CT Sizing for Generator and Transformer Protective Relays

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CT SIZING FOR GENERATOR AND TRANSFORMER PROTECTIVE RELAYS

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Abstract

Modern relays often have algorithms that enhance the security of elements that are otherwise susceptible to current transformer (CT) saturation. In this paper, we consider some of the similarities and differences between IEEE and IEC guidance on CT selection. We use CT models verified using high-current tests on a physical CT. Then using these models, we determine CT sizing guidelines and relay settings for a generator and transformer differential relay. Application guidance for generator black start is provided. Considerations such as remanence are discussed.

1 Introduction

In the past, the use of current transformer (CT) models was promoted for CT selection, analysis, and the development of relay settings. But modern differential relays have advanced algorithms that make it difficult to simply use CT models and apply the results. This paper shows the method used to determine CT requirements and setting guidelines for a differential scheme that is resilient to CT saturation due to an external fault or energization of an external transformer during a generator black start. We use CT models validated with a physical CT in simulations and hardware-in-the-loop testing. The test results facilitate precise application guidance, clearly defining the security limits of the differential scheme. This paper is a complementary and concise version of [1].

2 IEEE and IEC Guidance

Both IEEE [2] and IEC [3] guidelines start with the equivalent circuit of a CT; a simplified version is shown in Fig. 1 [1].

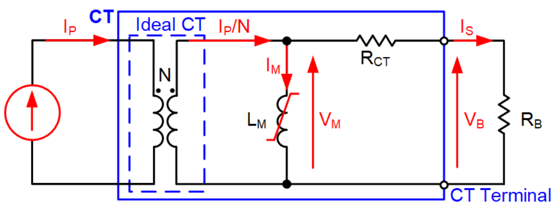

Fig. 1. Equivalent circuit of a CT.

L_M is the nonlinear magnetizing branch inductance, which can draw a large magnetizing current (I_M). It corresponds to an error current for a differential relay that measures the secondary current (I_S). I_P is the primary current, N is the CT turns ratio, V_M is the magnetizing branch voltage, and V_B is the burden voltage. R_{CT} is the CT internal resistance, and R_B is the burden resistance.

There are a few differences between IEEE and IEC guidance.

2.1 *Parameters for CT Sizing*

The CT nameplate data differ from an ANSI C class CT to an IEC P class CT as shown in Table 1.

Table 1 Nameplate data for an ANSI C and an IEC P CT

ANSI C Class	IEC P Class
CT ratio = 3,500:5	CT ratio = 1,000:1
V_{ANSI} = 200 V (C200)	Burden (VA) = 2.5
	Accuracy = 5% (5P)
	Accuracy limit factor (ALF) = 30

The IEC class P CT is primarily dimensioned via the ALF. ALF is the ratio of symmetrical current with respect to the CT rated current for which the manufacturer guarantees that the CT meets the accuracy parameter [3].

The ANSI class C CT [2] is primarily sized via the C rating (V_{ANSI}). Note that much of IEEE and IEC application guidance is defined at the magnetizing branch (V_M), whereas V_{ANSI} is defined at the terminals (V_B) [1] [2]. The ALF of an ANSI CT is fixed at 20 for an error of 10 percent. And the VA rating is the square of the CT nominal secondary rating (I_{NOM}) multiplied by the standard burden resistance. For example, the VA for a 5 A C200 CT is 50 ($5\ A^2 \cdot 2\ \Omega$).

Application-dependent parameters include maximum fault current (I_F) and R_B. R_{CT} is the internal CT winding resistance, a parameter typically obtained from a data sheet. R_{CT} is required to size an IEC CT but is not critical to size an ANSI CT given that V_{ANSI} is defined at the terminals. It is, however, a helpful parameter to determine relay settings, as is shown in Sections 5 and 7.

