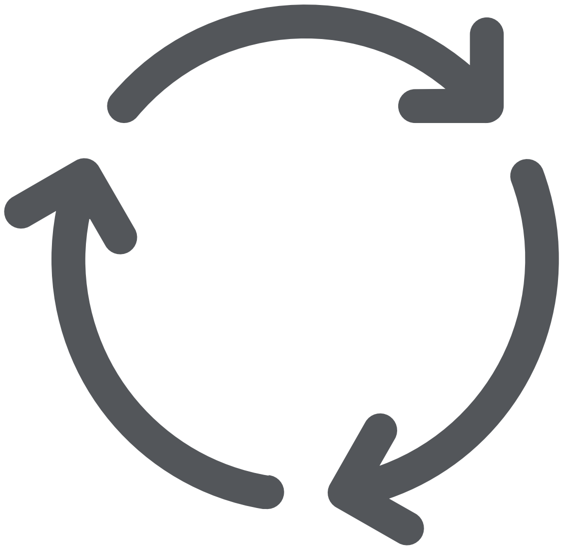
CT selection for Arcteq relays



Contents

Revision	1.0
Date	3 April 2023
Changes	• The first revision of the application note.
Revision	1.1
Date	4 August 2023
Changes	• Added the revision table. • Added the "Introduction" chapter. • Added the "Definitions" chapter. • Added the "Dimensioning CTs for line differential protection" chapter.

1 Introduction

Current transformer selection is an important part of a complete protection system design. A current transformer (CT) must be able to measure currents according to the application's needs in all situations. Specifying current transformers is sometimes challenging because it requires a lot of detailed data: the wiring impedance, the protection functions and their setting thresholds, the protected equipment as well as the background network. It also requires knowledge about different available CT characteristics. If CT selection is done incorrectly, it may lead to unselective protection or damage to the protection devices and the protected equipment:

- Overestimating the short-circuit current can lead to feasibility problems, overrating, and high CT costs.
- Underestimating the short-circuit currents can lead to a failure to detect a fault, thus destroying the equipment, placing the operator in danger, and causing operation downtime.
- An output power or an accuracy error can result in a malfunction or in a failure to trip the protection devices, thus destroying the equipment, placing the operator in danger, and causing operation downtime.
- An error in defining the accuracy class of a metering winding will lead to incorrect energy billing and thus a loss of income for the electrical utility or the customer.

2 Definitions

2.1 General definitions according to IEC 61869-2: 2012

Current transformer

An instrument transformer in which the secondary current, under normal conditions of use, is substantially proportional to the primary current and differs in phase from it by an angle which is approximately zero for an appropriate direction of the connections. [1, p. 8]

Current transformers are defined by their ratio, power, and accuracy class. Their class is selected according to the application.

Measuring current transformer

A current transformer intended to transmit an information signal to measuring instruments and meters. [1, p. 8]

This type of CT requires a good accuracy around the nominal current value. Measuring instruments do not need to withstand currents as high as protection relays do; for this reason, current transformers have the lowest possible safety factor (SF) to protect the measuring instruments through earlier saturation.

Protective current transformer

A current transformer intended to transmit an information signal to protective and control devices. [1, p. 8] Protective current transformers have various classes: P, PR, PX, PXR, TPX, TPY, and TPZ. Please see [1, pp. 8—9] for their specific definitions.

Protection current transformers must saturate sufficiently high to allow a relatively accurate measurement of the fault current by the protection relay whose operation threshold can be set to a very high value. Therefore, protection current transformers are usually expected to have a high accuracy limit factor (ALF). Please keep in mind that the protection relay must also be able to withstand these high secondary current values.

2.2 Definitions related to CT selection and dimensioning

ε	safety margin
ε_c	current error (at nominal current)
ω	network angular frequency
E_{al}	rated equivalent limiting secondary e.m.f.
i	number of CT circuits
$I_{d,int}^{peak}$	peak internal differential current
I_e	CT exciting peak current
$I_{e,k}^{RMS}$	exciting current (at CT knee point voltage)
I_f	differential current flow
I_{fC}	total primary fault current through the CT
$I_{f,ext}^{RMS}$	through fault secondary current
$I_{f,int}^{RMS}$	internal fault current
I_{load}	load secondary current
I_n^{RMS}	CT nominal current
I_{pr}	CT rated primary current
I_{SET}	setting current
$I_{SET}^{CT\ fail.}$	CT failure setting current
I_{sr}	CT rated secondary current
I_{ST}	stabilizing current
K_{rem}	remanence dimensioning factor
K_{ssc}	rated symmetrical short-circuit current factor
K_{td}	rated transient dimensioning factor
K_{tfmax}	maximum individual transient total over-dimensioning factor
K'_{tfmax}	maximum overall transient total over-dimensioning factor
K_{tot}	total over-dimensioning factor
$L1$	reactance of the positive sequence impedance for a three-phase fault in Zone 1
L_{pe}	reactance of the positive sequence impedance for a phase-to-earth fault
n	number of CTs parallel with the relay

n_{ALF}	accuracy limit factor
P_n	CT rated burden
P_{ST}	stabilizing resistor power rating
p_{ST}^{co}	continuous power rating
p_{ST}^{sh}	short time (≈ 1 s) power rating
$R1$	resistance of the positive sequence impedance for a three-phase fault in Zone 1
R_{addbu}	total additional burden
R_b	CT rated burden resistance
R_{ba}	total resistive burden
R_{CT}	CT secondary winding resistance
R_L	connection lead resistance
R_{pe}	resistance of the positive sequence impedance for a phase-to-earth fault
R_{ST}	stabilizing resistor
R_w	resistance in the secondary wire
$\frac{R}{S'}$	highest expected remanence value related to the saturation point
T	periodic time
$t_{delay}^{CT\ fail.}$	delay for CT failure detection
T_p	primary time constant
t_{sat}	time interval between the current's zero cross and the CT saturation start
V	MOV voltage (= the voltage across the stabilizing resistor)
$V_{f,ext}^{i}$	peak voltage
V_k^{RMS}	CT knee point voltage
V_{ST}	stabilizing voltage
$X1$	reactance of the positive sequence impedance for a three-phase fault in Zone 1
X_{pe}	reactance of the positive sequence impedance for a phase-to-earth fault in Zone 1
Z	positive sequence impedance
$Z0$	zero-sequence impedance
Z_{pe}	impedance of a phase-to-earth fault

3 HIGH-IMPEDANCE DIFFERENTIAL PROTECTION

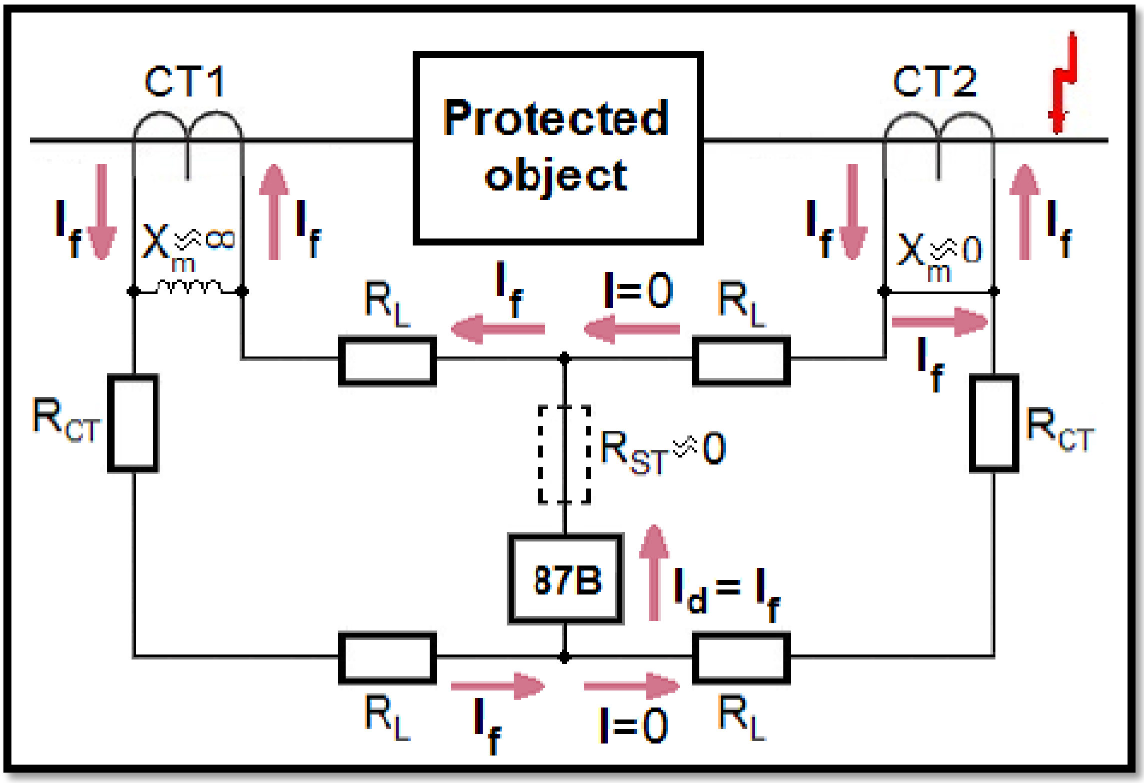
3.1 General

High-impedance differential protection can detect faults on busbars or on transformer windings. The basic principle can be explained by an object with two ends, as in ***Figure 3-1*** on the following page. On the secondary side the current transformers (CTs) are all connected in parallel to the stabilizing resistor (R_{ST}). A sensitive current relay is connected in series to the stabilizing resistor. It is common to use a non-linear resistor (MOV) across the differential branch. All CTs must have the same ratio and construction.

During external faults, ideal current transformers (that is, CT saturation does not occur) do not have current flowing through the differential branch, which means that the current relay does not operate. The worst case scenario, on the other hand, occurs when only one CT is completely saturated during the whole fault period while the other is not saturated at all. Of course, one can have three or more ends with non-saturated CTs.

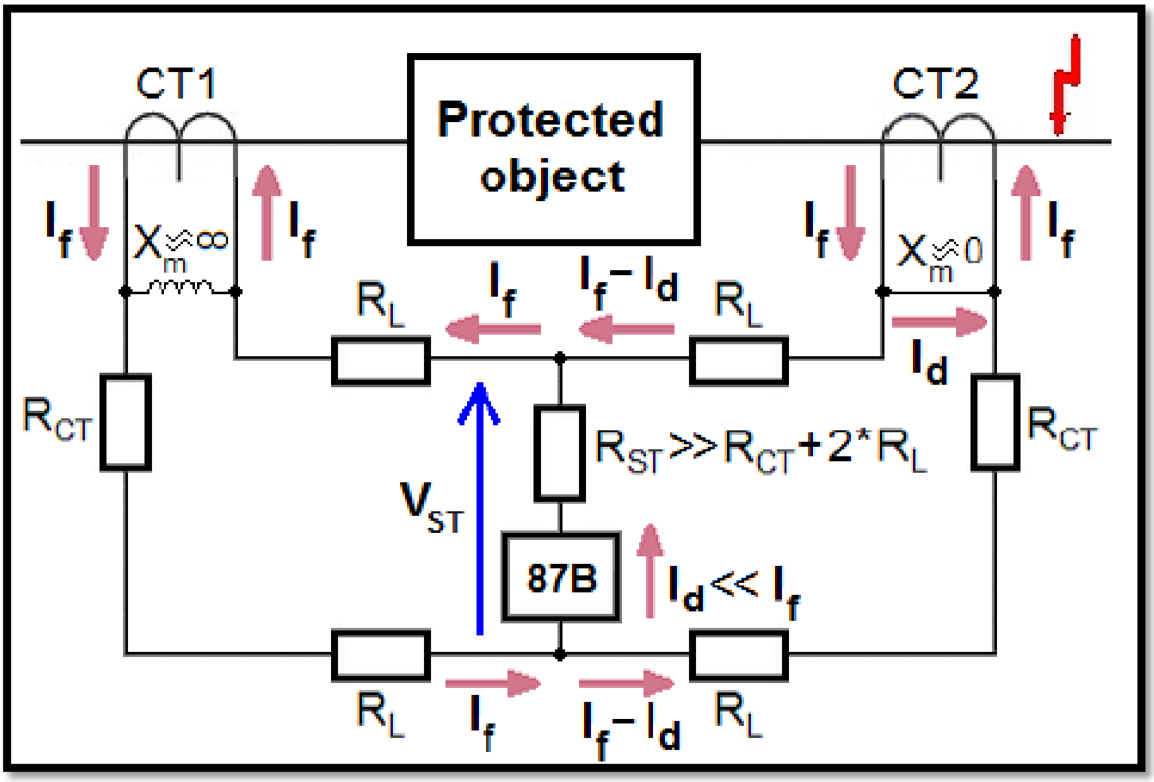
In the examples of this chapter these other ends are concentrated in one end, specifically the end with the CT named "CT1". In the first example, the stabilizing resistor is negligibly small and is actually the low-impedance differential protection (***Figure 3-1*** on the next page). In this scenario the magnetizing inductance of the saturated CT decreases nearly to zero, while the differential branch completely misses the higher exciting current. This results in significant differential current flows (I_f) and the relay must therefore be set carefully to avoid any false operations.

Figure 3-1: Low-impedance differential protection ($R_{ST} \approx 0$).



In the second example, the stabilizing resistor is high compared to the sum of the CT secondary winding resistance (R_{CT}) and the connection lead resistances ($2 \times R_L$). This means that nearly all of the fault current flows through the connection leads instead of the differential branch (***Figure 3-2*** on the following page). The stabilizing voltage (V_{ST}) across the differential branch can be used for setting the current relay.

Figure 3-2: High-impedance differential protection ($R_{ST} >> R_{CT} + 2*R_L$).



During an internal fault, all of the CT's currents flow in the same direction (***Figure 3-3*** on the following page). As the sum of these currents flows into the differential branch, there may be a high potential rise in the stabilizing resistor, and this can cause a fast saturation in the CTs. The MOV, used to limit the peak voltage to a value below the insulation levels of the CTs and the stabilizing resistor, can also operate during an internal fault. This means that the differential current is highly distorted. Due to the non-linear behavior of the CTs and the MOV, a special differential current measurement is also required. Arcteq uses a special hardware for these measurements: the current measurement module can detect the peaks of the differential currents.

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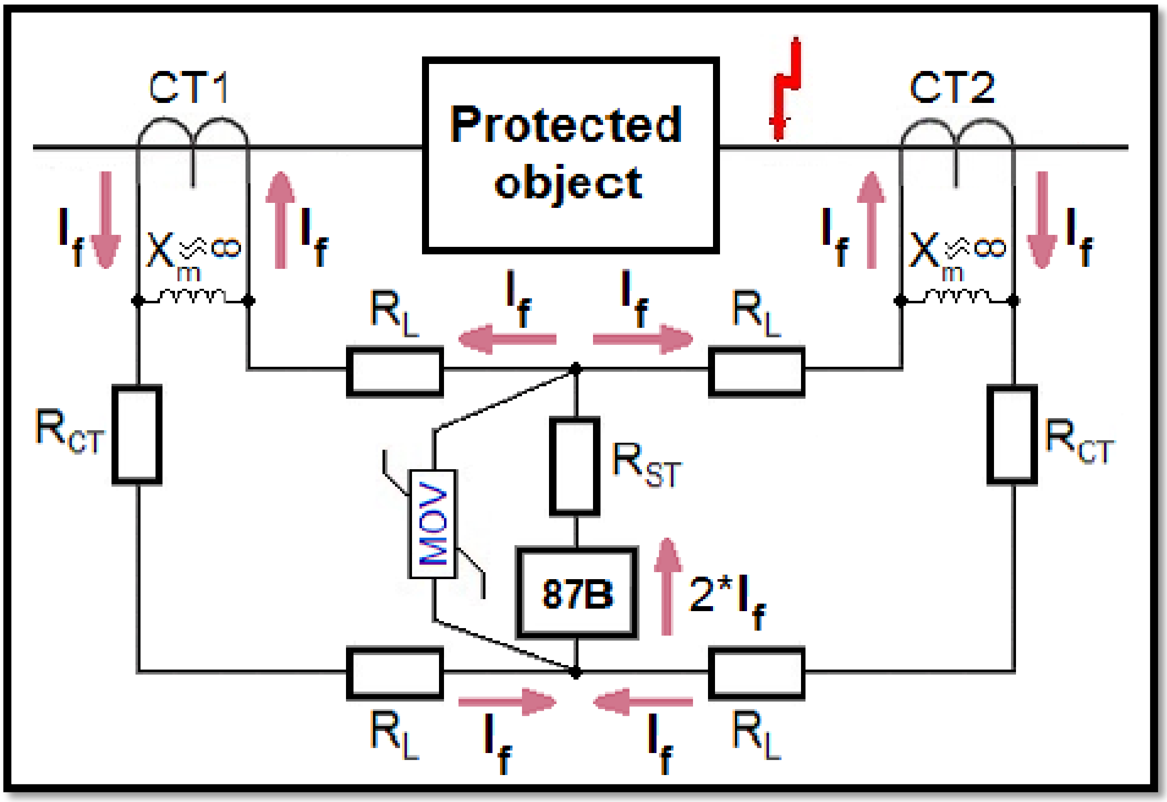
Figure 3-3: High-impedance differential protection (internal fault).



