Transformer Differential

ANSI 87T

Parameter Setting Guide

Sepam Series 80 Protection Relays

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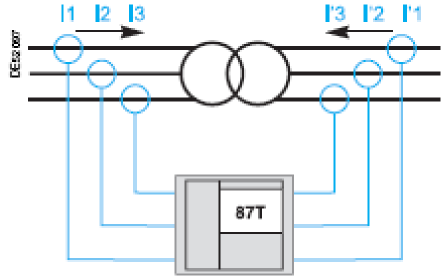
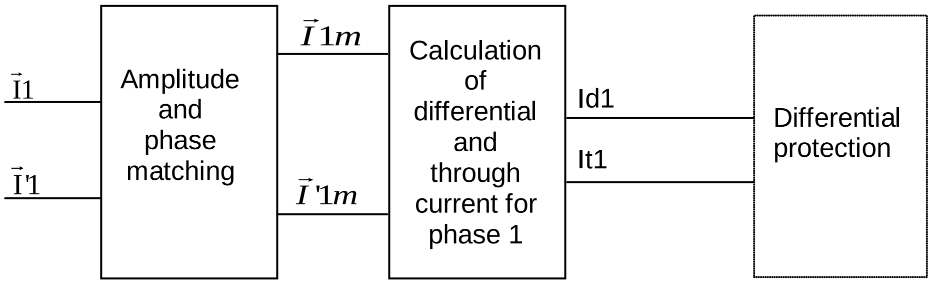
1. Differential function and matching:

1.1 Principle and operation:

The differential protection function protects the zone between the main and additional current sensors. It is used here to protect transformers from a few MVA to several tens of MVA from internal faults (inside the protected zone between the two sets of CTs).
The principle of differential protection consists of comparing two currents of the same phase, which are normally equal. If the current entering the protected zone is not equal to the current leaving the zone, the difference in the currents at the extremities of the protected zone give the measurement of the fault current. For transformer protection, things are slightly different though since the primary and secondary currents are necessarily different in terms of amplitude, because of the transformation ratio, and phase, according to the transformer coupling mode.
The primary and secondary currents of each phase therefore need to be processed in order to make them equal in normal operation. The current amplitude and phase need to be matched.

The transformer differential function protects the zone between the main current sensors I1, I2, I3 and the additional current sensors I'1, I'2, I'3	

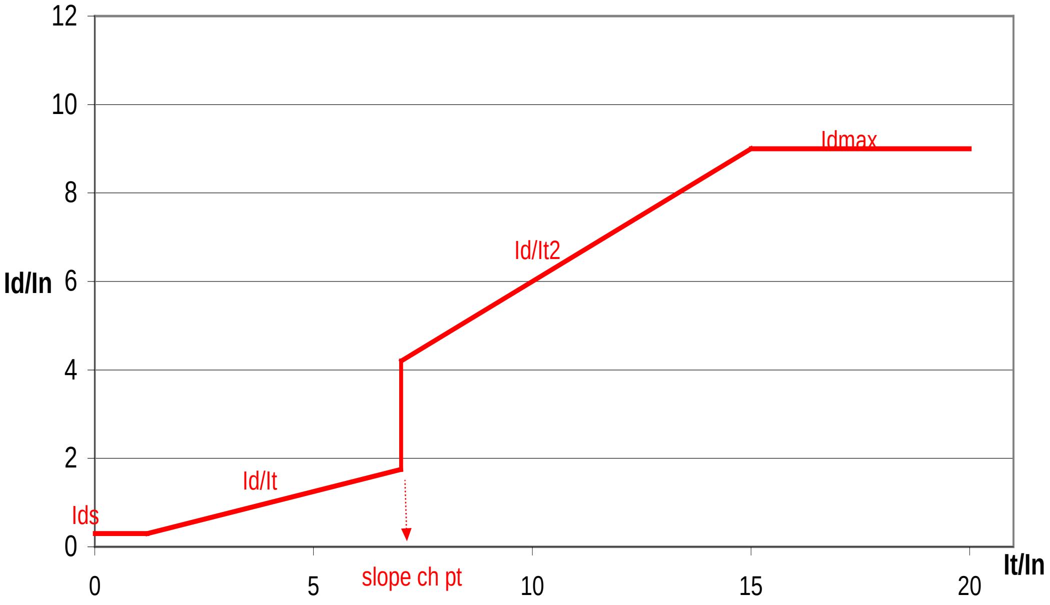
According to the current measurement convention, shown in the diagram above, and in compliance with the recommended wiring system, the differential currents Id and through currents It of each phase are calculated using the currents $\vec{I}m$ and $\vec{I}'m$.



(This block diagram is valid for all three phases)

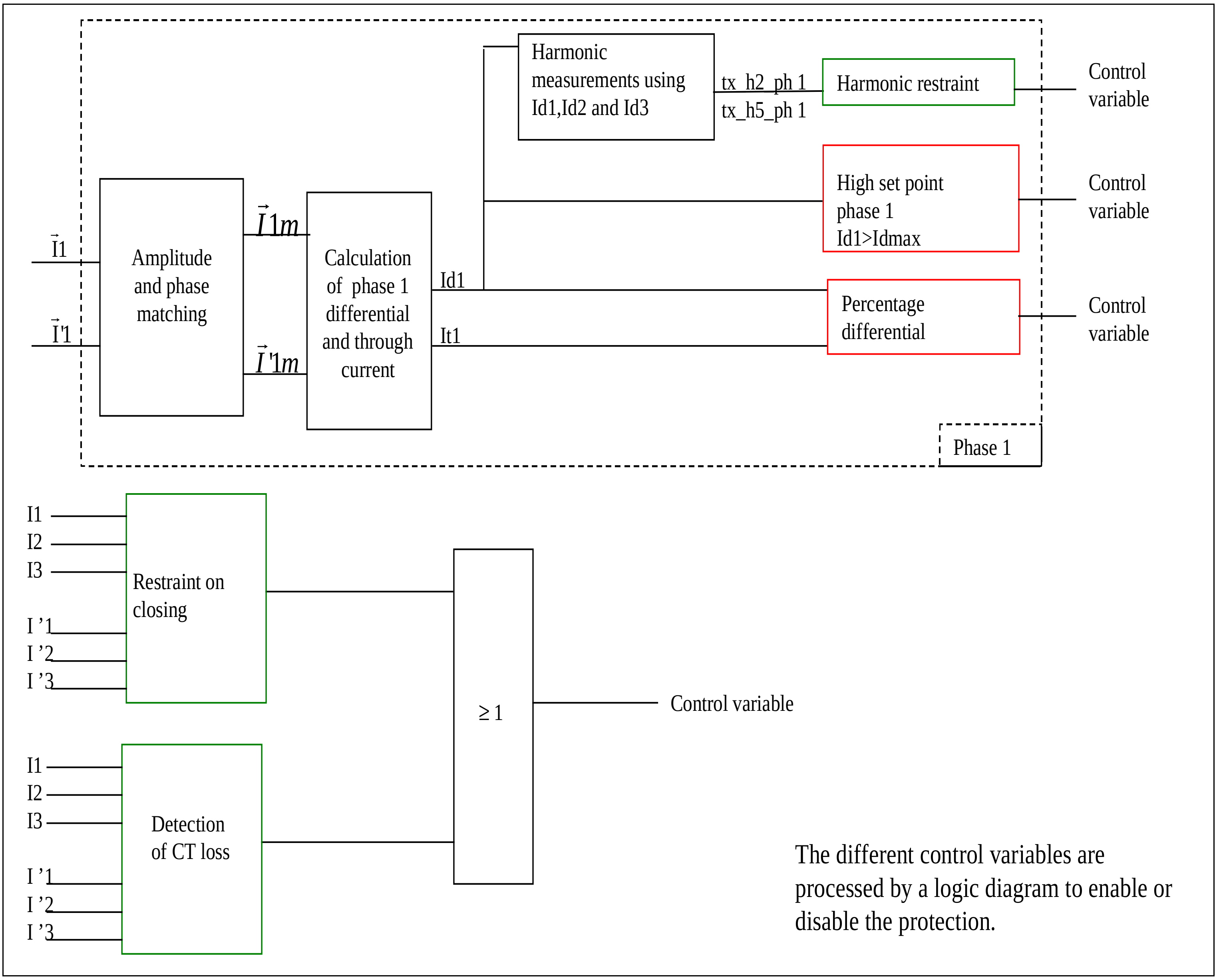
The differential function picks up if the differential current of at least one phase is greater than the adjustable operating threshold defined by:

- a high differential current set point threshold with no tripping restraint (Idmax)
- a percentage-based characteristic with two slopes (Id/It and Id/It2) and a low current set point (Ids)



Stability is ensured by the following tripping restraints:

- harmonic restraint (for closing and overexcitation phenomena)
- transformer energization restraint
- CT-loss restraint



Please note: the block diagram for the phase 1 function (outlined by the dotted line) is the same for each of the three phases.

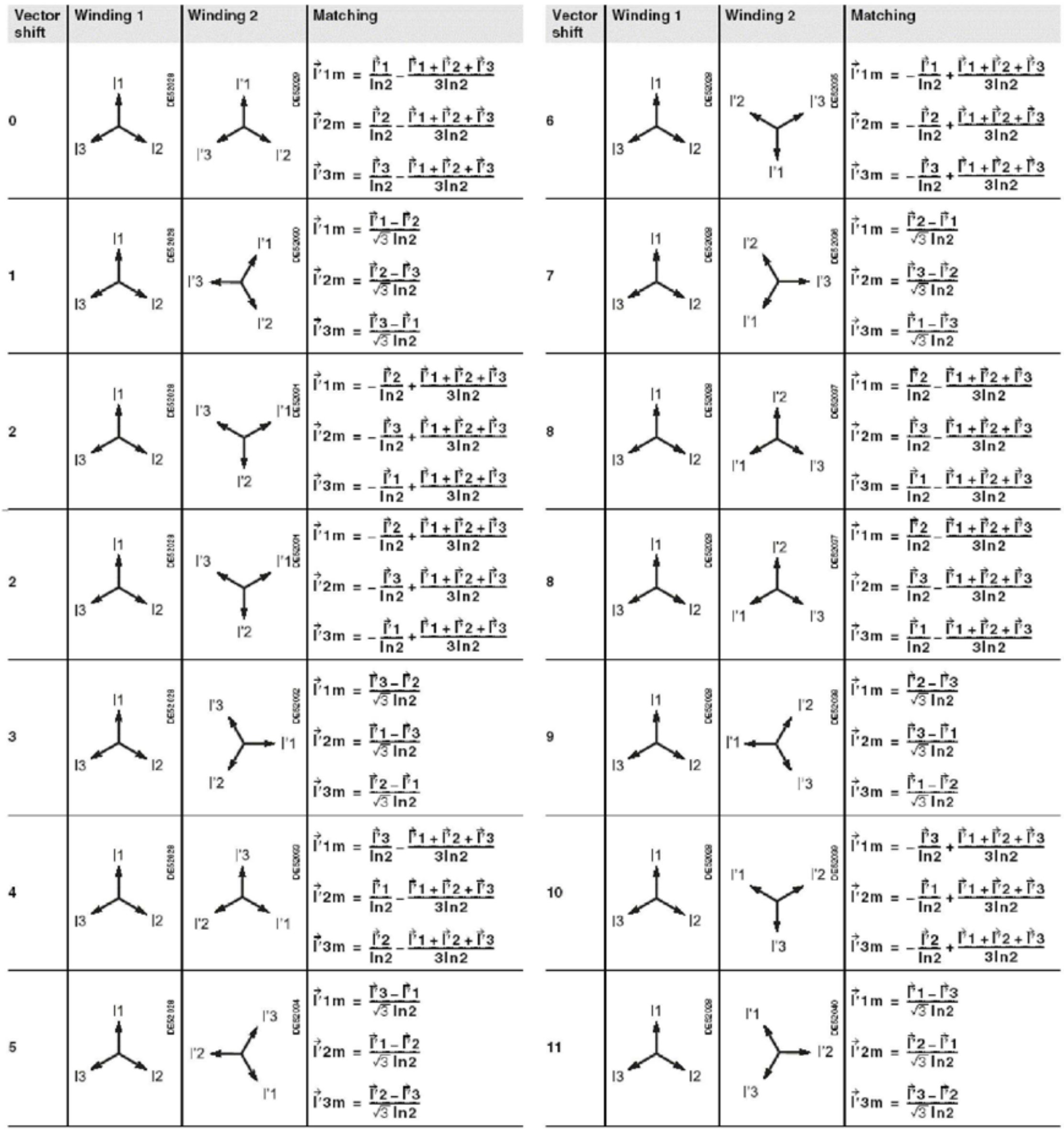
1.2 Need for matching:

The primary and secondary currents have **amplitude** differences because of the transformation ratio and **phase** differences because of the transformer coupling.
The currents therefore need to be processed in order for the signals to be compared. Based on the rated power and rated voltages, Sepam calculates the transformation ratio and adjusts the amplitude. The transformer vector shift is used for to match the phase currents.

- Transformer secondary (winding 2) current matching:

The matching of winding 2 affects the amplitude and phase and takes into account the transformer vector shift. The IEC 60076-1 standard presumes that the vector shift is given for a transformer connected to a power source, with a phase-rotation sequence of 123. Sepam uses this vector shift value for both 123 and 132 type networks. It is therefore not necessary to complement this value by 12 for a 132 type network.

The table below contains vectorial diagrams and matching formulae based on the vector shift of the transformer for networks with 123 type phase-rotation sequences.



