CT SATURATION CALCULATIONS – ARE THEY APPLICABLE IN THE MODERN WORLD? – PART I, THE QUESTION

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Abstract - Previously, ANSI/IEEE relay current transformer (CT) sizing criteria was based on traditional symmetrical calculations usually discussed by technical articles and manufacturers' guidelines. In 1996, IEEE Standard C37.110-1996 [1] introduced (1 + X/R) offset multiplying, current asymmetry and current distortion factors; officially changing the CT sizing guideline. A critical concern is the performance of fast protective schemes (instantaneous or differential elements) during severe saturation of low ratio CTs. Will the instantaneous element operate before the upstream breaker relay trips? Will the differential element mis-operate for out-of-zone faults? The use of electromagnetic and analog relay technology does not assure selectivity. Modern microprocessor relays introduce additional uncertainty into the design/verification process with different sampling techniques and proprietary sensing/recognition/trip algorithms. This paper discusses the application of standard CT accuracy classes with modern ANSI/IEEE CT calculation methodology. This paper is the first of a two-part series; Part II, the Findings provides analytical waveform analysis discussions to illustrate the concepts conveyed in Part I.

Index Terms – Accuracy Class, Asymmetrical Current, CT Burden, CT Saturation, DC Offset, Digital Filter, and X/R ratio.

I. INTRODUCTION

Initially, CT sizing criteria was based on traditional symmetrical calculations usually explained by technical articles from major electrical equipment manufacturers. In the mid-1980s, relay performance and asymmetrical secondary current waveforms appeared as part of a continuing investigation by Stanley Zocholl and William Kothheimer; this is evidenced by the series of technical papers they published concerning this topic [2, 3, 4, 5, 6, 7 and 8]. Later, the IEEE Power Engineering Society Relay Committee and other notable authors wrote technical papers addressing this topic [9, 10]. In 1996, IEEE Standard C37.110-1996 formalized some of this prior work by introducing (1 + X/R) offset multiplying factor for determining the CT secondary voltage requirement. This officially changed the guideline basis for sizing CTs. Because C37-110.1996 recognizes primary current asymmetry and CT saturation due to the DC offset current component, it is no longer acceptable to use symmetrical primary current as the basis when performing CT calculations.

Parts I and II of this paper review modern CT sizing calculations using 1+X/R to determine if the results are practical and if standard CTs can be used. To augment the 1+X/R consideration, a waveform approach is introduced.

Because modern industrial electrical power systems are typically resistance grounded, ground relaying is considered beyond the present scope of this paper. Although the paper focus is microprocessor based relays, the CT discussions are applicable to both traditional and modern relays.

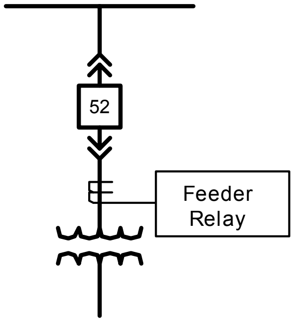


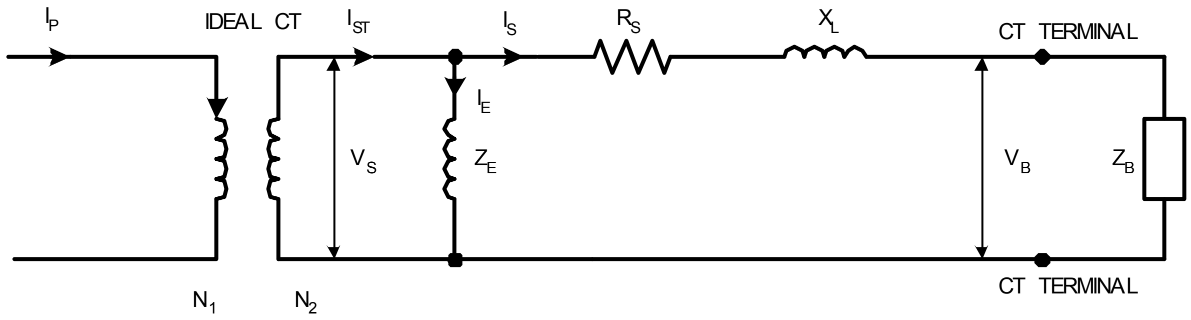
Fig. 1. Typical Feeder Relay Example.

