Differential Protection with REF 542*plus* Feeder Terminal

Application and Setting Guide

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Contents:

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1. Scope

This document introduces the application of the three-phase differential protection in REF542*plus*. The differential protection is designed to protect power transformers or high-voltage motors. The operation is based on the biased differential protection principle with a four-fold tripping characteristic. Moreover, harmonics detection is implemented to obtain inrush current stabilization. Proper relay settings and the selection of current transformers are described with examples. A recommendation for the selection of current transformers is also given.

KEYWORDS: differential protection, transformer protection, motor protection.

2. Introduction

The three-phase differential protection incorporated in REF542plus is primarily designed for the protection of two-winding power transformers and high-voltage motors. The operation of the protection is based on the biased differential current principle, which is shown in Fig. 2.-1

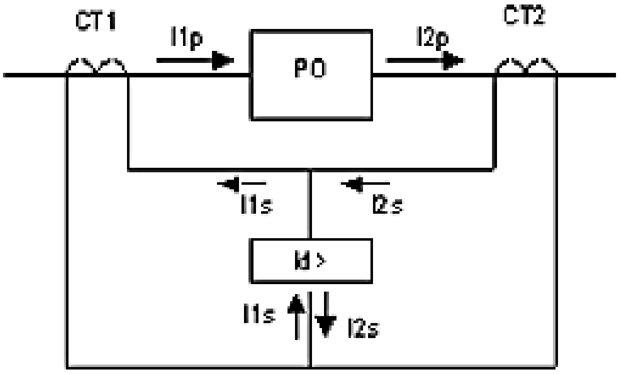


Fig. 2.-1 Operation principle of the bias differential protection

PO is the protected object, CT1 and CT2 the current transformers in the boundary zones I1p and I2p the current on the primary side of the concerned current transformers, and I1s and I2s the current on the secondary sides of the concerned current transformers. The secondary currents of the current transformers are routed through the differential protection Id>, as shown in Fig. 2.-1. Assuming that the current transformers have no error, it can be seen, that during normal load conditions or during through-fault conditions no current is flowing through the differential protection Id>. However, should an internal fault arise between the two current transformers a trip might be initiated, because then the differential current Id is no longer zero.

$$\underline{I}\mathrm{d} = \underline{I}\mathrm{1s} - \underline{I}\mathrm{2s}$$

In principle, this basic approach of a differential protection scheme is implemented using an overcurrent relay placed in the differential current path formed by the two current transformer secondary circuits.

Because current transformers always have a certain inherent error, the differential current is never zero, once load current is flowing. Especially under through-fault conditions with a high short- circuit current magnitude, the differential current may be very high too due to the current transformer errors. Furthermore, the on-load tap-changer of the power transformer causes an additional error due to the change of the transforming ratio of the winging. Depending on the sensitivity of the setting of the basic differential protection solution, i.e. the overcurrent protection relay, unwanted tripping may occur.

Therefore, it is necessary to stabilize the differential current protection by means of a so called bias current. For the biased differential protection the following measurement quantities are used:

- operating quantity: $\underline{I}\text{d} = |\underline{I}1\text{s} - \underline{I}2\text{s}|$
- biasing quantity: $\underline{I}\text{b} = (|\underline{I}1\text{s} + \underline{I}2\text{s}|)/2.$

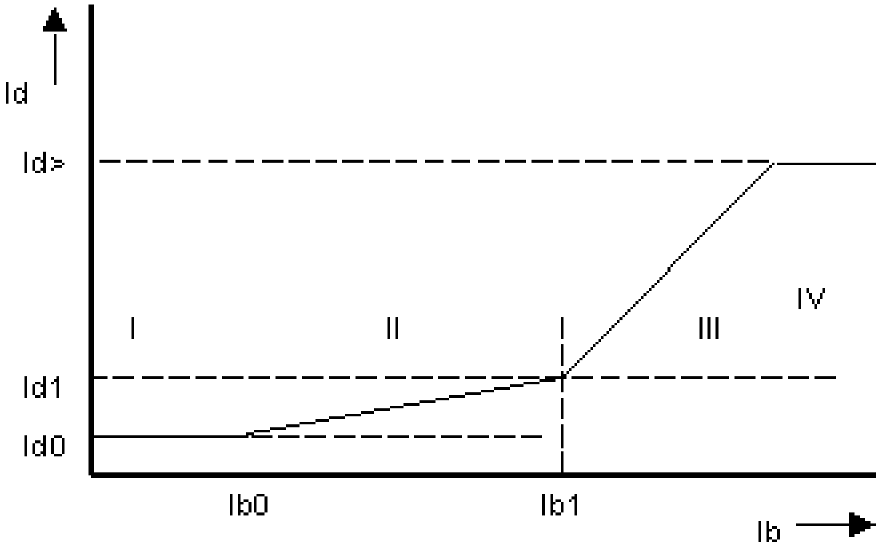


Fig. 2.-2 Tripping characteristic of a biased differential protection

The above equation shows that the biased current is almost the same as the load current under normal load conditions or under through-fault conditions. By using the biasing quantity it is possible to define the dependency between the tripping of the differential protection and the through-fault current. The higher the load current or the through fault current, the higher the level of the differential current required for tripping.

The tripping characteristic consists of four different areas. The first area is dedicated to low load conditions, the second one to normal and heavy load conditions, the third one to through-fault conditions and, finally, the fourth one by Id> to tripping due to a through fault current condition.

3. Technical implementation

3.1. Connection diagram

Connection diagram

Due to its flexibility, the REF542*plus* offers a lot of options for connecting the device to the current transformers. Fig. 3.1.-1 below shows one of these CT connection options.