2.2 *Transient Dimensioning*

IEC defines the transient dimensioning factor (K_{TD}), which is used with (1) to calculate the minimum required magnetizing branch voltage or emf at the accuracy limit [3]. K_{TD} is the worst-case value provided by a relay manufacturer for which the performance requirements of a protective relay scheme are met [1] [3]. Section 5 describes the approach used to determine K_{TD} for the differential scheme in Section 4.

$$E_{AL} > K_{TD} \bullet \left(\frac{I_P}{N}\right) \bullet \left(R_{CT} + R_B\right) \quad (1)$$

IEEE does not have an equivalent parameter that considers the dc transient during the fault and the relay scheme. General practice has been to use 1 + X/R ratio to overdimension the CT so it never saturates (as shown in (2)), where V_{SAT} is the saturation voltage at the magnetizing branch [2]. This may be an impractical approach to sizing CTs in systems with high X/R ratios, such as those near generating plants [1].

$$V_{SAT} > \left(1 + \frac{X}{R}\right) \bullet \left(\frac{I_P}{N}\right) \bullet \left(R_{CT} + R_B\right) \quad (2)$$

But IEEE does define a saturation factor (K_S) related to the time-to-saturate of a CT that has an equivalent dimensioning definition to K_{TD}, as shown in (3) [1]. Manufacturers can use the value shown in (3) to account for relay scheme performance described by (1), where (1 + X/R) in (2)may be substituted with a lower K_S [1].

$$\underset{\text{(IEC)}}{K_{TD}} = \underset{\text{(IEEE)}}{K_S} = \frac{V_{SAT}}{I_S \bullet \left(R_{CT} + R_B\right)} \quad (3)$$

2.3 *Remanence*

In the IEC world, there is a heavy emphasis on remanence because data indicate large remanence (e.g., Rem ≈ 80%) may be present [1] [3]. IEC introduces the remanence dimensioning factor (K_{REM}) in (4), which must be considered for fast protection elements with subcycle operation.

$$K_{REM} = \frac{1}{1 - \text{Rem}} \quad (4)$$

Multiplying (1) by (4) provides (5), the overall dimensioning requirement for the CT. To deal with the substantial overdimensioning to accommodate remanence, IEC classifies gapped CTs with antiremanence properties [1] [3].

$$E_{AL} = \left(K_{REM} \bullet K_{TD}\right) \bullet \left(\frac{I_P}{N}\right) \bullet \left(R_{CT} + R_B\right) \quad (5)$$

In the IEEE world, oversizing the CT to accommodate remanence is considered similarly, as shown in (6).

$$V_{SAT} > \frac{\left(1 + \frac{X}{R}\right) \bullet \left(\frac{I_P}{N}\right) \bullet \left(R_{CT} + R_B\right)}{1 - \text{Rem}} \quad (6)$$

Using (6) when there is substantial remanence makes sizing CTs impractical for many applications. Sizing examples in [2] also ignore remanence, which is consistent with the general practice in the IEEE world. However, if a lower value of K_S is considered to account for the relay scheme, remanence may be considered in a similar form as (5). In the IEEE world, the remanence level of C class CTs has generally been observed to be lower, in the range of 67 percent (K_{REM} = 3), which may be adjusted if the CT excitation characteristic is known [1] [2] [4].

3 CT Model

To determine the CT requirements using the method in this paper (shown in Section 5), we needed to model the CT accurately. Two types of CT models have been commonly used for protective relaying applications:

- Using physical parameters and representing the nonlinearity of the magnetizing branch by using the S-shaped Frolich equation [5] [6].
- Using CT excitation curve data typically available from data sheets or via testing [6] [7] [8].

We validated the two models with lab test data from an ANSI C10 150:5 CT where R_{CT} = 51 mΩ and R_B = 36 mΩ [9]. A fully offset rms current of 1,420 A primary (47.3 A secondary) with an X/R ratio of 11.31 and θ = –85° was applied to the CT. The parameters that affect the magnetizing branch are shown in Table 2.

Table 2 Magnetizing branch parameters used for CT models

Parameter	Data
μ_r (physical model)	5,000
L (physical model)	0.10 m
B_{MAX} (physical model)	1.5 T
S (excitation model)	15 A/V
V_{SAT} (both models)	18 V
Remanence (both models)	0 pu

Fig. 2 shows that both models perform reasonably well in relation to the real lab CT [5] [8].