II. THE CONCERNS

A critical concern is the performance of the relay's instantaneous element during severe saturation of low ratio CTs. Will the instantaneous element operate before the upstream main breaker relay trips? It is obvious the instantaneous element will eventually trip, but will it trip in an anticipated, repeatable manner before the upstream main breaker relay operates? Typical applications that involve either non-operation or nuisance tripping concerns are as follows (Fig. 1):

1) Feeder instantaneous overcurrent (ANSI 50) relay
2) Motor self-balancing differential (ANSI 87M) instantaneous relay
3) Generator differential (ANSI 87G) protection relay

This paper focuses on traditional CT sizing criteria during fault conditions for instantaneous element (ANSI device 50) only.



where

I_P	is the primary current	I_S	is the secondary load current
N_2:N_1	is the CT turns ratio	R_S	is the secondary resistance
V_s	is the secondary exciting voltage	X_L	is the leakage reactance (negligible in Class C CT's)
I_{ST}	is the total secondary current	V_B	is the CT terminal voltage across external burden
I_E	is the exciting current	Z_B	is the burden impedance (includes R_R-secondary devices and R_W-leads)
Z_E	is the exciting impedance		

Fig. 2. Equivalent circuit of a current transformer [1].

III. TRADITIONAL CT CALCULATION SIZING APPROACH

Protective relaying has always combined art and applied physics, with the goal of issuing tripping commands during abnormal electrical system conditions. Protective relaying systems are typically straight forward with current transformers, wiring and relays. Fig. 2 shows the equivalent circuit of a current transformer with a load impedance [2].

Traditionally, manufacturers' literature and industry standards provided calculation analysis guidance to ensure CTs were adequately sized for both ratio and accuracy class.

One author's professional development of performing CT saturation calculations began with (1) to determine the minimum CT Accuracy class.

$$V_S = I_{S\,RMS} \times (R_S + R_W + R_B) \tag{1}$$

When the offset waveform concept was introduced, (2) was used.

$$V_S = 2 \times I_{S\,RMS} \times (R_S + R_W + R_B) \tag{2}$$

Introduction of waveform peak resulted in (3) calculations.

$$V_S = 2\sqrt{2} \times I_{S\,RMS} \times (R_S + R_W + R_B) \tag{3}$$

Finally, the ANSI C37.110-1996 addition of (1 + X/R) for CT saturation calculation resulted in (4).

$$V_S = \left(1 + \frac{X}{R}\right) \times I_{S\,RMS} \times (R_S + R_W + R_B) \tag{4}$$

To show the impact of introducing the (1+X/R) term, two industrial examples are selected. Using (1) through (4), calculation results, the significant change introduced by (4) is shown. Examples 1 and 2 use a system X/R=14; this is less than the ANSI switchgear interrupting X/R rating (X/R=17). Modern industrial electrical power systems, particularly systems with generators or large synchronous motors, may have X/R magnitudes significantly greater than 14. Some large industrial system generators have X/R greater than 100, and large industrial transformers may have X/R of 30 to 40.

Example 1 – Typical Industrial 13.8kV Switchgear Feeder with high-ratio CT's.

600/5 CT with C200 Accuracy Class
18 kA $_{RMS}$ Short-Circuit Magnitude
System X/R = 14
R_{CT} =R_S= 0.193 ohms
R_{WIRE} =R_W= 0.032 ohms
R_{RELAY}=R_R= 0.01 ohms

$$V_S = \left(18kA \times \frac{5}{600}\right) \times 0.235\Omega = 35.3\ V_{RMS} \tag{5}$$

$$V_S = 2 \times \left(18kA \times \frac{5}{600}\right) \times 0.235\Omega = 70.5\ V_{RMS} \tag{6}$$

$$V_S = 2\sqrt{2} \times \left(18kA \times \frac{5}{600}\right) \times 0.235\Omega = 99.7\ V_{RMS} \tag{7}$$

$$V_S = (1 + 14) \times \left(18kA \times \frac{5}{600}\right) \times 0.235\Omega = 528.8\ V_{RMS} \tag{8}$$

IEEE Std. C57.13-1993 (R2003) [11], Section 6.4.1 defines relaying accuracy ratings as a designation by a classification and a terminal voltage rating. "These effectively describe the steady-state performance." "The secondary voltage rating is the voltage the current transformer can deliver to a standard burden at 20 times rated secondary current without exceeding 10% ratio correction factor [11]."

Fig. 3 shows a 600/5 CT saturation curve with a C200 accuracy class that may be used in Example 1. The "C" refers to a calculated ratio magnitude; the "200" means the ratio correction will not exceed 10% at any secondary current from 1 to 20 times rated secondary current value with a standard 2.0 ohm burden.

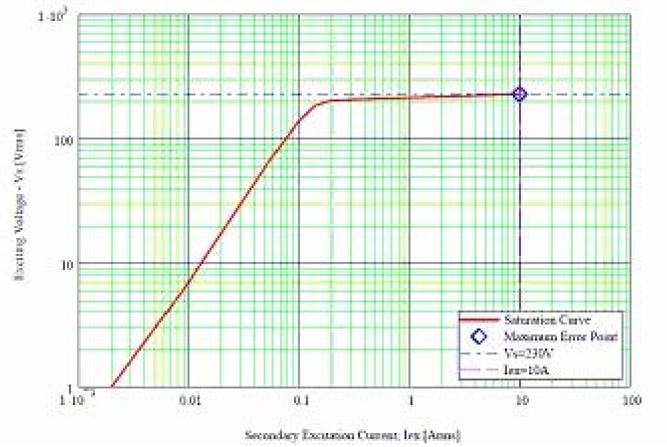


Fig. 3. CT saturation curve for 600/5, C200.