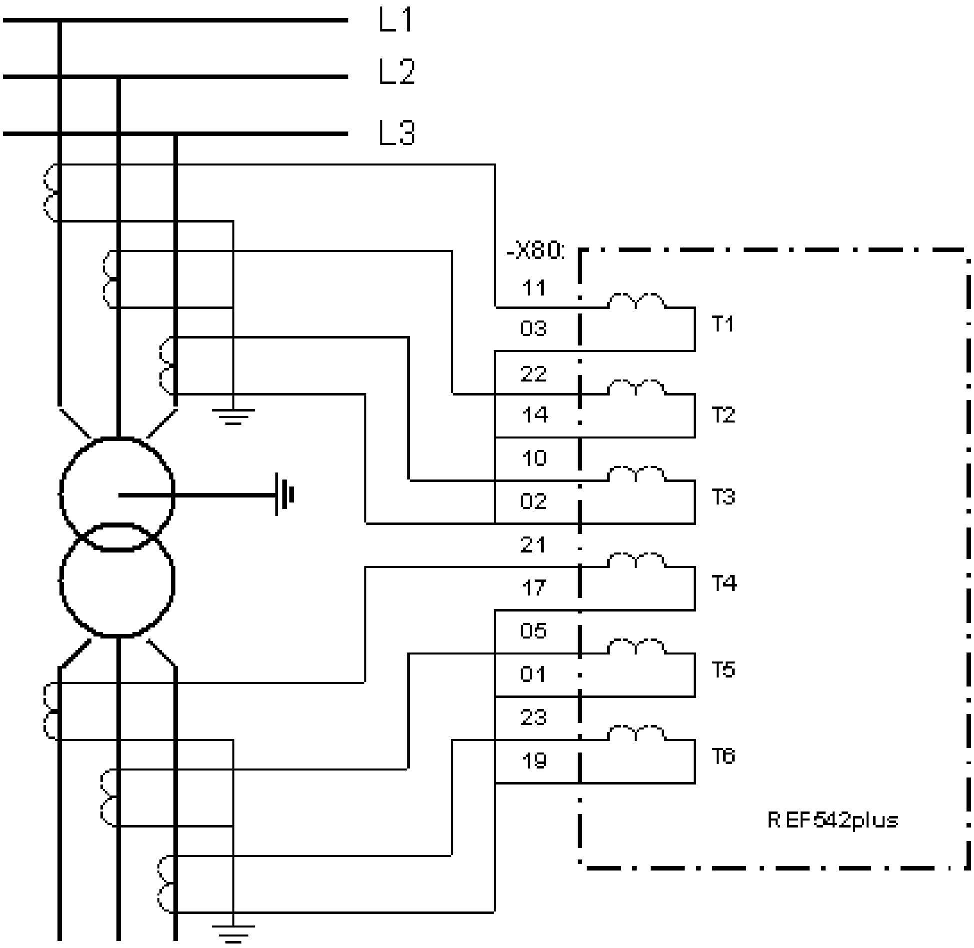


Fig. 3.1.-1 Connection diagram for REF542plus using 6 input CTs

In differential protection applications, REF542*plus* is to have at least six CT inputs. The first group including T1,T2 and T3 is connected to the three phase current transformers on the high-voltage side and the second group including T4, T5 and T6 is connected to the corresponding current transformers on the low-voltage side of the power transformer.

3.2. Setting example for transformer protection

An example for setting the REF542*plus* for transformer protection will be described in the following section. The power transformer is assumed to have the following technical data:

- transformer voltage: 30 kV/6 kV
- rated power: 10 MVA, power loss about 10% of rated current
- vector group: Yd11
- transformer impedance: 12.5%
- the transformer is earthed on the high-voltage side
- CT ratio on the 30 kV side: 150 A/1 A
- CT ratio on the 6 kV side: 600 A/1 A

The CTs are connected and earthed as shown in Fig. 3.1.-1.

3.2.1. Calculation

The rated current of the power transformer is:

- 30 kV side: I1r = 10 MVA / (30 kV x √3) = 192.4 A
- 6 kV side: I2r = 10 MVA / (6 kV x √3) = 962.3 A

In this example, it is assumed that the power transformer is fed on the 30 kV side and that a fault has occurred near the transformer terminals on the 6 kV side, Furthermore, the short-circuit power of the sourcing power system is assumed to be infinitely high. So, without taking the on-load tap-changer into consideration the short-circuit current for the rated condition will be:

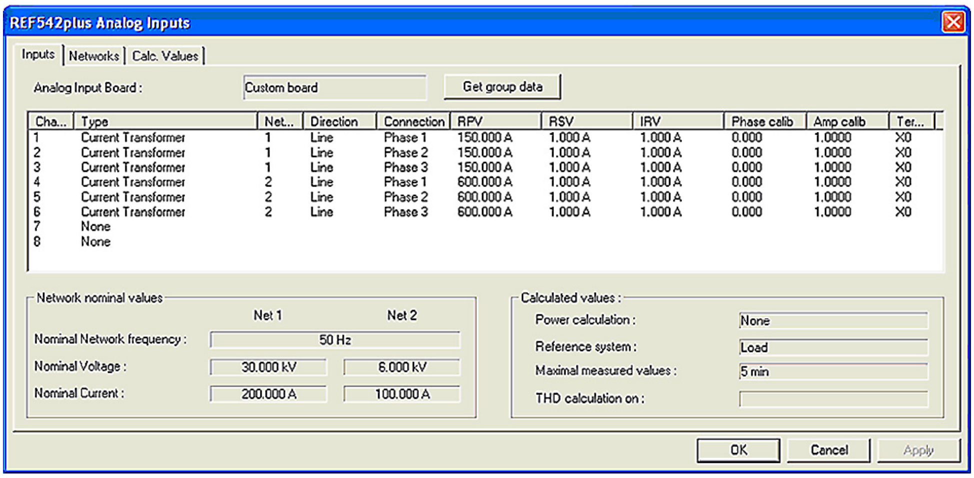
- 30 kV side: I1sc = 192.4 A (100% /12.5%) = 1539.2 A
- 6 kV side: I2sc = 962.3 A (100% /12.5%) = 7698.4 A

Contrary to the load condition, it can be assumed that the area can be defined as follows:

- Low load condition:	load current range: 0 to 0.6 x In
- Normal load condition:	load current range: 0.4 to 2.0 x In
- Heavy load condition:	load current range: 2.0 x In and higher (short-time operation)

3.2.2. Adaptation of the connection scheme

Based on the connection scheme shown in Fig. 3.1.-1 the analogue inputs of the REF542*plus* shall be set as shown in Fig. 3.2.2.-1:



Analog Input Board : Custom board

Cha...	Type	Net...	Direction	Connection	RPV	RSV	IRV	Phase calib	Amp calib	Ter...
1	Current Transformer	1	Line	Phase 1	150.000 A	1.000 A	1.000 A	0.000	1.0000	X0
2	Current Transformer	1	Line	Phase 2	150.000 A	1.000 A	1.000 A	0.000	1.0000	X0
3	Current Transformer	1	Line	Phase 3	150.000 A	1.000 A	1.000 A	0.000	1.0000	X0
4	Current Transformer	2	Line	Phase 1	600.000 A	1.000 A	1.000 A	0.000	1.0000	X0
5	Current Transformer	2	Line	Phase 2	600.000 A	1.000 A	1.000 A	0.000	1.0000	X0
6	Current Transformer	2	Line	Phase 3	600.000 A	1.000 A	1.000 A	0.000	1.0000	X0
7	None									
8	None									

Network nominal values

	Net 1	Net 2
Nominal Network frequency :	50 Hz	
Nominal Voltage :	30.000 kV	6.000 kV
Nominal Current :	200.000 A	100.000 A

Calculated values :

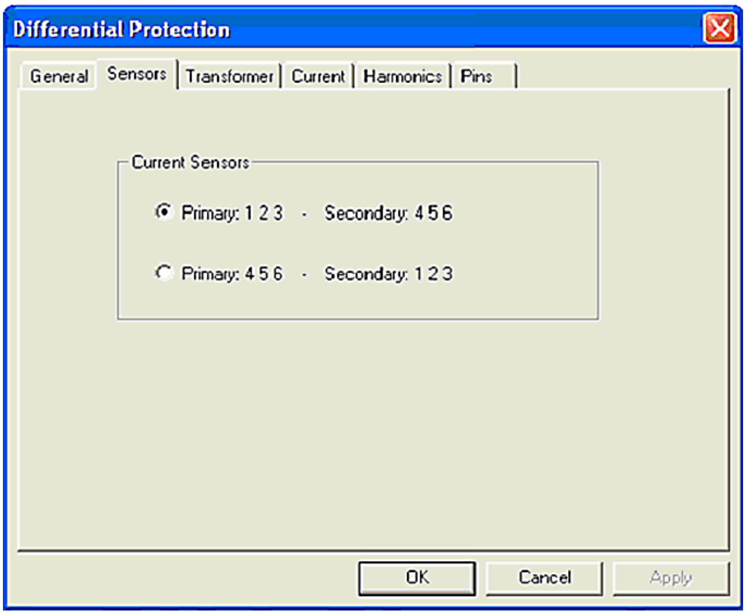
Power calculation : None
Reference system : Load
Maximal measured values : 5 min
THD calculation on :

Fig. 3.2.2.-1 Setting of the analogue inputs

The CTs on the high-voltage side are 150 A/1 A and they are connected to AI 01, AI 02 and AI 03, which are defined as NET 1. Due to the earth connection of the CT secondary sides as shown in Fig. 3.1.-1, the direction LINE has to be selected. The rated value of the input transformers used is 1A. The CTs on the low-voltage side have to be set correspondingly. If necessary, an additional phase and amplitude calibration can be performed for each input transformer.