Vector shift	Winding 1	Winding 2	Matching
0	I1 I3 I2	I'1 I'3 I'2	$\vec{I'}1m = \frac{\vec{I'}1}{In2} - \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$ $\vec{I'}2m = \frac{\vec{I'}2}{In2} - \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$ $\vec{I'}3m = \frac{\vec{I'}3}{In2} - \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$
1	I1 I3 I2	I'1 I'3 I'2	$\vec{I'}1m = \frac{\vec{I'}1-\vec{I'}2}{\sqrt{3}\,In2}$ $\vec{I'}2m = \frac{\vec{I'}2-\vec{I'}3}{\sqrt{3}\,In2}$ $\vec{I'}3m = \frac{\vec{I'}3-\vec{I'}1}{\sqrt{3}\,In2}$
2	I1 I3 I2	I'3 I'1 I'2	$\vec{I'}1m = -\frac{\vec{I'}2}{In2} + \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$ $\vec{I'}2m = -\frac{\vec{I'}3}{In2} + \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$ $\vec{I'}3m = -\frac{\vec{I'}1}{In2} + \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$
2	I1 I3 I2	I'3 I'1 I'2	$\vec{I'}1m = -\frac{\vec{I'}2}{In2} + \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$ $\vec{I'}2m = -\frac{\vec{I'}3}{In2} + \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$ $\vec{I'}3m = -\frac{\vec{I'}1}{In2} + \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$
3	I1 I3 I2	I'3 I'1 I'2	$\vec{I'}1m = \frac{\vec{I'}3-\vec{I'}2}{\sqrt{3}\,In2}$ $\vec{I'}2m = \frac{\vec{I'}1-\vec{I'}3}{\sqrt{3}\,In2}$ $\vec{I'}3m = \frac{\vec{I'}2-\vec{I'}1}{\sqrt{3}\,In2}$
4	I1 I3 I2	I'3 I'2 I'1	$\vec{I'}1m = \frac{\vec{I'}3}{In2} - \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$ $\vec{I'}2m = \frac{\vec{I'}1}{In2} - \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$ $\vec{I'}3m = \frac{\vec{I'}2}{In2} - \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$
5	I1 I3 I2	I'3 I'2 I'1	$\vec{I'}1m = \frac{\vec{I'}3-\vec{I'}1}{\sqrt{3}\,In2}$ $\vec{I'}2m = \frac{\vec{I'}1-\vec{I'}2}{\sqrt{3}\,In2}$ $\vec{I'}3m = \frac{\vec{I'}2-\vec{I'}3}{\sqrt{3}\,In2}$
6	I1 I3 I2	I'2 I'3 I'1	$\vec{I'}1m = -\frac{\vec{I'}1}{In2} + \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$ $\vec{I'}2m = -\frac{\vec{I'}2}{In2} + \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$ $\vec{I'}3m = -\frac{\vec{I'}3}{In2} + \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$
7	I1 I3 I2	I'2 I'3 I'1	$\vec{I'}1m = \frac{\vec{I'}2-\vec{I'}1}{\sqrt{3}\,In2}$ $\vec{I'}2m = \frac{\vec{I'}3-\vec{I'}2}{\sqrt{3}\,In2}$ $\vec{I'}3m = \frac{\vec{I'}1-\vec{I'}3}{\sqrt{3}\,In2}$
8	I1 I3 I2	I'2 I'1 I'3	$\vec{I'}1m = \frac{\vec{I'}2}{In2} - \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$ $\vec{I'}2m = \frac{\vec{I'}3}{In2} - \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$ $\vec{I'}3m = \frac{\vec{I'}1}{In2} - \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$
8	I1 I3 I2	I'2 I'1 I'3	$\vec{I'}1m = \frac{\vec{I'}2}{In2} - \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$ $\vec{I'}2m = \frac{\vec{I'}3}{In2} - \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$ $\vec{I'}3m = \frac{\vec{I'}1}{In2} - \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$
9	I1 I3 I2	I'2 I'1 I'3	$\vec{I'}1m = \frac{\vec{I'}2-\vec{I'}3}{\sqrt{3}\,In2}$ $\vec{I'}2m = \frac{\vec{I'}3-\vec{I'}1}{\sqrt{3}\,In2}$ $\vec{I'}3m = \frac{\vec{I'}1-\vec{I'}2}{\sqrt{3}\,In2}$
10	I1 I3 I2	I'1 I'2 I'3	$\vec{I'}1m = -\frac{\vec{I'}3}{In2} + \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$ $\vec{I'}2m = -\frac{\vec{I'}1}{In2} + \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$ $\vec{I'}3m = -\frac{\vec{I'}2}{In2} + \frac{\vec{I'}1+\vec{I'}2+\vec{I'}3}{3In2}$
11	I1 I3 I2	I'1 I'2 I'3	$\vec{I'}1m = \frac{\vec{I'}1-\vec{I'}3}{\sqrt{3}\,In2}$ $\vec{I'}2m = \frac{\vec{I'}2-\vec{I'}1}{\sqrt{3}\,In2}$ $\vec{I'}3m = \frac{\vec{I'}3-\vec{I'}2}{\sqrt{3}\,In2}$

- Transformer primary (winding 1) current matching:

  Winding 1 is always matched in the same way, whatever the vector shift of the transformer.

$$\vec{I}1m = \frac{\vec{I}1}{In1} - \frac{\vec{I}1 + \vec{I}2 + \vec{I}3}{3In1}$$

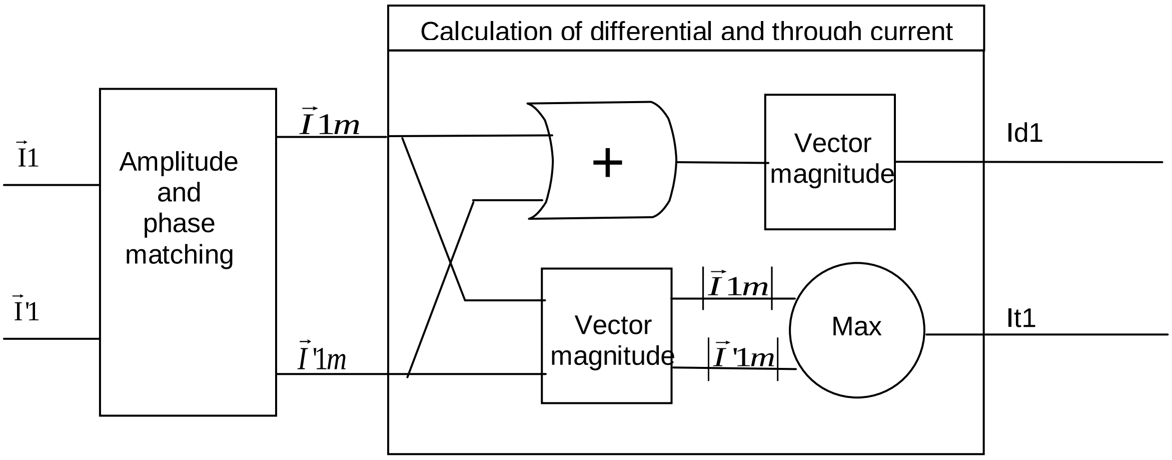
$$\vec{I}2m = \frac{\vec{I}2}{In1} - \frac{\vec{I}1 + \vec{I}2 + \vec{I}3}{3In1}$$

$$\vec{I}3m = \frac{\vec{I}3}{In1} - \frac{\vec{I}1 + \vec{I}2 + \vec{I}3}{3In1}$$

Please note: Matching is done by clearing the zero-sequence current in order to make the protection function immune to external earth faults outside the protected zone.

1.3 Use of matched currents:

For each phase, Sepam calculates the differential current and through current using the matched currents.

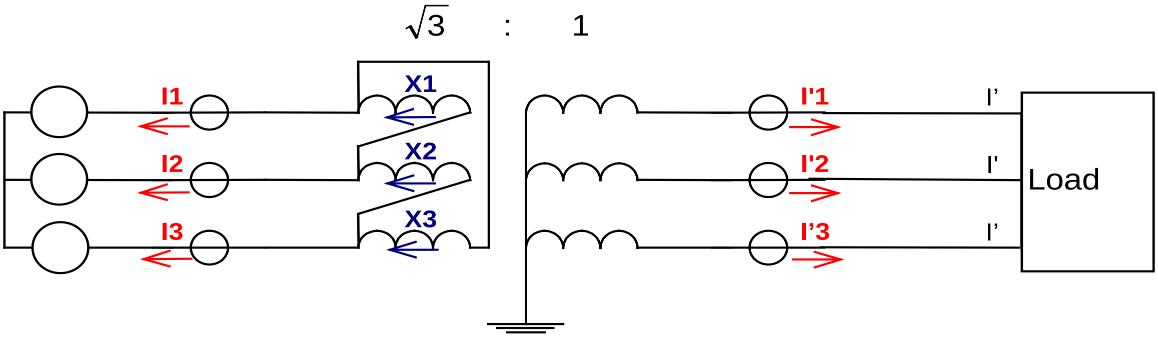


The differential and through currents per phase are defined by the following formulae:

Differential current: $Idi = \left|\vec{I}im + \vec{I}'im\right|$ for phase i

Through current: $Iti = \max\left(\left|\vec{I}im\right|, \left|\vec{I}'im\right|\right)$ for phase i (see note on the max. function)

The matching equations may be illustrated by applying them to a Dyn11 transformer. Let's take a transformer connected to a load that requires a secondary current with vector magnitude I'. To simplify, it is presumed that the transformation ratio is equal to one (i.e. Un=U'n).



Please note: the diagram above shows the vectors in bold print (**I**1,**I'**1,**X**1….)

Secondary currents:	Matching of secondary currents:
$\vec{I}'1 = I'$ $\vec{I}'2 = I'.a^2$ $\vec{I}'3 = I'.a$	(Vector shift=11) → $\vec{I}'1m = \frac{(1-a).I'}{\sqrt{3}.I'n}$ $\vec{I}'2m = \frac{(a^2-1).I'}{\sqrt{3}.I'n}$ $\vec{I}'3m = \frac{(a-a^2).I'}{\sqrt{3}.I'n}$

$\vec{I}1 = \vec{X}1 - \vec{X}3$ $\quad\quad$ $\vec{X}1 = -\vec{I}'1$ $\quad\quad$ $\vec{I}1 = \vec{I}'3 - \vec{I}'1$

$\vec{I}2 = \vec{X}2 - \vec{X}1$ $\quad$ and $\quad$ $\vec{X}2 = -\vec{I}'2$ $\quad$ hence $\quad$ $\vec{I}2 = \vec{I}'1 - \vec{I}'2$

$\vec{I}3 = \vec{X}3 - \vec{X}2$ $\quad\quad$ $\vec{X}3 = -\vec{I}'3$ $\quad\quad$ $\vec{I}3 = \vec{I}'2 - \vec{I}'3$

Primary currents:	Matching of primary currents:
$\vec{I}1 = (a-1).I'$ $\quad$ $\vec{I}1 = \frac{(a-1).I}{\sqrt{3}}$ $\vec{I}2 = (1-a^2).I'$ i.e. $\vec{I}2 = \frac{(1-a^2).I}{\sqrt{3}}$ $\vec{I}3 = (a^2-a).I'$ $\quad$ $\vec{I}3 = \frac{(a^2-a).I}{\sqrt{3}}$	$\vec{I}1m = \frac{(a-1).I}{\sqrt{3}.In} + \frac{1}{3.In}\left(\left[\underbrace{\frac{(a-1).I}{\sqrt{3}} + \frac{(1-a^2).I}{\sqrt{3}} + \frac{(a^2-}{\sqrt{}}}_{=0}\right.\right.$ $\vec{I}2m = \frac{(1-a^2).I}{\sqrt{3}.In}$ $\vec{I}3m = \frac{(a^2-a).I}{\sqrt{3}.In}$

$\frac{I}{I'} = \frac{In}{I'n} = \sqrt{3}$ i.e. $\frac{I}{In} = \frac{I'}{I'n}$

The differential current is calculated by: $Idi = \left|\vec{I}im + \vec{I}'im\right|$

- Phase 1: $\vec{I}'1m = \frac{(1-a).I'}{\sqrt{3}.I'n}$ and $\vec{I}1m = \frac{(a-1).I}{\sqrt{3}.In}$ Hence Id1=0
- Phase 2: $\vec{I}'2m = \frac{(a^2-1).I'}{\sqrt{3}.I'n}$ and $\vec{I}2m = \frac{(1-a^2).I}{\sqrt{3}.In}$ Hence Id2=0
- Phase 3: $\vec{I}'3m = \frac{(a^2-a).I'}{\sqrt{3}.I'n}$ and $\vec{I}3m = \frac{(a^2-a).I}{\sqrt{3}.In}$ Hence Id3=0

➔ Id1=Id2=Id3=**0**, the differential current is therefore zero for each phase.
The protection does not pick up in normal operation.

2. Setting of the «Ids threshold»:

2.1 Principle:

The low set point is defined as the maximum differential current that exists in normal transformer operation. The causes of differential current are:

Current transformer measurement errors
Current variants due to the use of an on-load tap changer
Presence of auxiliary windings (e.g. for substation supply)

2.2 Setting of the threshold:

The low set point must reflect the errors induced by the different transformer components:

▪ **CTs and on-load tap changers:** $(1+\beta)-\frac{1-\alpha}{1+b}$ **,** this is the maximum differential current created by CT measurement errors and the presence of on-load tap changers.

$$(1+\beta)-\frac{1-\alpha}{1+b}=\frac{\alpha+\beta+b+\beta b}{1+b}$$

with α: transformer primary current measurement error.
β: transformer secondary phase current measurement error.
b: range of transformer on-load tap changer taps.

Type of CT	5P	10P
α,β	5%	10%

N.B.: The details of the calculations used to obtain this formula are available in the document: Ids low set point and Id/It slope calculation uncertainty

▪ **Auxiliary winding:** Idaux, differential current induced by the use of an auxiliary winding on the transformer.

$\text{Idaux} = y\%$ where *y* is the percentage of secondary winding represented by the auxiliary winding

▪ **Differential current induced by the relay**, Idrelay:

$\text{Idrelay} = 1\%$, typically

▪ **Magnetizing current** of the transformer core which creates a differential current, Idm.