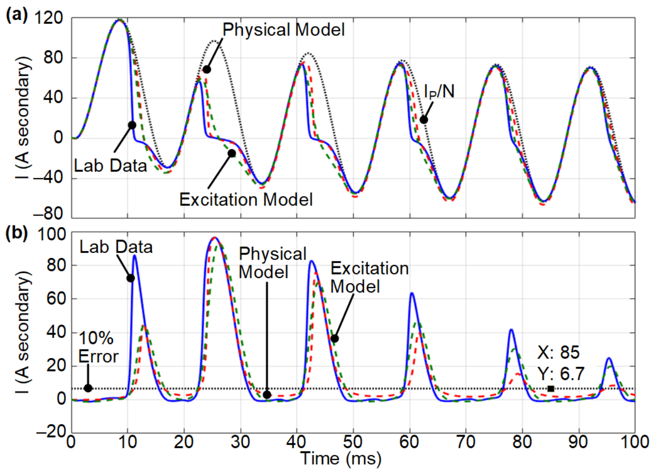

Fig. 2. Comparison of laboratory data and models using secondary currents (a) and excitation current (b).

4 Protective Relay Algorithm

The differential scheme in consideration has an adaptive characteristic and is shown in Fig. 3. If there is a possibility of CT saturation, the external fault detector (EFD) asserts and adjusts the operating characteristic from sensitive to secure.

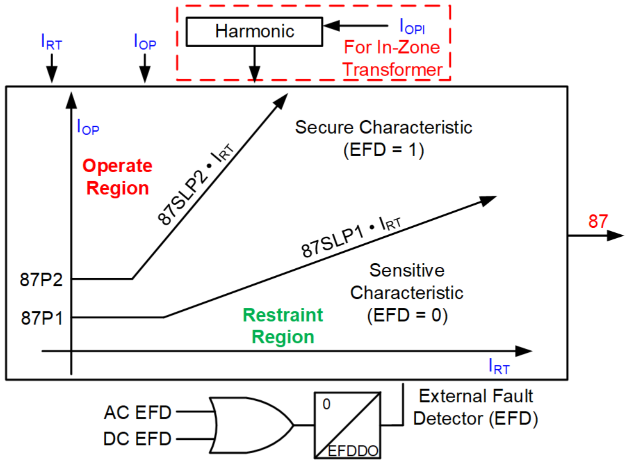

Fig. 3. Characteristic of a differential relay zone.

In Fig. 3, I_{OP} is the operating current and is defined as the phasor sum of all the currents in the zone. I_{OPI} is raw operating current derived from the current samples. I_{RT} is the sum of the current magnitudes comprising the zone. I_{RTI} is the raw restraint derived from the current samples.

The relay has two zones that run every 2.5 ms. A typical application would be to set the first zone to protect the generator and the second zone to protect the transformer. The two approaches used to enhance the security of the differential scheme in Fig. 3 are discussed in this section.

4.1 AC EFD

When an external fault occurs, the restraint current (I_{RT}) current seen by a differential relay is expected to suddenly increase, whereas the operate current (I_{OP}) should not. The scheme shown in Fig. 4 uses this principle and expects CT saturation to not occur immediately [1].

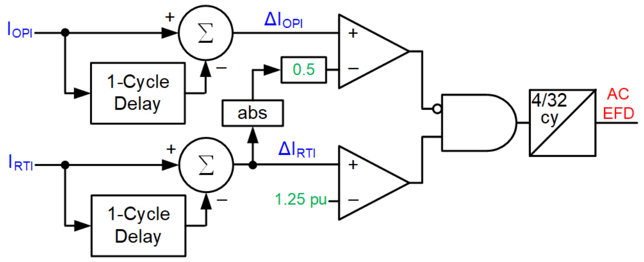

Fig. 4. AC EFD logic.

4.2 DC Saturation

Near generating plants, the system X/R ratio can be large. A high X/R ratio results in a slow decay of any dc in the currents, potentially causing CT saturation. Considering the dc in the currents via logic, such as Fig. 5, provides additional security to the generator differential, particularly for black-start applications where there is a low-side breaker and the generator is required to energize the generator step-up unit (GSU) transformer. Transformer inrush for the 87G element is an external condition and has no primary system contribution to the operate current. However, if the transformer energization is unipolar in nature, as is often the case in two phases, then it also contains a large amount of dc.