The correctness of the setting can be verified on the measurement page of the RHMI. The magnitude of the current on the 30 kV and 6 kV side and the resulting differential current are shown on the display.

Fig. 3.2.2.-2 shows the adaptation of the connection for the selected example.



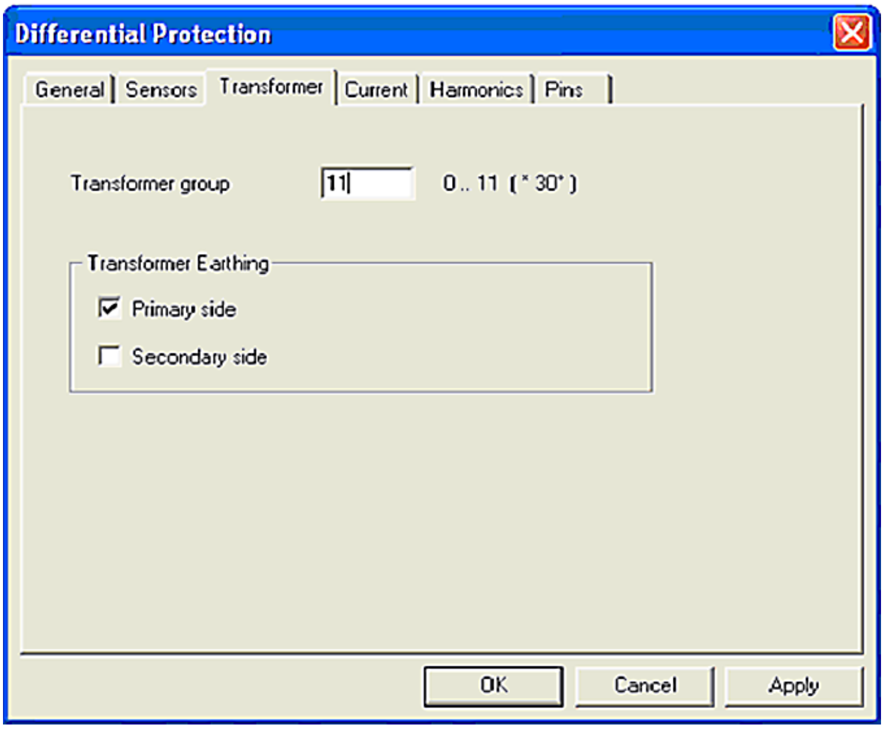
Current Sensors

● Primary: 1 2 3 - Secondary: 4 5 6

○ Primary: 4 5 6 - Secondary: 1 2 3

Fig. 3.2.2.-2 Adaptation of analogue inputs

Fig. 3.2.2.-3 shows the vector group setting and how the power transformer earthing is carried out.



Transformer group: 11

☑ Primary side

☐ Secondary side

Fig. 3.2.2.-3 Configuration of vector group and earthing of power transformer

The calculation of the vector group compensation is shown in Table 3.2.2.-1 below. HV denotes the high-voltage or the primary side, LV the low-voltage or the secondary side of the power transformer, $\underline{I}_{L1}$ to $\underline{I}_{L3}$ the current of phases L1 to L3 and the indexes 1 and 2 represent the HV or the primary and the LV or the secondary side of the transformer respectively. If the power transformer is earthed, either on the HV or primary or on the LV or secondary side, this must also be taken into consideration.

Table 3.2.2-1 Calculation of the vector-group dependent differential

Vector group	**Grounding**		**Calculation of the current comparison**	
	HV	**LV**	**HV**	**LV**
0	No	No	$\underline{I}_{L11}$ $\underline{I}_{L21}$ $\underline{I}_{L31}$	$\underline{I}_{L12}$ $\underline{I}_{L22}$ $\underline{I}_{L32}$
	No	Yes	$(\underline{I}_{L11} - \underline{I}_{L21})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L11})/\sqrt{3}$	$(\underline{I}_{L12} - \underline{I}_{L22})/\sqrt{3}$ $(\underline{I}_{L22} - \underline{I}_{L32})/\sqrt{3}$ $(\underline{I}_{L32} - \underline{I}_{L12})/\sqrt{3}$
	Yes	No	$(\underline{I}_{L11} - \underline{I}_{L21})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L11})/\sqrt{3}$	$(\underline{I}_{L12} - \underline{I}_{L22})/\sqrt{3}$ $(\underline{I}_{L22} - \underline{I}_{L32})/\sqrt{3}$ $(\underline{I}_{L32} - \underline{I}_{L12})/\sqrt{3}$
	Yes	Yes	$(\underline{I}_{L11} - \underline{I}_{L21})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L11})/\sqrt{3}$	$(\underline{I}_{L12} - \underline{I}_{L22})/\sqrt{3}$ $(\underline{I}_{L22} - \underline{I}_{L32})/\sqrt{3}$ $(\underline{I}_{L32} - \underline{I}_{L12})/\sqrt{3}$
1	No	No	$(\underline{I}_{L11} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L21})/\sqrt{3}$	$\underline{I}_{L12}$ $\underline{I}_{L22}$ $\underline{I}_{L32}$
	No	Yes	$\underline{I}_{L11}$ $\underline{I}_{L21}$ $\underline{I}_{L31}$	$(\underline{I}_{L12} - \underline{I}_{L22})/\sqrt{3}$ $(\underline{I}_{L22} - \underline{I}_{L32})/\sqrt{3}$ $(\underline{I}_{L32} - \underline{I}_{L12})/\sqrt{3}$
	Yes	No	$(\underline{I}_{L11} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L21})/\sqrt{3}$	$\underline{I}_{L12}$ $\underline{I}_{L22}$ $\underline{I}_{L32}$
	Yes	Yes	$(\underline{I}_{L11} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L21})/\sqrt{3}$	$\underline{I}_{L12} - \underline{I}_{L02}$ $\underline{I}_{L22} -- \underline{I}_{L02}$ $\underline{I}_{L32} - \underline{I}_{L02}$
2	No	No	$\underline{I}_{L11}$ $\underline{I}_{L21}$ $\underline{I}_{L31}$	$- \underline{I}_{L22}$ $- \underline{I}_{L32}$ $- \underline{I}_{L12}$
	No	Yes	$(\underline{I}_{L11} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L21})/\sqrt{3}$	$(\underline{I}_{L12} - \underline{I}_{L22})/\sqrt{3}$ $(\underline{I}_{L22} - \underline{I}_{L32})/\sqrt{3}$ $(\underline{I}_{L32} - \underline{I}_{L12})/\sqrt{3}$
	Yes	No	$(\underline{I}_{L11} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L21})/\sqrt{3}$	$(\underline{I}_{L12} - \underline{I}_{L22})/\sqrt{3}$ $(\underline{I}_{L22} - \underline{I}_{L32})/\sqrt{3}$ $(\underline{I}_{L32} - \underline{I}_{L12})/\sqrt{3}$
	Yes	Yes	$(\underline{I}_{L11} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L21})/\sqrt{3}$	$(\underline{I}_{L12} - \underline{I}_{L22})/\sqrt{3}$ $(\underline{I}_{L22} - \underline{I}_{L32})/\sqrt{3}$ $(\underline{I}_{L32} - \underline{I}_{L12})/\sqrt{3}$