$\text{Idm} = 3\%$, typically

▪ A **safety margin** is also taken: typically, 5%.

The Ids threshold is expressed as a percentage of In1 and is obtained by the following formula:

$$\boxed{Ids=\left[(1+\beta)-\frac{1-\alpha}{1+b}+\text{Idaux}+\text{Idrelay}+\text{Idm}+\text{safety margin}\right]}$$

Numerical application:
Case of transformer equipped with 5P20 type CTs on the primary and secondary windings, an on-load tap-changer with a tap range of 10% and an auxiliary winding representing 10% of the secondary winding.

5P type CTs on the transformer primary and secondary windings, therefore α=β=5%.

$$\mathrm{Ids} = \left(\frac{0.05 + 0.05 + 0.1 + (0.05.0.1)}{1 + 0.1} + 0.1 + 0.01 + 0.03 + 0.05 \right) = 0.376$$ i.e. Ids=38%

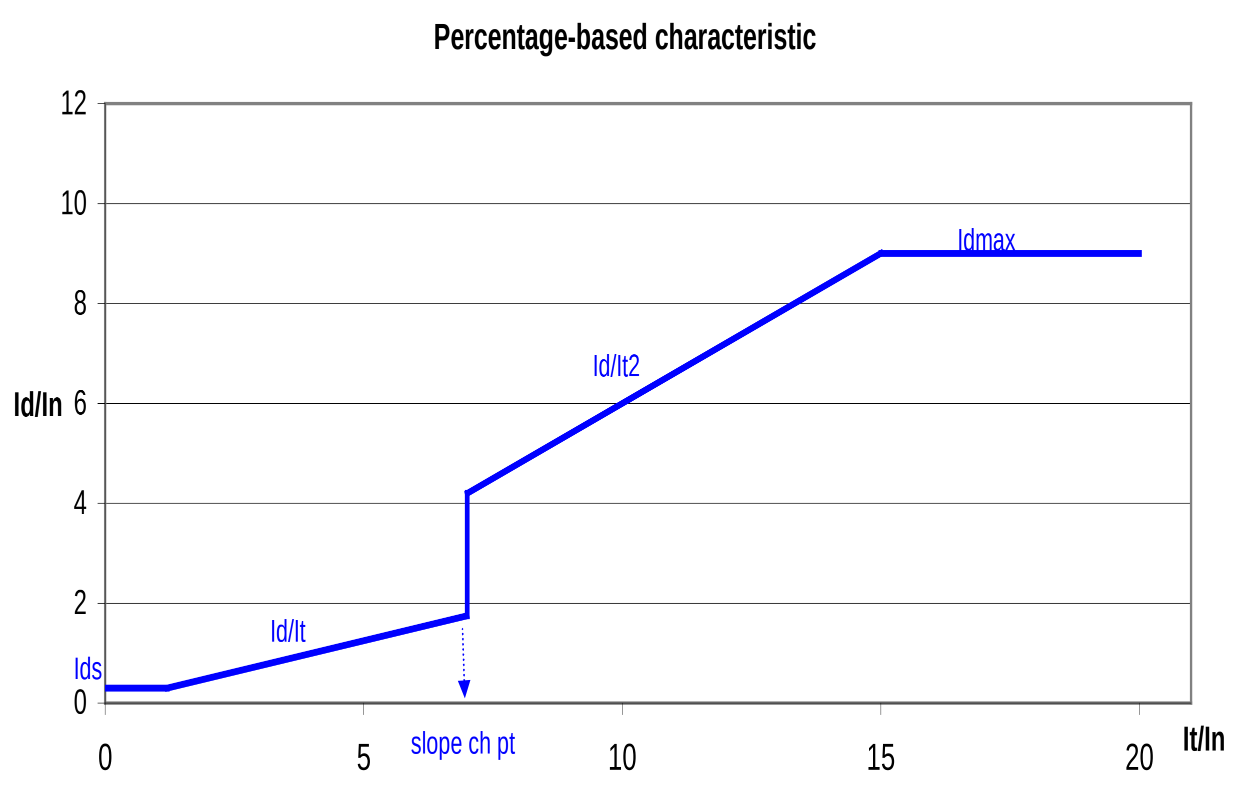
Please note: see the Excel tool for the calculation of Ids, OutilCalcul_Ids.xls

3. Percentage-based differential:

3.1 Principle:

The percentage-based curve comprises several segments defined are follows:

- a low set point (Ids), defined previously
- 2 straight lines with adjustable slopes that cross zero (Id/It and Id/It2)
- an adjustable slope change point (slope ch pt)
- a high set point (Idmax)



To prevent tripping due to high fault currents of external origin, Sepam uses a percentage-based curve. When a high external fault occurs, a high through current circulates. The differential current due to the transformer and its accessories (measurement CT, on-load tap changer and auxiliary winding) is also higher than in normal operation, so the Ids set point is exceeded. However the protection should not trip, since the fault is external. With the **Id/It slope**, the higher the through current, the higher the differential current tripping threshold will be, thereby ensuring that the function will not trip in the event of external faults.

The second segment, Id/It2, ensures that the function will not trip when an external fault causes at least one CT to saturate. If only the primary CTs saturate, not the secondary CTs, a very high differential current is created. To prevent unwanted tripping in these conditions, the percentage-based curve includes the Id/It2 slope.
The Id/It2 curve ensures that the protection function will not trip in the event of external faults with high through current which saturates at least one of the CTs.

The setting of the **slope change point** depends on the CTs' capacity to give a correct image of the primary currents during external faults. This zone corresponds to the CT saturation limit.

3.2 Setting of the percentage-based curve:

- **Id/It1 percentage:**

The setting should be sufficient to compensate for measurement errors caused by current with low but significant amplitude.
The Id/It slope value to be set in Sepam is the maximum Id/It value, i.e. maximum Id and minimum It.
In the previous paragraph, we established the following:

Ids = $(1+\beta)-\frac{1-\alpha}{1+b}$ + Idaux + Idrelay + Idm + safety margin, which corresponds to the maximum differential current measured in normal operation.
A series of calculations, available in the document Ids low set point and Id/It slope calculation uncertainty,

shows that the minimum through current value is $\mathrm{It\,min}=\frac{1-\alpha}{1+b}$.

This results in the following maximum slope value:

$$\frac{Id\max}{It\min}=\frac{\left[(1+\beta)-\frac{1-\alpha}{1+\mathrm{b}}+\mathrm{Idaux}+\mathrm{Idrelay}+\mathrm{Idm}+\mathrm{safety\ margin}\right]}{\frac{1-\alpha}{1+b}}$$

Numerical application:
Case of a transformer equipped with 5P20 type CTs on the primary and secondary windings, an on-load tap changer with a tap range of 10% and an auxiliary winding representing 10% of the secondary winding.

$\mathrm{Ids}=0.38$ therefore $\mathrm{Id/It}=0.38\Big/\frac{1-0.05}{1+0.1}=0.44$ i.e. a slope of approximately 44%.
Please note: See the Excel tool for the calcuation of the Id/It slope: Id/It_CalculTool.xls

- **Id/It2 percentage:**

The curve should be set sufficiently high to compensate for the worst case in which only the CTs at one end saturate and not the others. Typically, the slope is set between 60 and 70%.

- **Slope change point:**

This value is conventionally set at around 6 In.

4. Restraint principles:

Now we will look at the restraint part of the block diagram.

4.1 Problems relating to harmonics:

- **Second-harmonic set point restraint:**

Transformer closing causes a very high transient current (8 to 15 In), which only goes through the primary winding and only lasts for a few tenths of a second. It is detected by the protection relay as differential current with a duration that is clearly longer than the protection operating time. With detection based solely on the difference between the matched transformer primary and secondary currents, it would trip the protection. It is therefore necessary for the protection to be capable of distinguishing between differential current due to an internal fault and differential current due to transformer closing.
Experience has shown that the closing current wave contains at least 20% second-harmonic (100 Hz frequency current), whereas the percentage is never greater than 5% for overcurrent due to an internal transformer fault.

To block tripping, the function may simply be locked out when the second-harmonic with respect to the fundamental (50 Hz current) is greater than 15%.
N.B.: Transformer energization or external faults may cause CT saturation. In both cases, saturation increases the second harmonic in the differential current.
The values given previously for a 50Hz network are valid as well for a 60Hz network.

- **Fifth-harmonic set point restraint:**

Magnetizing current Im(1) is a difference between the transformer primary and secondary currents.
(1): $\mathrm{Im} = \mathrm{I.N} + \mathrm{I'}$ with I and I' transformer primary and secondary currents, respectively
N: the transformation ratio
The Im current is therefore detected as being fault current by the differential protection even though it is not due to a fault. In normal operation, magnetizing current is very low and does not reach the protection tripping threshold.
However, when the V/Hz ratio increases due to a cause outside the transformer, i.e. overvoltage or a drop in frequency, the magnetic material of the transformer saturates (transformers are generally sized to operate at the saturation limit for the rated supply voltage) and the magnetizing current value increases significantly. The protection operating threshold may be reached.
Experience has shown that magnetizing current due to magnetic saturation contains a high percentage of fifth harmonic (250 Hz frequency) current, at least 30%.
To prevent unwanted tripping due to overvoltage of external origin, saturation may be detected by the presence of fifth harmonic current and the function disabled if the fifth-harmonic set point is exceeded.
To prevent unwanted tripping due to overvoltage (or overfluxing) or external origin, the protection may simply be disabled for more than 30% fifth harmonic current.

Please note: Overexcitation resulting from an increase in the V/Hz ratio causes overfluxing in the power transformer core. The danger incurred results from a thermal process in the core. This process is slow and the transformer can withstand overfluxing for a certain length of time. Instantaneous tripping with this type of operation is unwanted, but detection of the phenomenon and indication or tripping may be useful.
In such cases the Sepam ANSI 24 overfluxing (V/Hz) function should be used.

4.2 Choice of self-adaptive or conventional restraint:

There are two types of harmonic restraint functions: self-adaptive and conventional. The choice depends on the transformer's **peak closing current**. The self-adaptive restraint is very interesting in that it adapts the parameters that define the tripping zone. However, it only operates for transformer energization currents less than eight times the transformer rated current.

The **self-adaptive** restraint is based on a neural network algorithm which ensures external fault stability by analyzing the second and fifth harmonics, diffential currents and through currents.
It guarantees stability in the following cases:

- transformer closing
- asymmetrical fault outside the zone which saturates the current sensors
- transformer operated on a voltage supply that is too high (overfluxing)

According to the closing current value, the following may be chosen:

Peak closing current: $\hat{I}inr$	$< \frac{8}{\sqrt{2}} \quad \hat{I}n = 8 \quad In$	$> \frac{8}{\sqrt{2}} \quad \hat{I}n = 8 \quad In$
Chosen type of restraint	Self-adaptive or Conventional	Conventional

With, $\hat{I}n$ rated peak current
In rated transformer current

Please note: Qualitatively speaking, the closing current of dry-type transformers is higher than that of oil-immersed transformers, and the lower the transformer power, the higher the closing current. (see Îe/În = f(P) graph).

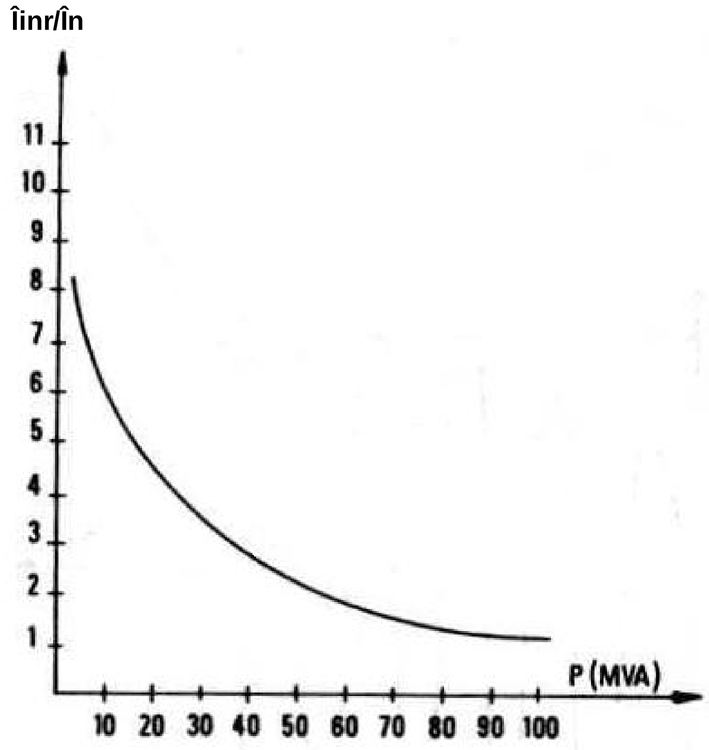


Figure 16.11. Relatve value of closing current according to transformer rated power for oriented-crystal sheets

For distribution transformers, France Transfo publishes the following values in its data sheets:

For TRIHAL dry-type cast resin transformers from 1000 to 2500kVA (Îinr peak closing current, $\hat{I}n$ peak primary rated current)

Rated power in kVA	1000	1250	1600	2000	2500
Îinr/În (peak values)	10	10	10	9.5	9.5

For oil-immersed transformers from 1000 to 2500kVA (Îinr peak closing current, $\hat{I}n$ peak primary rated current)

Rated power in kVA	1000	1250	1600	2000	2500
Îinr/În (peak values)	10	9	9	8	8

The **conventional** restraint comprises a second-harmonic set point for each phase and fifth-harmonic set point for each phase. The second-harmonic set point ensures that the function will not pick up in the event of transformer closing or current sensor saturation. The fifth-harmonic set point ensures that the protection function will not pick up in the event of the transformer being connected to a voltage supply that is too high (overfluxing).