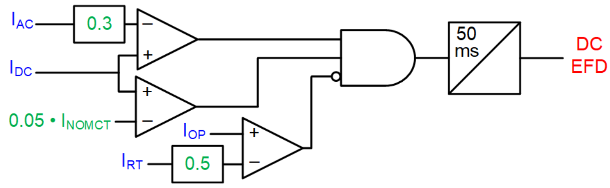

Fig. 5. DC EFD logic.

Over time, the unipolar current builds unidirectional flux in the CTs, resulting in saturation. Even if the CTs respond well, the relay internal CTs may saturate, as shown in Fig. 6. Unequal saturation of the CTs, internal or otherwise, comprising the 87G zone may result in a misoperation.

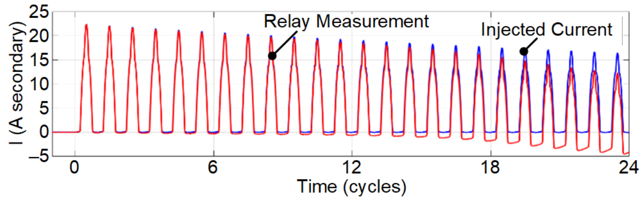

Fig. 6. Relay internal CT response for a unipolar inrush.

5 CT Requirements for 87G and 87T Elements

Using the CT model in Section 3, we evaluated the security limits of the algorithms described in Section 4. For the purpose of testing the differential, we used conservative guidance and assumed that one CT saturates to a degree whereas the other does not. We first modeled the CTs and the relay algorithms to obtain the CT requirements and setting guidance for the relay (Fig. 7a) [5]. Then, we spot-checked the guidance by executing hardware-in-the-loop tests with amplifiers and demagnetizing the CT (Fig. 7b) [6].

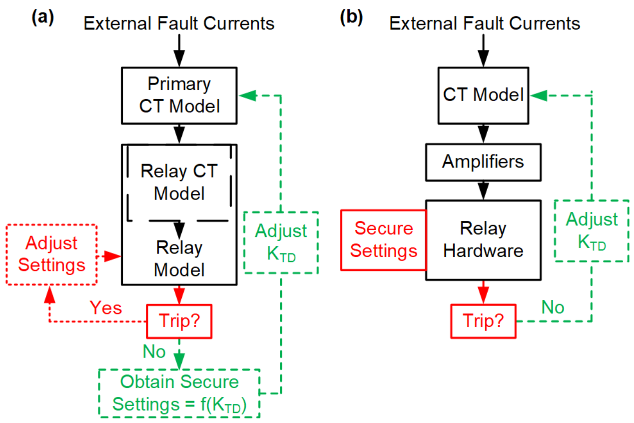

Fig. 7. Determining CT requirements via model (a) and hardware-in-the-loop tests (b).

5.1 CT Ratio

IEEE guidance indicates choosing a CT ratio (CTR) such that the rated secondary current (I_{LOAD}) does not exceed the secondary CT nominal rating (I_{NOM}) with some margin, e.g., 50 percent as shown in (7) [1] [2].

$$CTR_{LOAD} > 1.5 \bullet \left(\frac{I_{LOAD}}{I_{NOM}} \right) \quad (7)$$

For ANSI, there is an additional requirement where maximum symmetrical through-fault current seen by the CT should not exceed 20 times I_{NOM} [2]. This is due to the fixed ALF of 20 used for the C class CT.

During testing, we recognized that the dc offset and remanence also contribute to the ANSI ALF of 20. To account for these contributing factors, the CTR may be calculated via (8).

$$CTR_{FAULT} > (K_{REM} \bullet K_{TD}) \bullet \left(\frac{I_F}{20 \bullet I_{NOM}} \right) \tag{8}$$

The selected CTR is the higher of the two ratios obtained from (7) and (8), as shown in (9). If the CTRs for an application have already been established, the approach in [1] may be used.

$$CTR = \max(CTR_{LOAD}, CTR_{FAULT}) \tag{9}$$

5.2 87G and 87T CT Sizing and Settings

To obtain the CT sizing and setting guidance in this subsection, we used a power system model to apply external faults to the algorithms described in Section 4. The details of the tests are as follows:

- The point-on-wave of fault inception for the external fault was varied from 0 to 360 degrees.
- The system X/R ratio was varied up to 100.
- Both ground and phase faults were applied.
- 87P1 and 87SLP1 were set to 0.10 pu and 10 percent, respectively, to minimize interference with test results.
- The current from the saturated CT was scaled by a factor of 0.95 to add 5 percent margin to the test.
- For each CT size, the 87SLP2 settings were varied from 10 to 90 percent to check the value at which the differential element misoperated.