Table 3.2.2-1 Calculation of the vector-group dependent differential

Vector group	Grounding		Calculation of the current comparison	
	HV	LV	HV	LV
3	No	No	$(\underline{I}_{L21} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L11} - \underline{I}_{L21})/\sqrt{3}$	$\underline{I}_{L12}$ $\underline{I}_{L22}$ $\underline{I}_{L32}$
	No	Yes	$\underline{I}_{L11}$ $\underline{I}_{L21}$ $\underline{I}_{L31}$	$(\underline{I}_{L32} - \underline{I}_{L22})/\sqrt{3}$ $(\underline{I}_{L12} - \underline{I}_{L32})/\sqrt{3}$ $(\underline{I}_{L22} - \underline{I}_{L12})/\sqrt{3}$
	Yes	Yes	$(\underline{I}_{L21} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L11} - \underline{I}_{L21})/\sqrt{3}$	$\underline{I}_{L12}$ $\underline{I}_{L22}$ $\underline{I}_{L32}$
	Yes	Yes	$(\underline{I}_{L21} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L11} - \underline{I}_{L21})/\sqrt{3}$	$\underline{I}_{L12} - \underline{I}_{L02}$ $\underline{I}_{L22} -- \underline{I}_{L02}$ $\underline{I}_{L32} - \underline{I}_{L02}$
4	No	No	$\underline{I}_{L11}$ $\underline{I}_{L21}$ $\underline{I}_{L31}$	$\underline{I}_{L32}$ $\underline{I}_{L12}$ $\underline{I}_{L22}$
	No	Yes	$(\underline{I}_{L11} - \underline{I}_{L21})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L11})/\sqrt{3}$	$(\underline{I}_{L32} - \underline{I}_{L12})/\sqrt{3}$ $(\underline{I}_{L12} - \underline{I}_{L22})/\sqrt{3}$ $(\underline{I}_{L22} - \underline{I}_{L32})/\sqrt{3}$
	Yes	No	$(\underline{I}_{L11} - \underline{I}_{L21})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L11})/\sqrt{3}$	$(\underline{I}_{L32} - \underline{I}_{L12})/\sqrt{3}$ $(\underline{I}_{L12} - \underline{I}_{L22})/\sqrt{3}$ $(\underline{I}_{L22} - \underline{I}_{L32})/\sqrt{3}$
	Yes	Yes	$(\underline{I}_{L11} - \underline{I}_{L21})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L11})/\sqrt{3}$	$(\underline{I}_{L32} - \underline{I}_{L12})/\sqrt{3}$ $(\underline{I}_{L12} - \underline{I}_{L22})/\sqrt{3}$ $(\underline{I}_{L22} - \underline{I}_{L32})/\sqrt{3}$
5	No	No	$(\underline{I}_{L21} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L21})/\sqrt{3}$ $(\underline{I}_{L11} - \underline{I}_{L31})/\sqrt{3}$	$\underline{I}_{L12}$ $\underline{I}_{L22}$ $\underline{I}_{L32}$
	No	Yes	$\underline{I}_{L11}$ $\underline{I}_{L21}$ $\underline{I}_{L31}$	$(\underline{I}_{L32} - \underline{I}_{L12})/\sqrt{3}$ $(\underline{I}_{L12} - \underline{I}_{L22})/\sqrt{3}$ $(\underline{I}_{L22} - \underline{I}_{L32})/\sqrt{3}$
	Yes	No	$(\underline{I}_{L21} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L21})/\sqrt{3}$ $(\underline{I}_{L11} - \underline{I}_{L31})/\sqrt{3}$	$\underline{I}_{L12}$ $\underline{I}_{L22}$ $\underline{I}_{L32}$
	Yes	Yes	$(\underline{I}_{L21} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L21})/\sqrt{3}$ $(\underline{I}_{L11} - \underline{I}_{L31})/\sqrt{3}$	$\underline{I}_{L12} - \underline{I}_{L02}$ $\underline{I}_{L22} -- \underline{I}_{L02}$ $\underline{I}_{L32} - \underline{I}_{L02}$

Table 3.2.2-1 Calculation of the vector-group dependent differential

Vector group	Grounding		Calculation of the current comparison	
	HV	LV	HV	LV
6	No	No	$\underline{I}_{L11}$ $\underline{I}_{L21}$ $\underline{I}_{L31}$	$- \underline{I}_{L12}$ $- \underline{I}_{L22}$ $- \underline{\mathrm{I}}_{L32}$
	No	Yes	$(\underline{I}_{L11} - \underline{I}_{L21})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L11})/\sqrt{3}$	$(\underline{I}_{L22} - \underline{I}_{L12})/\sqrt{3}$ $(\underline{I}_{L32} - \underline{I}_{L22})/\sqrt{3}$ $(\underline{I}_{L12} - \underline{I}_{L32})/\sqrt{3}$
	Yes	No	$(\underline{I}_{L11} - \underline{I}_{L21})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L11})/\sqrt{3}$	$(\underline{I}_{L22} - \underline{I}_{L12})/\sqrt{3}$ $(\underline{I}_{L32} - \underline{I}_{L22})/\sqrt{3}$ $(\underline{I}_{L12} - \underline{I}_{L32})/\sqrt{3}$
	Yes	Yes	$(\underline{I}_{L11} - \underline{I}_{L21})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L11})/\sqrt{3}$	$(\underline{I}_{L22} - \underline{I}_{L12})/\sqrt{3}$ $(\underline{I}_{L32} - \underline{I}_{L22})/\sqrt{3}$ $(\underline{I}_{L12} - \underline{I}_{L32})/\sqrt{3}$
7	No	No	$(\underline{I}_{L11} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L21})/\sqrt{3}$	$- \underline{I}_{L12}$ $- \underline{I}_{L22}$ $- \underline{\mathrm{I}}_{L32}$
	No	Yes	$- \underline{I}_{L11}$ $- \underline{I}_{L21}$ $- \underline{\mathrm{I}}_{L31}$	$(\underline{I}_{L12} - \underline{I}_{L22})/\sqrt{3}$ $(\underline{I}_{L22} - \underline{I}_{L32})/\sqrt{3}$ $(\underline{I}_{L32} - \underline{I}_{L12})/\sqrt{3}$
	Yes	No	$(\underline{I}_{L11} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L21})/\sqrt{3}$	$- \underline{I}_{L12}$ $- \underline{I}_{L22}$ $- \underline{\mathrm{I}}_{L32}$
	Yes	Yes	$(\underline{I}_{L11} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L21})/\sqrt{3}$	$- \underline{I}_{L12} + \underline{I}_{L02}$ $- \underline{I}_{L22} + \underline{I}_{L02}$ $- \underline{I}_{L32} + \underline{I}_{L02}$
8	No	No	$\underline{I}_{L11}$ $\underline{I}_{L21}$ $\underline{I}_{L31}$	$\underline{I}_{L22}$ $\underline{I}_{L32}$ $\underline{I}_{L12}$
	No	Yes	$(\underline{I}_{L11} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L21})/\sqrt{3}$	$(\underline{I}_{L22} - \underline{I}_{L12})/\sqrt{3}$ $(\underline{I}_{L32} - \underline{I}_{L22})/\sqrt{3}$ $(\underline{I}_{L12} - \underline{I}_{L32})/\sqrt{3}$
	Yes	No	$(\underline{I}_{L11} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L21})/\sqrt{3}$	$(\underline{I}_{L22} - \underline{I}_{L12})/\sqrt{3}$ $(\underline{I}_{L32} - \underline{I}_{L22})/\sqrt{3}$ $(\underline{I}_{L12} - \underline{I}_{L32})/\sqrt{3}$
	Yes	Yes	$(\underline{I}_{L11} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L21})/\sqrt{3}$	$(\underline{I}_{L22} - \underline{I}_{L12})/\sqrt{3}$ $(\underline{I}_{L32} - \underline{I}_{L22})/\sqrt{3}$ $(\underline{I}_{L12} - \underline{I}_{L32})/\sqrt{3}$

