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Line protection with transformer in the protection zone

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SIPROTEC 5 Application

Three-end line protection with transformer in the protection range

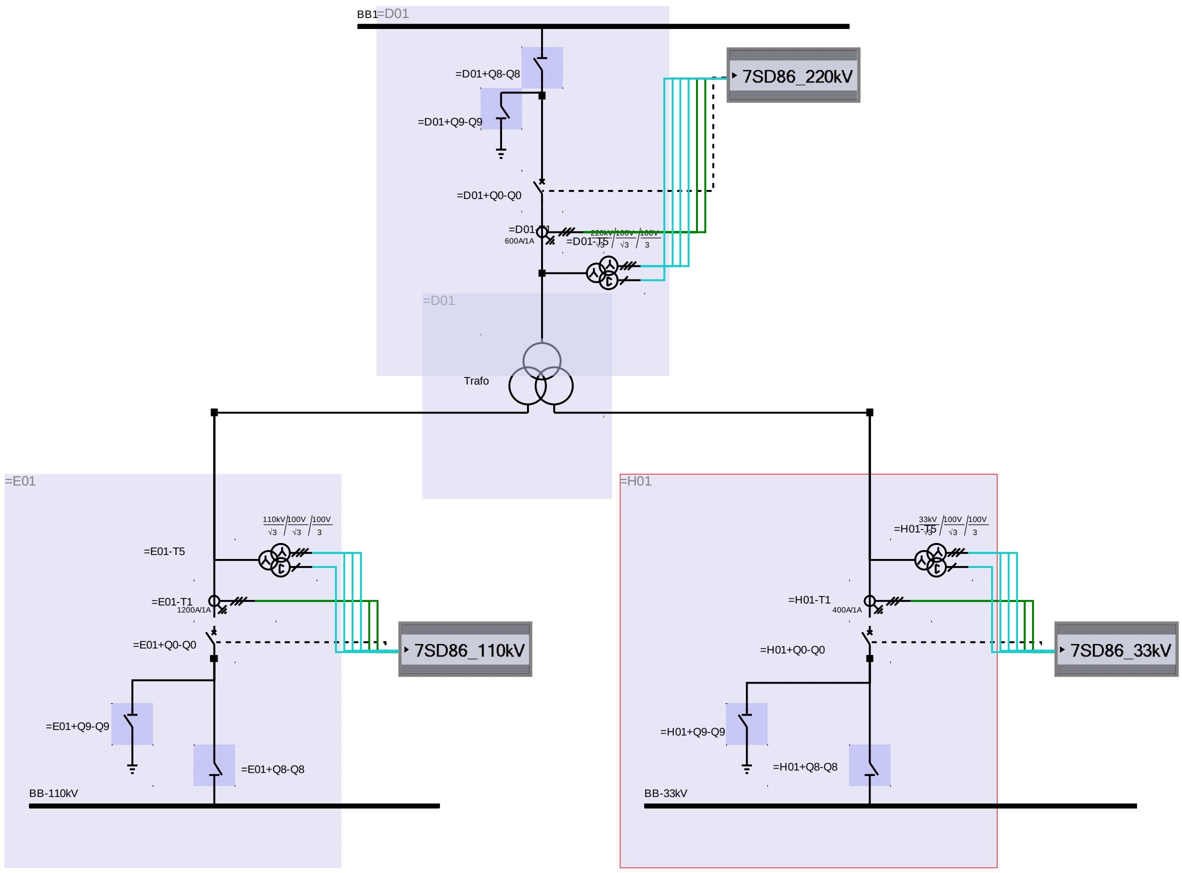
APN-048, Edition 1

Content

1 Three-end line protection with transformer in the protection zone

1.1 Introduction

Power transformers are the largest single components of power systems in transmission and distribution networks. This means their integration poses major challenges for planning engineers, in particular with expansion projects. System configurations connecting transformers which are several hundred meters apart from the switchgear panels with cable or overhead lines are increasingly used.