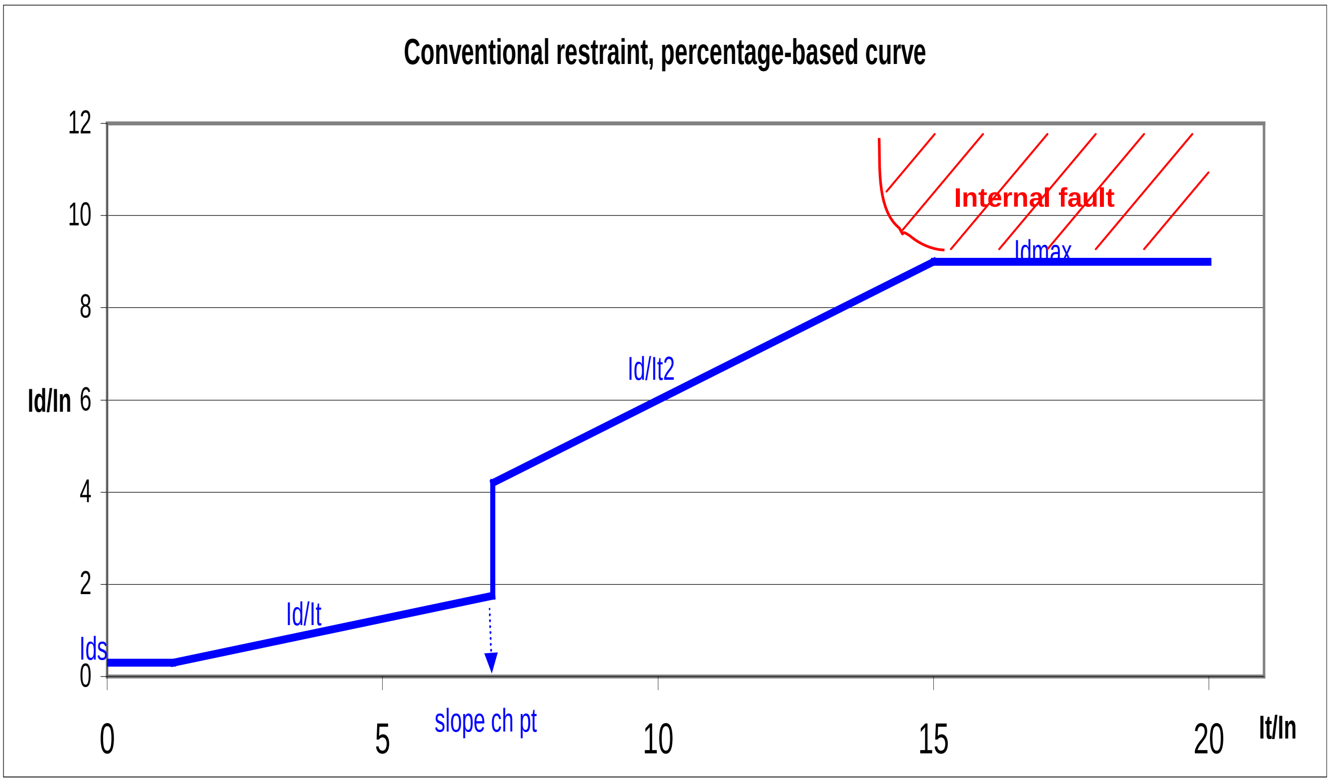
5. Principle and setting of high set point:

5.1 Principle:

The high set point allows faults inside the protected zone to be detected by the rise in differential current (an example of this type of fault is a fault across the transformer primary terminals). If the differential current exceeds a predetermined set point (Idmax), the protection function trips faster than an overcurrent protection relay would. In addition, there is no restraint on the high threshold, meaning that once it is activated, it is not affected by any restraint.

5.2 Setting:

A fault inside the zone produces high differential and through currents, situated in the upper right-hand part of the percentage-based curve.



With a **conventional restraint**, we always opt for **activation of the high set point** since it ensures tripping for the high through and differential curents created by internal faults.

With the **self-adaptive restraint**, activation of the high set point may **depend on whether or not the CT-loss restraint is implemented**. (see paragraph 9.Additional explanations of self-adaptive restraint)
When it is active, the high set point is set above the closing current, typically with a margin of 40% so that the protection function will not be tripped by transformer energizing.

$$\mathrm{Id\,max} = 140\% \cdot \frac{\hat{\mathrm{Ie}}}{\hat{\mathrm{In}}} \quad \text{i.e.} \quad \mathrm{Id\,max} = 1{,}4 \cdot \frac{\hat{\mathrm{Ie}}}{\hat{\mathrm{In}}}$$

6. Setting of the conventional restraint:

6.1 Second-harmonic:

The second-harmonic set point is typically between 15 and 25%. A common value is 15%.

Two points are to be noted:
If the CTs are saturated by energizing, the second-harmonic measured in the differential current increases.
If the cable to the secondary circuit is long, this can reduce the second-harmonic below 15%. In such cases, the second-harmonic set point should be lowered.

6.2 Fifth-harmonic:

The fifth-harmonic set point is typically between 25 and 35%. A typical value is 30%.

6.3 Global restraint (cross-blocking):

For each of the second and fifth-harmonics, the restraint may or may not be global.
When the restraint is global (cross-blocking), **all three** phases are restrained as soon as the harmonic in **one** phase reaches or exceeds the set point.
When the restraint is not global (no cross-blocking), only **the** phase with a harmonic greater to or equal to the set point is restrained.
Global restraint operates in the same way for both second and fifth-harmonic restraint.

It is advisable to apply the following settings:
Cross-blocking enabled for second-harmonic restraint.
Cross-blocking disabled for fifth-harmonic restraint.

7. Restraint on closing:

- **With certain modern transformer technologies**, the closing current has very little second harmonic current (less than 15%) and cannot be detected by Sepam.
- Furthermore, if there are **several transformers** in **parallel**, the energizing of a transformer in the vicinity of another one that is already operating causes demagnetization of the one already in service. There will be closing current in the demagnetized transformer again but, this time, with practically no second harmonic, meaning that it will not be detected by the harmonic restraints. Both cases can therefore cause unwanted tripping.

To compensate for such special cases, the restraint on closing may be used to disable the protection relay for a time delay equivalent to the duration of magnetization.
The current set point condition is: **Current set point < No-load current**
The no-load current generally represents a few percent of In.

The time delay is typically between 200 ms and 300 ms, representing the average energizing time: **200ms<Time delay <300ms**

Please note: This type of restraint should not be used downstream from the transformer if it supplies a process with frequent ON/OFF cycles, e.g. an oven. To maintain a constant temperature in the oven, the heating resistors are switched on and off cyclically. Each time the resistors switch on, the inrush current in the upstream transformer increases suddenly and the restraint on closing current set point would be activated. During the time delay, the protection is restrained. If the heating resistor switching on and off time is less than or close to the duration of the time delay, the protection would be continuously restrained. The transformer would no longer be protected effectively since only the high set point would remain activated.

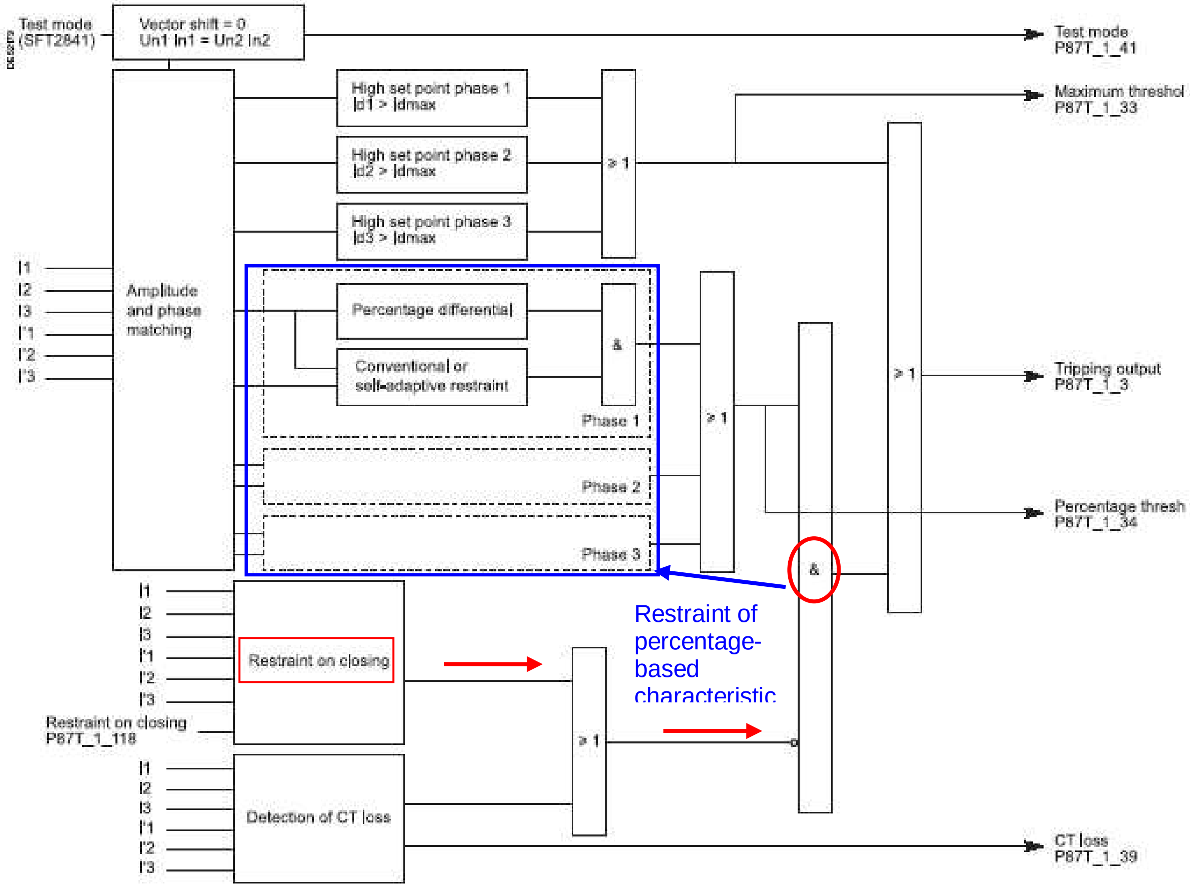
8. Restraint on CT loss:

This restraint inhibits the percentage-based curve part of the protection if the measurement of one of the six measurement CTs is lost. The choice of this restraint depends directly on the required application.

9. Additional explanations of self-adaptive restraint:

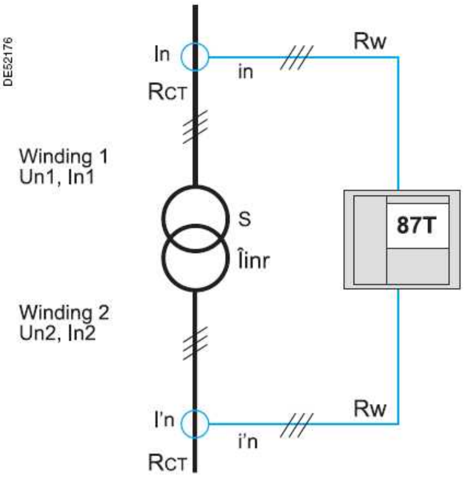
The self-adaptive restraint is based on a neural network algorithm which ensures protection operation by analyzing second and fifth harmonics, differential currents and through currents.
In the presence of harmonics, according to the through and differential currents, the self-adaptive restraint automatically increases the low set point and percentage-based slopes to guarantee stability in the event of external faults, transformer closing and overfluxing. This restraint incorporates a high through current stabilization slope which prevents current sensor saturation. This means that it is **not necessary to activate the Id/It2 slope** which serves the same purpose. It is however still necessary to set the low set point, Ids, and the Id/It slope.
The self-adaptive restraint also has a lower pick-up than the high set point. It is therefore **not essential to use the high set point.** However, when the **self-adaptive restraint** and **restraint on CT loss** are used, **activation of the high set point is advisable**. In such cases, if a CT on the installation is lost, the entire percentage-based characteristic part is restrained. This means that there will never be any internal fault tripping. With the addition of the high set point, protection can be maintained even in the case of percentage-based restraint (see Block diagram).

Block diagram



10. Dimensioning phase-current sensors:

Here is the single-line diagram that defines the different values, R_{CT} being the internal resistance of the CT and R_W the resistance of the wiring and the CT load.



The setting limit for the primary rated current of the current transformers is given by the following formulae:

For winding 1: $0.1 \cdot \frac{S}{Un1 \cdot \sqrt{3}} \leq In \leq 2.5 \cdot \frac{S}{Un1 \cdot \sqrt{3}}$

For winding 2: $0.1 \cdot \frac{S}{Un2 \cdot \sqrt{3}} \leq I'n \leq 2.5 \cdot \frac{S}{Un2 \cdot \sqrt{3}}$

10.1 Exceptional operation and on-load tap changer:

The transformer may tolerate exceptional operation at a power level above its rated load (a few tens of percent of the rated power), or it may be equipped with a tap changer with a tap range of + or - x % (from a few percent to ten or so percent). In both cases, a condition needs to be applied to the currents In and I'n.

Examples:

- The transformer operates normally at its rated load, but will tolerate operation at 120% of its rated power.

Sensor selection:

→The rated current of the windings is: $\frac{\text{S}}{\text{Un1}\quad\sqrt{3}} = \text{In}\,1$ and $\frac{\text{S}}{\text{Un2}\quad\sqrt{3}} = \text{In}\,2$

→The current sensors can support an overload of 120%.

The condition is therefore: In > In1 x 1.2
I'n > In2 x 1.2

- The transformer has a tap changer with a tap range of ±15% of the rated voltage of winding 2.

Sensor selection:

→The rated current of the windings is, as previously, In1 and In2

→Thanks to the tap changer, the current sensors can support an overload of 115%.