The following indicates the secondary terminal voltage at 20 times rated current of 5A:

$$V_S = 2.00\Omega \times 5A \times 20 = 200.0 V_{RMS} \tag{9}$$

With a known CT internal resistance and CT saturation curve, the CT maximum terminal voltage can be estimated. Obviously, the CT accuracy rating must be greater than the required CT voltage. In Example 1, with 18kA primary fault current and 600/5 ratio, the CT secondary current is 150A. This is 30 times the CT 5A nominal secondary current rating *(150A/5A = 30 x 5A CT rating)*. This exceeds the 20 times CT secondary rating requirement of Section 6.4.1 [11]; hence, predictable CT performance with no more than 10% ratio correction is not guaranteed because CT performance may become non-linear.

Equations (5), (6) and (7) results indicate the selected 600/5 CT is adequate. However, (8) results indicate a C200 accuracy class is significantly underrated for the (1+X/R) DC offset conditions. Because protective relays are designed for an undistorted waveform input, it is important to provide CTs that are capable of accurately reproducing the primary system short-circuit waveform on the CT secondary.

Example 1 shows the results with high-ratio CTs on feeder circuits. At this point the application question could be asked, what is required for typical 13.8kV switchgear feeders with low-ratio CTs?

Example 2 - Typical industrial 13.8kV feeder with low-ratio CTs.

200/5 CT with C20 Accuracy Class
18 kA $_{RMS}$ Short-Circuit Magnitude
System X/R = 14
$R_{CT} = R_S = 0.054$ ohms
$R_{WIRE} = R_W = 0.032$ ohms
$R_{RELAY} = R_B = 0.01$ ohms

$$V_S = \left(18kA \times \frac{5}{200}\right) \times 0.096\Omega = 43.2\ V_{RMS} \tag{10}$$

$$V_S = 2 \times \left(18kA \times \frac{5}{200}\right) \times 0.096\Omega = 86.4\ V_{RMS} \tag{11}$$

$$V_S = 2\sqrt{2} \times \left(18kA \times \frac{5}{200}\right) \times 0.096\Omega = 122.2\ V_{RMS} \tag{12}$$

$$V_S = (1+14) \times \left(18kA \times \frac{5}{600}\right) \times 0.074\Omega = 648.0\ V_{RMS} \tag{13}$$

Obviously, the low-ratio CT is underrated for an 18kA fault magnitude with a system X/R of 14. This is the commonly unrecognized dilemma – using underrated low-ratio CTs with protection relays. Industrial systems with large supply transformers, large motors or local generators could have a short-circuit X/R ratio in excess of 50 value, making the DC offset condition more severe.

IV. IEEE STANDARD C37.20.2-1999

Traditionally, switchgear CT sizing assistance has been provided from IEEE Standard C37.20.2-1999 [12], "IEEE Standard for Metal-Clad Switchgear [12]," Table 4, shows standard CTs supplied by manufacturers considered adequate for most applications. Table I reproduces only the CT ratio and relaying accuracy class portions of Table 4 and footnote "c."

TABLE I
EXCERPT FROM C37.20.2-1999 [12]

CT Ratio	Relaying accuracy^c
50/5	C or T10
75/5	C or T10
100/5	C or T10
150/5	C or T20
200/5	C or T20
300/5	C or T20
400/5	C or T50
600/5	C or T50
800/5	C or T50
1200/5	C100
1500/5	C100
2000/5	C100
3000/5	C100
4000/5	C100

^{c} (see text for footnote)

At first glance, the industrial user may attempt to use Table 4 for a company standard or project specification. When compared to examples 1 and 2 above, it is intuitively obvious that the minimum CTs supplied as standard by manufacturers for industrial relaying purposes are typically not adequate.

Upon further inspection, Table 4, footnote c states, "These accuracies may not be sufficient for proper relaying performance under all conditions. To ensure proper relaying performance, the user should make a careful analysis of CT performance considering the relaying requirements for the specific short-circuit currents and secondary circuit impedances (see 8.7.1)." Section 8.7.1 of C37.20.2-1999 [12] is titled “Current Transformers” and provides a synopsis of the application of current transformers in metal-clad switchgear. “That the accuracies listed in Table 4 are the standard supplied in the usual design of this equipment, and are adequate for most applications.” “If an application requires higher accuracies, it should be specified by the user [12].” Considerations in the proper selection of CTs are listed, i.e., circuit load current, continuous, mechanical and short-time current rating factors, accuracy class, secondary burden, protection type, and available fault current. “When the current transformer ratio is selected primarily to meet the full load and overload protection requirements of the protected load, the ratio and accuracy may be too low to ensure proper operation of the short-circuit protection at the maximum available fault current. Improper protective relay operation resulting from current transformer saturation may cause mis-operation or non-operation of the circuit breaker [12].” The standard indicates two considerations to overcome the undesirable condition of relay/circuit breaker maloperation because of CT saturation: 1) special accuracy CTs from the manufacturer or 2) two sets of CTs (a low-ratio CT set for overload protection and a much higher CT ratio/accuracy set determined from the fault current and the CT secondary burden). At the end of Section 8.7.1 two references are included, [9] and [10]. These references discuss the transient response of CTs and relay performance when applying low-ratio CTs in high-magnitude fault conditions.