The selection of line differential protection due to the large distances and the derived settings taking a three-winding transformer as an example is described in this application.

1.2 Selection of the appropriate type of differential protection

The positioning of the transformer and the related protection elements like cables or overhead lines causes several problems:

Limited secondary cabling length for current transformers

§ The length of the secondary cabling of current and voltage transformers is limited by the connected load at the transformers.

Auxiliary voltage supply and suitable relay rooms

- Often in the immediate vicinity of the transformer, there is no auxiliary voltage available and at the same time no suitable rooms for installing the protection devices. This makes the use of a plain transformer differential protection harder or even impossible.

Communication with feeder bays and CB control

- In these configurations, the affected feeder bays and the related circuit breakers are often positioned far away from the transformer, which requires the use of telecontrol commands.

1.2.1 Transformer differential protection

When the current transformers of the high and low-voltage switchgear panels are used for the differential protection range and when they and their protection cabinets/devices are not too far away, it is possible to deploy a transformer differential protection device like SIPROTEC 7UT8x. The maximum possible distance between both transformer sets and the transformer differential protection depends on the nominal transformer load and the secondary cabling. In this case, the resulting load must be checked individually.

When the bushing transformers are used for the transformer differential protection, then the length of the secondary cabling between transformer and protection devices must also be taken into account. As before, it depends on the nominal transformer load. Additionally it must be observed that the transformer feed lines should then not be placed in the protection range of the transformer differential protection and should have their own protection!

1.2.2 Line differential protection

For distances between the high and low-voltage switchgear panels or in case of secondary cabling lengths which would lead to an inadmissibly high transformer load, the line differential protection with transformer in the protection range must be used. The required nominal transformer load is normally significantly lower here due to the shorter secondary cabling. This should be checked nevertheless during the configuration phase. In addition, the line differential protection requires a communication connection here.

The transformer must be dimensioned according to the rules set down in the related manual.

1.3 Application example: Three-winding transformer

1.3.1 System and performance data

The following section derives the settings taking a three-winding transformer as an example. The length of the cables to the individual substations is assumed to be 2km each. In this example, a traditional transformer differential protection cannot be used due to the far distance between the transformer sets and the protection device(s). The following table lists the transformer data used for this example and the data of the current transformer sets on various voltage levels.

	Primary winding	Secondary winding	Tertiary winding
Transformer			
Vector group	YN0	yn6	d5
Rated apparent power	220 MVA	200 MVA	40 MVA
Rated voltage	220 kV	110 kV	33 kV
Rated current	577 A	1050 A	700 A
Relative short-circuit voltage u_{kr}	Prim-Sec: 17%	Sec-Tert: 15%	Tert-Prim: 15%
Current transformer			
Transformer type	10P10 5VA	10P10 5VA	10P10 5VA

Transformer ratio	600A/1A	1200A/1A	800A/1A

Table 1 – Transformer and current transformer data

A SIPROTEC 5 line protection device (7SD8X or 7SL8X) must be used at each end to build a line differential protection for a three-winding transformer. The *Line differential protection Function* must be instantiated in each of these devices. In order to be able to take the ratios and the vector groups of the three windings, in all devices at the three ends the *Transformer Function block* must be instantiated in the *Line differential protection Function*. In addition, the *Inrush detection Function* in the *Line Function group* can be instantiated.

In all three devices, the same rated apparent power must be entered under *Line Function group* à *General* à *rated apparent power*. In this example, the setting value for the rated apparent power is the *rated apparent power of the primary winding of 220MVA*.