This document presents the principles of high-impedance differential protection and introduces an example to show how to set the relay as well as how to choose the appropriate stabilizing resistor (and the MOV if one is required).

As the setting procedure includes many calculations and requirements, there is a Microsoft Excel software available to help all the users to go through the whole process (see Chapter 3.4, "Using the pre-filled Excel file for calculations").

3.2 Setting procedure

The calculations must be done in the following order:

1. Calculation of the stabilizing voltage (V_{ST})
2. Calculation of the CT knee point voltage (V_k^{RMS})

3. Selection of the stabilizing resistor (R_{ST})
4. Calculation of the setting current (I_{SET})
5. Requirement for the CT knee point voltage
6. The stabilizing resistor power rating (P_{ST})
7. Deciding whether to use an MOV
8. (If the MOV is used) Requirements for the MOV values (C, β)
9. Detection of a CT open circuit (CT failure)

3.2.1 Calculation of the stabilizing voltage (V_{ST})

During external faults, the main goal is to avoid false operations. To reach this goal, it is necessary to calculate the possible maximum voltage of the stabilizing resistor when an external fault occurs. Please note that when calculating this voltage, you must consider the worst case scenario as presented previously in ***Figure 3-2*** (on p. 11). We know that the voltage across the differential branch is at its highest when the stabilizing resistor (R_{ST}) is much greater than the secondary circuit resistance ($R_{CT} + 2 \times R_L$), which results in a negligible differential current. The other conditions to consider are the following:

- One CT is completely saturated during the whole period ($X_m \approx 0$).
- Other CTs are not saturated at all ($X_m \approx \infty$).
- The decaying DC component of the maximum through fault is the highest.
- The primary time constant is almost infinite ($T_p \approx \infty$).
- The leakage current of the MOV can also be neglected.

The maximum voltage depends on the maximum through fault current ($I_{f,ext}^{RMS}$) and the secondary circuit resistance. The secondary circuit resistance value must include the CT secondary winding resistance (R_{CT}) as well as the connection lead resistance (R_L) between the CT and the relay. Please note that the connection lead resistance must be considered twice because of the back and forth direction!

In this example the complete fault current flows through the secondary circuit resistance. Therefore, the stabilizing resistor voltage is equal to the fault current multiplied by the secondary current resistance. Because the secondary circuit resistances are different in all CT circuits, the peak voltage calculation must be performed for all these circuits with **Equation (3-1)**:

$$V_{f,ext}^{i} = 2 \times \sqrt{2} \times I_{f,ext}^{RMS} \times \left(R_{CT} + 2 \times R_{L}^{i}\right) \tag{3-1}$$

where:

- $I_{f,ext}^{RMS}$ = the maximum through fault secondary current
- R_{CT} = the CT secondary winding resistance
- i = the number of CT circuits (1, 2, ..., *n*)
- R_L = the connection lead resistance between the CT and the relay.

As noted previously, the stabilizing voltage must be higher than the maximum of all peak voltage calculations. The stabilizing voltage is calculated with **Equation (3-2)**:

$$V_{ST} = (1 + \varepsilon) \times MAX\{V_{f,ext}^{i}\} \tag{3-2}$$

where:

- ε = the safety margin (ε = 0.15)
- $V_{f,ext}^{i}$ = the peak voltage calculation for each CT circuit (i = 1, 2, ..., *n*).

3.2.2 Calculation of the CT knee point voltage (V_k^{RMS})

During an internal fault, the CT saturation has a leading effect on the distortion of the differential current. The knee point voltage is not always given by the manufacturers, and in these situations, you have to estimate an equivalent knee point voltage.

The manufacturer usually tells the CT's nominal current (I_n^{RMS}) and its accuracy limit factor (n_{ALF}) in their specifications, where the CT's error is also named precisely. For example, a CT with an accuracy class "5P10" means that the CT has a 5 % error at $10 \times I_n^{RMS}$, while the accuracy limit factor is 10. A CT manufacturer usually also includes the following additional information: the CT's rated burden resistance (R_b) and its

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secondary winding resistance (R_{CT}). The CT knee point voltage can be estimated with **Equation (3-3)**:

$$V_k^{RMS} = n_{ALF} \times I_n^{RMS} \times (R_{CT} + R_b) \quad \textbf{(3-3)}$$

where:

- n_{ALF} = the CT accuracy limit factor
- I_n^{RMS} = the CT nominal secondary current
- R_{CT} = the CT secondary winding resistance
- R_b = the rated burden resistance.

The rated burden resistance, in turn, is calculated with **Equation (3-4)**:

$$R_b = P_n / I_n^2 \quad \textbf{(3-4)}$$

where:

- P_n = the CT rated burden
- I_n = the CT nominal current.

3.2.3 Selection of the stabilizing resistor (R_{ST})

The selection of a stabilizing resistor depends on the minimum internal fault current ($I_{f,MINint}^{RMS}$). To ensure that the selected stabilizing resistor can sense all internal faults, the stabilizing current (I_{ST}) must be calculated and its value must be below the peak of the minimum internal fault current. The differential branch does not see all of the CT exciting peak currents (I_e), and therefore the exciting currents at stabilizing voltage must be subtracted from the minimum internal fault current. The leakage current of the MOV (at V_{ST}) can be neglected. The stabilizing current is calculated with **Equation (3-5)**:

$$I_{ST} = (1 - \varepsilon) \times \sqrt{2} \times I_{f,MINint}^{RMS} - n \times I_e \quad \textbf{(3-5)}$$

where:

- ε = the safety margin (ε = 0.15)
- $I_{f,MINint}^{RMS}$ = the minimum internal fault secondary current
- n = the number of CTs parallel with the relay
- I_e = the CT exciting peak current at the stabilizing voltage (V_{ST}, see ***Figure 3-4*** on the following page).

Please note that the exciting peak current is calculated with **Equation (3-6)**:

$$I_e = V_{ST} \times \frac{I_{e,k}^{RMS}}{V_k^{RMS}} \qquad \textbf{(3-6)}$$

where:

- V_{ST} = the stabilizing voltage
- $I_{e,k}^{RMS}$ = the exciting current at the CT knee point voltage (V_k^{RMS})
- V_k^{RMS} = the CT knee point voltage.

If the CT excitation characteristic is not given by the CT manufacturer, you must estimate the missing current at the stabilizing voltage. The CT accuracy class (5P, 10P, or X) is always presented in manufacturer specifications! If CTs of accuracy class 5P or 10P are implemented, then the current error (ε_c) at the nominal current can be determined. The error limits for the standard CT accuracy classes are defined by the IEC-61869-2 standard ([1], p. 23) as follows:

- A maximum of 1 % at rated primary current (Class 5P).
- A maximum of 3 % at rated primary current (Class 10P).

The excitation curve is expected to be linear between 0 and the CT knee point voltage (***Figure 3-4***). The current error is therefore also linear below the knee point voltage value. The missing exciting current can be estimated with **Equation (3-7)**:

$$I_e = n_{ALF} \times \frac{\varepsilon_c}{100} \times \frac{I_n^{RMS}}{V_k^{RMS}} \times V_{ST} \qquad \textbf{(3-7)}$$

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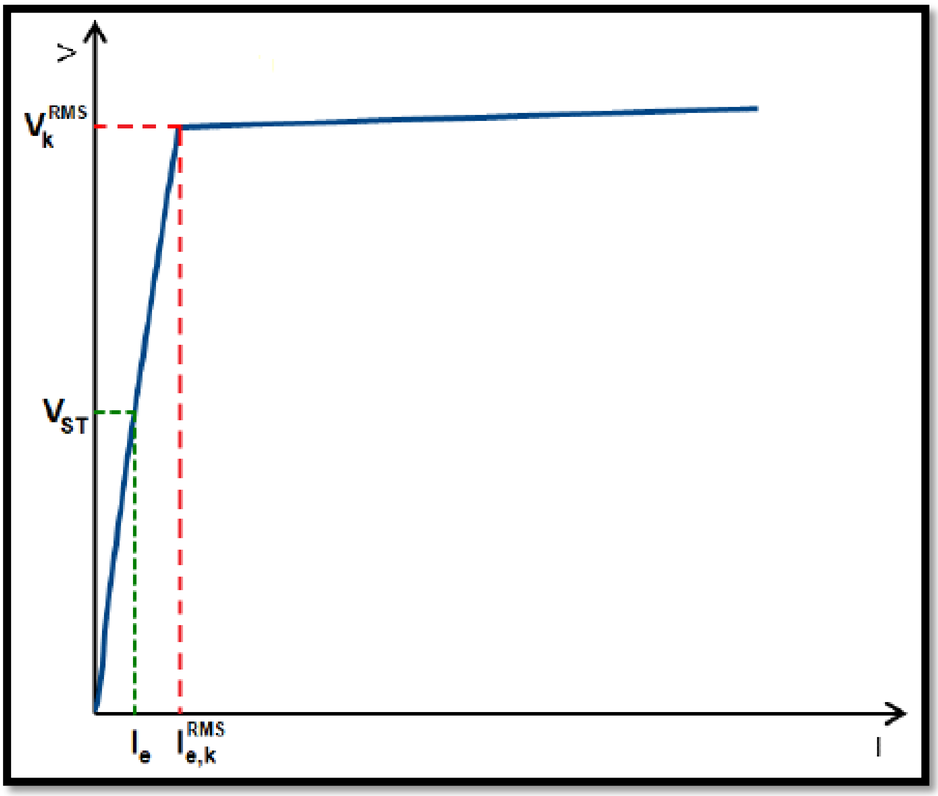
where:

- n_{ALF} = the CT accuracy limit factor
- I_n^{RMS} = the CT nominal secondary current
- ε_c = the CT current error at the nominal current (I_n)
- V_{ST} = the stabilizing voltage
- V_k^{RMS} = the CT knee point voltage.

Figure 3-4: CT exciting peak current at V_{ST}.



If the accuracy class of the implemented CTs is X, the maximum exciting current ($I_{e,k}^{RMS}$) at the rated CT knee point voltage (V_k^{RMS}) is always mentioned in the manufacturer specifications as per the IEC 61869-2 standard ([1], p. 24—25). The exciting current at the stabilizing voltage can therefore be calculated according to **Equation (3-7)** on the previous page.

Please note that the result of the calculated stabilizing current (**Equation (3-5)**) can be negative, when the sum of the exciting currents is higher than the minimal internal fault current. This means that the CT's magnetizing branch impedance is too small and therefore the voltage across the stabilizing resistor Is lower than the stabilizing voltage during a minimal internal fault. When this is the case, the relay cannot operate. This situation has two acceptable solutions:

- You can try to reduce the connection lead resistance (R_L), so the stabilizing voltage (V_{ST}) will decrease (**Equation (3-1)**).
- You can select other CTs with better accuracy classes (e.g., class 5P instead of class 10P), or you can also select other CTs with a higher rated burden (e.g., 15 VA instead of 5 VA).

The possible resistance value can be determined by dividing the stabilizing voltage with the stabilizing current. The stabilizing resistor must be selected according to the following **Equation (3-8)**:

$$R_{ST} \geq \frac{V_{ST}}{I_{ST}} \quad \textbf{(3-8)}$$

where:

- V_{ST} = the stabilizing voltage
- I_{ST} = the stabilizing current.

Additionally, the value of the selected resistor must be greater than the calculated quotient. It is also recommended to select a resistor which as close as possible to the result of V_{ST}/I_{ST}.

3.2.4 Calculation of the relay's setting current (I_{SET})

Once you have selected an appropriate stabilizing resistor, the relay's setting current must be set. This is simple to calculate with **Equation (3-9)**:

$$I_{SET} = \frac{V_{ST}}{R_{ST}} \qquad \textbf{(3-9)}$$

where:

- V_{ST} = the stabilizing voltage
- R_{ST} = the stabilizing resistance.

If the calculated value for the setting current cannot be exactly set in the relay, please use a higher current value that is as close as possible to the result of V_{ST}/R_{ST}.

3.2.5 Requirement for the CT knee point voltage

The CTs can be highly saturated during internal faults because the whole fault current flows through the selected stabilizing resistor (see ***Figure 3-3***, p. 12). The voltage drop in the resistance of the secondary circuit can be ignored as the stabilizing resistance is much greater than the secondary circuit resistance. The voltage in the CT is therefore equal to the internal fault current multiplied by the stabilizing resistance.

CT saturation can cause significant distortion in the differential current even during a minimal internal fault. It is therefore important to have a suitable CT knee point voltage where the CT saturation occurs after the relay has been able to sense a minimum internal fault (***Figure 3-5*** on the following page). If the CT saturation occurs after the primary internal fault current has reached its maximum, the selected relay setting current is sufficient to sense the minimum internal fault (see Chapter 3.2.4 above). The CT knee point voltage requirement is calculated with **Equation (3-10)**:

$$V_k^{RMS} \geq 0.5 \times I_{f,MINint}^{RMS} \times R_{ST} \qquad \textbf{(3-10)}$$

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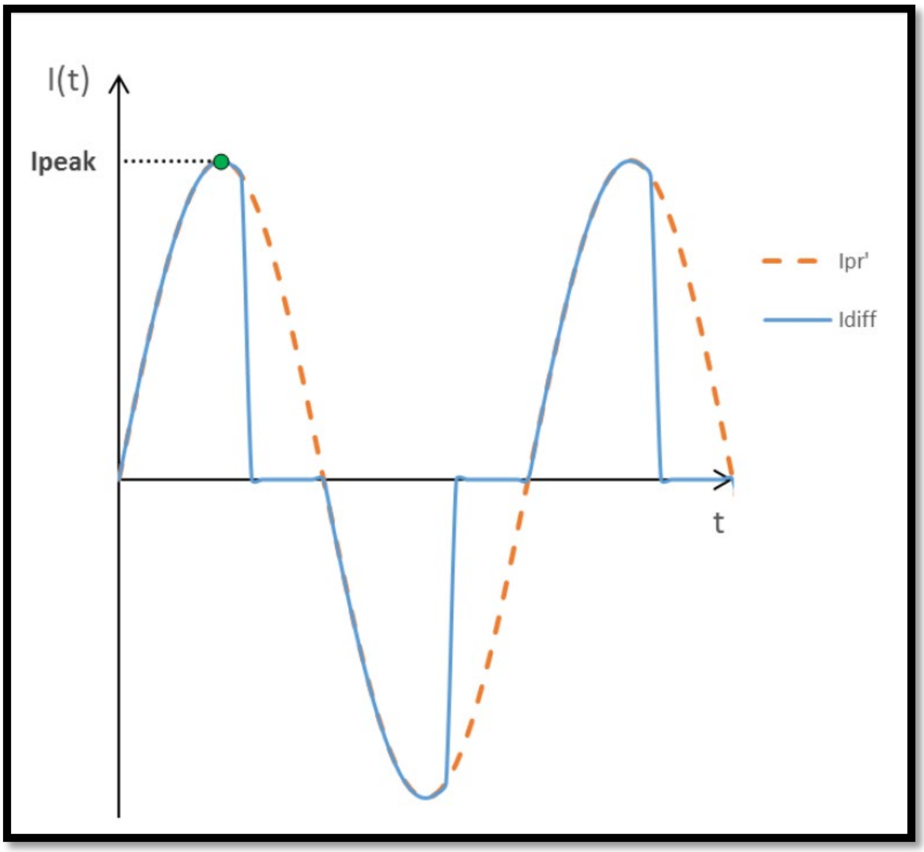
where:

- $I_{f,MINint}^{RMS}$ = the minimum internal fault secondary current
- R_{ST} = the stabilizing resistance.

Figure 3-5: Current transformers during a minimum internal fault.



If the CT knee point voltage does not meet the voltage requirement, you have four (4) possible solutions to consider:

1. You can select a lower stabilizing resistance (R_{ST}) but one that is still above V_{ST}/I_{ST}. Please note that in this case you must calculate the relay's setting current (I_{SET}) again.