The condition is therefore: **In >In1 x 1.15**
I'n > In2 x 1.15

10.2 Dimensioning:

The current transformer depends next on the transformer's peak closing current $\hat{I}inr$ in relation to the rms rated current In.
The dimensioning differs according to the closing current:

Peak closing current: $\hat{I}inr$	$< 6.7 \quad \sqrt{2} \quad In = 6.7\,\hat{I}n$	$> 6.7 \quad \sqrt{2} \quad In = 6.7\,\hat{I}n$
Type of dimensioning	Case 1	Case 2

With, $\hat{\mathrm{In}}$ peak rated current
In transformer rms rated current

Case 1: $\hat{I}inr < 6.7 \quad \sqrt{2} \quad In$

- To guarantee standard CT dimensioning and minimum current measurement error with high currents, it is necessary to choose CTs of the **5P 20** type with a rated burden of $\mathrm{VA}_{\mathrm{CT:}}$

$$\mathrm{VA}_{\mathrm{CT}} > R_t \quad i_n{}^2$$

with i_n the CT secondary current and R_t the sum of the wiring resistance, R_W, and the internal CT resistance, R_{CT}, ($\mathrm{VA}_{\mathrm{CT}}$ corresponds to the apparent power supplied to the secondary circuit for the secondary rated current, the standardized values being 1-2.5- 5-10-15-30 VA)

Please note:
If only the Sepam is connected to the CT secondary circuts, the Sepam's internal resistance is negligible with respect to the wiring resistance. ($R_{CT} << R_W$)
CT manufacturers, in compliance with the IECI185 standard, give a rated burden P in VA, which imposes a maximum load according to the relation $\mathrm{Zmax.In}^2 = \mathrm{P}$, where Zmax is the CT's maximum load. This load includes the impedance of the cable connecting the CT to the relay and the relay input impedance. It is therefore obvious that there should not be too great a distance between the CT and the relay, and that it is sometimes necessary to increase the connection cable cross-section to minimize the total impedance of the load. This solution is generally more cost-effective than increasing the CT rated burden or kneepoint voltage.

- To optimize sensor selection and ensure tailored dimensioning, Class X CTs should be chosen with a kneepoint voltage such that the CT saturates at 20 times the transformer rated current. The condition regarding kneepoint voltage V_k is therefore:

$$V_K > \left(R_{CT} + R_W\right) \quad 20 \quad i_n$$

with R_{CT} : CT internal resistance
R_W : wiring resistance

Please note: The choice of class X CTs corresponds to a tailored offer. Class X CTs entail additional manufacturing time and extra cost.

Case 2: $\hat{I}inr > 6{,}7 \quad \sqrt{2} \quad In$

- To guarantee standard sensor dimensioning and minimum current mesurement errors with high values, it is necessary to choose **5P K$_n$** type CTs with a rated burden VA_{CT} and an accuracy limit factor FLP such that:

$$VA_{CT} \geq R_W \cdot {i_n}^2$$

and $FLP > 3 \quad \dfrac{\hat{I}inr}{\sqrt{2} \quad In}$

with i_n the CT secondary current and R_t the sum of the wiring resistance, R_W, and the CT internal resistance, R_{CT}. (VA_{CT} corresponds to the apparent power supplied to the secondary circuit for the secondary rated current, the standardized values being 1-2.5- 5-10-15-30 VA)

The last criterion corresponds to $FLP \geq 20.1$ in the limit case in which $\dfrac{\hat{I}inr}{\sqrt{2} \quad In} = 6.7$

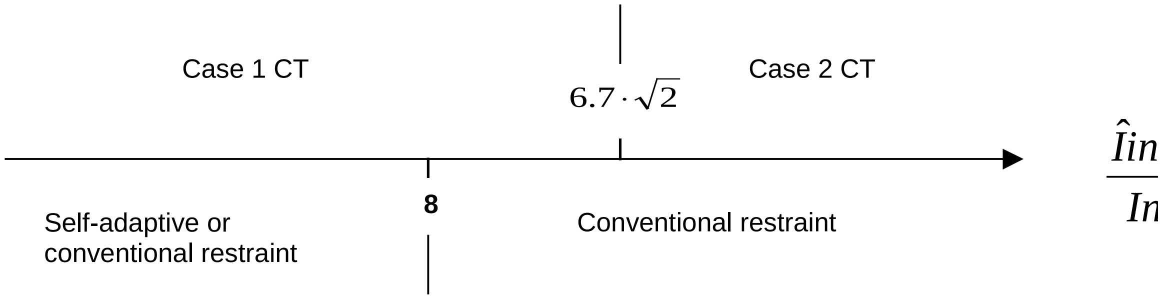
- For optimization, Class X CTs are chosen, and the condition regarding the kneepoint voltage **V$_k$** is:

$$V_K > \left(R_{CT} + R_W\right) \quad 3 \quad \frac{\hat{I}inr}{\sqrt{2} \quad In} \quad i_n$$

with R_{CT} : CT internal resistance

R_W : CT wiring resistance

Summary of dimensioning laws according to peak closing current value:



ANNEX of hypertext links

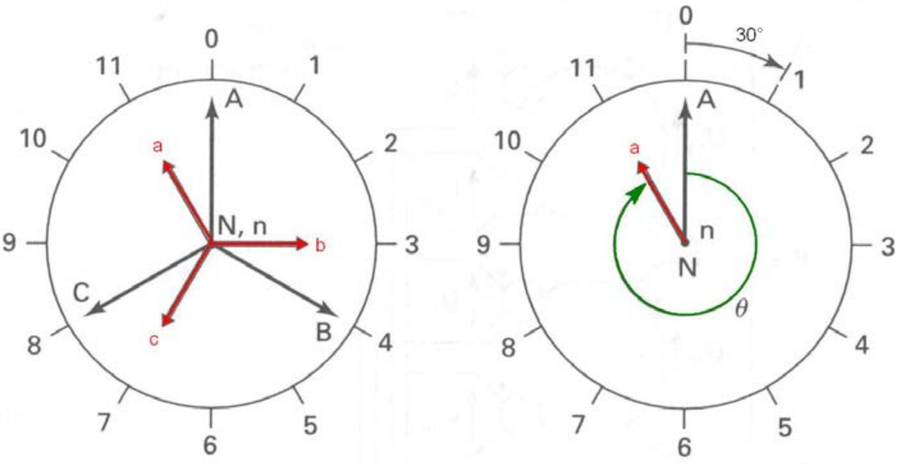
Rated power:

Two rated power values are generally given by the manufacturer for transformers, according to whether or not the coolers are operating. The rated power, S, to be set in Sepam is the greatest of the two values. The choice is made to make the protection even more insensitive to external faults.

Vector shift:

▪ **Definition:**
Vector shift is obtained by reading the time given by the vector of phase a (secondary phase 1) when the vector of phase A (primary phase 1) is pointing to noon.

In the example below, in the left-hand figure, the primary voltage systems are shown in red (a, b, c) and the secondary voltages in **black** (A, B, C). In the figure on the right, the vector shift value can be read directly. Here the vector of phase a points to 11 o'clock when the vector of phase A is at noon, so there is a vector shift of 11.



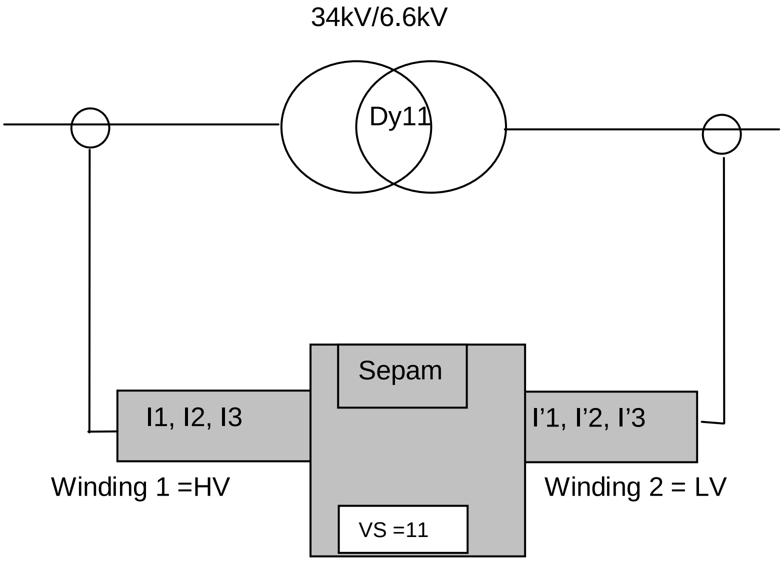
▪ **Use in Sepam:**
Sepam adjsuts the secondary currents differently according to the vector shift value.

▪ **Verification and setting:**
When the current sensors are connected correctly, i.e. the CTs measuring I1, I2, I3 are connected to the HV winding (winding 1) and the CTs measuring I'1, I'2, I'3 are connected to the LV winding (winding 2), the phase displacement measured by Sepam between the currents of winding 1 and winding 2 (corresponding to angle θ in the figure above), after division by 30°, correspond to the vector shift setting to be made.

- **Particular use of a transformer to step up voltage:**

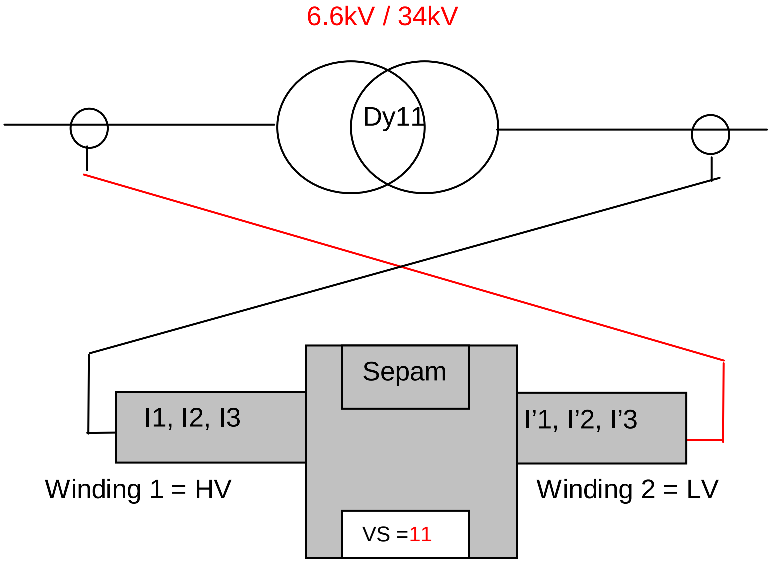
Let's take an example: a transformer with a rating plate that indicates:
Dy11, 34kV / 6.6kV.

<u>If the transformer is used to step down voltage:</u> the CTs measuring I1, I2, I3 should be connected to the HV winding (winding 1) and the CTs measuring I'1, I'2, I'3 to the LV winding (winding 2). In this case, the vector shift (VS) to be set in Sepam is equal to 11 as indicated in the rating plate.

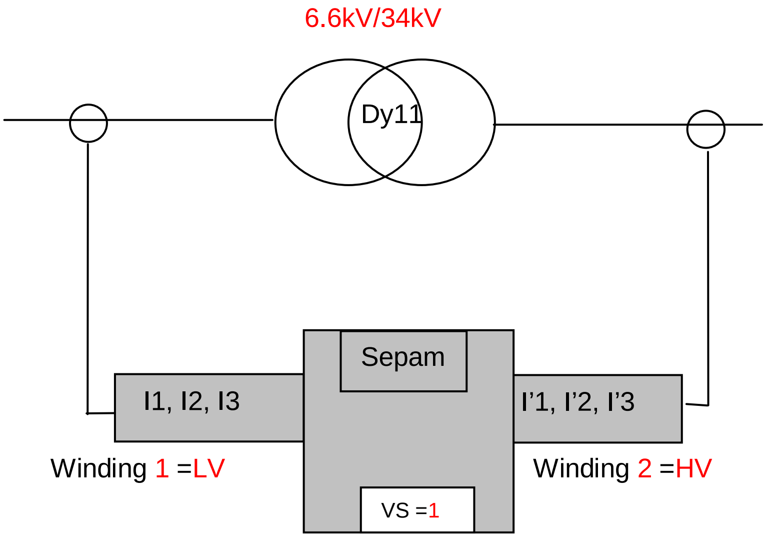


<u>HOWEVER if the transformer is used to step up voltage:</u>

If the wiring recommended in the commissioning manual is used, the CTs measuring I1, I2, I3 should be connected to the HV winding (winding 1) and the CTs measuring I'1, I'2, I'3 should be connected to the LV winding (winding 2). In this case, the vector shift (VS) to be set in Sepam is equal to 11 as indicated in the rated plate.

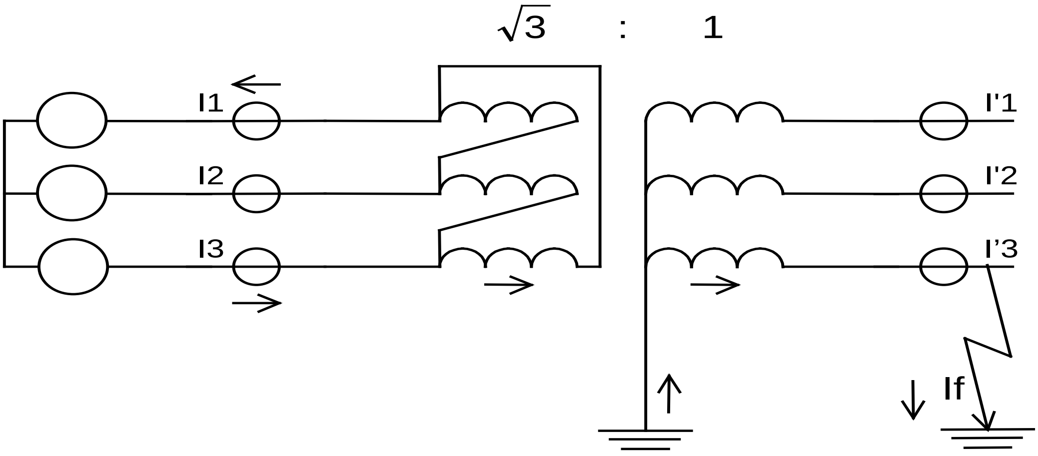


On the other hand, if the CTs measuring I1, I2, I3 are wired to the LV winding (winding 2) and the CTs measuring I'1, I'2, I'3 to the HV winding (winding 1), the vector shift (VS) to be set in Sepam is the complement of 12 compared to the value indicated in the rating plate, i.e. 12-11=1, VS=1 in Sepam.