Table 3.2.2-1 Calculation of the vector-group dependent differential

Vector group	Grounding		Calculation of the current comparison	
	HV	LV	HV	LV
9	No	No	$(\underline{I}_{L21} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L11} - \underline{I}_{L21})/\sqrt{3}$	$- \underline{I}_{L12}$ $- \underline{I}_{L22}$ $- \underline{\mathrm{I}}_{L32}$
	No	Yes	$- \underline{I}_{L11}$ $- \underline{I}_{L21}$ $- \underline{\mathrm{I}}_{L31}$	$(\underline{I}_{L32} - \underline{I}_{L22})/\sqrt{3}$ $(\underline{I}_{L12} - \underline{I}_{L32})/\sqrt{3}$ $(\underline{I}_{L22} - \underline{I}_{L12})/\sqrt{3}$
	Yes	Yes	$(\underline{I}_{L21} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L11} - \underline{I}_{L21})/\sqrt{3}$	$- \underline{I}_{L12}$ $- \underline{I}_{L22}$ $- \underline{\mathrm{I}}_{L32}$
	Yes	Yes	$(\underline{I}_{L21} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L11} - \underline{I}_{L21})/\sqrt{3}$	$- \underline{I}_{L12} + \underline{I}_{L02}$ $- \underline{I}_{L22} + \underline{I}_{L02}$ $- \underline{I}_{L32} + \underline{I}_{L02}$
10	No	No	$\underline{I}_{L11}$ $\underline{I}_{L21}$ $\underline{I}_{L31}$	$- \underline{I}_{L32}$ $- \underline{I}_{L12}$ $- \underline{\mathrm{I}}_{L22}$
	No	Yes	$(\underline{I}_{L11} - \underline{I}_{L21})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L11})/\sqrt{3}$	$(\underline{I}_{L12} - \underline{I}_{L32})/\sqrt{3}$ $(\underline{I}_{L22} - \underline{I}_{L12})/\sqrt{3}$ $(\underline{I}_{L32} - \underline{I}_{L22})/\sqrt{3}$
	Yes	No	$(\underline{I}_{L11} - \underline{I}_{L21})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L11})/\sqrt{3}$	$(\underline{I}_{L12} - \underline{I}_{L32})/\sqrt{3}$ $(\underline{I}_{L22} - \underline{I}_{L12})/\sqrt{3}$ $(\underline{I}_{L32} - \underline{I}_{L22})/\sqrt{3}$
	Yes	Yes	$(\underline{I}_{L11} - \underline{I}_{L21})/\sqrt{3}$ $(\underline{I}_{L21} - \underline{I}_{L31})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L11})/\sqrt{3}$	$(\underline{I}_{L12} - \underline{I}_{L32})/\sqrt{3}$ $(\underline{I}_{L22} - \underline{I}_{L12})/\sqrt{3}$ $(\underline{I}_{L32} - \underline{I}_{L22})/\sqrt{3}$
11	No	No	$(\underline{I}_{L21} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L21})/\sqrt{3}$ $(\underline{I}_{L11} - \underline{I}_{L31})/\sqrt{3}$	$- \underline{I}_{L12}$ $- \underline{I}_{L22}$ $- \underline{\mathrm{I}}_{L32}$
	No	Yes	$- \underline{I}_{L11}$ $- \underline{I}_{L21}$ $- \underline{\mathrm{I}}_{L31}$	$(\underline{I}_{L32} - \underline{I}_{L12})/\sqrt{3}$ $(\underline{I}_{L12} - \underline{I}_{L22})/\sqrt{3}$ $(\underline{I}_{L22} - \underline{I}_{L32})/\sqrt{3}$
	Yes	No	$(\underline{I}_{L21} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L21})/\sqrt{3}$ $(\underline{I}_{L11} - \underline{I}_{L31})/\sqrt{3}$	$- \underline{I}_{L12}$ $- \underline{I}_{L22}$ $- \underline{\mathrm{I}}_{L32}$
	Yes	Yes	$(\underline{I}_{L21} - \underline{I}_{L11})/\sqrt{3}$ $(\underline{I}_{L31} - \underline{I}_{L21})/\sqrt{3}$ $(\underline{I}_{L11} - \underline{I}_{L31})/\sqrt{3}$	$- \underline{I}_{L12} + \underline{I}_{L02}$ $- \underline{I}_{L22} + \underline{I}_{L02}$ $- \underline{I}_{L32} + \underline{I}_{L02}$

3.2.3. Setting the tripping characteristic

To define the setting characteristic, the result of the previous calculation shall be used. The rated values of the current on the HV or primary and LV or secondary side of the power transformer are as following:

- 30 kV side: I1r = 10 MVA/(30kV x √3) = 192.4 A
- 6 kV side: I2r = 10 MVA/(6kV x √3) = 962.3 A

Because the transformer impedance is 12.5%, the fault current in the event of a through-fault condition near the transformer terminals is:
I(through fault) = 100% /12.5% = 8 x Ir.

To ensure that the fault condition is always detected, the start value is set to 80% of the calculated value. Therefore the setting for Trip by Id is:

- Trip by Id> = 0.8 x 8 In = 6.4 x Ir.

The tripping characteristic, as shown in Fig. 2.-2, can now be defined accordingly. During low load conditions the differential protection shall be very sensitive. However, the magnetizing current under no load conditions needs be taken into account. Moreover, the range of the voltage control shall be considered too. Based on operational experience the low load condition can normally be limited up to 0.5 x Ir, so the setting value of the threshold Ib0 for the unbiased region limit is selected accordingly. Assuming that the voltage control range is ±10% and the magnetizing current is 5% of the rated current, the threshold current Id0 can be calculated as follows:

- Magnetizing current Id0 = 5% x Ir

Error due to tap changer position at the unbiased region limit is 10% x 0.5 x Ir = 5 % x Ir.

CT error in the low current area is 3% on each side.

A safety margin of 120% shall be considered.

Threshold current Id0 = 2 x (0.05 + 0.03) x 1.2 x Ir
= 0.192 x Ir (selected value = 0.2 x Ir)

Unbiased region limit Ib0 = 0.5 x Ir

The load current under heavy load conditions shall be not more than 2 x Ir. Assuming that the CT up to this load current has a maximum error of ±1%, the total error of the differential current under worst case conditions can be assumed to be around 2%. Besides, as already mentioned above, the tap changer position of the voltage control must be considered too. So, the total error is:

- Total error = 2% + 10% = 12%.

Within the load current area from 0.5 x Ir - 2 x Ir, the tripping characteristic shall have a slightly biasing slope. The safety margin of 120% shall also be considered.

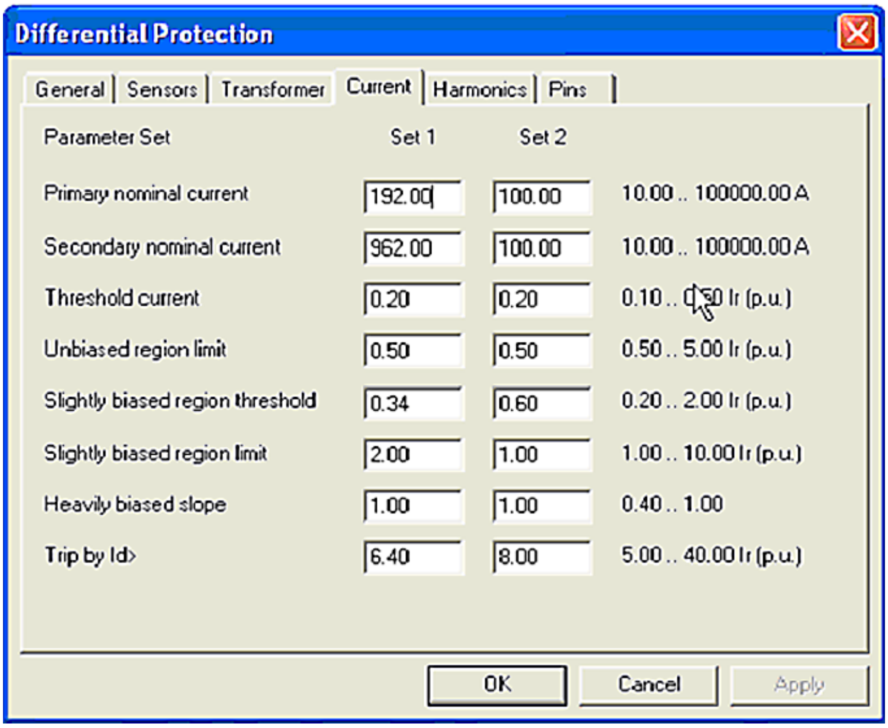
The threshold value Id1 can be calculated as below:

- slightly biased region threshold Id1 = (2 x Ir – 0.5 x Ir) x 0.12 x 1.2 + 0.12 x Ir
= 0.336 Ir ≈ 0.34 x Ir.
- slightly biased region limit Ib1 = 2 x Ir.