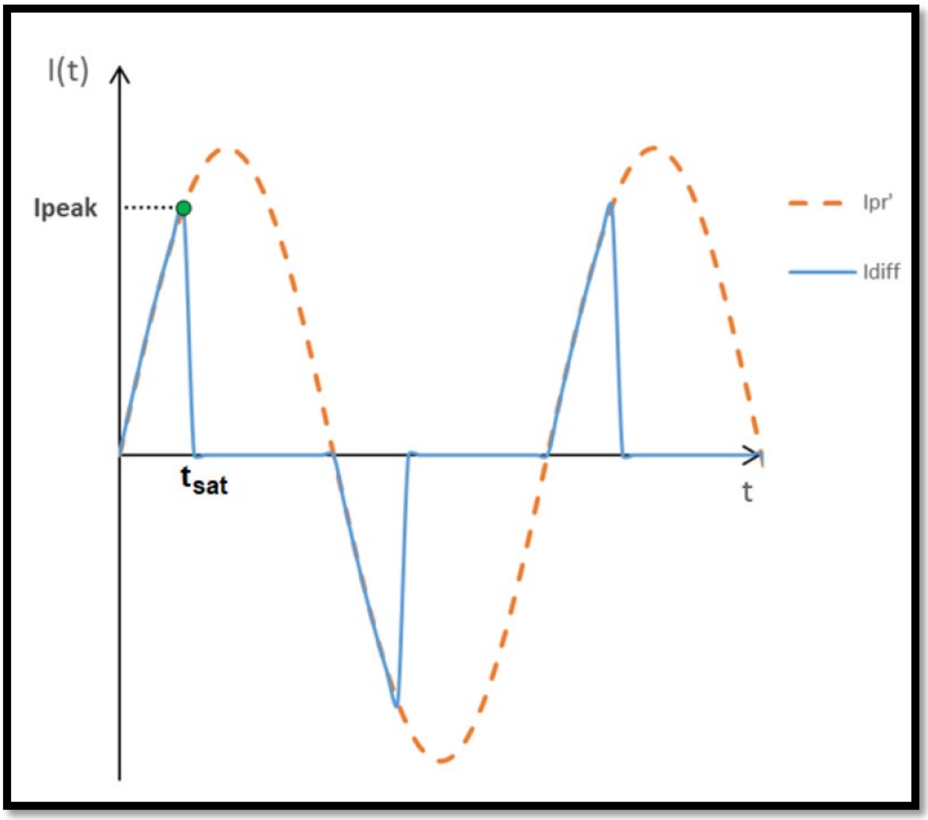
2. You can select another type of connection lead that has a lower resistivity (ρ) or a larger cross-sectional area (A). This will decrease the resistance because $R_L = \rho \times I/A$.
3. You can choose to perform a special calculation method to check the current sensitivity for a minimum internal fault. See Chapter 3.5 for instructions on this method.
4. You can use other CTs with a higher knee point voltage.

3.2.6 The stabilizing resistor power rating (P_{ST})

During internal faults all of the fault current flows through the selected stabilizing resistor until CT saturation occurs. The power of the stabilizing resistor depends on the fault current raised to the power 2 as well as the stabilizing resistance. The power is therefore the highest when the current is the highest (that is, there is a maximum internal fault current $I_{f,MAXint}^{RMS}$).

If the CTs are not saturated, the whole fault current flows through the stabilizing resistor. If the CTs are saturated, however, just a part of the current flows through the stabilizing resistor (***Figure 3-6*** on the following page). It is therefore necessary to calculate the effective value of the maximum internal fault current. The continuous power rating must also be determined. Both the network angular frequency ($\omega = 2 \times n \times f$) and the periodic time ($T = 1/f$) are known. All power rating calculations assume that the MOV is not connected to the stabilizing resistor.

Figure 3-6: Distorted differential current.



If the CT knee point voltage is equal to or greater than the product of the maximum internal fault secondary current and the stabilizing resistor (that is, $V_k^{RMS} \geq I_{f,MAXint}^{RMS} \times R_{ST}$), the short time (short ≈ 1 s) power rating is calculated with **Equation (3-11)**:

$$p_{ST,highCT}^{sh} = \left(I_{f,MAXint}^{RMS}\right)^2 \times R_{ST} \quad \textbf{(3-11)}$$

where:

- $I_{f,MAXint}^{RMS}$ = the maximum internal fault secondary current
- R_{ST} = the stabilizing resistor.

However, if the product is lower than the CT knee point voltage ($V_k^{RMS} < I_{f,MAXint}^{RMS} \times R_{ST}$), the short time (short ≈ 1 s) power rating is calculated with **Equation (3-12)**:

$$P_{ST,lowCT}^{sh} = \left(I_{f,MAXint}^{RMS} \times \sqrt{2 \times \frac{t_{sat}}{T} - \frac{\sin(2 \times \omega \times t_{sat})}{2\pi}} \right)^2 \times R_{ST} \quad \textbf{(3-12)}$$

where:

- $I_{f,MAXint}^{RMS}$ = the maximum internal fault secondary current
- R_{ST} = the stabilizing resistor
- T = periodic time (usually 0.02 s)
- ω = the angular frequency (usually 314.159 rad/s)
- t_{sat} = the time interval between the zero cross of the current and the beginning of CT saturation.

The time interval mentioned above is calculated with **Equation (3-13)**; please note that the result of *cos*$^{-1}$ must be in radian:

$$t_{sat} = \frac{1}{\omega} \times \cos^{-1}\left(1 - \frac{2 \times V_k^{RMS}}{I_{f,MAXint}^{RMS} \times R_{ST}}\right) \quad \textbf{(3-13)}$$

where:

- ω = the angular frequency (usually 314.159 rad/s)
- V_k^{RMS} = the CT knee point voltage
- $I_{f,MAXint}^{RMS}$ = the maximum internal fault secondary current
- R_{ST} = the stabilizing resistor.

The continuous power rating is calculated with **Equation (3-14)**:

$$P_{ST}^{co} = \left(\frac{I_{SET}}{\sqrt{2}}\right)^2 \times R_{ST} \quad \textbf{(3-14)}$$

where:

- I_{SET} = the relay's setting current
- R_{ST} = the stabilizing resistor.

3.2.7 Deciding whether to use an MOV

Before selecting an MOV, you must calculate the highest peak voltage on the stabilizing resistor without an MOV. This is done because an MOV is not always required. During internal faults, the voltage is the highest when the internal fault current is the highest, which means that the calculation is needed to check the maximum peak voltage. You must also consider the CT saturation. The calculation assumes that an MOV is not connected to the circuit.

If the CT knee point voltage is equal to or greater than the product of the maximum internal fault secondary current and the stabilizing resistor ($V_k^{RMS} \geq 0.5 \times I_{f,MAXint}^{RMS} \times R_{ST}$), the peak voltage can be calculated from **Equation (3–15)**:

$$V_{max,highKPV} = \sqrt{2} \times I_{f,MAXint}^{RMS} \times R_{ST} \qquad \textbf{(3–15)}$$

where:

- $I_{f,MAXint}^{RMS}$ = the maximum internal fault secondary current
- R_{ST} = the stabilizing resistor.

However, if $V_k^{RMS} < 0.5 \times I_{f,MAXint}^{RMS} \times R_{ST}$, the peak voltage is calculated from **Equation (3–16)**; please note that the calculation must be performed in radians:

$$V_{max,lowKPV} = \sqrt{2} \times I_{f,MAXint}^{RMS} \times R_{ST} \times \sin(\omega \times t_{sat}) \qquad \textbf{(3–16)}$$

where:

- $I_{f,MAXint}^{RMS}$ = the maximum internal fault secondary current
- R_{ST} = the stabilizing resistor
- ω = the angular frequency (usually 314.159 rad/s)
- t_{sat} = the time interval calculated with **Equation (3–13)**.

There is a safety limit voltage (V_L) for both the CTs and the stabilizing resistor, and it cannot be exceeded during internal faults. Usually, this safety limit voltage is 2 kV. If the

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calculated peak voltage is lower than the safety limit ($V_{max} < V_L$), an MOV is not required. However, if the peak voltage exceeds the safety limit ($V_{max} > V_L$), an MOV must be used to limit the peak voltage.

3.2.8 Requirements for the MOV values (C, β)

If an MOV is required to limit the peak voltage, the MOV values must be specified. The current across the MOV is calculated with **Equation (3-17)**:

$$I = \left(\frac{V}{C}\right)^{\frac{1}{\beta}} \quad \textbf{(3-17)}$$

where:

- V = the MOV voltage (= voltage across the stabilizing resistor)
- C, β = constant values.

The constant value β is usually adjustable between 0.20 and 0.25. As the setting of this constant value has no remarkable effect on the voltage, there is no specific setting value required for β.

The constant value C is a parameter very similar to the CT knee point voltage: when $C = V_k^{RMS}$, the calculated current across the MOV is 1 A. However, if the knee point voltage is higher than the constant value C, the current goes up drastically and the resistance of the MOV drops dramatically. If the knee point voltage is lower than the constant value C, the resistance of the MOV starts to rise significantly.

As it is important to sense all internal faults, the MOV must not operate at the same voltage level as the relay. This sets requirements for the constant value C, which is calculated with **Equation (3-18)**:

$$C \geq 2 \times I_{SET} \times R_{ST} \quad \textbf{(3-18)}$$

where:

- I_{SET} = the relay's setting current
- R_{ST} = the stabilizing resistor.

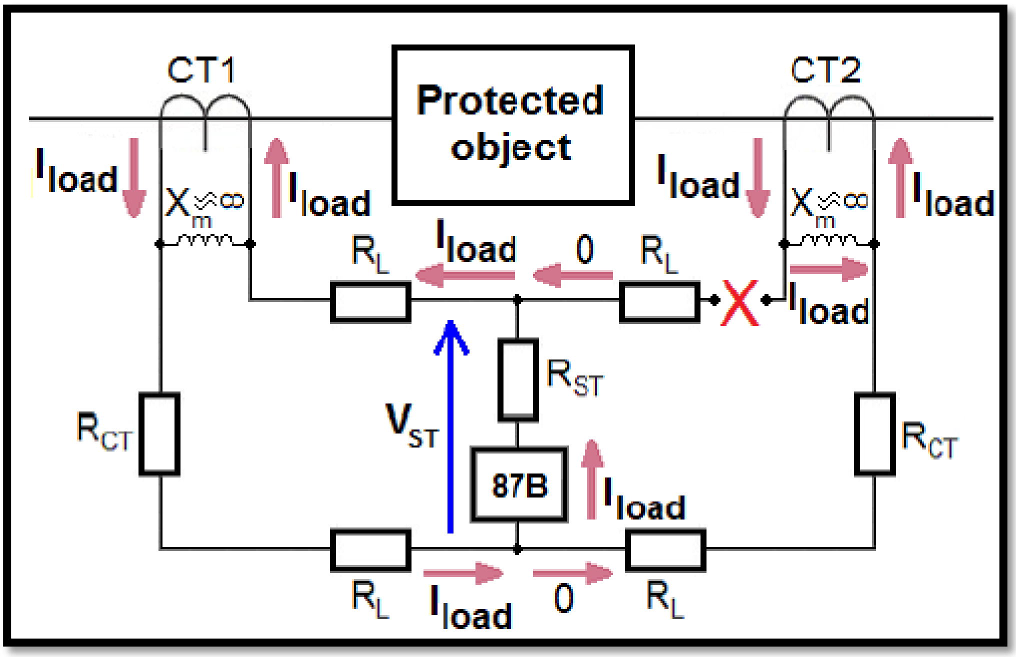
NOTE! There is an additional method to limit the peak voltage. Arcteq recommends using a thyristor to protect the CTs and the stabilizing resistor.

3.2.9 Detection of a CT open circuit (CT failure)

If one of the current transformers has an open circuit, the result is an increased current flowing through the differential element. If this current is greater than the setting value of the element, the high-impedance differential protection function can cause the relay to operate incorrectly.

The differential current is determined by the load current that flows through the missing CT input, as can be seen in ***Figure 3-7*** below, where CT2 is open-circuited:

Figure 3-7: High-impedance differential protection during a CT failure.



In this situation the relay should not operate, and to prevent that the setting current of the differential protection must be higher than the maximum load secondary current (**Equation (3-19)**):

$$I_{SET} > I_{load}^{MAX} \quad \textbf{(3-19)}$$

where:

- I_{SET} = the relay setting current
- I_{load}^{MAX} = the maximum load secondary current.

On the other hand, a CT failure must be detected in order to block the relay and to avoid the relay's false operation during external faults. For this reason, another sensitive high-impedance differential protection element must be applied. This other differential protection (which we will call a "CT failure detection function") should detect an open CT circuit even if the actual load current is at its lowest. This load secondary current will determine the maximum setting current (**Equation (3-20)**):

$$I_{SET}^{CT\,fail.} \leq I_{load}^{MIN} \quad \textbf{(3-20)}$$

where:

- $I_{SET}^{CT\,fail.}$= the CT failure setting current
- I_{load}^{MIN} = the minimum load secondary current.

A timer must delay the blocking signal output of the CT failure detection function to avoid any unwanted blocking of the protection function during an actual internal fault. This delay should be one second or longer (**Equation (3-21)**):

$$t_{delay}^{CT\,fail.} \geq 1\ second \quad \textbf{(3-21)}$$

where:

- $t_{delay}^{CT\,fail.}$ = the delay for CT failure detection.

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This solution provides enough time for the relay to operate during an internal fault. The protection function will not detect an internal fault as a CT failure, but the function keeps its stable and fast operation.

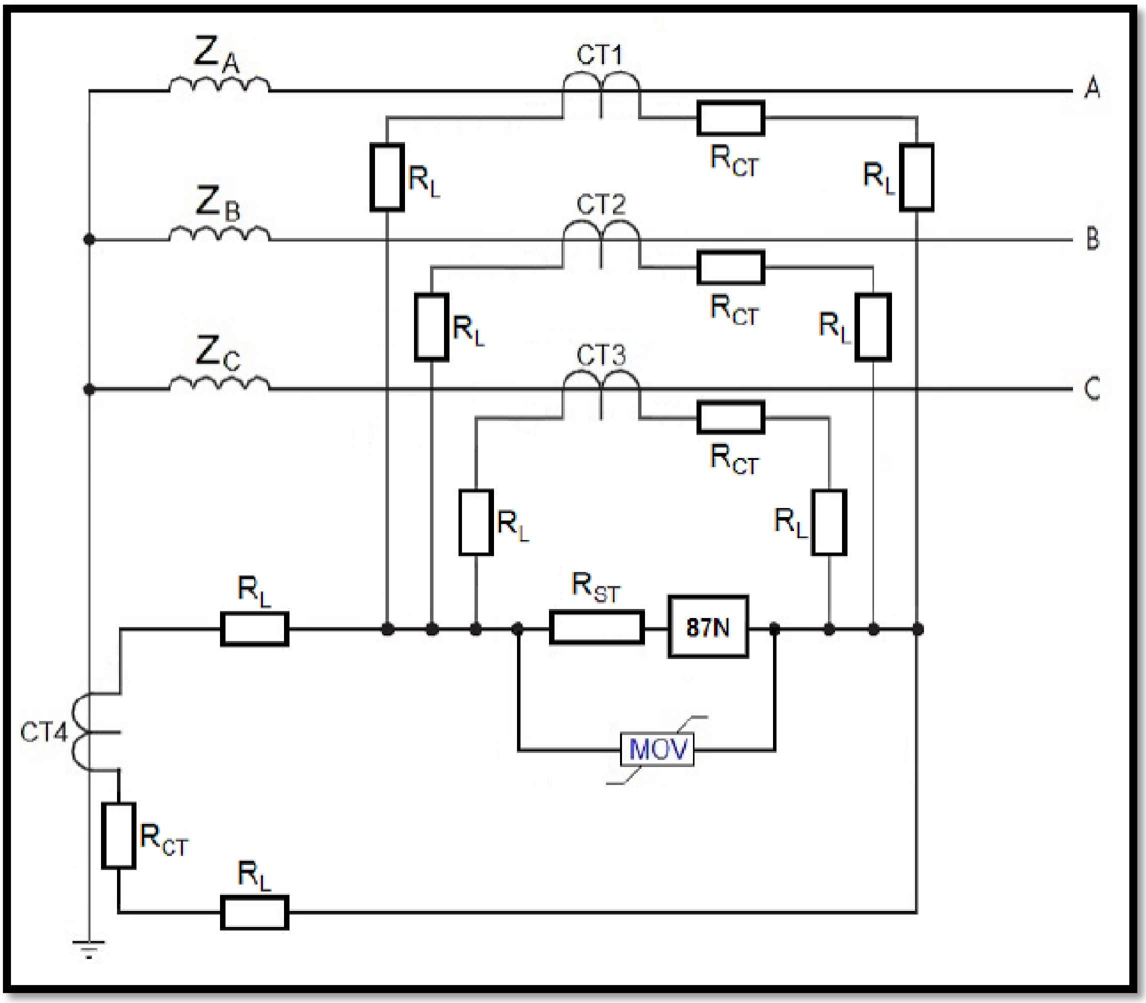
For further information on the configuration of the CT open circuit detection, please refer to Chapter 3.6, "Configuration of the CT failure detection".

NOTE! Due to the detection method detailed above and the resulting, relatively high setting current for the differential protection, the relay will not be sensitive to internal faults with low fault currents. To avoid this sensitivity problem, another solution for the detection of a CT failure is to duplicate the number of differential protections with separated CT circuits. In this situation the relay operates only if both of the differential protections detect an internal fault at the same time. This solution also allows you to decrease the setting current and make the differential protection sensitive enough to also detect internal faults with low fault currents.

3.3 Example calculation (restricted earth fault protection)

In this example, we will go through the CT setting procedure for a restricted earth fault protection scheme. The scheme is pictured below in ***Figure 3-8***. All the information known about the system, the current transformers, and the connection are listed after the scheme image.