The CT sizing requirements and corresponding 87SLP2 settings obtained via this procedure are shown in Fig. 8. If the CT is oversized relative to the minimum required size, the 87SLP2 setting may be reduced as shown in Section 7.

In keeping with the IEC definitions [3], the overall selection criteria for sizing a CT is defined as shown in (10).

$$E_{AL} = (K_{REM} \bullet K_{TD}) \bullet \left(\frac{I_F}{N} \right) \bullet (R_B + R_{CT}) \tag{10}$$

The rated voltage for the ANSI CT (V_{ANSI}) may be calculated via (11).

$$V_{ANSI} > (K_{REM} \bullet K_S) \bullet \left(\frac{I_F}{N} \right) \bullet (R_B) \tag{11}$$

Depending on the application, (10) and (11) may result in unreasonably low CT ratings. A lower bound of C100 for ANSI class C CTs and an ALF of 20 for IEC class P CTs is applied. A minimum VA rating of 2.5 for 1 A CTs and 25 for 5 A nominal CTs is also applied. It is important to note that these lower boundaries are unlikely to be a problem due to the turns ratio requirement for generator applications.

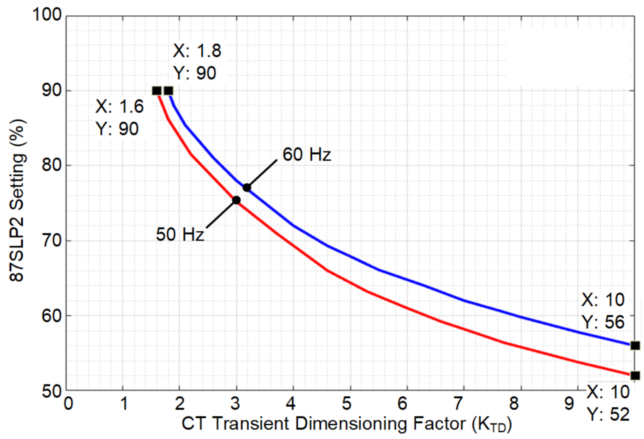

Fig. 8. Application guidance for the differential element without remanence.

87SLP1 may be set to 10 percent to account for errors from steady-state operation or slow transients not associated with CT saturation.

5.3 87G Application Guidance for Black-Start Units

The transient dimensioning factor (K_{TD}) works well for linear currents associated with a power system fault but not for nonlinear currents associated with transformer inrush. We varied the level of inrush currents to stimulate the different algorithms in Section 4.

If the inrush current is high, the ac EFD (Fig. 4) picks up and secures the differential scheme.

For moderate inrush, the ac EFD (Fig. 4) remains deasserted whereas dc EFD (Fig. 5) remains asserted. In this case, the 87P2 setting shown in (12) provides adequate security for the differential element.

$$87P2 = 0.50 \text{ pu} \tag{12}$$

If the inrush current is low, neither ac EFD or dc EFD assert. In such cases, a secure threshold 87P1 shown in (13) provides adequate security [1].

$$87P1 = 0.15 \bullet \left(\frac{I_{NOM}}{I_{LOAD}} \right) \text{pu} \tag{13}$$

6 Conclusion

Security is the paramount property of a protective relay. Relay elements that are susceptible to CT saturation should have simple and easy-to-use application guidance, allowing a clear definition of the security limit for the element. Once the security limit is defined, other performance metrics, such as sensitivity and speed, may be evaluated for a given scheme and application settings.

In this paper, we looked at the similarities and differences between the guidance provided by IEEE and IEC. Both guides provide mechanisms to account for the dc transient during a fault and remanence. Other factors, such as the relay algorithm and hardware, also affect CT requirements.

