addition, further applications are possible such as power measurement, power quality measurement, and earth fault measurement [5].

At this point considering the advantages of the fourth solution (low power CT) possesses than the other solutions in resolving the accuracy errors during normal operation. Including the saturation problem during short circuit fault condition (asymmetrical rms) without compromising the accuracy class of the metering function, it would be preferable to select the LPCT for the installation on the medium voltage switchgear.

Acknowledgments

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