The C37.20.2-1999, Section 8.7.1 directives send a mixed message. Section 8.7.1 initial statements instruct the user that Table 4 CT’s represent the “standard supplied in the usual design of this equipment, and are adequate for most applications;” however, the remainder of Section 8.7.1 provides a list of qualifications for applying the Table 4 standard. Table 4 may be adequate for utility industry applications with X/R ratios of 4 to 8, but it should be used cautiously by industrial users.

The application question arises, what should the industrial user do?

1) Use Table 4? Example 2 showed that low-ratio CTs are inadequate with an 18kA fault current and system X/R=14. With typical industrial equipment symmetrical interrupting ratings of 50kA or 63kA, the low-ratio CT’s may be inadequate for typical heavy industry applications.

2) Provide two sets of CTs; one set for overload conditions and the second CT set for fault conditions? This could resolve the concern of relay maloperation during fault conditions, but may require an additional metering device, adding cost to the switchgear. Although two sets of CTs are a viable solution, it has not been adopted as common practice by the heavy industries. However, this is the recommendation of [9] as indicated in section VI.

3) Apply Table 4, footnote c, and perform a careful analysis by applying [7] and [8]? This would be consistent with a rigorous engineering investigation approach.

Part I and Part II of this paper provide discussions concerning the use of Table 4 CT accuracy recommendations for modern heavy industrial applications.

V. BUFF BOOK – ANSI/IEEE STANDARD 242-2001, CHAPTER 3

Another source of CT sizing guidance is the Buff Book, ANSI/IEEE Standard 242-2001 [13]. Buff Book Chapter 3 discusses Instrument Transformers, and Section 3.2.9 “Examples of Accuracy Calculations” provides three point-by-point calculated relaying examples with symmetrical calculations only. However, the symmetrical calculations are followed by Section 3.1.10 titled “Saturation”, where CT saturation effects are very briefly considered with the following general guides.

1) “Where fault currents of more than 20 times the current transformer nameplate rating are anticipated, a different current transformer, or different current transformer ratio, or less burden may be required.”

2) “A comprehensive review of saturation and its effect on transient response of current transformers is presented in IEEE Publication 76 CH 1130-4 PWR. [9]”

Again, there is a mixed message when CT saturation is introduced. The example calculations are symmetrical without reference to the DC component or X/R ratio, yet there is a caveat when short-circuit currents result in greater than 20 times the CT nameplate rating or other transient conditions.

Table II is a simple tabulation based on the 20 times CT rating criteria. Table II shows typical CT capabilities for maximum ANSI standard switchgear ratings from 25kA to 63kA without including DC component (1+X/R) concerns. This most basic criterion illustrates that only high-ratio CT’s are adequate for protective relaying during maximum fault conditions and the DC offset component ignored.

VI. IEEE PUBLICATION 76 CH 1130-4 PWR, “TRANSIENT RESPONSE OF CURRENT TRANSFORMERS”

IEEE Publication 76 CH 1130-4 PWR, “Transient Response of Current Transformers” January 1976 [9] provides analysis details for determining CT performance during transient conditions. This publication was a primary reference in the 1995, IEEE Transactions on Industry Applications, Vol. 31, No. 2, March/April 1995, “Relay Performance Considerations with Low-Ratio CTs and High Fault Currents [10],” which focused on the typical industrial application of low-ratio CTs and high-magnitude fault currents. The purpose of the paper was to notify industrial, power plant, and cogeneration engineers of the concerns of using low-ratio CTs and alternative application solutions.

On the first page, definitive statements are provided for correct CT application during both overload and short-circuit conditions. “For applications addressed by this report, this requirement will usually mean the provision of two CTs: A low ratio for overload and a high ratio (in the order of 2000-4000 to 5A) for short-circuit protection.” Although based on detailed investigations, this recommendation has typically not been implemented by the heavy industries.

To assist application engineers in determining the CT output waveform into the relay, a BASIC computer program was included as a fundamental tool to aid in analyzing relay performance. By including this type of rudimentary analytical tool, it is intuitive to conclude that symmetrical hand calculations are not completely adequate for evaluating CT/Relay performance during severe transient fault conditions.