Using CT models that were validated with a physical CT, along with simulations and hardware-in-the-loop testing, we determined the CT requirements for a generator and transformer differential scheme in a relay. We show that modern relays use algorithms that can drastically reduce CT requirements. Finally, we use the application guidance to size both ANSI and IEC CTs and obtain relay settings for a generator and transformer differential relay for an example generating plant.

7 Appendix

We take the example of Fig. 9 to size an ANSI CT and an IEC CT. The generator is high-impedance grounded, so we do not have to consider ground faults on the low-voltage side. The relevant data for CT sizing are shown in Table 3.

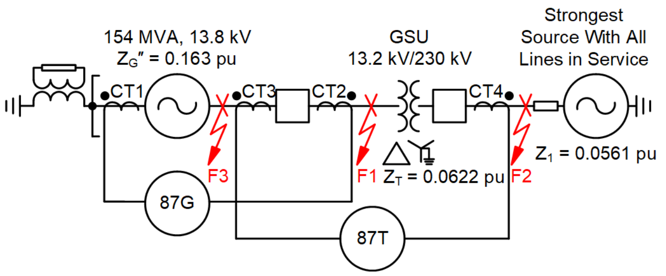

Fig. 9. Example system used to demonstrate CT sizing with all impedances referenced to the generator ratings.

Table 3 Useful data for CT selection

Parameter	Data
Rated current of generator/GSU transformer	6,443/370 A
Generator current for three-phase (3P) fault at F1	39,530 A
GSU current for 3P fault at F2	28,610/1,642 A
Generator and GSU transformer current for single-line-to-ground (SLG) fault at F2	21,770/2,164 A
GSU transformer current for 3P fault at F3 with strongest system connected and all lines in service	54,460/3,126 A

7.1 ANSI CT

We assume 300 feet of 10 AWG wire at 75°C. This gives a one-way lead resistance (R_{LEAD}) of approximately 0.372 Ω. Note that R_B for a 3P fault equals R_{LEAD}, but for an SLG fault it equals 2 • R_{LEAD} [1]. Based on Section 2.3, we assume K_{REM} = 3 and a minimum K_{TD} of 1.8 for the 60 Hz CT with I_{NOM} of 5 A. R_{CT} is assumed to be 2.5 mΩ per turn.

7.1.1 CT1 and CT2 (87G)

Applying (7), (8), and (9) for the parameters of Table 3, we get (14), (15), and (16), respectively. For CT1 and CT2, the worst-case external fault is a 3P fault at F1.

$$CTR_{LOAD} = 2000 > 1933 = 1.5 \bullet 1289 \tag{14}$$

$$CTR_{FAULT} = 2400 > 2135 = 3 \bullet 1.8 \bullet 395.30 \tag{15}$$

$$CTR = 2400 = \max(2000, 2400) \tag{16}$$

The ANSI voltage rating per (11) is shown in (17).

$$V_{ANSI} > (3 \bullet 1.8) \bullet 16.5\text{ A} \bullet 0.372\ \Omega = 33.1\text{ V} \tag{17}$$

A C100 CT is adequate for this application. Once R_{CT} from the CT data sheet is available, we can calculate the effective overdimensioning (K_{S_EFF}) from the applied CT via (18), (19), and (20).

$$V_{SAT\_CT} > 100 + 20 \bullet 5\text{ A} \bullet 6\ \Omega = 700\text{ V} \tag{18}$$

$$V_{SAT} > (3 \bullet 1.8) \bullet 16.5\text{ A} \bullet (0.372\ \Omega + 6\ \Omega) = 567\text{ V} \tag{19}$$

$$K_{S\_EFF} = \left(\frac{700\text{ V}}{566.7\text{ V}}\right) \bullet 1.8 = 2.22 \tag{20}$$

Both CT1 and CT2 correspond to the 87G Zone. Referring to Fig. 8, we select an 87SLP2 setting for 87G of 85 percent.