The transformers with control the rated voltage of the controlled side must be set to the medium value of the controllable voltage. The 220kV side of the 220 MVA transformer has a voltage control range of ± 10%. The medium value of the controllable voltage is calculated based on formula (1) (for further details, see manual on the line differential protection, chapter 6.2).

$$V_{nT220} = \frac{2}{\frac{1}{U_{max}} + \frac{1}{U_{min}}} = \frac{2}{\frac{1}{1.1 \times 220kV} + \frac{1}{0.9 \times 220kV}} = 217.8kV \quad (1)$$

The uniform setting of the rated apparent power values on all three windings results in the following rated object currents (or rated side currents):

$$I_{nO,220} = \frac{S_{nT}}{\sqrt{3} \times U_{nT}} = \frac{220MVA}{\sqrt{3} \times 217.8\,kV} = 583A \quad (2)$$

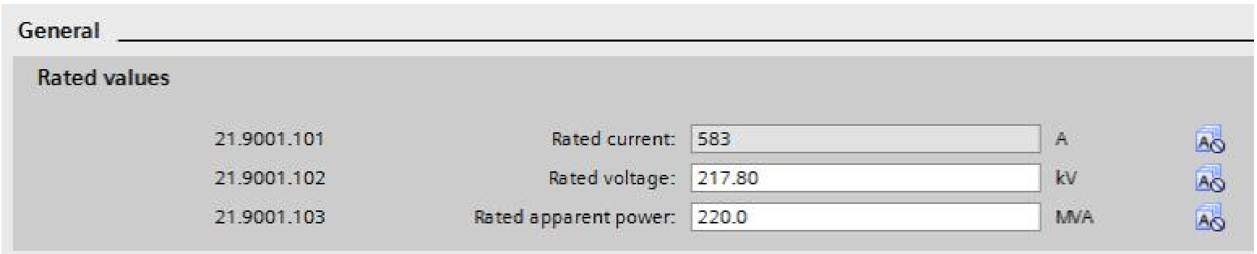


Figure 1 – Primary winding: Settings à Line à General à Rated values

$$I_{nO,110} = \frac{S_{nT}}{\sqrt{3} \times U_{nT}} = \frac{220MVA}{\sqrt{3} \times 110\,kV} = 1155A \quad 3$$

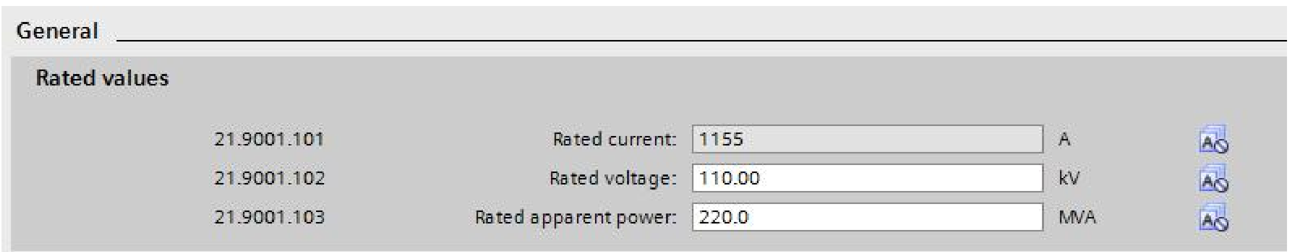


Figure 2 - Secondary winding: Settings à Line à General à Rated values

$$I_{nO,33} = \frac{S_{nT}}{\sqrt{3} \times U_{nT}} = \frac{220MVA}{\sqrt{3} \times 33\,kV} = 3849A \qquad (4)$$