Immunity to external earth faults:

To illustrate, let's take the case of a Dyn11 transformer.
To simplify calculations, it is presumed that the transformation ratio is equal to one (i.e. Un1=Un2).



- Currents of the different phases:

$$I'1 = 0$$
$$I'2 = 0$$
$$I'3 = -If$$

- Matched currents:

$$I'1m = \frac{(I'1 - I'3)}{\sqrt{3}.I'n} = \frac{If}{\sqrt{3}.I'n}$$
$$I'2m = \frac{(I'2 - I'1)}{\sqrt{3}.I'n} = 0$$
$$I'3m = \frac{(I'3 - I'2)}{\sqrt{3}.I'n} = \frac{-If}{\sqrt{3}.I'n}$$

$$I1 = -If$$
$$I2 = 0$$
$$I3 = If$$

$$I1m = \left[I1 - \frac{1}{3}(I1 + I2 + I3)\right] = \frac{-If}{In}$$
$$I2m = \left[I2 - \frac{1}{3}(I1 + I2 + I3)\right] = 0$$
$$I3m = \left[I3 - \frac{1}{3}(I1 + I2 + I3)\right] = \frac{If}{In}$$

- Differential and through currents: given that $\frac{In}{I'n} = \sqrt{3}$

$$It1 = If.$$
$$It2 = 0$$
$$It3 = If$$

$$Id1 = \frac{If}{\sqrt{3}.I'n} + \frac{-If}{In} = 0$$
$$Id2 = 0 + 0$$
$$Id3 = \frac{If}{In} + \frac{-If}{\sqrt{3}.I'n} = 0$$

➔ Id1=Id2=Id3**=0**, the differntial current is therefore zero for each phase.
The protection will not pick up with external earth faults.

Note on the max. function:

Given Im and I'm, the matched primary and secondary currents.

The through current for a phase is given by: $It = \max\left(\left|\vec{\mathrm{I}}\mathrm{m}\right|, \left|\vec{I}'m\right|\right)$

The notation $\left|\vec{\mathrm{I}}\mathrm{m}\right|$ indicates that we are taking the vector magnitude of the vector $\vec{\mathrm{I}}\mathrm{m}$, i.e. $\left|\vec{\mathrm{I}}\mathrm{m}\right| = \mathrm{Im}$ and $\left|\vec{I}'m\right| = I'm$

The max. function may be used to take the through current equal to the greatest of the two vector magnitudes:

If Im > I'm, It=Im
If I'm > Im, It= I'm

Ids low set point and Id/It slope calculation uncertainty:

Three examples are presented below, for three different types of coupling transformers.

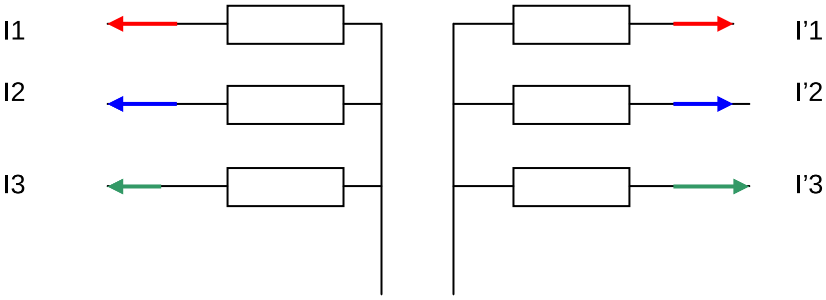
1. Yyo transformer:

I_n , I'_n : transformer primary and secondary rated currents, respectively.
(Generally speaking, the primed symbol characterizes an additional value)

Transformation ratio: $N = \frac{n_2}{n_1}$

$\alpha_{i:}$ measurement error on transformer primary phase i.
$\beta_{i:}$ measurement error on transformer secondary phase i.
b: transformer on-load tap changer tap range (+ or – 0.1)

$$\frac{U'i}{Ui} = \frac{Ii}{I'i} = \frac{N}{(1+b)} \quad and \quad I'n = \frac{In}{N}$$



Secondary currents:	Matching of secondary currents:
$\vec{I}'1 = (1+\beta1).I'n$ $\vec{I}'2 = (1+\beta2).I'n.a^2$ $\vec{I}'3 = (1+\beta3).I'n.a$	$I1'm = (1+\beta1) - \frac{1}{3}IR'$ $I2'm = (1+\beta2)a^2 - \frac{1}{3}IR'$ $I3'm = (1+\beta3)a - \frac{1}{3}IR'$

With $IR' = (1+\beta1) + a^2(1+\beta2) + a(1+\beta3) = \beta1 + a^2.\beta2 + a.\beta3$

↓

$$\vec{I}i = -\frac{N}{1+b}.\vec{I}'i$$

↓

Primary currents:	Matching of primary currents:
$I1 = -\frac{(1+\alpha1)}{(1+b)}.In$ $I2 = -\frac{(1+\alpha2)}{(1+b)}.In.a^2$ $I3 = -\frac{(1+\alpha3)}{(1+b)}.In.a$	$I1m = -\frac{(1+\alpha1)}{(1+b)} + \frac{1}{3.(1+b)}IR$ $I2m = -\frac{(1+\alpha2)}{(1+b)}.a^2 + \frac{1}{3.(1+b)}IR$ $I3m = -\frac{(1+\alpha3)}{(1+b)}.a + \frac{1}{3.(1+b)}IR$

With $IR = (1+\alpha1) + a^2(1+\alpha2) + a(1+\alpha3) = \alpha1 + a^2.\alpha2 + a.\alpha3$

Differential currents:

Differential current is calculated by: $Idi = \left| Iim + Ii'm \right|$

- A simulation has been done with Matlab to establish a combination of [α1,α2,α3] signs and [β1,β2,β3] signs to maximize differential current. The simulation results are as follows:

	Ai= [α1,α2,α3]	Bi= [β1,β2,β3]
Idi	[-α -α -α]	[β β β]

This corresponds to the case in which all the primary sensors have an α at the minimum (negative) and all the secondary sensors an error β at the maximum (positive).

Differential current may therefore be expressed as: $\boxed{\mathrm{Id} = \frac{\alpha + \beta + b + \beta b}{1 + b}}$

Through currents and Id/It slope:

Through current is calculated by: $It_i = \max(|I1m|, |I'1m|)$

For the same Id maximizing conditions (Id is maximized and It is minimized), through current may be expressed as: $\mathrm{It} = \frac{1 - \alpha}{1 + b}$

Hence the maximum slope $\boxed{\frac{\mathrm{Id}}{\mathrm{It}} = \frac{\alpha + \beta + b + \beta b}{1 - \alpha}}$

Numerical application:

For b=0.1 which corresponds to an on-load tap changer tap range of + or - 10%
and α=β=0.1, which corresponds to a CT accuracy error of 10%
the false differential current is equal to 28.18%
the minimum slope is equal to 34.44%

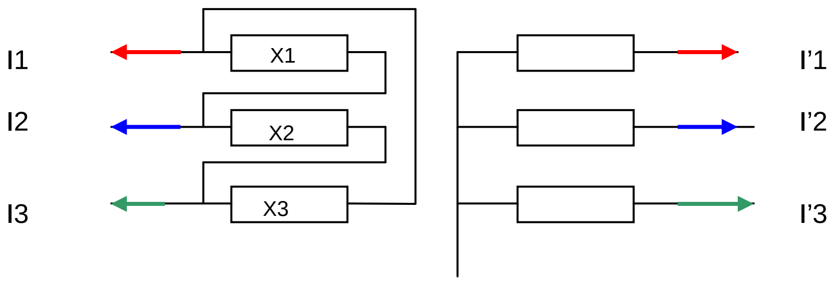
2. **Dy11 transformer:**

I_n , I'_n : transformer primary and secondary rated currents, respectively.
(Generally speaking, the primed symbol characterizes an additional value)

Transformation ratio: $N = \frac{n_2}{n_1}$

$\alpha_{i:}$ measurement error on transformer primary phase i .
$\beta_{i:}$ measurement error on transformer secondary phase i.
b: transformer on-load tap changer tap range (+ or – 0.1)

$$\frac{U'i}{Ui} = \frac{Ii}{I'i} = \frac{N.\sqrt{3}}{(1+b)} \quad and \quad I'n = \frac{In}{N.\sqrt{3}}$$



Secondary currents:	Matching of secondary currents:
$I'1 = (1+\beta 1).I'n$ $I'2 = (1+\beta 2).I'n.a^2$ $I'3 = (1+\beta 3).I'n.a$	$I'1m = \frac{(1+\beta 1) - (1+\beta 3).a}{\sqrt{3}}$ $I'2m = \frac{(1+\beta 2).a^2 - (1+\beta 1)}{\sqrt{3}}$ $I'3m = \frac{(1+\beta 3).a - (1+\beta 2).a^2}{\sqrt{3}}$

$$\begin{aligned} I1 &= X1 - X3 \\ I2 &= X2 - X1 \\ I3 &= X3 - X2 \end{aligned} \quad \text{and} \quad \begin{aligned} X1 &= -\frac{N}{1+b}.I'1 \\ X2 &= -\frac{N}{1+b}.I'2 \\ X3 &= -\frac{N}{1+b}.I'3 \end{aligned} \quad \text{hence} \quad \begin{aligned} I1 &= \frac{N}{1+b}.[I'3 - I'1] \\ I2 &= \frac{N}{1+b}.[I'1 - I'2] \\ I3 &= \frac{N}{1+b}.[I'2 - I'3] \end{aligned}$$

Primary currents:	Matching of primary currents:
$I1 = \frac{(1+\alpha 1)}{(1+b)}.\frac{(a-1)}{\sqrt{3}}.In$ $I2 = (1+\alpha 2).\frac{(1-a^2)}{\sqrt{3}}.In$ $I3 = \frac{(1+\alpha 3)}{(1+b)}.\frac{(a^2-a)}{\sqrt{3}}.In$	$I1m = \frac{1}{\sqrt{3}.(1+b)}.[(1+\alpha 1).(a-1) - \frac{1}{3}.IR]$ $I2m = \frac{1}{\sqrt{3}.(1+b)}.[(1+\alpha 2).(1-a^2) - \frac{1}{3}.IR]$ $I3m = \frac{1}{\sqrt{3}.(1+b)}.[(1+\alpha 3).(a^2-a) - \frac{1}{3}.IR]$

With $IR = (1+\alpha 1).(a-1) + (1+\alpha 2).(1-a^2) + (1+\alpha 3).(a^2-a)$

Differential currents:

Differential current is calculated by: $Idi = \left| Iim + Ii'm \right|$

- The results of the Matlab simulation used to find the maximum differential current are as follows:

	Ai= [α1,α2,α3]	Bi= [β1,β2,β3]
Id1	[-α -α -α]	[β -β β]
Id2	[-α -α -α]	[β β -β]
Id3	[-α -α -α]	[-β β β]

This corresponds to the case in which all the primary sensors are at the maximum and one of the three secondary sensors is at the minimum, the other two being at the maximum.

Differential current, whatever the phase, may be expressed as $\boxed{\mathrm{Id} = \frac{\alpha + \beta + b + \beta b}{1 + b}}$

Through currents and Id/It slope:

Through current is calculated by: $It_i = \max(|I1m|, |I'1m|)$

For the same Id maximizing conditions (Id is maximized and It is minimized), the through current can be expressed as $\mathrm{It} = \frac{1 - \alpha}{1 + b}$

Hence the maximum slope $\boxed{\frac{\mathrm{Id}}{\mathrm{It}} = \frac{\alpha + \beta + b + \beta b}{1 - \alpha}}$

Numerical application:

For b=0.1 and α=β=0.1,
the false differential current is equal to 28.18%
the minimum slope is equal to 34.44%

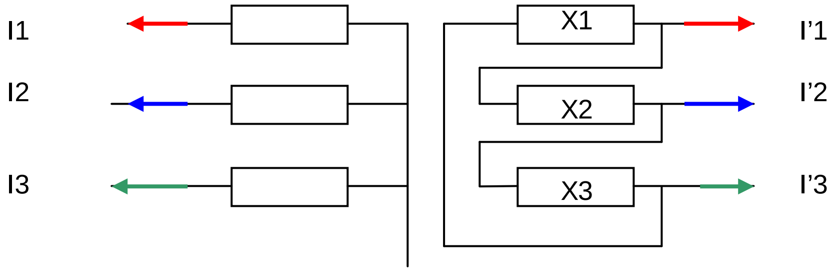
3. Yd5 transformer:

I_n , I'_n : transformer primary and secondary rated currents, respectively.
(Generally speaking, the primed symbol characterizes an additional value)

Transformation ratio: $N = \frac{n_2}{n_1}$

$\alpha_{i:}$ measurement error on transformer primary phase i .
$\beta_{i:}$ measurement error on transformer secondary phase i.
b: transformer on-load tap changer tap range (+ or – 0.1)

$$\frac{U'i}{Ui} = \frac{Ii}{I'i} = \frac{N.}{(1+b).\sqrt{3}} \quad and \quad I'n = In.\frac{\sqrt{3}}{N}$$