To avoid unwanted tripping in the event of a through fault due to possible CT saturation, the heavily biased slope is set as high as possible:

- heavily biased slope = 1.0

Fig. 3.2.3.-1 shows the tripping characteristic setting for the example given above.



Parameter Set	Set 1	Set 2	
Primary nominal current	192.00	100.00	10.00 .. 100000.00 A
Secondary nominal current	962.00	100.00	10.00 .. 100000.00 A
Threshold current	0.20	0.20	0.10 .. 0.50 Ir (p.u.)
Unbiased region limit	0.50	0.50	0.50 .. 5.00 Ir (p.u.)
Slightly biased region threshold	0.34	0.60	0.20 .. 2.00 Ir (p.u.)
Slightly biased region limit	2.00	1.00	1.00 .. 10.00 Ir (p.u.)
Heavily biased slope	1.00	1.00	0.40 .. 1.00
Trip by Id>	6.40	8.00	5.00 .. 40.00 Ir (p.u.)

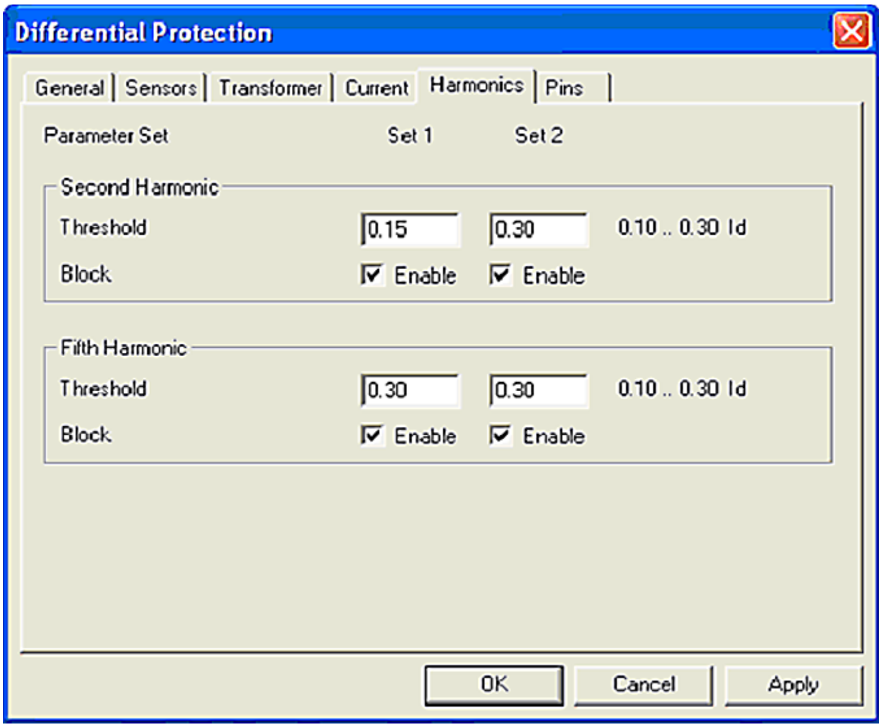
Fig. 3.2.3.-1 Setting of the tripping characteristic

3.2.4. Stabilization against inrush current

If a no load power transformer is energized, heavy inrush current can appear. On the contrary, no current will flow on the no load side. Consequently, the transformer differential will make an unwanted trip. This is why it is necessary to stabilize the differential protection against inrush current.

To detect inrush current the ratio of the second harmonic in the differential current Id is used. The correct setting shall be verified during the commissioning phase. The setting recommendation is given based on the empirical knowledge. The ratio setting of the second harmonic shall not be too sensitive. In the case of CT saturation this setting could delay or even block the tripping. A setting value between 0.15 x Id and 0.20 x Id could give the needed stabilization.

If the system voltage of the power transformer at operation is higher than the rated voltage, an overflux condition may occur. In order to give the protection a more stabilized behaviour, the fifth harmonics can be used. The setting value should be selected in the range between 0.20 x Id and 0.30 x Id.



Parameter Set	Set 1	Set 2	
Second Harmonic			
Threshold	0.15	0.30	0.10 .. 0.30 Id
Block	☑ Enable	☑ Enable	
Fifth Harmonic			
Threshold	0.30	0.30	0.10 .. 0.30 Id
Block	☑ Enable	☑ Enable	

Fig. 3.2.4.-1 Setting of the inrush current stabilization

Fig. 3.2.4.-1 shown above gives an example of the setting of the parameter for stabilization against inrush current and overflux.

The blocking of the second and the fifth harmonics is valid only if the differential current is below the Trip by Id> setting. Once the setting value Id> is exceeded, a trip will be generated. It should be noted that the differential current is calculated by using the fundamental frequency components of the phase currents. The harmonics are suppressed in this case.

3.2.5. CT Requirement

The CT has a strong influence on the correct behaviour of the transformer differential protection. To guarantee selectivity and a fast tripping time the CT has to fulfil the following requirements:

- the through-fault current must be measured without CT saturation,
- the first 25 ms of the through-fault current containing a DC component shall be transmitted correctly.

It is not difficult to fulfil the first requirement. When the setting given in the above example is used, the CT with 150 A rated current will be able to transfer a short circuit current of 1539.2 A, that is, about 10 times the rated current of the HV side. The LV side CT with a rated current of 600 A must carry 7698 A, i.e. about 13 x Ir. But in most cases, the fault current includes a DC component, which can cause CT saturation. To avoid saturation within the first 25 ms, the diagram presented in Fig. 3.2.5.-1 can be used. The figure shows the oversizing factor K(ct) as a function of the DC time constant.

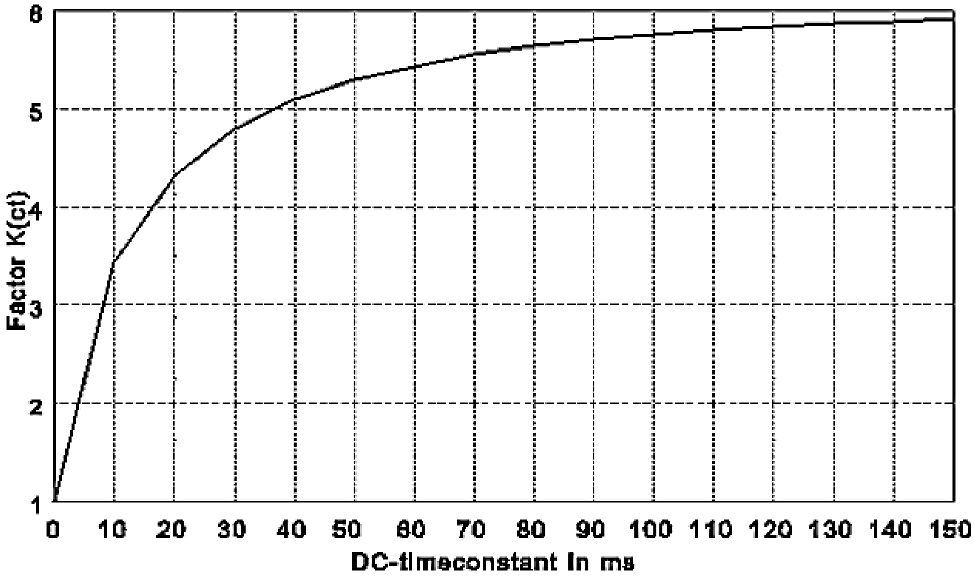


Fig. 3.2.5.-1 Factor K(ct) to avoid CT saturation within the first 25 ms.