In the mid-1980s, Stanley Zocholl, William Kothheimer and others began publishing technical conference papers discussing CT saturation and the impact on relay response. Previously, electro-mechanical relays were tested to confirm expected operation during severe fault conditions; however, testing is a costly activity. Microprocessor-based relays use modern digital simulation confirmation; a more cost effective approach.

The Zocholl, Kothheimer, et. al., papers continued to highlight the concern of relay response with saturated CTs, particularly the effect of significant X/R ratio (DC component) and CT remanence. Kothheimer even produced CT saturation waveform programs for both one CT and two CTs (differential application). This introduced the era of CT saturation and relay response via waveform analysis.

VII. MODERN CT CALCULATION SIZING APPROACH

In 1996, ANSI C37.110-1996 adopted the continuing work of Stanley Zocholl and William Kotheimer to include the (1+X/R) DC offset component and waveform analysis into CT sizing criteria. Now, industrial applications should comply with a CT standard that requires significantly increased CT accuracy class requirements. Table III and Table IV apply modern ANSI CT sizing requirements to ANSI standard switchgear ratings during maximum rated fault conditions. Table III and Table IV results show that typically used switchgear accuracy class CTs may not be adequate for industrial applications.

Obviously, modern ANSI CT sizing criteria is more stringent than ANSI C57.13-1993 (R 2003) [11], but what method should be used? Basic calculations are only part of the CT selection process because relay response must also be considered. The answer is provided by an ongoing application research activity formalized by the Power System Relay Committee in the 1976 IEEE publication 76 CH 1130-4 PWR [9] and continued by Stanley Zocholl, William Kotheimer and others – Relay Response to CT Output Waveforms. It is a two step process.

1) Determine the CT secondary output waveform.

2) Using the CT secondary output waveform as input to the relay or relay model, determine the relay response to confirm the relay responds as anticipated for an ANSI device 50 relay, i.e. an immediate trip with only relay response time delay is anticipated.

VIII. CT WAVEFORM SATURATION SOFTWARE

Determining the relay response to CT output waveforms is complex and requires computer simulation. Typically available CT saturation software is freeware or developed by programming commercial computational software tool. The following list indicates some types of available software; others may be available [14, 15, 16 and 17].

1) The Power System Relay Committee BASICA freeware software from [5] yields unrefined CT output waveform results, utilizing many assumptions.

2) More refined, proprietary CT output waveform software from relay manufacturers may be available upon request with a proprietary agreement.

3) Commercial computational application software may be procured and programmed from basic physics and electrical engineering principles.

4) Electro-magnetic transient program (EMTP), such as, free licensing alternative transient program (ATP) or commercial versions may be programmed with basic physics and electrical engineering principles.

Obviously, with the use of any computer simulation tool, simulation computations should be verified. Compare the computer results with test results from the user's specific application or known test results is desired, a check is performed to confirm the computer results match the "real-world" response. This means the application engineer should determine the CT output waveform and the subsequent relay response via significantly more analysis than traditional calculation methods. Section IX begins to address the relay response concerns by providing some fundamental building block modules for microprocessor relays.

IX. MICROPROCESSOR RELAY BASICS

Analyzing relay response to CT output waveforms is a multi-part task. Here are some typical concerns, when investigating relay response to a CT secondary output waveform.

1) What does the primary power circuit short-circuit waveform look like?

2) What does the CT secondary waveform into the relay look like?

3) How does the relay process the input waveform?

4) What is the relay response?

5) Is a trip provided as anticipated?

6) Is an additional delay incurred by the relay?

These and other questions are discussed in this section and Part II of this paper.

Fig. 4 shows a typical CT/Relay application with pertinent microprocessor relay modules. It provides a minimal fundamental discussion of a modern CT/microprocessor relay protection system by briefly describing the function of the CT/relay modules and illustrating example waveforms at pertinent CT/relay test points [18, 19, 20 and 21].

Fig. 4 CT/Relay Test Point Discussion:

- Primary CT - The purpose of the Primary CT is to reproduce the primary current waveform to the RELAY AUX CT. This is extremely important because microprocessor relays are typically designed for symmetrical waveforms. Significantly distorted current sinusoidal wave input into the relay presents a challenge to microprocessor relays because the relay recognition algorithm is anticipating a non-symmetrical sinusoidal wave input. This illustrates another reason for true reproduction of the primary fault current waveform on the CT secondary.
- Relay Aux CT block - The microprocessor relay has a Relay Aux CT block that converts the waveform input into a useable scaled voltage quantity. Providing a waveform input that exceeds the design limits of the switchgear installed CT secondary current is discouraged because of potential RELAY AUX CT block saturation and decreased relay response performance.