Figure 1-8: The restricted earth fault protection scheme.



System details:

- Rated current: 550 A
- Maximum through fault current ($I_{f,ext}$): 5 100 A
- Minimum internal fault current ($I_{f,MINint}$): 20 % of the rated current = 110 V
- Maximum internal fault current ($I_{f,MAXint}$): 11 200 A
- Safety margin (ε): 0.15
- Time interval to CT saturation start (t_{sat}): 6.8×10^{-4} s
- Time period (T): 2×10^{-2} s
- Network angular frequency (ω): 314.159 rad/s

CT details:

- Number of CTs parallel with the relay (n): 4
- Rated primary rated (I_{pr}): 600 A
- Rated secondary current ($I_n^{RMS} = I_{sr}$): 1 A
- Rated burden (P_n): 30 VA
- Secondary winding resistance (R_{CT}): 2 Ω
- Accuracy limit factor (n_{ALF}): 20
- Accuracy class: 5P
- Current error (ε_c): 1.0

Connection detail:

- Connection lead resistance (R_L^i): 1.5 Ω

3.3.1.1 Calculation of the stabilizing voltage (V_{ST})

You can calculate the stabilizing voltage with **Equations (3-1)** and **(3-2)**:

$$\begin{aligned} V_{f,ext}^{i} &= 2 \times \sqrt{2} \times I_{f,ext}^{RMS} \times \left(R_{CT} + 2 \times R_{L}^{i}\right) \\ &= 2 \times \sqrt{2} \times \left(\frac{I_{f,ext}}{I_{pr}}\right) \times (2 + 2 \times 1.5) \\ &= 2 \times \sqrt{2} \times \left(\frac{5\,100}{600}\right) \times (2 + 2 \times 1.5) \\ &= 120.208 \ldots\ V \\ &\approx 120.2\ V \end{aligned} \tag{3-2}$$

$$\begin{aligned} V_{ST} &= (1 + \varepsilon) \times MAX\left\{V_{f,ext}^{i}\right\} \\ &= (1 + 0.15) \times 120.2 \\ &= 138.23\ V \\ &\underline{\underline{\approx 138.2\ V}} \end{aligned} \tag{3-2}$$

3.3.1.2 Calculation of the CT knee point voltage (V_{k}^{RMS})

The knee point voltage is calculated with **Equation (3-3)**:

$$\begin{aligned} V_{K}^{RMS} &= n_{ALF} \times I_{n}^{RMS} \times (R_{CT} + R_{b}) \\ &= n_{ALF} \times I_{n}^{RMS} \times \left(R_{CT} + \frac{P_{n}}{I_{n}^{2}}\right) \\ &= 20 \times 1 \times \left(2 + \frac{30}{1^{2}}\right) \\ &\underline{\underline{= 640\ V}} \end{aligned} \tag{3-3}$$

3.3.1.3 Selection of the stabilizing resistor (R_{ST})

Because the CT excitation characteristic is not given in the information at the beginning, we have to estimate the exciting current at V_{ST}. The 5P class CT has a maximum of 1 %

current error below CT the knee point voltage ([1], p. 23). Therefore, the calculation for the exciting current is done with **Equation (3-7)**:

$$I_e = n_{ALF} \times \frac{\varepsilon_c}{100} \times \frac{I_n^{RMS}}{V_k^{RMS}} \times V_{ST} \quad \textbf{(3-7)}$$

$$= 20 \times \frac{1}{100} \times \frac{1}{640} \times 138.2$$

$$= 0.0431 \ldots A$$

$$\approx 0.043\ A$$

The stabilizing current is determined with **Equation (3-5)**:

$$I_{ST} = (1-\varepsilon) \times \sqrt{2} \times I_{f,MINint}^{RMS} - n \times I_e \quad \textbf{(3-5)}$$

$$= (1-\varepsilon) \times \sqrt{2} \times \left(\frac{I_{f,MINint}}{I_{pr}}\right) - n \times I_e$$

$$= (1-0.15) \times \sqrt{2} \times \left(\frac{110}{600}\right) - 4 \times 0.043$$

$$= 0.0483 \ldots A$$

$$\approx 0.048\ A$$

You can calculate the possible stabilizing resistor values with **Equation (3-8)**:

$$R_{ST} \geq \frac{V_{ST}}{I_{ST}} \quad \textbf{(3-8)}$$

$$R_{ST} \geq \frac{138.2}{0.048} = 2\,879.166 \ldots \Omega$$

Because the selected value must be higher than the calculated quotient, the selected stabilizing resistor is therefore $\underline{\underline{R_{ST} = 3\,000\ \Omega}}$.

3.3.1.4 Calculation of the relay's setting current (I_{SET})

Now that we know the stabilizing resistor, we can choose the relay's setting current with **Equation (3-9)**:

$$I_{SET} = \frac{V_{ST}}{R_{ST}} = \frac{138.2}{3\,000} = 0.0460\ldots A \tag{3-9}$$

Since this current value cannot be set exactly in the relay, we need to set it to a higher current, while staying as close as possible to V_{ST}/R_{ST}. The selected setting current is therefore set at $\underline{\underline{I_{SET} = 0.05\ A}}$. This can also be presented as a percentage of the nominal current, in this case $\underline{\underline{I_{SET} = 5\ \%}}$.

3.3.1.5 Requirement for the CT knee point voltage

Next, we calculate the CT knee point voltage requirement with **Equation (3-10)**:

$$V_k^{RMS} \geq 0.5 \times I_{f,MINint}^{RMS} \times R_{ST} \tag{3-10}$$

$$V_k^{RMS} \geq 0.5 \times \left(\frac{I_{f,MINint}}{I_{pr}}\right) \times R_{ST}$$

$$V_k^{RMS} \geq 0.5 \times \left(\frac{110}{600}\right) \times 3\,000 = 275\ V$$

As the result is below or equal to the CT knee point voltage (calculated earlier as 640 V), <u>it meets the voltage requirement</u>.

3.3.1.6 The stabilizing resistor power rating (P_{ST})

With the results we have calculated thus far, we can see that the CT knee point voltage is lower than the calculated voltage ($V_k^{RMS} < 0.5 \times I_{f,MINint}^{RMS} \times R_{ST}$). From this we can now say that the power rating for the selected resistor short time must be calculated using **Equation (3-12)**. Please note that this calculation must be performed in radians!

$$p_{ST,lowCT}^{sh} = \left(I_{f,MAXint}^{RMS} \times \sqrt{2 \times \frac{t_{sat}}{T} - \frac{\sin(2\times\omega\times t_{sat})}{2\pi}}\right)^2 \times R_{ST} \quad \textbf{(3-12)}$$

$$= \left(\left(\frac{I_{f,MAXint}}{I_{pr}}\right) \times \sqrt{2 \times \frac{t_{sat}}{T} - \frac{\sin(2 \times \omega \times t_{sat})}{2\pi}}\right)^2 \times R_{ST}$$

$$= \left(\frac{11\ 200}{600} \times \sqrt{2 \times \frac{6.8 \times 10^{-4}}{2 \times 10^{-2}} - \frac{\sin(2 \times 314.159 \times 6.8 \times 10^{-4})}{2 \times \pi}}\right)^2 \times 3\ 000$$

$$= 2143.069 \ldots\ W$$

$$\underline{\underline{\approx 2143\ W}}$$

The time interval between the zero cross of the current and the beginning of CT saturation (t_{sat}) is calculated according to **Equation (3-13)**. Please note that this calculation must be performed in radians!

$$t_{sat} = \frac{1}{\omega} \times \cos^{-1}\left(1 - \frac{2\times V_k^{RMS}}{I_{f,MAXint}^{RMS}\times R_{ST}}\right) \quad \textbf{(3-13)}$$

$$= \frac{1}{314.159} \times \cos^{-1}\left(1 - \frac{2 \times V_k^{RMS}}{\frac{I_{f,MAXint}}{I_{pr}} \times R_{ST}}\right)$$

$$= \frac{1}{314.159} \times \cos^{-1}\left(1 - \frac{2 \times 640}{\frac{11\ 200}{600} \times 3\ 000}\right)$$

$$= 6.818 \ldots \times 10^{-4} s$$

$$\approx 6.8 \times 10^{-4} s$$

With this result we can calculate the minimum value for the continuous power rating of the selected resistor with **Equation (3-14)**:

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$$P_{ST}^{co} = \left(\frac{I_{SET}}{\sqrt{2}}\right)^2 \times R_{ST} \tag{3-14}$$

$$= \left(\frac{0.05}{\sqrt{2}}\right)^2 \times 3\,000$$

$$= 3.75\,W$$

3.3.1.7 Deciding whether to use an MOV

In order to be able to decide whether or not to use an MOV, we first need to know the peak voltage (V_{max}). Again, because the CT knee point voltage is lower than the calculated voltage ($V_k^{RMS} < 0.5 \times I_{f,MINint}^{RMS} \times R_{ST}$), the peak voltage must be calculated with **Equation (3-16)**. Please note that this calculation must be performed in radians!

$$V_{max} = \sqrt{2} \times I_{f,MAXint}^{RMS} \times R_{ST} \times \sin(\omega \times t_{sat}) \tag{3-16}$$

$$= \sqrt{2} \times \frac{I_{f,MAXint}}{I_{pr}} \times R_{ST} \times \sin(\omega \times t_{sat})$$

$$= \sqrt{2} \times \frac{11\,200}{600} \times 3\,000 \times \sin(314.159 \times 6.8 \times 10^{-4})$$

$$= 16\,790.092 \ldots V$$

$$\approx 16.79\,kV$$

Because we assume that $V_L = 2\,kV$, V_{max} is therefore much greater than the limit voltage. This means that you must use an MOV.

3.3.1.8 Requirements for the MOV values (C, β)

As stated previously, the constant value β value is not important for the settings and can therefore be set at any value between 0.20 and 0.25. For this example, let us set it as follows:

β = 0.22

When choosing the constant value C, you need to remember that this value must be at least twice the value of the operating voltage. The limit can be calculated with **Equation (3-18)**:

$$C \geq 2 \times I_{SET} \times R_{ST} \qquad \textbf{(3-18)}$$

$$C \geq 2 \times 0.05 \times 3\ 000 = 300$$

Any value greater than 300 will do, so let us select C = 450.

3.4 Using the pre-filled Excel file for calculations

In order to make it easier for you to set any type of high-impedance differential protection, we have made a pre-filled Excel file which includes all the calculations mentioned previously in this chapter. It can also check all the requirements that are related to the setting procedure.

Below are step-by-step instructions for using this Excel file. If you have any questions about the setting procedure and/or the Excel file, please contact us with the contact information provided in the footer of this document.

1. Download the Excel file: www.arcteq.fi/documents-and-software/ → *AQ 200 series* → *Resources* → "Calculations for high-impedance differential protection". While this file is designed with and for Microsoft Office's Excel software, you can also use it with any free software that handles XLS files (such as LibreOffice Calc).
2. Open the XLS file and its tab titled *Input data* (***Figure 3-9***).

Figure 3-9: "Input data" tab of the Excel file.

POWER SYSTEM DETAILS		
Frequency (f)		Hz
Maximum through fault current ($I_{f,ext}$)		A
Maximum internal fault current ($I_{f,MAXint}$)		A
Minimum internal fault current ($I_{f,MINint}$)		A

CT DETAILS		
Primary rated current ($I_{n,prim}$)		A
Secondary rated current ($I_{n,sec}$)	(select)	A
Secondary winding resistance (R_{CT})		Ω
Accuracy class	(select)	

→

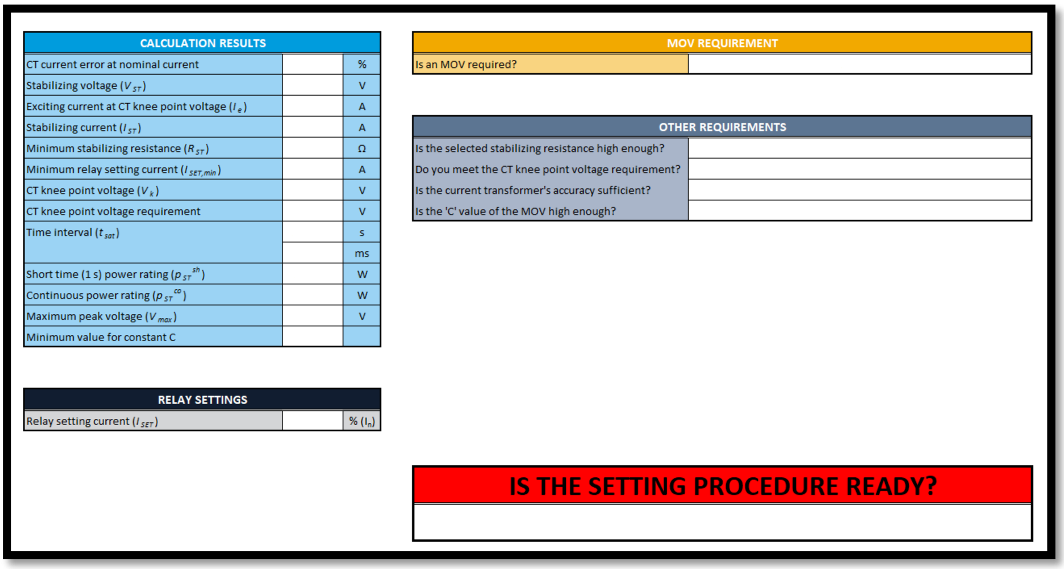
CT SPECIFICATIONS (for accuracy class 5P or 10P)		
Accuracy limit factor (n_{ALF})		
Rated burden (P_n)		VA

CONNECTION DETAILS		
Maximum connection lead resistance (R_L)		Ω
Number of current transformers (n)	(select)	

SELECTED VALUES		
Stabilizing resistance (R_{ST})		Ω
C (only if MOV is required)		

3. Fill in the required information on the sheet in their appropriate cells in the following order:
    a. "Power system details":
        i. The frequency in hertz (50 Hz **or** 60 Hz).
        ii. The maximum through fault primary current for all CT circuits in amperes.
        iii. The minimum internal fault primary current in amperes (the exact value is not always known so a practical selection would be 20 % to 30 % of the rated current).
        iv. Maximum internal fault primary current in amperes.
    b. "CT details":
        i. The primary rated current of the CT in amperes.
        ii. The secondary rated current of the CT in amperes (1 A **or** 5 A).
        iii. The secondary winding resistance of the CT in ohms.
        iv. The accuracy class of the CT (5P, 10P, **or** X):
            - If the accuracy class of the CT is 5P or 10P, its respective CT specifications box remains visible. Fill in the values for the accuracy limit factor (no unit) as well as the rated burden in volt-amperes.
            - If the accuracy class of the CT is X, its respective CT specifications box appears. Fill in the CT knee point voltage in volts (effective value) as well as the exciting current at the CT knee point voltage in amperes.
    c. "Connection details":
        i. The maximum connection lead resistance of all CT circuits in ohms.
        ii. The number of CTs connected to the stabilizing resistor (can be anything between 2 and 20).
4. Switch over to the *Calculation results* tab and check the value for the minimum stabilizing resistance (***Figure 3-10***, on the following page).

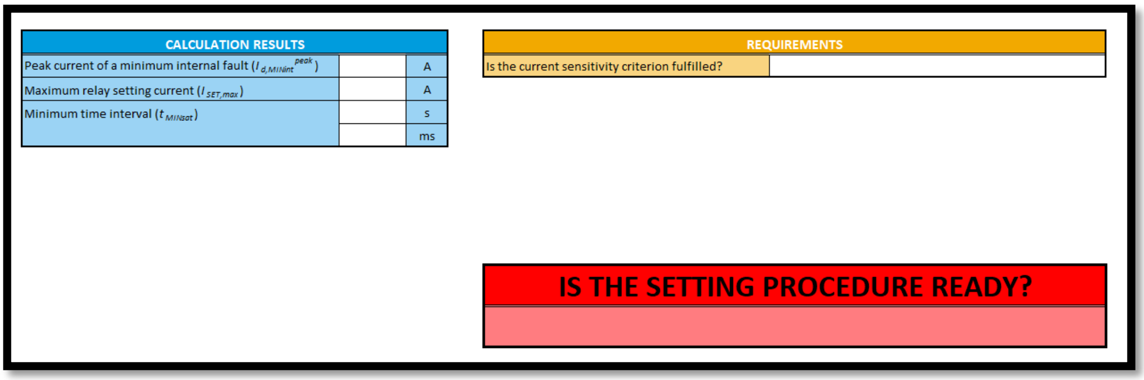
Figure 3-10: “Results” tab of the Excel file.