Secondary currents:	Matching of secondary currents:
$I'1 = (1+\beta1).I'n$ $I'2 = (1+\beta2).I'n.a^2$ $I'3 = (1+\beta3).I'n.a$	$I'1m = \frac{(1+\beta3)a - (1+\beta1)}{\sqrt{3}}$ $I'2m = \frac{(1+\beta1) - (1+\beta2)a^2}{\sqrt{3}}$ $I'3m = \frac{(1+\beta2).a^2 - (1+\beta3)a}{\sqrt{3}}$

$$Ii = \frac{N}{(1+b)}.Xi \quad \text{and} \quad X1 = \frac{1-a}{3}I'n \quad X2 = \frac{a^2-1}{3}I'n \quad X3 = \frac{a-a^2}{3}I'n$$

Primary currents:	Matching of primary currents:
$I1 = \frac{1}{\sqrt{3}.(1+b)}(1-a)(1+\alpha1).In$ $I2 = \frac{1}{\sqrt{3}.(1+b)}(a^2-1)(1+\alpha2).In$ $I3 = \frac{1}{\sqrt{3}.(1+b)}(a-a^2)(1+\alpha3).In$	$I1m = \frac{1}{\sqrt{3}.(1+b)}.[(1+\alpha1).(1-a) - \frac{1}{3}.IR]$ $I2m = \frac{1}{\sqrt{3}.(1+b)}.[(1+\alpha2).(a^2-1) - \frac{1}{3}.IR]$ $I3m = \frac{1}{\sqrt{3}.(1+b)}.[(1+\alpha3).(a-a^2) - \frac{1}{3}.IR]$

With $IR = (1-a)(1+\alpha1) + (a^2-1)(1+\alpha2) + (a-a^2)(1+\alpha3)$

Differential currents:

Differential current is calculated by: $Idi = \left| Iicor + Ii'cor \right|$

- The results of the Matlab simulation used to find the maximum differential current are as follows:

	Ai= [α1,α2,α3]	Bi= [β1,β2,β3]
Id1	[-α -α -α]	[β -β β]
Id2	[-α -α -α]	[β β -β]
Id3	[-α -α -α]	[-β β β]

This corresponds to the case in which all the primary sensors are at the maximum and one of the three secondary sensors is at the minimum, the other two being at the maximum.

Differential current, whatever the phase, may be expressed as: $\boxed{\mathrm{Id} = \dfrac{\alpha + \beta + b + \beta b}{1 + b}}$

Through currents and Id/It slope:

Through current is calcualted by: $It_i = \max(|I1m|, |I'1m|)$

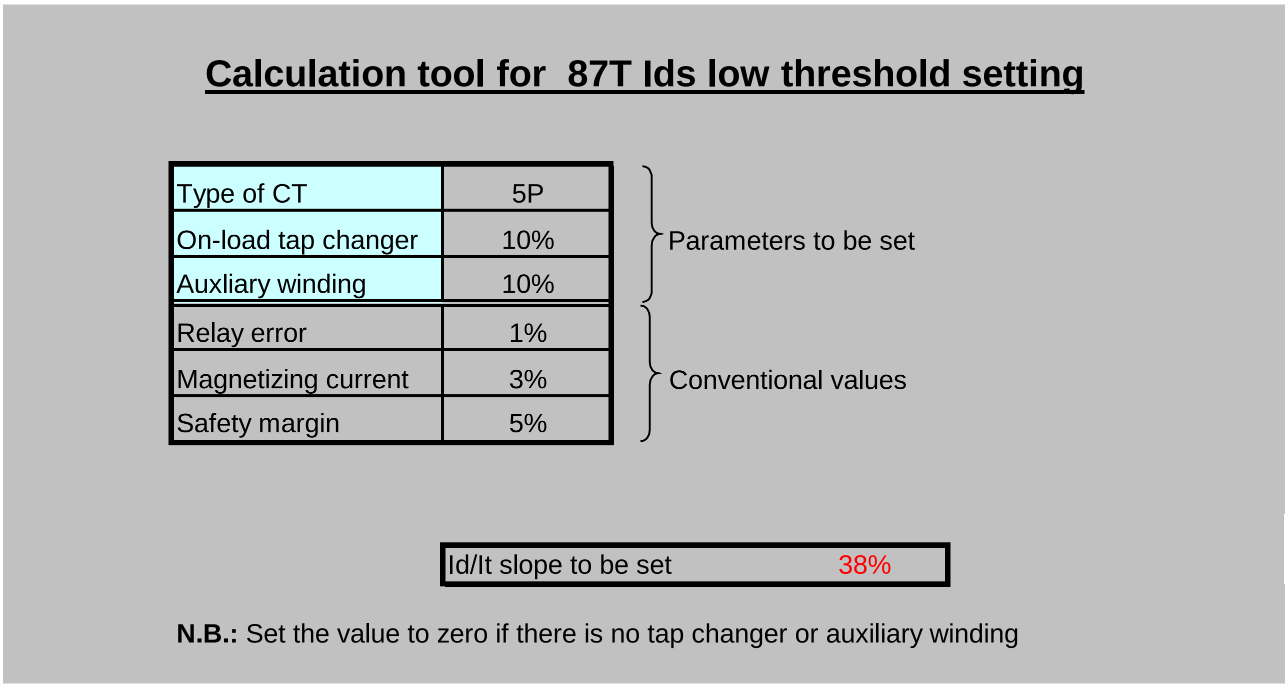
For the same Id maximizing conditions (Id is maximized and It is minimized), the through current may be expressed as $\mathrm{It} = \dfrac{1 - \alpha}{1 + b}$

Hence the maximum slope $\boxed{\dfrac{\mathrm{Id}}{\mathrm{It}} = \dfrac{\alpha + \beta + b + \beta b}{1 - \alpha}}$

Numerical application:

For b=0.1 and α=β=0.1,
the false differential current is equal to 28.18%
the minimum slope is equal to 34.44%

Ids low set point calculation tool:



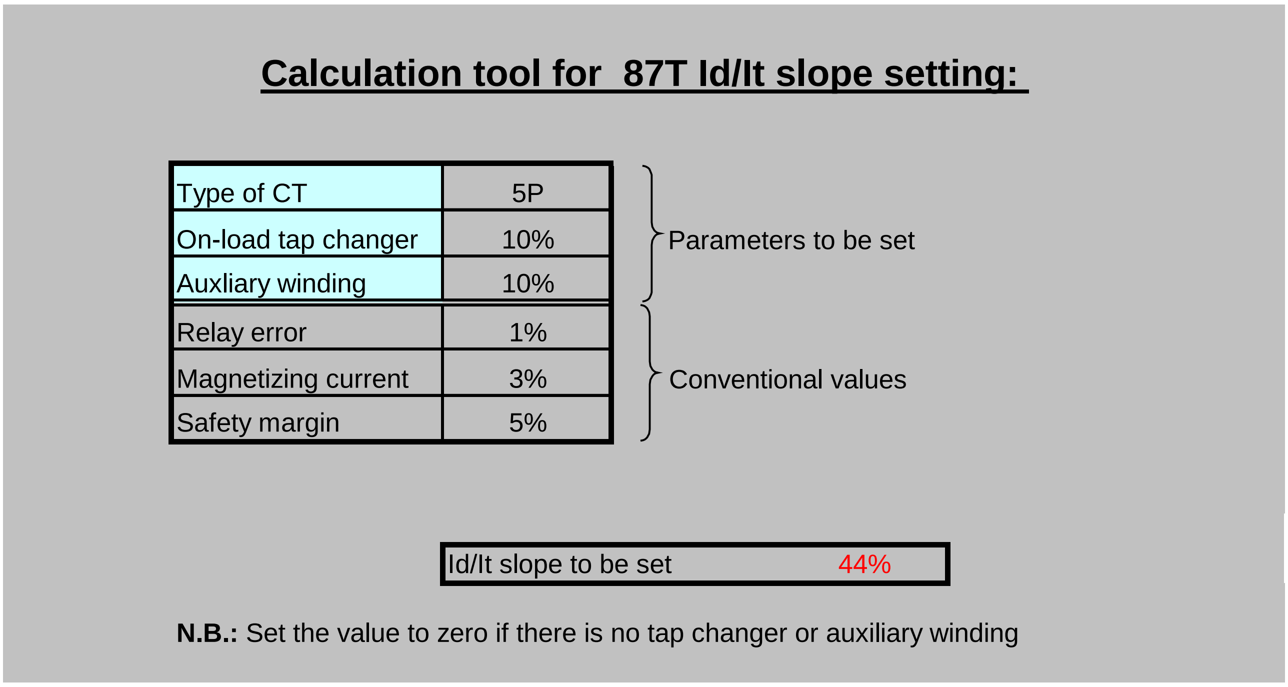
Calculation tool for 87T Ids low threshold setting

Type of CT	5P	Parameters to be set
On-load tap changer	10%	
Auxliary winding	10%	
Relay error	1%	Conventional values
Magnetizing current	3%	
Safety margin	5%	

Id/It slope to be set	38%

N.B.: Set the value to zero if there is no tap changer or auxiliary winding

Id/It slope calculation tool:



Calculation tool for 87T Id/It slope setting:

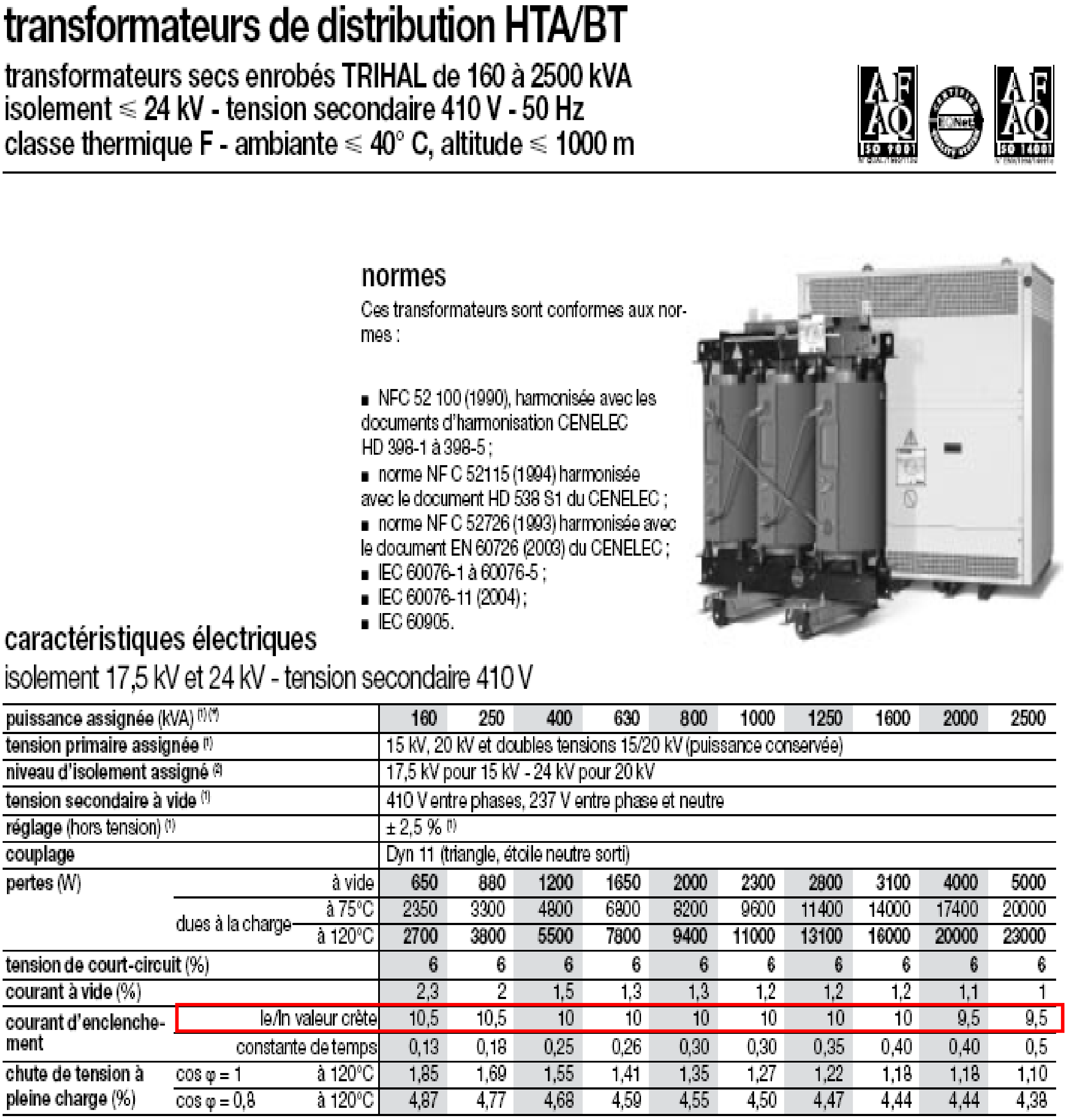
Type of CT	5P	Parameters to be set
On-load tap changer	10%	
Auxliary winding	10%	
Relay error	1%	Conventional values
Magnetizing current	3%	
Safety margin	5%	

Id/It slope to be set 44%

N.B.: Set the value to zero if there is no tap changer or auxiliary winding

TRIHAL dry-type cast resin transformers:

Data sheet extract



transformateurs de distribution HTA/BT

transformateurs secs enrobés TRIHAL de 160 à 2500 kVA
isolement ≤ 24 kV - tension secondaire 410 V - 50 Hz
classe thermique F - ambiante ≤ 40° C, altitude ≤ 1000 m

normes

Ces transformateurs sont conformes aux normes :

- NFC 52 100 (1990), harmonisée avec les documents d'harmonisation CENELEC HD 398-1 à 398-5 ;
- norme NF C 52115 (1994) harmonisée avec le document HD 538 S1 du CENELEC ;
- norme NF C 52726 (1993) harmonisée avec le document EN 60726 (2003) du CENELEC ;
- IEC 60076-1 à 60076-5 ;
- IEC 60076-11 (2004) ;
- IEC 60905.