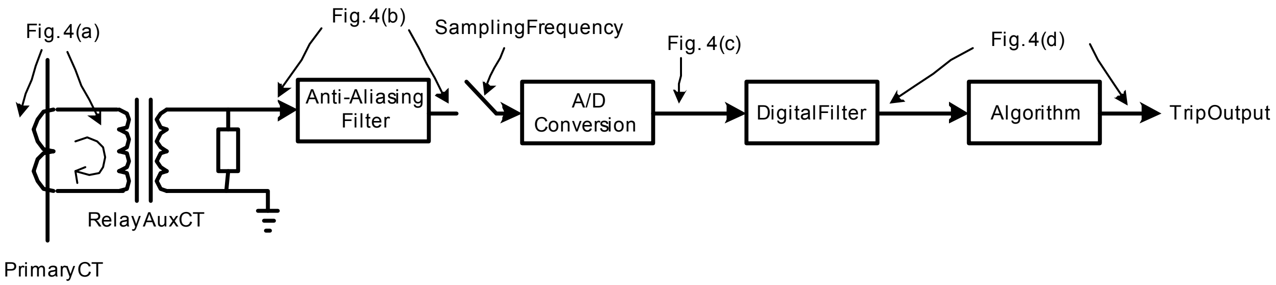


Fig. 4. Rudimentary CT/microprocessor relay block diagram with waveform test points [5].

- Anti-Aliasing Filter - An Anti-Aliasing Filter conditions the analog waveform via a low-pass filter to remove any high frequency content.
- A/D Conversion - An analog-to-digital converter (A/D) converts the signal to a digital value of current at a sample rate.
- Digital Filter - A Digital Filter extracts the fundamental frequency and rejects all harmonics.
- Algorithm - The fundamental is then compared with the tripping algorithm. If the trip setting is exceeded, a trip command is issued to the output trip relay.

Example waveforms at pertinent Fig. 4 test points are included to promote insight into operation of the CT/relay system.

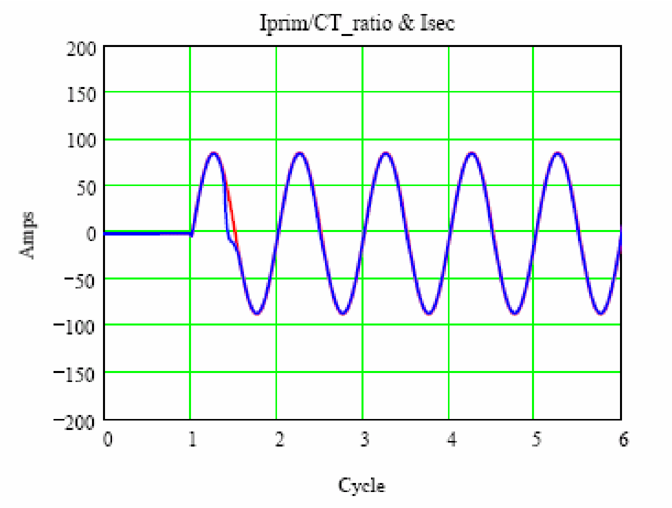


Fig. 4(a). I Primary (scaled to secondary) and I Secondary currents.

Fig. 4(a) shows a primary system fault current waveform and a scaled waveform on the Primary CT Secondary.

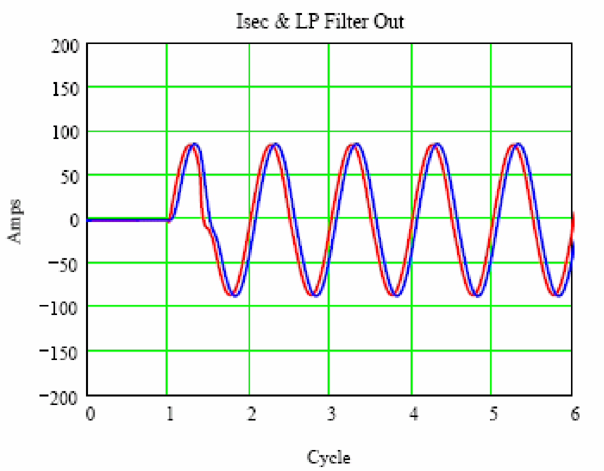


Fig. 4(b). Relay Aux CT and anti-aliasing filter output.

Fig. 4(b) shows the RelayAuxCT output to the anti-aliasing filter, a scaled voltage waveform of the primary CT secondary; and illustrates anti-aliasing filter removal of high-frequencies.

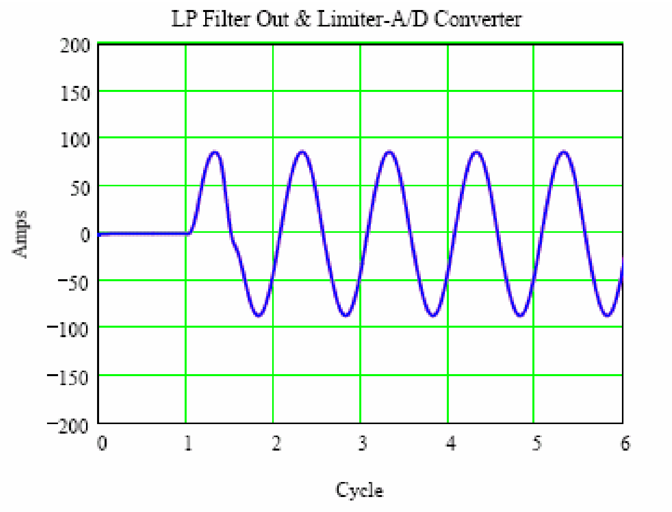


Fig. 4(c). A/D converter output.