5. Next, select the suitable values in the following order:
   a. Select a stabilizing resistance which is above the calculated value for the minimum stabilizing resistance. Please note that this value can be negative when the stabilizing current is negative. This means that the magnetizing branch impedance of the CT is too small, and so the voltage across the stabilizing resistor is lower than the stabilizing voltage during a minimum internal fault. As a result, the relay cannot operate during a minimum internal fault. This situation has two acceptable solutions:
      i. Try to reduce the connection lead resistance to lower the stabilizing voltage (see **Equation (3-1)**).
      ii. Select another CT with a better accuracy class or a higher rated burden.
   b. Check the answer given for whether or not an MOV is required according to the calculations. This can be found in the *Calculation results* tab, within the “MOV requirement” box.
      i. If the answer is **YES**, select a value which is greater than the minimum value for the constant C.
      ii. If the answer is **NO**, the selection process is finished.

6. Write the selected values to their appropriate cells in the *Input data* tab, within the "Selected values" box: the stabilizing resistance is in ohms, while the constant C (if an MOV is required) has no unit.
7. Check all the requirement answers in the *Calculation results* tab.
   a. If all the requirements are satisfied, the setting procedure is finished. This can be seen in the *Results* tab when the "Is the setting procedure ready?" box has the value **YES**.
   b. If one of the requirements is not satisfied, follow the instructions given in the answer cell.
   c. If the requirement for the CT knee point voltage is not satisfied while all the others are, check the current sensitivity criterion (see Chapter 3.5, "Special calculation method") in the *Special calculation method* tab (***Figure 3-11***). When the answer cell has the value **YES**, the setting procedure is finished.

Figure 1-10: "Results" tab of the Excel file.



8. Next, set the relay setting current to the calculated value. You can see this value in the *Calculation results* tab within the "Relay settings" box (***Figure 3-10*** on the previous page). Please note that the setting current is given in a percentage value related to the secondary nominal current: "% (I_n)".
9. Finally, check the selected resistor power ratings (both short-time and continuous) in the *Calculation results* tab to see whether or not they are sufficient. These minimal values are calculated within the "Calculation results" box and are labelled

"Short-time (1 s) power rating ($p_{ST}{}^{sh}$)" and "Continuous power rating ($p_{ST}{}^{co}$)", respectively.

3.5 Special calculation method

Sometimes CT saturation occurs before the primary minimum internal fault current reaches its maximum (that is, ($V_k^{RMS} < 0.5 \times I_{f,MINint}^{RMS} \times R_{ST}$). In this case the relay's setting current must be set below the calculated current, which is also the maximum differential current before CT saturation can occur. This was seen earlier in ***Figure 3-6*** (p. 22).

The current sensitivity criterion must be checked because the maximum differential current may be lower than the relay's setting current. This means that the relay will not operate during a minimum internal fault. You can calculate the peak current before CT saturation occurring with **Equation (3-22)**; please note that the calculation must be performed in radians:

$$I_{d,MINint}^{peak} = \sqrt{2} \times I_{f,MINint}^{RMS} \times \sin(\omega \times t_{MINsat}) \quad \textbf{(3-22)}$$

where:

- $I_{f,MINint}^{RMS}$ = the minimum internal fault secondary current
- ω = the angular frequency (usually 314.159 rad/s)
- t_{MINsat} = the minimum time interval between the current's zero cross and the CT saturation start.

The minimum time interval between the zero cross of the current and the beginning of CT saturation, in turn, is calculated with **Equation (3-23)**. Please note that the result of the cos^{-1} function must be in radians):

$$t_{MINsat} = \frac{1}{\omega} \times \cos^{-1}\left(1 - \frac{2 \times V_k^{RMS}}{I_{f,MINint}^{RMS} \times R_{ST}}\right) \quad \textbf{(3-23)}$$

where:

- ω = the angular frequency (usually 314.159 rad/s)
- V_k^{RMS} = the CT knee point voltage
- $I_{f,MINint}^{RMS}$ = the minimum internal fault secondary current
- R_{ST} = the stabilizing resistor.

All of the CT's exciting currents are ignored by the differential branch, which means that they must be subtracted from the result of the peak current calculation, as in **Equation (3-24)**:

$$I_{SET} \leq (1 - \varepsilon) \times I_{d,MINint}^{peak} - n \times I_e \qquad \textbf{(3-24)}$$

where:

- ε = the safety margin ($\varepsilon = 0.15$)
- $I_{d,MINint}^{peak}$ = the peak current before CT saturation occurs
- n = the number of CTs parallel with the relay
- I_e = the CT exciting peak current at V_{ST}.

Please note that if the stabilizing voltage is greater than the CT knee point voltage ($V_{ST} > V_k^{RMS}$), the exciting peak current is calculated with **Equation (3-25)**:

$$I_e = V_{ST} \times \frac{I_{e,k}^{RMS}}{V_k^{RMS}} \qquad \textbf{(3-25)}$$

where:

- V_{ST} = the stabilizing voltage
- $I_{e,k}^{RMS}$ = the exciting current at V_k^{RMS}
- V_k^{RMS} = the CT knee point voltage.

If the current sensitivity criterion is not satisfied (that is, $I_{SET} > (1 - \varepsilon) \times I_{d,MINint}^{peak} - n \times I_e$), the relay is not sensitive enough for a minimum internal fault. Therefore, another CT with a higher knee point voltage must be used!

3.6 Configuration of CT failure detection

In order to sense a failure in a connected current transformer, you can use a second high-impedance differential protection blocking with a low setting current. This differential protection module, called "Current transformer supervision" (abbreviated "CTS"), is only activated during a CT failure. It can, therefore, give a blocking signal to the general high-impedance differential protection element.

The CTS function provides a solution for detecting a phase-selective CT open circuit. If the high-impedance differential protection is used to protect neutral-grounded star transformers, the CTS function has only one output and therefore the high-impedance differential protection function has only one blocking input.

For more detailed information on the CTS function, please refer to the instruction manual of any device that includes this function, such as AQ-T257 [5].

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4 DIMENSIONING CTS FOR DISTANCE PROTECTION

4.1 Procedure for CT dimensioning

The IEC 60255-121 standard ([2], p. 125) presents how to calculate the general rated equivalent limiting secondary e.m.f. with **Equation 4–1**:

$$E_{alreq} = \frac{I_{fC}}{I_{pr}} \times K_{totC} \times I_{sr} \times (R_{CT} + R_w + R_{addbu}) \quad \textbf{(4-1)}$$

where:

- I_{fC} = the maximum primary fault current through the CT in case of close-in forward and reverse faults (both three-phase and phase-to-earth faults)
- I_{pr} = the CT rated primary current
- K_{totC} = the necessary total over-dimensioning factor for close-in forward and reverse faults
  - If the primary time constant $T_p \leq 50\ ms$, the factor $K_{totC} = 2$.
  - If the primary time constant $T_p > 50\ ms$, the factor $K_{totC} = 3$.
  - If the primary time constant $T_p \leq 30\ ms$, the factor $K_{totZone1} = 4$.
  - If the primary time constant $T_p > 30\ ms$, the factor $K_{totZone1} = 7$.
- I_{sr} = the CT rated secondary current
- R_{CT} = the CT secondary winding resistance
- R_w = the resistance of the secondary wire
- R_{addbu} = the total additional burden from the distance relay and any other relays connected to the same CT core.

This chapter describes the practical procedure when dimensioning current transformers for distance protection. We present the following two different examples in this text:

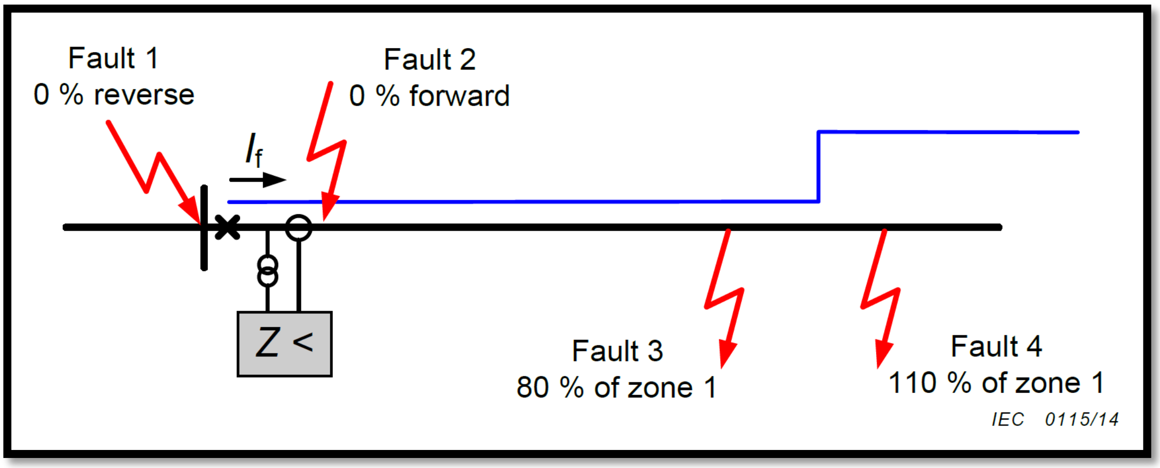
- The first example describes a method for verifying whether a given CT fulfills the requirements of a specific application.

- The second example describes a method for providing the CT manufacturer with all the necessary CT data for the desired application.

Both of these examples are based on the IEC 60255-121 standard ("Functional requirements for distance protection") and its Appendix G ([2] ,pp 125—130). Based on this standard, we recommend applying the following method for dimensioning CTs.

First, calculate the limiting secondary electromotive force (e.m.f.) for all four fault positions (***Figure 4-1***). The equations for this part of the process have been summarized below.

Figure 4-1: The four fault positions ([2], p. 26).



<u>Fault 1</u> is a close-in reverse fault, a security case (**Equation (4-2)**):

$$E_{alreqCrev} = \frac{I_{fCrev}}{I_{pr}} \times K_{totCrev} \times I_{sr}(R_{CT} + R_{ba}) \quad \textbf{(4-2)}$$

where:

- $E_{alreqCrev}$ = the required rated equivalent limiting secondary e.m.f. for Fault 1
- I_{fCrev} = the symmetrical primary fault current through the CT for Fault 1
- I_{pr} = the CT rated primary current
- $K_{totCrev}$ = the necessary total over-dimensioning factor for Fault 1

- R_{CT} = the CT secondary winding resistance
- R_{ba} = $R_w + R_{addbu}$ = the total resistive burden which is the sum of the secondary wire and other additional burdens in the circuit.

Fault 2 is a close-in forward fault, a dependability case (**Equation (4-3)**):

$$E_{alreqCfw} = \frac{I_{fCfw}}{I_{pr}} \times K_{totCfw} \times I_{sr}(R_{CT} + R_{ba}) \qquad \textbf{(4-3)}$$

where:

- $E_{alreqCfw}$ = the required rated equivalent limiting secondary e.m.f. for Fault 2
- I_{fCfw} = the symmetrical primary fault current through the CT for Fault 2
- I_{pr} = the CT rated primary current
- K_{totCfw} = the necessary total over-dimensioning factor for Fault 2
- R_{CT} = the CT secondary winding resistance
- R_{ba}= $R_w + R_{addbu}$ = the total resistive burden which is the sum of the secondary wire and other additional burdens in the circuit.

Fault 3 is a Zone 1 underreach fault, a dependability case (**Equation (4-4)**):

$$E_{alreqZone1U} = \frac{I_{fZone1U}}{I_{pr}} \times K_{totZone1U} \times I_{sr}(R_{CT} + R_{ba}) \qquad \textbf{(4-4)}$$

where:

- $E_{alreqZone1U}$ = the required rated equivalent limiting secondary e.m.f. for Fault 3
- $I_{fZone1U}$ = the symmetrical primary fault current through the CT for Fault 3
- I_{pr} = the CT rated primary current
- $K_{totZone1U}$ = the necessary total over-dimensioning factor for Fault 3
- R_{CT} = the CT secondary winding resistance
- R_{ba} = $R_w + R_{addbu}$ = the total resistive burden which is the sum of the secondary wire and other additional burdens in the circuit.

Fault 4 is a Zone 1 overreach fault, a security case (**Equation (4–5)**):

$$E_{alreqZone1O} = \frac{I_{fZone1O}}{I_{pr}} \times K_{totZone1O} \times I_{sr}(R_{CT} + R_{ba}) \quad \textbf{(4–5)}$$

where:

- $E_{alreqZone1O}$ = the required rated equivalent limiting secondary e.m.f. for Fault 4
- $I_{fZone1O}$ = the symmetrical primary fault current through the CT for Fault 4
- I_{pr} = the CT rated primary current
- $K_{totZone1O}$ = the necessary total over-dimensioning factor for Fault 4
- R_{CT} = the CT secondary winding resistance
- $R_{ba} = R_w + R_{addbu}$ = the total resistive burden which is the sum of the secondary wire and other additional burdens in the circuit.

The transient over-dimensioning factors (p. 44) have been compiled in ***Table 4–1*** below.

Table 4–1: The transient over-dimensioning factors ([2], p. 125).

	Fault position	Three-phase fault (LLL)	Phase-to-earth fault (LN)
Fault 1	Close-in reverse fault	$K_{totCrev} = 2$ $K_{totCrev} = 3$	$K_{totCrev} = 2$ $K_{totCrev} = 3$
Fault 2	Close-in forward fault	$K_{totCfw} = 2$ $K_{totCfw} = 3$	$K_{totCfw} = 2$ $K_{totCfw} = 3$
Fault 3	Zone 1 underreach fault	$K_{totZone1} = 4$ $K_{totZone1} = 7$	$K_{totZone1} = 4$ $K_{totZone1} = 7$
Fault 4	Zone 1 overreach fault	$K_{totZone1} = 4$ $K_{totZone1} = 7$	$K_{totZone1} = 4$ $K_{totZone1} = 7$

Next, calculate the same limiting secondary e.m.f. for both three-phase and single-phase fault types according to the equations summarized above. Again, apply the transient over-dimensioning factors in the equations according to ***Table 4-1***. Please note that the CT must have a rated equivalent limiting secondary force E_{al} that is greater than the maximum E_{alreq} for the four fault positions!

If automatic reclosing is applied to CTs with a high remanence, the total over-dimensioning factor is the product of two factors, as can be seen in **Equation (4-6)**:

$$K_{tot} = K'_{tfmax} = K_{tfmax} \times K_{rem} \quad \textbf{(4-6)}$$

where:

- K_{tot} = the total over-dimensioning factor
- K'_{tfmax} = the maximum, overall transient over-dimensioning factor
- K_{tfmax} = the maximum, individual transient dimensioning factor
- K_{rem} = the remanence dimensioning factor.

The remanence factor (K_{rem}), in turn, is calculated with **Equation (4-7)**:

$$K_{rem} = \frac{1}{1 - \frac{R}{S'}} \quad \textbf{(4-7)}$$

where:

- $\frac{R}{S'}$ = the highest expected remanence value related to the saturation point.

4.2 Examples

We will assume that the secondary wire and the additional burden are the same for both examples. The resistance of the secondary wires can be calculated with **Equation (4-8)**:

$$R_w = \rho \times \frac{l}{A} \quad \textbf{(4-8)}$$

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where:

- ρ = the resistivity of the wire
- l = the length of the wire
- A = the cross-sectional area of the wire.

In these examples, the secondary wire is a copper wire with the following characteristics:

- Length: 200 m
- Cross-sectional area: 2.5 mm^2
- Resistivity for copper at 75 °C: 0.021 Ω mm^2/m.

With these values the resistance of the secondary wire can be calculated with **Equation (4-8)**:

$$R_w = \rho \times \frac{l}{A} \qquad \textbf{(4-8)}$$

$$= 0.021 \times \frac{200}{2.5}$$

$$= 1.68\ \Omega$$

$$\underline{\underline{\approx 1.7\ \Omega}}$$

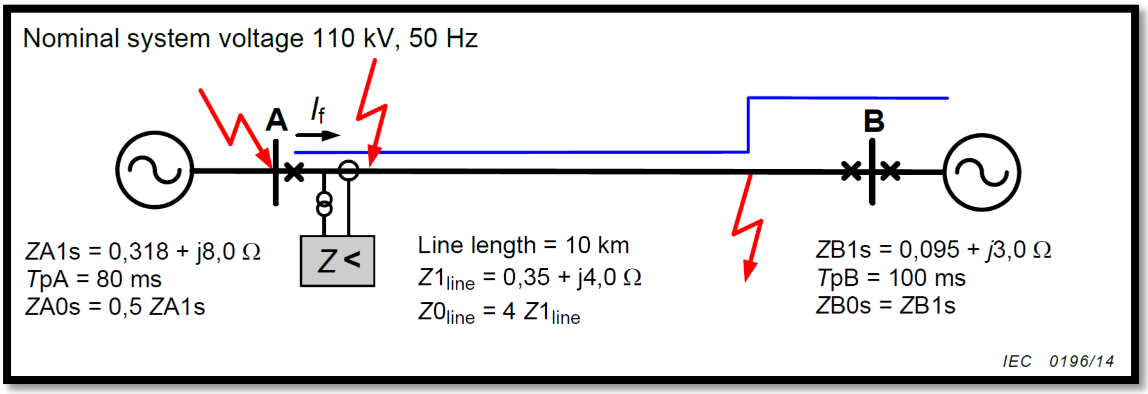
The total additional burden (R_{addbu}) in these examples is $\underline{\underline{0.3\ \Omega}}$.