7.1.2 CT3 (87T)

We apply (9) using the worst-case external fault current for a 3P fault at F3 with I_F = 54,460 A.

$$CTR_{FAULT} = 3000 > 2941 = (3 \bullet 1.8) \bullet 544.60 \tag{21}$$

$$CTR = 3000 = \max(2000, 3000) \tag{22}$$

V_{ANSI} for the CTs per (11) is calculated via (23).

$$V_{ANSI} > (3 \bullet 1.8) \bullet 18.15\text{ A} \bullet 0.372\ \Omega = 36.5\text{ V} \tag{23}$$

A C100 CT is adequate for this application with an effective overdimensioning value shown via (24), (25), and (26).

$$V_{SAT\ CT} > 100 + 20 \bullet 5\text{ A} \bullet 7.5\ \Omega = 850\text{ V} \tag{24}$$

$$V_{SAT} > (3 \bullet 1.8) \bullet 18.15\text{ A} \bullet (0.372\ \Omega + 7.5\ \Omega) = 771.7\text{ V} \tag{25}$$

$$K_{S\_EFF} = \left(\frac{850\text{ V}}{771.7\text{ V}}\right) \bullet 1.8 = 1.98 \tag{26}$$

7.1.3 CT4 (87T)

The maximum current seen by CT4 is for a 3P fault at F3 with I_F = 3,126 A. The CTR is selected via (27), (28), and (29).

$$CTR_{LOAD} = 120 > 111 = 1.5 \bullet 74 \tag{27}$$

$$CTR_{FAULT} = 200 > 169 = 3 \bullet 1.8 \bullet 31.26 \tag{28}$$

$$CTR = 200 = \max(120, 200) \tag{29}$$

The worst-case external 3P fault is at F3 and the worst-case SLG fault is at F2. V_{ANSI} for the 3P and SLG faults are calculated via (30) and (31), respectively.

$$V_{ANSI} > (3 \bullet 1.8) \bullet 15.63\text{ A} \bullet 0.372\ \Omega = 31.4\text{ V} \tag{30}$$

$$V_{ANSI} > (3 \bullet 1.8) \bullet 10.82\text{ A} \bullet (2 \bullet 0.372\ \Omega) = 43.5\text{ V} \tag{31}$$

We choose a C100 CT. Since our CT is oversized, we calculate the overdimensioning via (32), (33), and (34).

$$V_{SAT\_CT} > 100 + 20 \bullet 5\text{ A} \bullet 0.5\ \Omega = 150\text{ V} \tag{32}$$

$$V_{SAT} > (3 \bullet 1.8) \bullet 10.82\text{ A} \bullet (2 \bullet 0.372\ \Omega + 0.5\ \Omega) = 72.7\text{ V} \tag{33}$$

$$K_{S\_EFF} = \left(\frac{150\text{ V}}{72.7\text{ V}}\right) \bullet 1.8 = 3.71 \quad (34)$$

For 87T, the low-voltage CT has a K_{S_EFF} of 1.98 and the high-voltage CT has a K_{S_EFF} of 3.1. We use the lower value (1.98) and refer to Fig. 8 to obtain an 87SLP2 setting for the 87T of 87 percent.

7.2 IEC CT

We assume 100 m of 2.5 mm^2 wire at 75°C. This gives a one-way lead resistance of approximately 0.841 Ω. Note that R_B for a 3P fault equals R_{LEAD}, but for an SLG fault it equals 2 • R_{LEAD}. We size a 50 Hz class P 5P CT with I_{NOM} of 1 A. R_{CT} is assumed to be 6 mΩ per turn. The ALF for the CT may be calculated via (35).

$$ALF = \frac{E_{AL}}{\left(\frac{VA}{I_{NOM\_CT}}\right) + \left(I_{NOM\_CT} \bullet R_{CT}\right)} \quad (35)$$

The VA rating for the application based on Section 2.1 is 0.841 (1A^2 • 0.841 Ω), since all CTs are assumed to have the same lead length. But the minimum VA rating per Section 5.3 is 2.5, so we use that instead.

7.2.1 CT1 and CT2 (87G)

Using (7), we choose a CTR of 10,000:1, resulting in an R_{CT} = 60 Ω. E_{AL} per (10) and ALF per (35) are calculated via (36) and (37), respectively.

$$E_{AL} > (5 \bullet 1.6) \bullet 3.953\text{ A} \bullet \left(0.841\,\Omega + 60\,\Omega\right) = 1924\text{ V} \quad (36)$$

$$ALF = \frac{1924}{2.5 + 60} = 30.78 \quad (37)$$

Choosing the next highest ALF, we select a 2.5 VA 5P 40 CT for this application. The effective K_{TD} is calculated via (38).

$$K_{TD\_EFF} = \left(\frac{40}{30.78}\right) \bullet 1.6 = 2.08 \quad (38)$$

We look at Fig. 8 for an 87SLP2 setting of 83 percent.