Fig. 4(c) shows the A/D conversion.

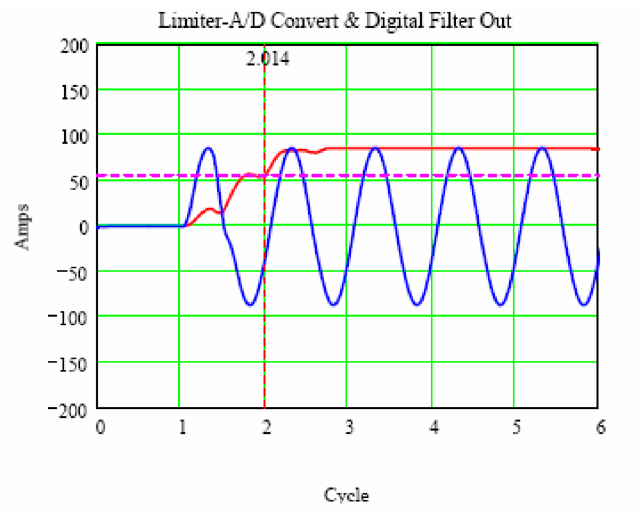


Fig. 4(d). Digital filter and relay output.

Fig. 4(d) shows the waveform input to the digital filter where the fundamental frequency waveform is extracted by the digital filter and the RMS value of the waveform is calculated. The RMS value is compared to the settings of ANSI element 50 in the relay Tripping Logic and a trip is initiated by logic. In this example, a trip occurs in approximately one cycle from the fault occurrence, an acceptable response for instantaneous protection.

This is the modern CT/relay protection system which application engineers should understand.

Further waveform analysis at CT/relay test points can be found in the following application references:

1) The Impact of High Fault Current and CT Rating Limits on Overcurrent Protection, G. Benmouyal and S. Zocholl, 2002 [2].

2) Primary High Current Testing of Relays with Low Ratio Current Transformers, S. Zocholl and J. Mooney, 2003 [6].

Although this process may seem a straightforward, it is imperative that the input waveform to the relay reproduces the primary current fault for anticipated predictable relay response during fault conditions. Hence, the CT must be adequate for the application, with a ratio and accuracy class consistent with the fault current characteristic and the CT/relay protection system hardware and software algorithms. Part II of this paper expands on this discussion by providing waveform analysis to determine CT accuracy class guidance for CTs.

X. SUMMARY

Modern IEEE Standard C37.110-1996 CT saturation calculations include a (1+X/R) multiplier that significantly increases the required CT accuracy class during fault conditions in medium-voltage industrial power feeder circuit applications, particularly when low-ratio CT's are implemented. Tables III and IV show typical industrial CT accuracy class examples using ANSI C37.110-1996 (1+X/R) methodology and that practical CT accuracy class sizes are not achieved.

IEEE Standard C37.20.2-1999, Table 4 indicates minimum accuracy class CT's provided as a standard for usual applications and considered adequate for most applications; however, many qualifications and confirmations are required.

Table II suggests a minimum of 1200/5 CT ratio per ANSI/IEEE Standard 242-2001, Section 3.1.10 "Saturation".

IEEE Publication 76 CH 1130-4 PWR, "Transient Response of Current Transformers" January 1976 and IEEE Transactions on Industry Applications, Vol. 31, No. 2, March/April 1995, "Relay Performance Considerations with Low-Ratio CTs and High Fault Currents." propose the use of a low-ratio CT for overload and a high-ratio CT for short-circuit conditions. This has not been typical industrial practice.

A modern CT sizing approach is introduced with waveform analysis as the evaluation basis, rather than a symmetrical hand calculation. A fundamental CT/microprocessor relay block diagram and sequential test point waveforms are included to illustrate this modern approach.

XI. CONCLUSIONS

When IEEE Standard C37.110-1996 formally introduced the (1+X/R) multiplier for CT saturation calculations, CT accuracy class requirements significantly increased for heavy industrial applications with low-ratio CTs on typical medium-voltage feeder applications because the X/R ratio is "high" (14 or greater). This did not appreciably affect utility transmission applications because the utility industry X/R range is "low" (4 to 8).

Because the (1+X/R) multiplier may require significant CT accuracy requirements, a modern method is needed to confirm the CT ratio and accuracy class and relay response during fault conditions.