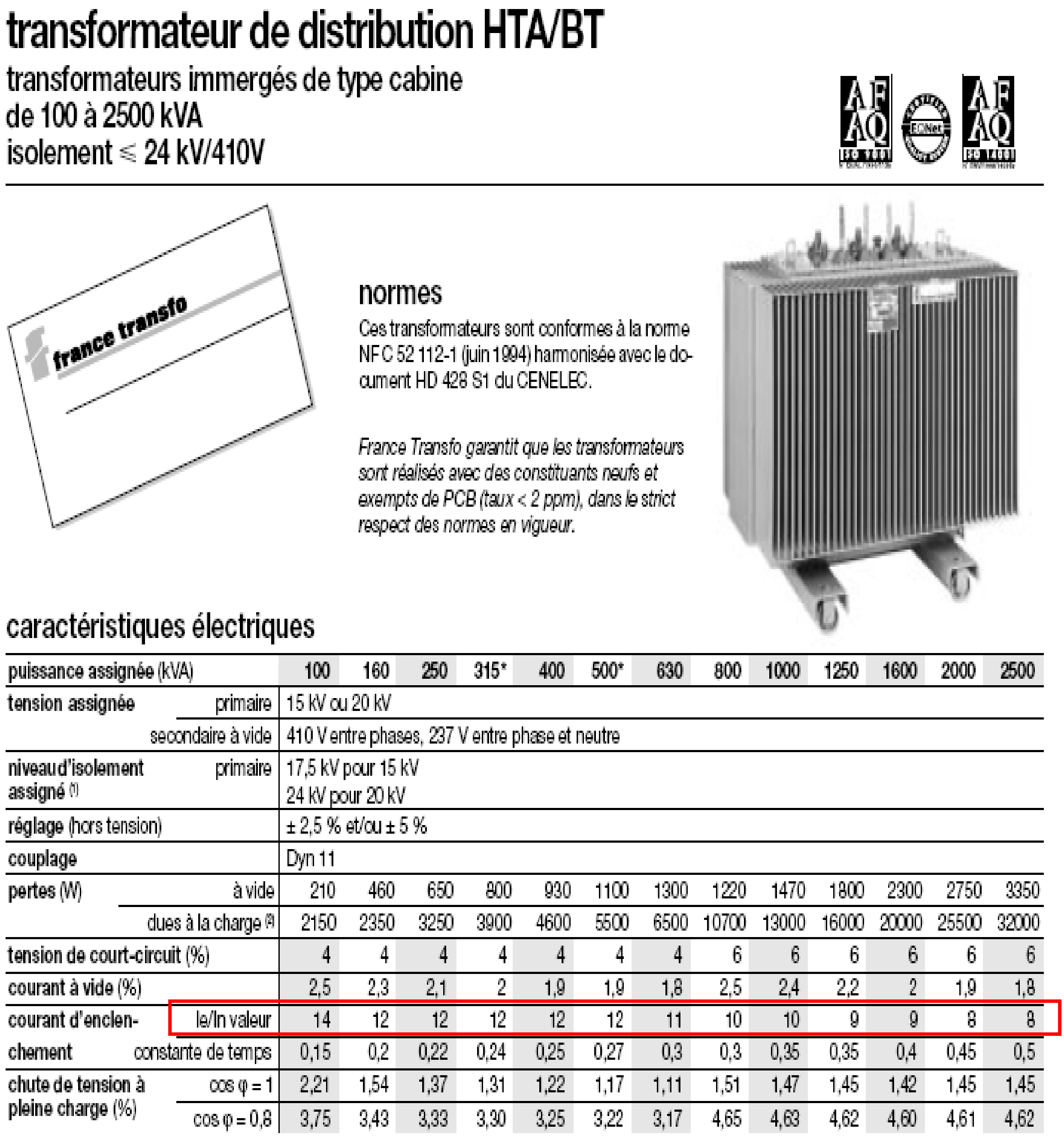
caractéristiques électriques

isolement 17,5 kV et 24 kV - tension secondaire 410 V

puissance assignée (kVA) (1)(*)			160	250	400	630	800	1000	1250	1600	2000	2500
tension primaire assignée (1)			15 kV, 20 kV et doubles tensions 15/20 kV (puissance conservée)									
niveau d'isolement assigné (2)			17,5 kV pour 15 kV - 24 kV pour 20 kV									
tension secondaire à vide (1)			410 V entre phases, 237 V entre phase et neutre									
réglage (hors tension) (1)			± 2,5 % (1)									
couplage			Dyn 11 (triangle, étoile neutre sorti)									
pertes (W)		à vide	**650**	**880**	**1200**	**1650**	**2000**	**2300**	**2800**	**3100**	**4000**	**5000**
	dues à la charge	à 75°C	2350	3300	4800	6800	8200	9600	11400	14000	17400	20000
		à 120°C	**2700**	**3800**	**5500**	**7800**	**9400**	**11000**	**13100**	**16000**	**20000**	**23000**
tension de court-circuit (%)			**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**
courant à vide (%)			2,3	2	1,5	1,3	1,3	1,2	1,2	1,2	1,1	1
courant d'enclenchement	Ie/In valeur crête		10,5	10,5	10	10	10	10	10	10	9,5	9,5
	constante de temps		0,13	0,18	0,25	0,26	0,30	0,30	0,35	0,40	0,40	0,5
chute de tension à pleine charge (%)	cos φ = 1	à 120°C	1,85	1,69	1,55	1,41	1,35	1,27	1,22	1,18	1,18	1,10
	cos φ = 0,8	à 120°C	4,87	4,77	4,68	4,59	4,55	4,50	4,47	4,44	4,44	4,38

Oil-immersed transformers

Data sheet extract



transformateur de distribution HTA/BT

transformateurs immergés de type cabine
de 100 à 2500 kVA
isolement ⩽ 24 kV/410V

france transfo

normes

Ces transformateurs sont conformes à la norme NF C 52 112-1 (juin 1994) harmonisée avec le document HD 428 S1 du CENELEC.

France Transfo garantit que les transformateurs sont réalisés avec des constituants neufs et exempts de PCB (taux < 2 ppm), dans le strict respect des normes en vigueur.

caractéristiques électriques

puissance assignée (kVA)		100	160	250	315*	400	500*	630	800	1000	1250	1600	2000	2500
tension assignée	primaire	15 kV ou 20 kV												
	secondaire à vide	410 V entre phases, 237 V entre phase et neutre												
niveau d'isolement assigné (1)	primaire	17,5 kV pour 15 kV 24 kV pour 20 kV												
réglage (hors tension)		± 2,5 % et/ou ± 5 %												
couplage		Dyn 11												
pertes (W)	à vide	210	460	650	800	930	1100	1300	1220	1470	1800	2300	2750	3350
	dues à la charge (2)	2150	2350	3250	3900	4600	5500	6500	10700	13000	16000	20000	25500	32000
tension de court-circuit (%)		4	4	4	4	4	4	4	6	6	6	6	6	6
courant à vide (%)		2,5	2,3	2,1	2	1,9	1,9	1,8	2,5	2,4	2,2	2	1,9	1,8
courant d'enclenchement	Ie/In valeur	14	12	12	12	12	12	11	10	10	9	9	8	8
	constante de temps	0,15	0,2	0,22	0,24	0,25	0,27	0,3	0,3	0,35	0,35	0,4	0,45	0,5
chute de tension à pleine charge (%)	cos φ = 1	2,21	1,54	1,37	1,31	1,22	1,17	1,11	1,51	1,47	1,45	1,42	1,45	1,45
	cos φ = 0,8	3,75	3,43	3,33	3,30	3,25	3,22	3,17	4,65	4,63	4,62	4,60	4,61	4,62

Artificial Neural Networks:

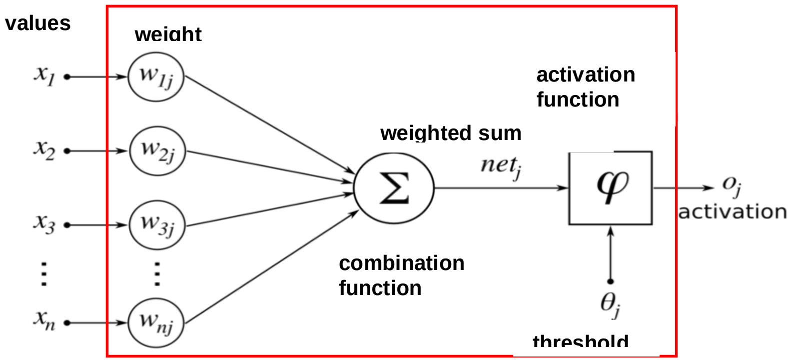
Artificial neural networks are a set of calculation tools and methods used to teach an artificial system different types of behaviors according to input parameter values. During the development of transformer differential protection, the function was "taught" to react in a particular way to four input parameters which are:

Differential and through current fundamental, $\mathrm{Id}_{\mathrm{h1}}$ and $\mathrm{It}_{\mathrm{h1}}$

Second-harmonic, $\mathrm{Id}_{\mathrm{h2}}$, the same for each phase

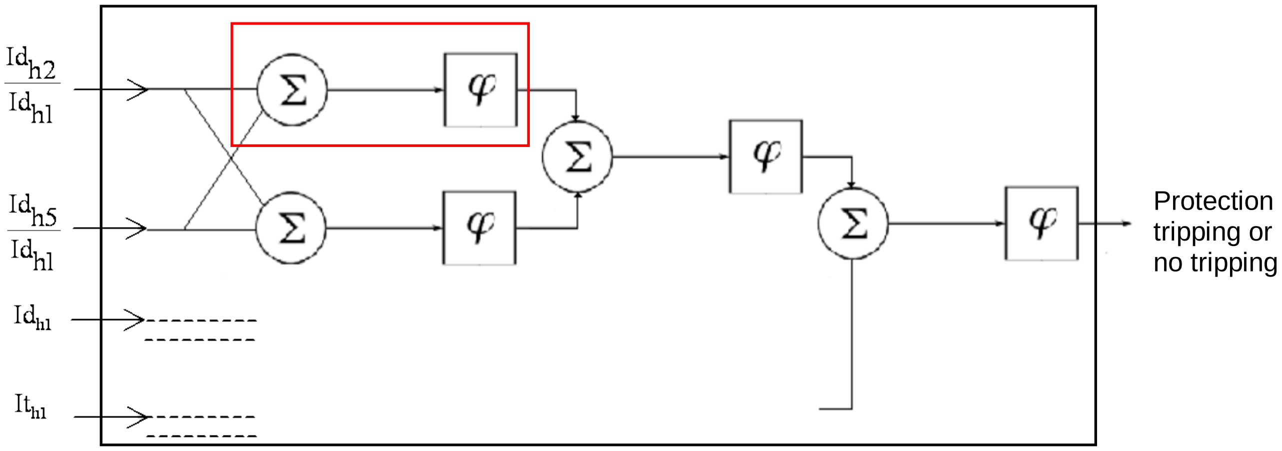
Differential current fifth-harmonic, $\frac{\mathrm{Id}_{\mathrm{h5}}}{\mathrm{Id}_{\mathrm{h1}}}$

- Representation of an artificial neuron:



with the following notations: The neuron input values are x_i
The output value is O_j
The internal parameters are the weights w_{ij} and the threshold θ_j

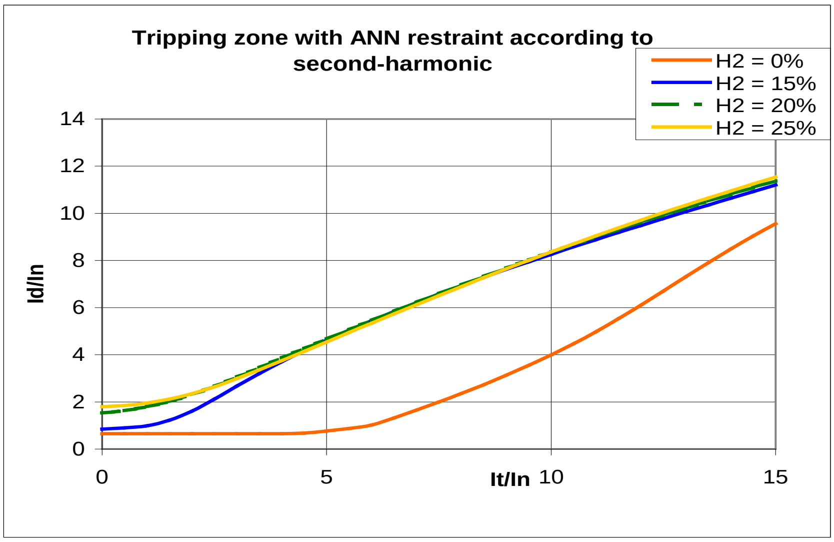
- Representation of the Artifical Neural Network of the Sepam algorithm:



The input parameter values corresponding to the 5 following types of situation were entered in the neural network learning database:

Normal operation, no faults, with and without connected loads
Transformer closing
Fault outside the protected zone
Internal two-phase fault
Internal phase-to-earth fault

An output value corresponding to protection tripping or no tripping was then given.
The neural network managed all of these cases by setting the internal parameters of each neuron (weight and threshold) to define a behavior that complied with the input and output conditions entered in the learning database. The algorithm obtained was then implemented in Sepam. This type of restraint increases the tripping threshold according to the harmonic current measured. Tests were then performed to determine the profile of the tripping curve that uses this self-adaptive restraint according to harmonic current. The test protocols which produced these curves are those detailed in the paragraph on protection testing.



If the second-harmonic increases, the low set point increases as well. The protection will therefore be more stable with respect to closing or CT saturation.

In normal operation, during which the second-harmonic is low (cf H2=0%), the function is more effective than the conventional restraint since the global tripping threshold is lower.

The same comments as above apply for fifth harmonic and transformer overfluxing.