4.2.1 Example 1

First, we need to verify that our current transformer (CT) fulfils the requirements for distance protection in our application (***Figure 4-6*** on the following page). Please note that Zone 1 is 80 % of the line length.

Additionally, please note that unless the equations used in this calculation process are new, we will not include the variable explanations beneath the equations.

Figure 4-6: Application for the distance relay in Example 1 ([2], p.126).



The existing CTs have the following data:

- CT ratio: 1000/1 A
- Class: TPX, 30 VA
- The rated symmetrical short-circuit current factor (K_{ssc}): 10
- The rated transient dimensioning factor (K_{td}): 2
- The secondary winding resistance (R_{CT}): 15 Ω
- The rated burden (R_b): 30 Ω.

These mean that the existing CTs are approximately the same as a CT with class 5P20, rated output of 30 VA, and the secondary winding resistance R_{CT} = 15 Ω.

From this data, we can calculate the rated equivalent limiting secondary e.m.f. (E_{al}) with **Equation (4-9)**:

$$E_{al} = K_{ssc} \times K_{td} \times I_{sr\times}(R_{CT} + R_b) \quad \textbf{(4-9)}$$

$$= 10 \ \times 2 \times 1 \times (15 + 30)$$

$$\underline{\underline{= 900\ V}}$$

where:

- K_{ssc} = the rated symmetrical short-circuit current factor

- K_{td} = the rated transient dimensioning factor
- I_{sr} = the CT rated secondary current
- R_{CT} = the secondary winding resistance
- R_b = the rated burden.

As note previously, the CT must have a rated equivalent limiting secondary force (E_{al}) that is greater than the maximum E_{alreq} for the four fault positions. This is why we will be checking our fault results against this value throughout Example 1 to make sure the results stay below the 900 V limit.

4.2.1.1 Finding the transient over-dimensioning factors

Next, we need to calculate the fault currents that flow through our CT at the four different fault positions, both during a three-phase fault (LLL) and a phase-to-earth (LN) fault. We know from the application image (***Figure 4-6***, on the previous page) that the nominal system voltage is 110 kV; we will use the equivalent voltage source value of 121 kV in our calculations. By using established fault equations (for example, [3]), we can calculate the following fault current values (***Table 4-2***):

Table 4-2: The fault currents at the four fault positions of Example 1 ([2], p. 127).

Fault location	Fault current through the current transformer	
	Three-phase fault	Phase-to-earth fault
Fault 1: Close-in reverse fault, I_{fCrev}	10.0 kA	8.0 kA
Fault 2: Close-in forward fault, I_{fCfw}	8.7 kA	11.4 kA
Faults 3 and 4: Zone 1 fault, I_{fZone1}	6.2 kA	5.3 kA

The primary time constant (Tp) is required for us to be able to choose which total over-dimensioning factor we will use in calculating the required limiting secondary e.m.f. As seen in ***Figure 4-6*** (p. 50), the primary time constant for the close-in forward fault ($T_{p,A}$) is given as 80 ms. This is higher than 50 ms, so the total over-dimensioning factor (K_{totC}) to be selected is 3, as seen in ***Table 4-1*** (p. 47).

Next, we need to calculate the primary time constant for both the three-phase fault and the phase-to-earth fault for Zone 1. These helps us choose which over-dimensioning factor ($K_{totZone1}$) to use. First, we calculate the positive sequence impedance with **Equation (4-10)**, using data from the application image to fill in the variables:

$$Z1_{Zone1} = ZA1s + 0.8 \times Z1_{line} \quad \textbf{(4-10)}$$

$$= (0.318 + j8.0) + 0.8 \times (0.35 + j4.0)$$

$$= 0.598 + j11.2$$

where:

- $ZA1s$ = the positive sequence impedance at Node A at 1 second
- $Z1_{line}$ = the positive sequence impedance for the line.

We now calculate the primary time constant for the three-phase fault with **Equation (4-11)**:

$$T_{pZone1}pp = \frac{L1}{R1} \quad \textbf{(4-11)}$$

$$= \frac{X1}{\omega \times R1}$$

$$= \frac{11.2}{100 \times \pi \times 0.598}$$

$$= 0.0596 \ldots s$$

$$\underline{\underline{\approx 60\ ms}}$$

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where:

- $L1 = X1$ = the reactance of the positive sequence impedance for the three-phase fault in Zone 1
- $R1$ = the resistance of the positive sequence impedance for the three-phase fault in Zone 1.

Next, we calculate the phase-to-earth fault's impedance with **Equation (4–12)**:

$$
\begin{aligned}
Z_{pe} &= 2 \times Z1_{Zone1} + Z0_{Zone1} \\
&= 2 \times (ZA1s + 0.8 \times Z1_{line}) + (ZA0s + 0.8 \times Z0_{line}) \\
&= 2 \times (ZA1s + 0.8 \times Z1_{line}) + (0.5 \times ZA1s + 0.8 \times 4 \times Z1_{line}) \\
&= 2 \times (0.598 + j11.2) + 0.5 \times (0.318 + j8.0) + 0.8 \times 4 \times (0.35 + j4.0) \\
&= 2.475 + j39.2
\end{aligned}
\quad \textbf{(4–12)}
$$

where:

- $Z1_{Zone1}$ = the positive sequence impedance for Zone 1
- $Z0_{Zone1}$ = the zero-sequence impedance for Zone 1
- $ZA1s$ = the positive sequence impedance at node A at 1 second
- $ZA0s$ = the positive sequence impedance at node A at 0 seconds
- $Z1_{line}$ = the positive sequence impedance for the line
- $Z0_{line}$ = the zero-sequence impedance for the line.

We can now calculate the primary time constant for the phase-to-earth fault using **Equation (4–13)**:

$$
\begin{aligned}
T_{pZone1}pe &= \frac{L_{pe}}{R_{pe}} \\
&= \frac{X_{pe}}{\omega \times R_{pe}}
\end{aligned}
\quad \textbf{(4–13)}
$$

$$= \frac{39.2}{100 \times \pi \times 2.475}$$

$$= 0.05041 \ldots s$$

$$\approx \underline{\underline{50\ ms}}$$

where:

- $L_{pe} = X_{pe}$ = the reactance of the positive sequence impedance for the phase-to-earth fault in Zone 1
- R_{pe} = the resistance of the positive sequence impedance for the phase-to-earth fault in Zone 1.

Both of these results are over 30 ms, and therefore the correct total over-dimensioning factor to use is $K_{totZone1}$ = 7.

4.2.1.2 Calculating the required limiting e.m.f.

Using **Equation 4–1** we can calculate the required secondary e.m.f. for all fault positions and all fault types.

Let's begin with the close-in faults, Fault 1 and Fault 2. We only need to consider the forward phase-to-earth fault as it has the highest fault current value (please refer to ***Table 4–2***, p. 51 for all fault current values). Please note that the R_w in this case is the loop resistance with the double length of the secondary wire (that is, $\underline{R_w = 2 \times 1.7\ \Omega = 3.4\ \Omega}$)! Also note that **Equation 4–1** has had its variables modified to indicate that the calculation is for the close-in faults.

$$E_{alreqC} = \frac{I_{fCfw}}{I_{pr}} \times K_{totC} \times I_{sr} \times (R_{CT} + 2 \times R_w + R_{addbu}) \qquad \textbf{(4–1)}$$

$$= \frac{11400}{1000} \times 3 \times 1 \times (15 + 2 \times 1.7 + 0.3)$$

$$= 639.54\ V$$

$$\approx \underline{\underline{640\ V}}$$

For the Zone 1 faults we need to check both the three-phase fault and the phase-to-earth fault. Please note that for the three-phase fault, while the fault current is higher, the burden is smaller as we only need to consider a single length of the secondary wire. In the phase-to-earth calculation we still need to consider the loop resistance.

$$E_{\substack{alreq \\ Zone1}} = \frac{I_{fZone1pp}}{I_{pr}} \times K_{totZone1} \times I_{sr} \times (R_{CT} + R_w + R_{addbu}) \quad \textbf{(4-1)}$$

$$= \frac{6200}{1000} \times 7 \times 1 \times (15 + 1.7 + 0.3)$$

$$= 737.8\ V$$

$$\underline{\underline{\approx 738\ V}}$$

$$E'_{\substack{alreq \\ Zone1}} = \frac{I_{fZone1pe}}{I_{pr}} \times K_{totZone1} \times I_{sr} \times (R_{CT} + 2 \times R_w + R_{addbu}) \quad \textbf{(4-1)}$$

$$= \frac{5300}{1000} \times 7 \times 1 \times (15 + 2 \times 1.7 + 0.3)$$

$$= 693.77\ V$$

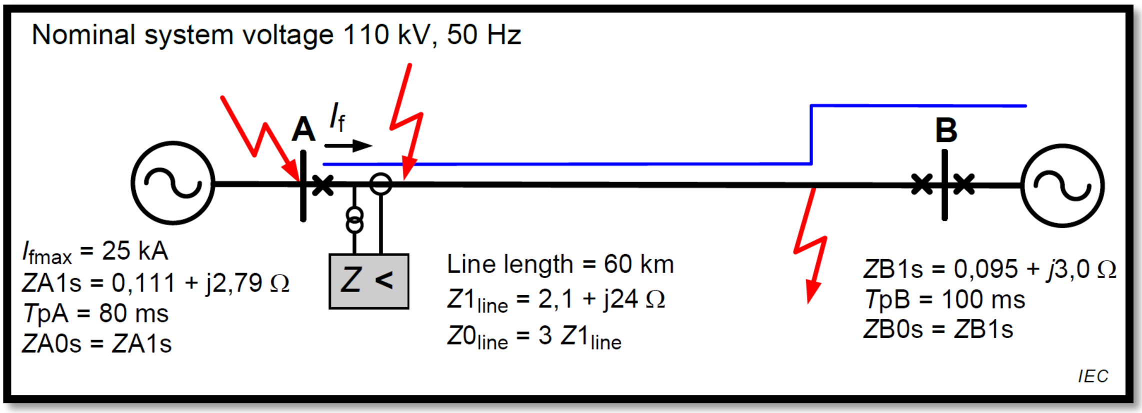
$$\underline{\underline{\approx 694\ V}}$$

We can see from these calculations that in this application the current transformers have a rated equivalent secondary e.m.f. (E_{al}) that is larger than 738 V. The existing CTs have an E_{al} = 900 V as we calculated previously (p. 50). As our calculated e.m.f. does not exceed this limit, we can conclude that the CTs fulfil the requirements for distance protection.

4.2.2 Example 2

In this example we are looking at a distance protection application as shown in ***Figure 4-7*** on the following page. Please note that unless the equations used in this calculation process are new, we will not include the variable explanations beneath the equations.

Figure 4-7: Application for the distance relay in Example 2 ([2], p.128).



Station A can source a maximal fault current of 25 kA. The selected CT has a ratio of 1000/1 A, and the burden is assumed to be lower than the value in Example 1. The values for the resistance of the secondary wire (R_w) and the total additional burden (R_{addbu}) are the same as in Example 1, 1.7 Ω and 0.3 Ω, respectively.

However, we do not know the value of the CT secondary winding resistance (R_{CT}). We have to therefore estimate a realistic value for it. The value can vary depending on the design of the current transformer, but a realistic range is somewhere between 20 % and 80 % of the rated burden.

This means that we have to first decide the rated burden of the CT. We can calculate the maximum burden with **Equation 4-14**:

$$R_{bmax} = 2 \times R_w + R_{addbu} \quad \textbf{(4-14)}$$

$$= 2 \times 1.7 + 0.3$$

$$\underline{= 3.7\ \Omega}$$

It is often economical to specify a low rated burden and a higher overcurrent factor instead of doing the opposite. If we assume a rated burden of R_b = 5 Ω (5 VA) and that the CT secondary winding resistance is 60 % of R_b, we get R_{CT} = 3 Ω.

4.2.2.1 Finding the transient over-dimensioning factors

First, we need to calculate the fault currents that flow through the CT at the different fault positions, both during a three-phase fault (LLL) and a phase-to-earth (LN) fault. We know from the application image (***Figure 4–7***, on the previous page) that the nominal system voltage is 110 kV; we will use the equivalent voltage source value of 121 kV in our calculations. By using established fault equations (for example, [3]), we can calculate the following fault current values (***Table 4–3***):

Table 4–3: The fault currents at the four fault positions of Example 2 ([2], p. 128).

Fault location	Fault current through the current transformer	
	Three-phase fault	Phase-to-earth fault
Fault 1: Close-in reverse fault, I_{fCrev}	2.6 kA	2.0 kA
Fault 2: Close-in forward fault, I_{fCfw}	25.0 kA	25.0 kA
Faults 3 and 4: Zone 1 fault, I_{fZone1}	3.2 kA	2.1 kA

Due to the significant difference between the fault currents presented in ***Table 4–3***, it is obvious that the close-in forward fault will be the dimensioning case. However, we have also included the calculation for the required rated equivalent limiting secondary e.m.f. for the faults in Zone 1 for edification purposes.

The primary time constant for the forward close-in fault is 80 ms, as seen in ***Figure 4–7***, (p. 56). As this value is greater than 50 ms, the total over-dimensioning factor to use in the calculations is K_{totC} = 3 (please refer to ***Table 4–1***, p. 47). The primary time constants for the Zone 1 faults are calculated for both the three-phase fault and the phase-to-earth fault.

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First, we calculate the positive sequence impedance with **Equation (4-10)**, using data from the application image to fill in the variables:

$$Z1_{Zone1} = ZA1s + 0.8 \times Z1_{line} \qquad \textbf{(4-10)}$$

$$= (0.111 + j2.79) + 0.8 \times (2.1 + j24)$$

$$= 1.791 + j21.99$$

We can now calculate the primary time constant for the three-phase fault with **Equation (4-11)**:

$$T_{pZone1}pp \ = \frac{L1}{R1} \qquad \textbf{(4-11)}$$

$$= \frac{X1}{\omega \times R1}$$

$$= \frac{21.99}{100 \times \pi \times 1.791}$$

$$= 0.03908 \ldots s$$

$$\underline{\underline{\approx 39\ ms}}$$

Next, we calculate the phase-to-earth fault's impedance with **Equation (4-12)**:

$$Z_{pe} = 2 \times Z1_{Zone1} + Z0_{Zone1} \qquad \textbf{(4-12)}$$

$$= 2 \times (ZA1s + 0.8 \times Z1_{line}) + (ZA0s + 0.8 \times Z0_{line})$$

$$= 2 \times (ZA1s + 0.8 \times Z1_{line}) + (0.5 \times ZA1s + 0.8 \times 4 \times Z1_{line})$$

$$= 2 \times (1.791 + j21.99) + 0.5 \times (0.111 + j2.79) + 0.8 \times 3 \times (2.1 + j24)$$

$$= 8.6775 + j102.975$$

We can now calculate the primary time constant for the phase-to-earth fault using **Equation (4-13)**:

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$$T_{pZone1}pe = \frac{L_{pe}}{R_{pe}} \qquad \textbf{(4–13)}$$

$$= \frac{X_{pe}}{\omega \times R_{pe}}$$

$$= \frac{102.975}{100 \times \pi \times 8.6775}$$

$$= 0.03777 \ldots s$$

$$\approx \underline{\underline{38\ ms}}$$

Both of these results are over 30 ms, and therefore the correct total over-dimensioning factor to use is $K_{totZone1}$ = 7.

4.2.2.2 Calculating the required limiting e.m.f.

By using **Equation 4–1** we can calculate the required secondary e.m.f. for all necessary fault positions and fault types. As stated before, the fault current is so large for Fault 2 that we can already see that that fault will be the dimensioning case. However, we will also calculate the e.m.f. for the Zone 1 faults. Please also note that the R_w in the phase-to-earth faults is the loop resistance (that is, $\underline{R_w = 2 \times 1.7\ \Omega = 3.4\ \Omega}$)!

$$E'_{alreqC} = \frac{I_{fCfw}}{I_{pr}} \times K_{totC} \times I_{sr} \times (R_{CT} + 2 \times R_w + R_{addbu}) \qquad \textbf{(4–1)}$$

$$= \frac{25000}{1000} \times 3 \times 1 \times (3 + 2 \times 1.7 + 0.3)$$

$$= 502.5\ V$$

$$\approx \underline{\underline{503\ V}}$$

For the Zone 1 faults we need to check both the three-phase fault and the phase-to-earth fault. Please note that for the three-phase fault, while the fault current is higher, the burden is smaller as we only need to consider a single length of the secondary wire.

$$E_{alreqZone1} = \frac{I_{fZone1}pp}{I_{pr}} \times K_{totZone1} \times I_{sr} \times (R_{CT} + R_w + R_{addbu}) \quad \textbf{(4-1)}$$

$$= \frac{3200}{1000} \times 7 \times 1 \times (3 + 1.7 + 0.3)$$

$$\underline{\underline{= 112\,V}}$$

$$E'_{alreqZone1} = \frac{I_{fZone1}pe}{I_{pr}} \times K_{totZone1} \times I_{sr} \times (R_{CT} + 2 \times R_w + R_{addbu}) \quad \textbf{(4-1)}$$

$$= \frac{2100}{1000} \times 7 \times 1 \times (15 + 2 \times 1.7 + 0.3)$$

$$= 98.49\,V$$

$$\underline{\underline{\approx 98\,V}}$$

As we predicted before these calculations, the highest voltage result came from Fault 2, specifically from the phase-to-earth fault. This means that in this application we need a current transformer whose $E_{al} > 503\,V$.