In Part 2 of this paper, typical examples utilizing waveform analysis will be discussed to provide guidance for the required CT accuracy class and to evaluate if low-ratio CT's are adequate for typical industrial medium-voltage feeder instantaneous applications.

X. ACKNOWLEDGMENTS

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XII. VITAE

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TABLE II

20 TIMES CT PRIMARY RATING COMPARED TO SWITCHGEAR SYMMETRICAL RMS RATING.

CT Ratio	20 Times CT Primary	25kA Fault	31.5kA Fault	40A Fault	50kA Fault	63kA Fault
50/5	1000 A	-	-	-	-	-
75/5	1500 A	-	-	-	-	-
100/5	2000 A	-	-	-	-	-
150/5	3000 A	-	-	-	-	-
200/5	4000 A	-	-	-	-	-
250/5	5000 A	-	-	-	-	-
300/5	6000 A	-	-	-	-	-
400/5	8000 A	-	-	-	-	-
500/5	10000 A	-	-	-	-	-
600/5	12000 A	-	-	-	-	-
800/5	16000 A	-	-	-	-	-
1000/5	20000 A	-	-	-	-	-
1200/5	24000 A	CONFIRM	-	-	-	-
1500/5	30000 A	OK	CONFIRM	-	-	-
2000/5	40000 A	OK	OK	CONFIRM	-	-
3000/5	60000 A	OK	OK	OK	OK	CONFIRM
4000/5	80000 A	OK	OK	OK	OK	OK

Notes:
1. Metal-Clad switchgear half-cycle rating is based on X/R=25.
2. Metal-Clad switchgear interrupting rating is based on X/R=17.
3. "-" indicates the CT is not adequate for minimum accuracy class CT's.

TABLE III

SECONDARY EXCITING VOLTAGE (Vs) SUMMARY USING ANSI C37.110-1996, 1+X/R CALCULATION METHOD (STANDARD ACCURACY CLASS CT)

Standard	CT Ratio	25kA Fault	31.5kA Fault	40A Fault	50kA Fault	63kA Fault	COMMENTS
No Class	50/5	1875	2363	3000	3750	4725	CT not adequate
C10	75/5	1450	1827	2320	2900	3654	CT not adequate
C10	100/5	1294	1630	2070	2588	3260	CT not adequate
C20	150/5	1050	1323	1680	2100	2646	CT not adequate
C20	200/5	900	1134	1440	1800	2268	CT not adequate
C20	250/5	818	1030	1308	1635	2060	CT not adequate
C20	300/5	869	1095	1390	1738	2189	CT not adequate
C50	400/5	802	1010	1283	1603	2020	CT not adequate
C50	500/5	761	959	1218	1523	1918	CT not adequate
C100	600/5	734	925	1175	1469	1851	CT not adequate
C100	800/5	703	886	1125	1406	1772	CT not adequate
C100	1000/5	683	860	1092	1365	1720	CT not adequate
C200	1200/5	670	845	1073	1341	1689	CT not adequate
C200	1500/5	813	1024	1300	1625	2048	CT not adequate
C200	2000/5	591	744	945	1181	1488	CT not adequate
C200	3000/5	717	903	1147	1434	1807	CT not adequate
C200	4000/5	523	659	837	1046	1318	CT not adequate

TABLE IV

SECONDARY EXCITING VOLTAGE (Vs) SUMMARY USING ANSI C37.110-1996, 1+X/R CALCULATION METHOD (HIGH ACCURACY CLASS CT)

HI	CT Ratio	25kA Fault	31.5kA Fault	40A Fault	50kA Fault	63kA Fault	COMMENTS
C10	50/5	2625	3308	4200	5250	6615	CT not adequate
C20	75/5	2125	2678	3400	4250	5355	CT not adequate
C20	100/5	1856	2339	2970	3713	4678	CT not adequate
C50	150/5	1613	2032	2580	3225	4064	CT not adequate
C50	200/5	1481	1866	2370	2963	3733	CT not adequate
C50	250/5	1410	1777	2256	2820	3553	CT not adequate
C100	300/5	1356	1709	2170	2713	3418	CT not adequate
C100	400/5	1289	1624	2063	2578	3248	CT not adequate
C100	500/5	1249	1573	1998	2498	3147	CT not adequate
C200	600/5	1222	1540	1955	2444	3079	CT not adequate
C200	800/5	1191	1500	1905	2381	3000	CT not adequate
C400	1000/5	1170	1474	1872	2340	2948	CT not adequate
C400	1200/5	1158	1459	1853	2316	2918	CT not adequate
C400	1500/5	1428	1799	2284	2855	3597	CT not adequate
C400	2000/5	1041	1311	1665	2081	2622	CT not adequate
C400	3000/5	1285	1619	2056	2570	3238	CT not adequate
C400	4000/5	936	1179	1498	1872	2359	CT not adequate