From the diagram in Fig. 3.2.5.-1 it can be seen that an additional factor 6 is needed. This means that the CT must be able to carry a steady state current of 60 x Ir on the HV side and about 80 x Ir on the LV side.

If the second requirement cannot be fulfilled, the tripping may be delayed.

It should be noted that the selected rated primary current of the CT should be roughly of the same magnitude as the rated current of the power transformer, i.e. in the range of 0.7 to 2.0. The selection of a CT with a rated current higher than that of the power transformer is preferred. Otherwise the CT, as shown in the above example, must be able to carry a steady state fault current higher than 80 x Ir of the LV side. If, instead of 600 A/1 A, a rated current of 1000 A/1 A is used, the steady state fault current to be transferred without saturation will be reduced to (600 A/1000 A) x 80 Ir = 48 x Ir.

3.3. Example of motor protection setting

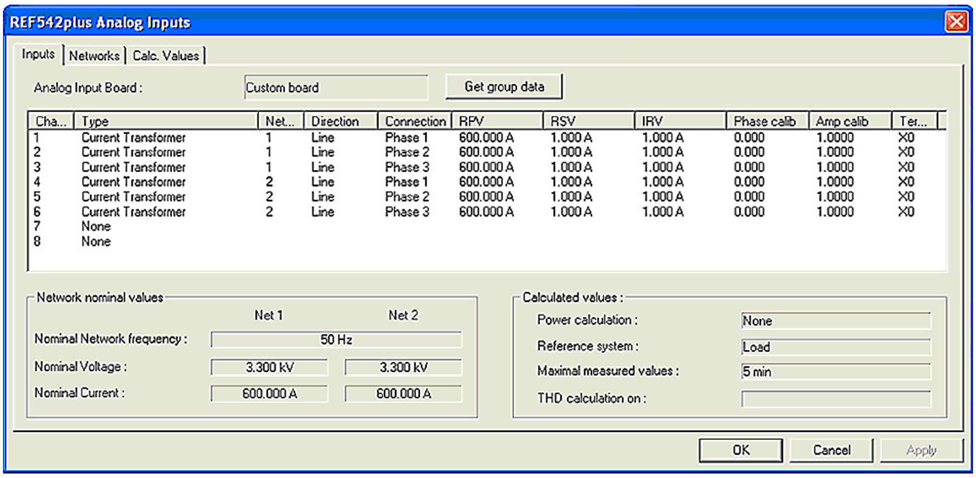
An example for setting the REF542*plus* for motor protection will be described in the following section. The motor is assumed to have the following technical data:

- rated voltage	3.3 kV
- rated frequency	50 Hz
- rated power	2500 kW
- rated current	492 A
- locked rotor current	4.8 p.u.

The current transformers are located in either end of the stator windings. All CTs have the same rated current 600 A/1 A.

3.3.1. Configuration of analog inputs

The configuration of the analog inputs is shown in Fig. 3.3.1.-1.



Analog Input Board : Custom board

Cha...	Type	Net...	Direction	Connection	RPV	RSV	IRV	Phase calib	Amp calib	Ter...
1	Current Transformer	1	Line	Phase 1	600.000 A	1.000 A	1.000 A	0.000	1.0000	X0
2	Current Transformer	1	Line	Phase 2	600.000 A	1.000 A	1.000 A	0.000	1.0000	X0
3	Current Transformer	1	Line	Phase 3	600.000 A	1.000 A	1.000 A	0.000	1.0000	X0
4	Current Transformer	2	Line	Phase 1	600.000 A	1.000 A	1.000 A	0.000	1.0000	X0
5	Current Transformer	2	Line	Phase 2	600.000 A	1.000 A	1.000 A	0.000	1.0000	X0
6	Current Transformer	2	Line	Phase 3	600.000 A	1.000 A	1.000 A	0.000	1.0000	X0
7	None									
8	None									

Network nominal values

	Net 1	Net 2
Nominal Network frequency :	50 Hz	
Nominal Voltage :	3.300 kV	3.300 kV
Nominal Current :	600.000 A	600.000 A

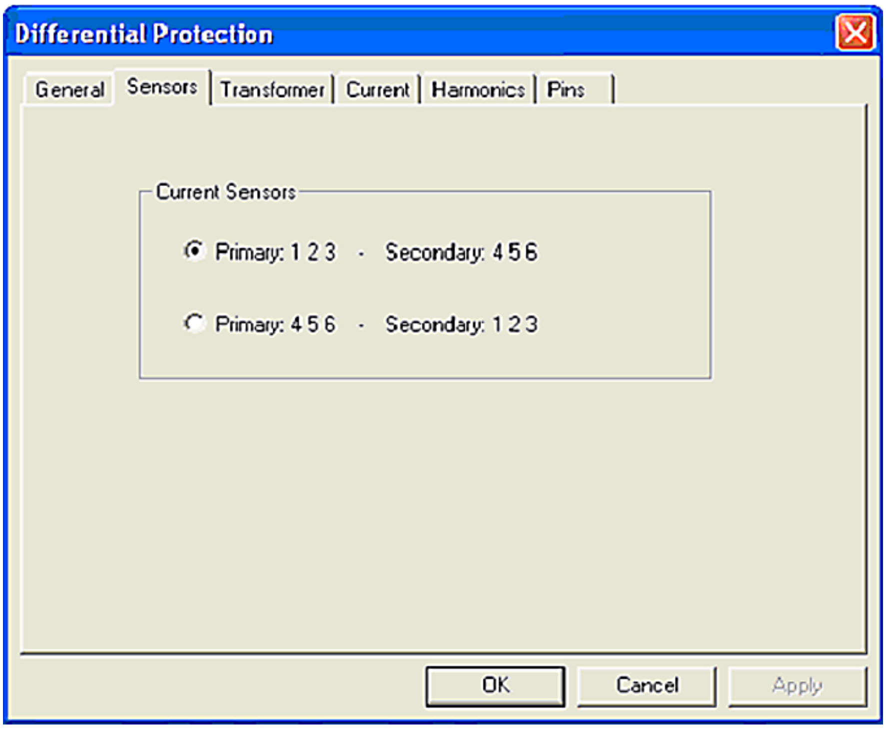
Calculated values :

Power calculation : None
Reference system : Load
Maximal measured values : 5 min
THD calculation on :

Fig. 3.3.1.-1 Setting of the analog inputs for motor protection

The CTs at one stator end are to be connected to AI 01, AI 02 and AI 03, which is defined as NET 1, while each CT at the other stator end is connected accordingly to AI 04, AI05 and AI06. For all CTs the direction line is selected.

The Fig. 3.3.1.-2 shows the adaptation of the connection for the selected example.