4.2.2.3 CT type selection

Now that we have an idea as to how large the CT's rated equivalent limiting secondary force needs to be, we have to start looking for the best CT for the application.

Let us imagine we choose a current transformer of the class type "TPX", whose rated output is 5 VA and its secondary winding resistance (R_{CT}) is below 3 Ω. As the highest fault current was 25 kA, we can assume that the rated symmetrical short-circuit current factor (K_{ssc}) is 25, and we can therefore calculate the necessary transient dimensioning factor (K_{td}) for the CT to meet the E_{al} requirement with **Equation (4-9)**:

$$E_{al} \geq K_{ssc} \times K_{td} \times I_{sr} \times (R_{CT} + R_b) \quad \textbf{(4-9)}$$

$$503 \geq 25 \times K_{td} \times 1 \times (3 + 5)$$

$$K_{td} \geq \frac{503}{25 \times 1 \times (3+5)} = 2.515 \approx 2.52$$

We now know that a current transformer with the following data will fulfil the requirements for distance protection in this application: the CT must be of type "TPX", its rated output must be 5 VA, its secondary winding resistance must be less than 3 Ω, its rated symmetrical short-circuit current factor must be 25, and its transient dimensioning factor must be 2.6.

The CT, however, can also be specified to be of another class. For example, a CT with the following data will also fulfil the requirements: the CT is of type "5P", its rated output is 5 VA, its secondary winding resistance is below 3 3 Ω, and its accuracy limit factor is 65. The CT is therefore classified as "5P65".

The second alternative is to provide a CT manufacturer with the data according to **Equation 4-1**, either version:

$$E_{al} \geq \frac{I_f}{I_{pr}} \times K_{tot} \times I_{sr} \times (R_{CT} + 2 \times R_w + R_{addbu}) \quad \textbf{(4-1)}$$

$$= \frac{25000}{1000} \times 3 \times 1 \times (R_{CT} + 2 \times 1.7 + 0.3)$$

$$= \frac{25000}{1000} \times 3 \times 1 \times (R_{CT} + 3.7)$$

$$\frac{E_{al}}{I_{sr} \times (R_{CT} + 2 \times R_w + R_{addbu})} \geq \frac{I_f}{I_{pr}} \times K_{tot} \quad \textbf{(4-1)}$$

$$\frac{E_{al}}{I_{sr} \times (R_{CT} + 2 \times 1.7 + 0.3)} \geq \frac{25000}{1000} \times 3$$

$$\frac{E_{al}}{I_{sr} \times (R_{CT} + 3.7)} \geq \frac{25000}{1000} \times 3$$

$$\frac{E_{al}}{I_{sr} \times (R_{CT} + 3.7)} \geq 75$$

This will give the manufacturer information with which to optimizer the relationship between the CT winding's resistance and the iron core's area. Particularly in applications that require specific data (for example, turns ratios outside common ranges), it can be suitable to avoid restrictions imposed by specific class types and allow the CT manufacturer the possibility to optimize your CT.

5 DIMENSIONING CTS FOR LINE DIFFERENTIAL PROTECTION

The rated equivalent secondary e.m.f. of the current transformers must be greater than the calculated general rated equivalent secondary e.m.f. for both internal and external faults from **Equations 5-1** and **5-2** below:

$$E_{alreq\_int} = \frac{I_{f\_int}}{I_{pr}} \times I_{sr} \times (R_{CT} + R_w + R_{addbu}) \quad \textbf{(5-1)}$$

$$E_{alreq\_ext} = 2 \times \frac{I_{f\_ext}}{I_{pr}} \times I_{sr} \times (R_{CT} + R_w + R_{addbu}) \quad \textbf{(5-2)}$$

where:

- I_{f_int} = the maximum primary fault current through the CT in case of internal faults
- I_{f_ext} = the maximum primary fault current through the CT in case of external faults
- I_{pr} = the CT rated primary current
- I_{sr} = the CT rated secondary current
- R_{CT} = the CT secondary winding resistance
- R_w = the resistance of the secondary wire
- R_{addbu} = the total additional burden from the distance relay and any other relays connected to the same CT core.

If the protected zone includes a power transformer, the CTs must also satisfy **Equation 5-3**:

$$E_{alreq\_trafo} = 30 \times \frac{I_{f\_trafo}}{I_{pr}} \times I_{sr} \times (R_{CT} + R_w + R_{addbu}) \quad \textbf{(5-3)}$$

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where:

- I_{f_trafo} = the power transformer's rated current.

In double-busbar, double-breaker, or breaker-and-a-half substations the fault current may pass up to two of the main CTs without passing the protected line. In this situation (and if the CTs have equal ratios and magnetization characteristics), the CTs must also satisfy **Equation 5-4** in addition to **Equation 5-1**:

$$E_{alreq\_double} = \frac{I_{f\_double}}{I_{pr}} \times I_{sr} \times (R_{CT} + R_w + R_{addbu}) \quad \textbf{(5–4)}$$

where:

- I_{f_double} = the maximum primary fault current through the CT without passing the protected line.

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6 CT SIZING REQUIREMENTS

6.1 General

According to the IEC 60255-187-1 standard [4] (published in 2021), a manufacturer must specify the CT requirements that are necessary for the correct operation of their transformer differential protection. In this context, "correct operation" is defined by the acceptance criteria of the various test cases (both internal and external faults) that the standard describes.

As the standard states, the CT requirements must be expressed by the total over-dimensioning factor. This factor is determined by multiple tests, and it includes the transient dimensioning factor, the remanence dimensioning factor, and a combination of other influencing factors. The manufacturer must provide the test results for all fault positions defined by the standard as well as for both three-phase (LLL) and phase-to-earth (LN) fault types.

As we learned in the previous main chapter, the total over-dimensioning factor helps us calculate the required rated equivalent limiting secondary electromotive force (E_{alreq}). Similarly, we learned that the CT's e.m.f. (E_{al}) must be equal to or greater than its required e.m.f. (that is $E_{al} \geq E_{alreq}$). To learn more about how to determine a CT's e.m.f. (E_{al}), please read Chapter 4 ("Dimensioning CTs for distance protection") of this document or read the IEC 61869-2 standard [1]. If you need additional information about dimensioning a CT's transformer differential protection function, you can also refer to Annex E of the IEC 60255-187-1 standard [4]. Its text provides examples of verifying that a given CT fulfils the CT requirements set by the standard. It also presents a method to providing a CT manufacturer with the necessary CT data to ensure the end product fulfils the standard's CT requirements.

This chapter focuses on describing the CT sizing requirements when the rated frequency is 50 Hz, the CT rated secondary currents are 1 A, and the transformer vector group is YnynO.

6.2 Acceptance criteria

According to the IEC 60255-187-1 standard [4], two different fault positions must be considered when looking at CT sizing requirements. These two positions are internal and external faults. Both fault positions have their own acceptance criteria.

With internal faults, the CT saturations is not allowed to cause more than one (1) cycle of additional time delay for any fault. The comparison is to the operating time of the same internal fault type with a CT so large that no saturation occurs.

With external faults, the transformer differential protection must not operate for at least one (1) second after the external fault has been applied. Please note that during external faults you must consider a 75 % remanence flux!

6.3 Total over-dimensioning factors

The total over-dimensioning factors as well as the primary time constant depend heavily on the setting value for the parameter covering the 2nd harmonic ratio in the transformer differential protection function. If the network's primary time constant is high (that is, greater than 70 ms), you are strongly advised to set this parameter between 5...15 %. In Arcteq relays, the default setting value for the 2nd harmonic is 15 %; the range for the parameter is 0.01...50 % ([5], p. 261). In the following subchapters we go through the effect the various setting options have on the relationship between the total over-dimensioning factor (K_{tot}) and the primary time constant (in milliseconds), both in internal and external faults.

6.3.1 Effects of setting the 2nd harmonic ratio to 5 %

Table 6-1: Total over-dimensioning factors for internal faults when the 2nd harmonic ratio = 5 %.

Primary time constant (ms)	Total over-dimensioning factor (K_{tot}) (internal; 2nd h. ratio = 5 %)	
	Phase-to-earth fault	Three-phase fault
30	1	2
40	1	3
50	1	3
70	1	3
100	1	3
150	1	3
200	2	3

Figure 6-1: Diagram of the total over-dimensioning factors in Table 6-1.

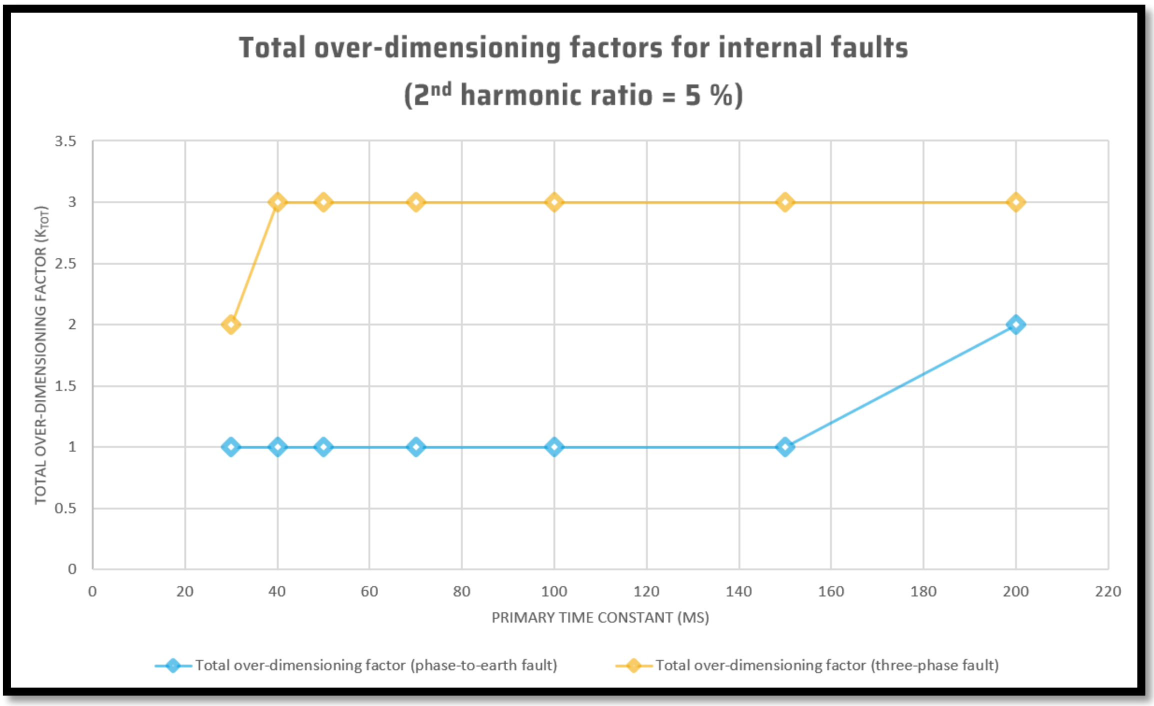
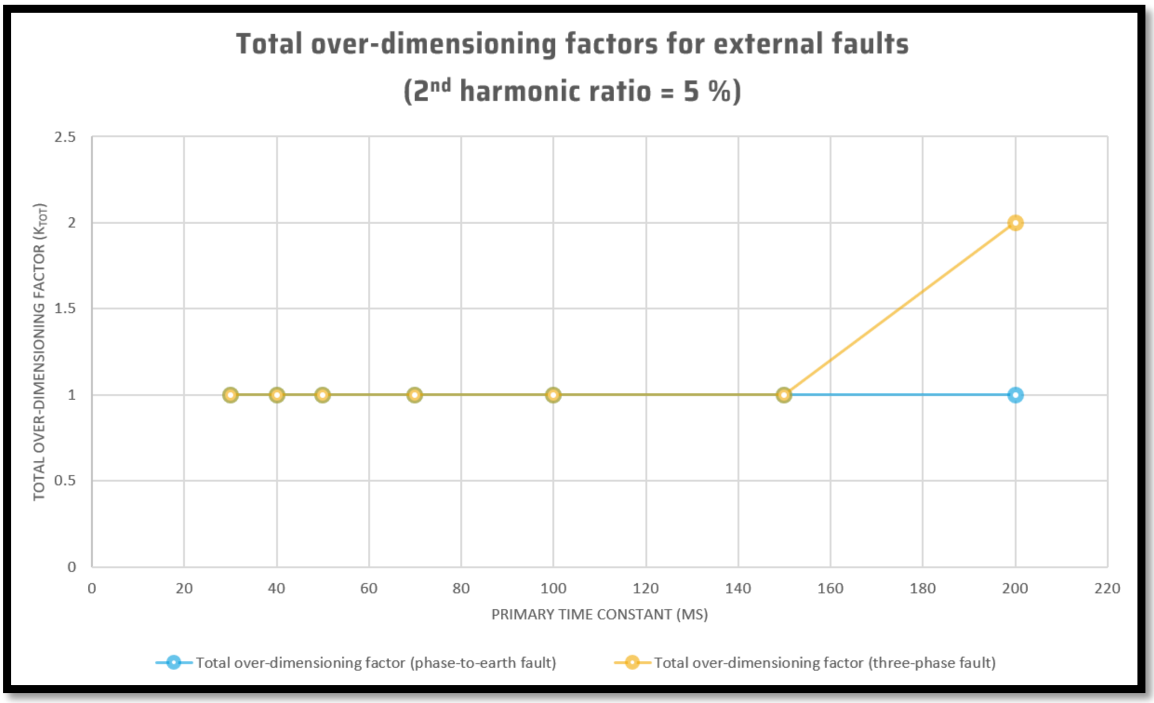


Table 6-2: Total over-dimensioning factors for external faults when the 2nd harmonic ratio = 5 %.

Primary time constant (ms)	Total over-dimensioning factor (K_{tot}) (external; 2nd h. ratio = 5 %)	
	Phase-to-earth fault	Three-phase fault
30	1	1
40	1	1
50	1	1
70	1	1
100	1	1
150	1	1
200	1	2

Figure 6-2: Diagram of the total over-dimensioning factors in Table 6-2.



6.3.2 Effects of setting the 2nd harmonic ratio to 15 %

Table 6-3: Total over-dimensioning factors for internal faults when the 2nd harmonic ratio = 15 %.

Primary time constant (ms)	Total over-dimensioning factor (K_{tot}) (internal; 2nd h. ratio = 15 %)	
	Phase-to-earth fault	Three-phase fault
30	1	1
40	1	3
50	1	3
70	1	3
100	2	3
150	2	3
200	2	3

Figure 6-3: Diagram of the total over-dimensioning factors in Table 6-3.