7.2.2 CT3 (87T)

Using (7), we choose a CTR of 10,000:1 with R_{CT} = 60 Ω. E_{AL} per (10) and ALF per (35) are calculated via (39) and (40), respectively. The worst-case fault current is the 3P fault at F3.

$$E_{AL} > (5 \bullet 1.6) \bullet 5.4460\text{ A} \bullet \left(0.841\,\Omega + 60\,\Omega\right) = 2651\text{ V} \quad (39)$$

$$ALF = \frac{2651}{2.5 + 60} = 42.41 \quad (40)$$

A 2.5 VA 5P 50 CT is adequate for this application. We get an effective K_{TD} via (41).

$$K_{TD\_EFF} = \left(\frac{50}{42.41}\right) \bullet 1.6 = 1.89 \quad (41)$$

7.2.3 CT4 (87T)

Using (7), we choose a CTR of 600:1 with R_{CT} = 3.6 Ω. The worst-case three-phase external fault and SLG fault are at F2. The E_{AL} for both fault types and the ALF can be found via (42), (43), and (44).

$$E_{AL} > (5 \bullet 1.6) \bullet 5.21\text{ A} \bullet \left(0.841\,\Omega + 3.6\,\Omega\right) = 185.1\text{ V} \quad (42)$$

$$E_{AL} > (5 \bullet 1.6) \bullet 3.6\text{ A} \bullet \left(2 \bullet 0.841\,\Omega + 3.6\,\Omega\right) = 152.4\text{ V} \quad (43)$$

$$ALF > \frac{185.1}{2.5 + 3.6} = 30.3 \quad (44)$$

A 2.5 VA 5P 40 CT may be used for this application. We get an effective K_{TD} shown in (45).

$$K_{TD\_EFF} = \left(\frac{40}{30.3}\right) \bullet 1.6 = 2.1 \quad (45)$$

For 87T, the low-voltage CT has a K_{TD_EFF} of 1.89 and the high-voltage CT has a K_{TD_EFF} of 2.1. We use the lower value (1.89) and refer to Fig. 8 to obtain an 87SLP2 setting for the 87T of 85 percent.

8 References

[1] Chowdhury, R., Finney, D., Fischer, N., et al.: "Determining CT Requirements for Generator and Transformer Protective Relays," proceedings of the 46th Annual Western Protective Relay Conference, Spokane, WA, October 2019.

[2] IEEE C37.110-2007, IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes.

[3] IEC TR 61869-100:2017, Guidance for Application of Current Transformers in Power System Protection.

[4] Zocholl, S. E., Smaha, D. W.: "Current Transformer Concepts," proceedings of the 46th Annual Georgia Tech Protective Relaying Conference, Atlanta, GA, April 1992.

[5] Garrett, R., Kotheimer, W. C., Zocholl, S. E.: "Computer Simulation of Current Transformers and Relays for Performance Analysis," proceedings of 14th Annual Western Protective Relay Conference, Spokane, WA, October 1988.

[6] *Real Time Digital Simulator - Power System User's Manual, Section 7.2: Current Transformers*, RTDS Technologies, Inc., Winnipeg, Canada, December 2013.

[7] Neves, W. L. A., Dommel, H. W.: "On Modelling Iron Core Nonlinearities," *IEEE Transactions on Power Systems*, Vol. 8, Issue 2, May 1993, pp. 417−425.

[8] IEEE Power System Relaying and Control Comm., "CT Saturation Theory and Calculator," 2003. Available: http://www.pes-psrc.org/kb/published/reports.html.

[9] Kasztenny, B., Taylor, D., Fischer, N.: "Impact of Geomagnetically Induced Currents on Protection Current Transformers," proceedings of the 13th International Conference on Developments in Power System Protection, Edinburgh, UK, March 2016.

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