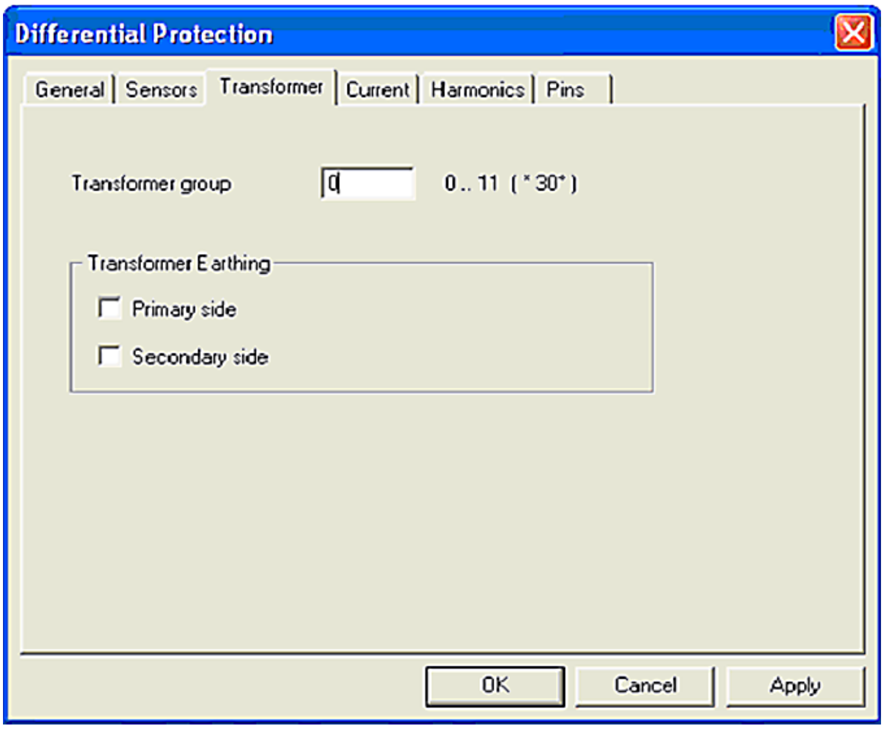
Current Sensors

● Primary: 1 2 3 - Secondary: 4 5 6

○ Primary: 4 5 6 - Secondary: 1 2 3

Fig. 3.3.1.-2 Adaptation of the analog inputs

The Fig. 3.3.1-3 shows the vector group setting. Because the currents to be compared in the motor are not shifted from each other, vector group 0 shall be selected.



Transformer group: 0 — 0 .. 11 (* 30°)

Transformer Earthing

☐ Primary side

☐ Secondary side

Fig. 3.3.1.-3 Configuration of the vector group and the earthing of the power transformer

3.3.2. Setting the tripping characteristic

In case of a locked rotor the current will be 4.8 x Ir. A locked rotor is identical to the condition of a three-phase short circuit at the end of the stator winding of the motor. To be able to detect this fault situation the maximum possible differential current Id> is set as follows:

Trip by Id> = 0.8 x 4.8 x In = 3.8 x Ir.

The tripping characteristic, as shown in Fig. 2.-2, will now be defined accordingly. During the low load condition in the range up to 0.5 x Ir the differential protection shall be given a very sensitive setting. The differential current of the motor protection arrangement depends only on the accuracy of the CT. So the lowest threshold value can be used:

- threshold current Id0 = 0.10 x Ir
- unbiased region limit Ib0 = 0.5 x Ir

The maximum load current for normal load condition shall be from 1.2 to 1.5 x Ir. Assuming that the CT up to this load current range has a maximum error of ±1%, the total error of the differential current in a worst case situation can be assumed to be approximately 2%. So, the total error is:

- Total error = 2%.

From 0.5 x Ir to 1.5 x Ir, the tripping characteristic shall have a slightly biasing slope. The safety margin of 120% shall also be considered. The threshold value Id1 can be calculated as follows:

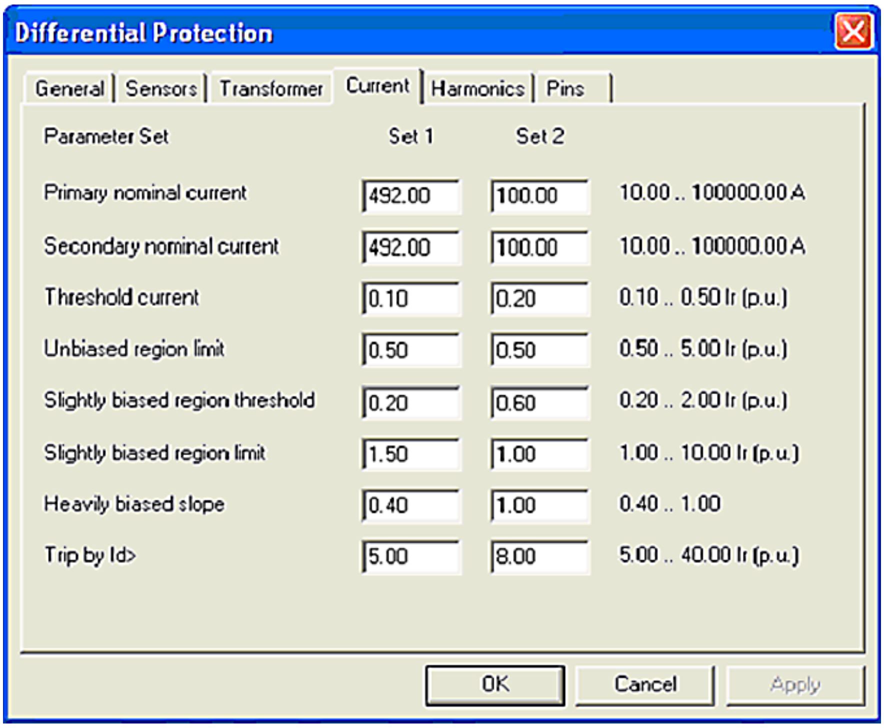
Slightly biased region threshold Id1 = (1.5 x Ir – 0.5 x Ir) x 0.02 x 1.2 + 0.10 x Ir
= 0.125 x Ir.

The lowest possible setting is 0.2 x Ir.

Slightly biased region limit Ib1 = 1.5 x Ir.

The heavily biased slope can also be defined by the lowest value 0.4.

Fig. 3.3.2.-1 shows the setting for the tripping characteristic for the above given example.



Parameter Set	Set 1	Set 2	
Primary nominal current	492.00	100.00	10.00 .. 100000.00 A
Secondary nominal current	492.00	100.00	10.00 .. 100000.00 A
Threshold current	0.10	0.20	0.10 .. 0.50 Ir (p.u.)
Unbiased region limit	0.50	0.50	0.50 .. 5.00 Ir (p.u.)
Slightly biased region threshold	0.20	0.60	0.20 .. 2.00 Ir (p.u.)
Slightly biased region limit	1.50	1.00	1.00 .. 10.00 Ir (p.u.)
Heavily biased slope	0.40	1.00	0.40 .. 1.00
Trip by Id>	5.00	8.00	5.00 .. 40.00 Ir (p.u.)

Fig. 3.3.2.-1 Setting of the tripping characteristic

3.3.3. Stabilization against inrush current

For motor protection, stabilization against inrush current is not necessary, because during normal operation the currents through the two CTs always are equal. Therefore it is not necessary to enable the harmonics blocking function.

3.3.4. CT requirement

For motor protection there is only one requirement to be fulfilled and that is that the CTs must be able to carry the locked rotor current without saturating. Thereby the time constant of the DC component shall be taken into account. It is recommended, that the CT group, placed at either end of the motor winding, have the same characteristic, so that in the case of a through fault no differential current appears.

4. Summary

The application of the three-phase differential protection being part of the REF542*plus* terminal for transformer and motor protection is described in this Application Note. The settings of the protection are demonstrated by means of appropriate calculation and setting examples.

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