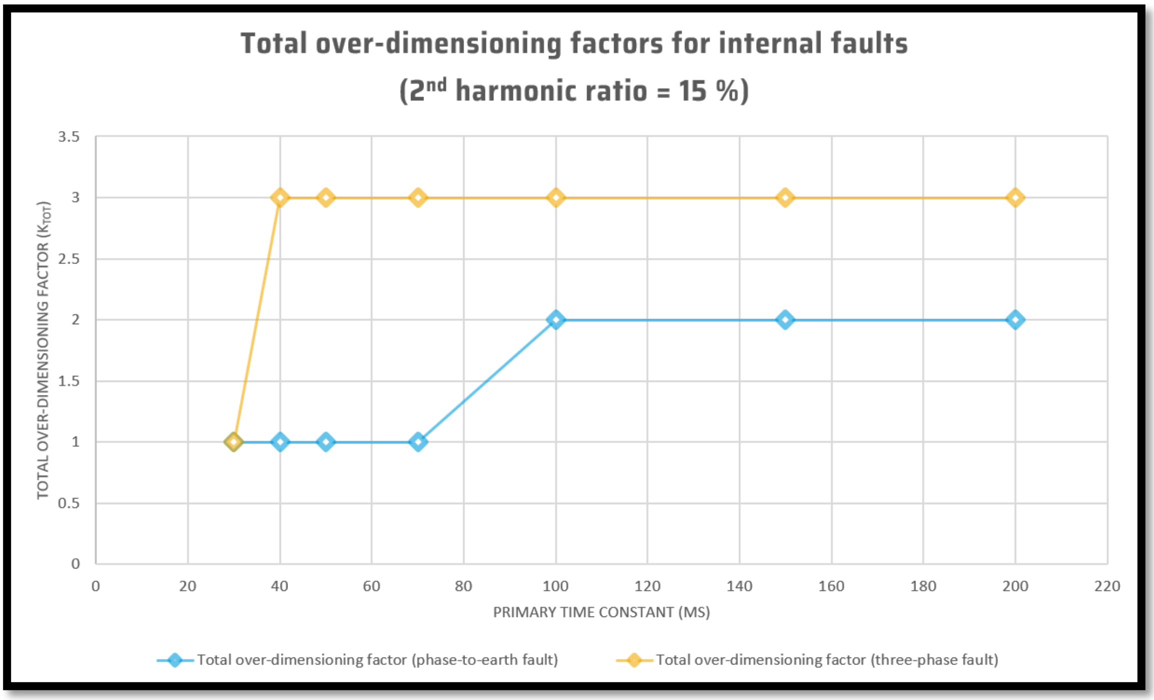
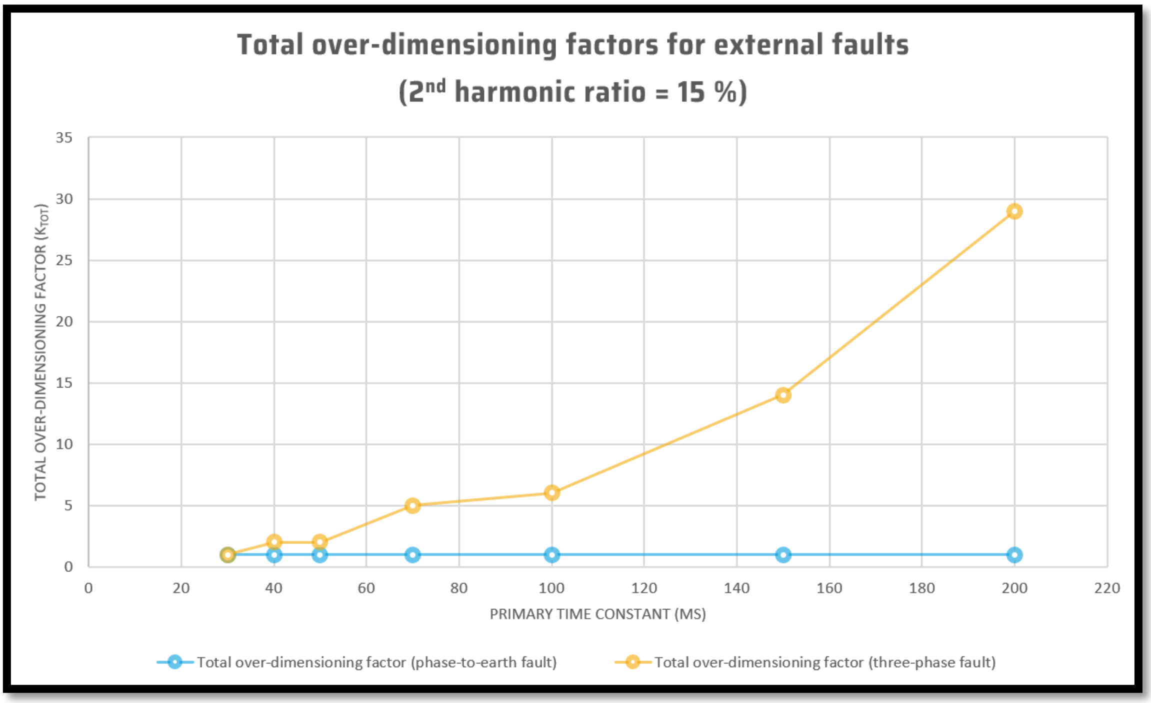


Table 6-4: Total over-dimensioning factors for external faults when the 2nd harmonic ratio = 15 %.

Primary time constant (ms)	Total over-dimensioning factor (K_{tot}) (external; 2nd h. ratio = 15 %)	
	Phase-to-earth fault	Three-phase fault
30	1	1
40	1	2
50	1	2
70	1	5
100	1	6
150	1	14
200	1	29

Figure 6-4: Diagram of the total over-dimensioning factors in Table 6-4.



6.3.3 Effects of setting the 2nd harmonic ratio to 30 %

Table 6-5: Total over-dimensioning factors for internal faults when the 2nd harmonic ratio = 30 %.

Primary time constant (ms)	Total over-dimensioning factor (K_{tot}) (internal; 2nd h. ratio = 30 %)	
	Phase-to-earth fault	Three-phase fault
30	1	3
40	1	3
50	1	3
70	2	3
100	2	3
150	2	3
200	2	3

Figure 6-5: Diagram of the total over-dimensioning factors in Table 6-5.

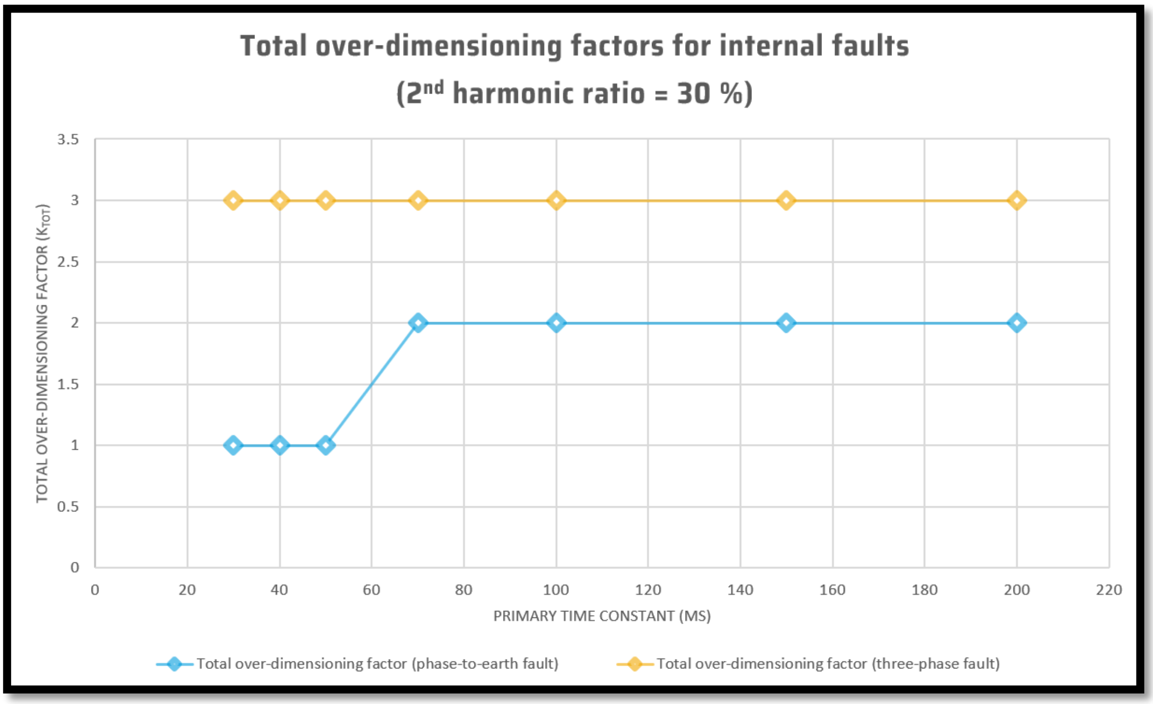
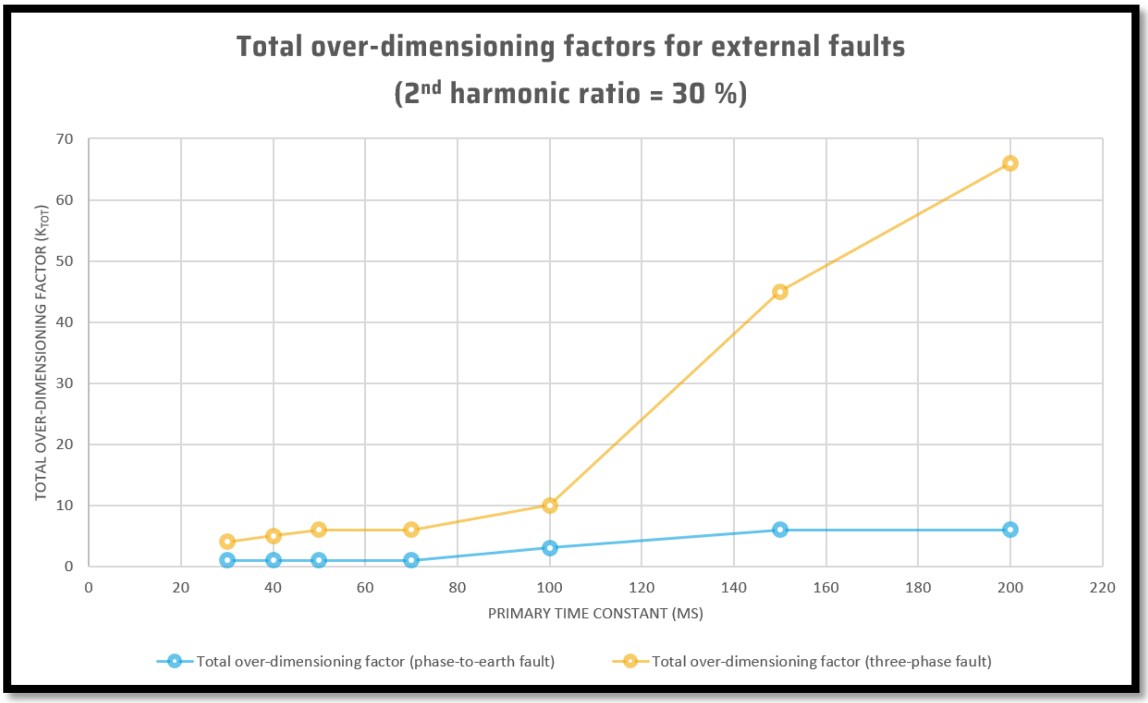


Table 6-6: Total over-dimensioning factors for external faults when the 2nd harmonic ratio = 30 %.

Primary time constant (ms)	Total over-dimensioning factor (K_{tot}) (external; 2nd h. ratio = 30 %)	
	Phase-to-earth fault	Three-phase fault
30	1	4
40	1	5
50	1	6
70	1	6
100	3	10
150	6	45
200	6	66

Figure 6-6: Diagram of the total over-dimensioning factors in Table 6-6.



6.3.4 Effects of setting the 2nd harmonic ratio to 50 %

Table 6-7: Total over-dimensioning factors for internal faults when the 2nd harmonic ratio = 50 %.

Primary time constant (ms)	Total over-dimensioning factor (K_{tot}) (internal; 2nd h. ratio = 50 %)	
	Phase-to-earth fault	Three-phase fault
30	1	2
40	1	3
50	1	3
70	2	3
100	2	3
150	2	3
200	2	3

Figure 6-7: Diagram of the total over-dimensioning factors in Table 6-7.

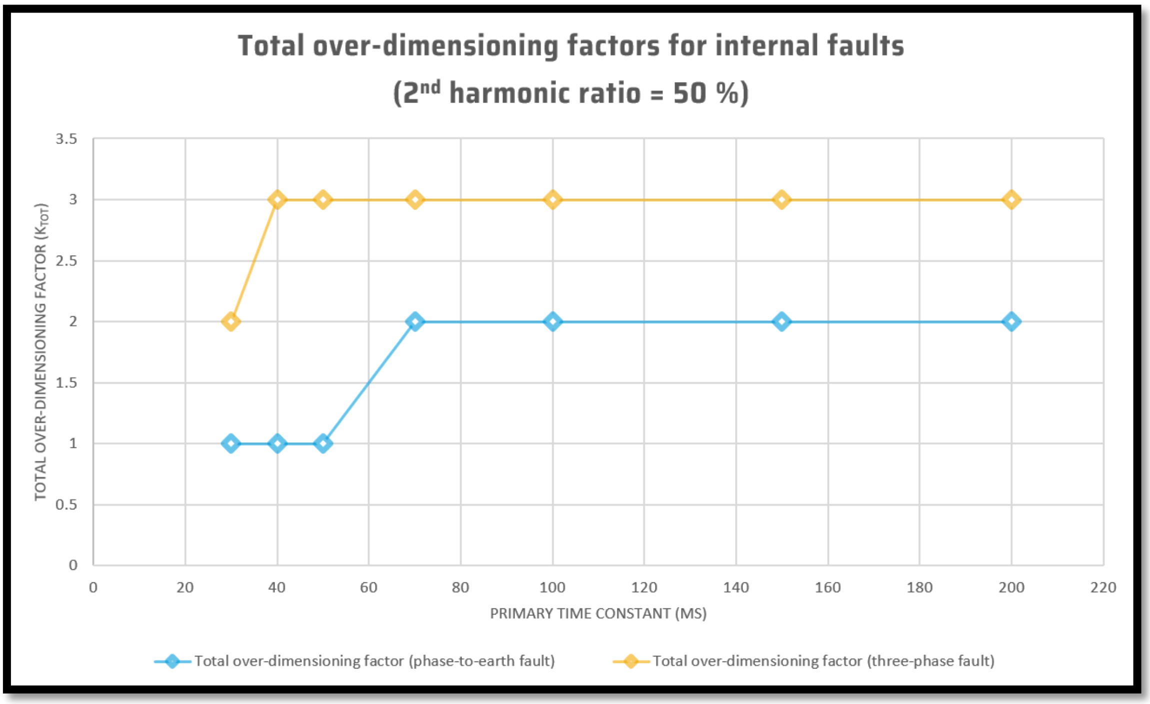


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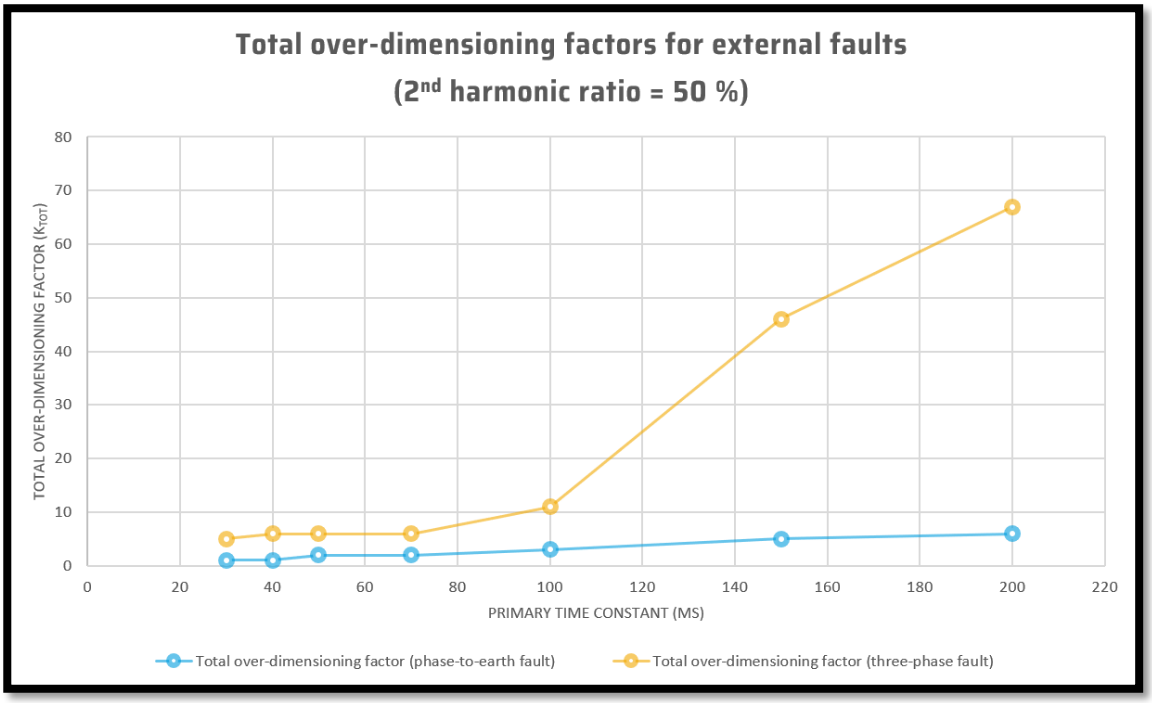
Table 6-8: Total over-dimensioning factors for external faults when the 2nd harmonic ratio = 50 %.

Primary time constant (ms)	Total over-dimensioning factor (K_{tot}) (external; 2nd h. ratio = 50 %)	
	Phase-to-earth fault	Three-phase fault
30	1	5
40	1	6
50	2	6
70	2	6
100	3	11
150	5	46
200	6	67

Figure 6-8: Diagram of the total over-dimensioning factors in Table 6-8.



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Additional sources

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[4] IEC 60255-187-1, *Functional requirements for differential protection — Restrained and unrestrained differential protection of motors, generators and transformers*. International Electrotechnical Commission, 28 June 2021.

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[5] Arcteq Relays Ltd., *Instruction manual for the AQ-T257 transformer protection device*, v2.09. Cited 28 March 2023 at: https://www.arcteq.fi/wp-content/uploads/2023/03/AQ-T257A-Transformer-protection-device-instruction-manual-v2.09-English.pdf