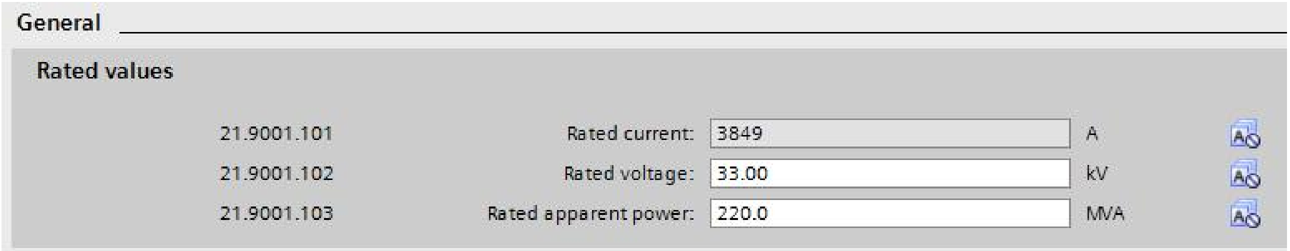


Figure 3 - Tertiary winding: Settings à Line à General à Rated values

Please take note for the further calculation and configuration that the settings of the line differential protection always relate to the rated side current. It is calculated from the rated voltage and the rated apparent power when using the Transformer Function block. For checking purposes, this value is shown under _.9001.101 rated current in Figure 3 as a grayed out value.

It is recommended to keep the rated transformer current within factor 8 (1/8) of the rated side current. Exceeding this factor can result in the failure to keep the stated tolerances due to the conversion factors.

$$f_{220} = \frac{600A}{583A} = 1.03 \; < 8 \qquad (5)$$

$$f_{110} = \frac{1200A}{1155A} = 1.04 \; < 8 \qquad (6)$$

$$f_{33} = \frac{800A}{3849A} = 0.21 \; > \frac{1}{8} \qquad (7)$$

Inrush detection

For transformers with a relatively high share of harmonics when starting or magnetizing, the adaptive stabilization of the I-DIFF stage is already sufficient stabilization against inrush effects. Yet, there are transformers that have a smaller share of harmonics during inrush due to their design and their core material, and in these cases, the inrush detection function must be activated. In the vicinity of large converters which cause a high share of 2nd harmonic in the current in case of a fault, it is recommended to deactivate inrush detection, because it can lead to blocking the I-DIFF stage. This example assumes that there are no large converters in the vicinity. It is also assumed that the share of the 2nd harmonic at inrush is not sufficient for stabilization. This is the reason why inrush detection has been activated here.

Because it cannot be ruled out from an operational point of view that the transformer will be magnetized via the tertiary winding as well, inrush detection can also be instantiated at this end as well. The _.4141.106 Operational limit Imax parameter is used to set the maximum inrush current for each winding.

Inrush detect.

21.4141.1	Mode:	on	
21.4141.106	Operat.-range limit Imax:	5.660	A
21.4141.111	Blocking with CWA:	yes	
21.4141.110	Blocking with 2. harmonic:	yes	
21.4141.102	2nd harmonic content:	15	%
21.4141.112	Crossblocking:	no	
21.4141.109	Crossblocking time:	0.06	s
21.4141.114	Start flt.rec:	yes	

Figure 4 - Primary winding: Setting à Line à Inrush detect.

Inrush detect.

21.4141.1	Mode:	on	
21.4141.106	Operat.-range limit Imax:	5.830	A
21.4141.111	Blocking with CWA:	yes	
21.4141.110	Blocking with 2. harmonic:	yes	
21.4141.102	2nd harmonic content:	15	%
21.4141.112	Crossblocking:	no	
21.4141.109	Crossblocking time:	0.06	s
21.4141.114	Start flt.rec:	yes	

Figure 5 - Secondary winding: Setting à Line à Inrush detect.

Inrush detect.

21.4141.1	Mode:	on	
21.4141.106	Operat.-range limit Imax:	5.830	A
21.4141.111	Blocking with CWA:	yes	
21.4141.110	Blocking with 2. harmonic:	yes	
21.4141.102	2nd harmonic content:	15	%
21.4141.112	Crossblocking:	no	
21.4141.109	Crossblocking time:	0.06	s
21.4141.114	Start flt.rec:	yes	

Figure 6 - Tertiary winding: Setting à Line à Inrush detect.

1.3.2 Current measuring points

CT errors

Class 10P10 current transformers are used according to the example. The resulting CT errors can be found in Table 2.

Transformer Class	Standard	Rated-Current Error		Rated-Overcurrent Factor Error	Setting Recommendations for Settings		
5P	IEC 60044-1	1.0 %	± 60 min	≤ 5 %	1.50	3.0 %	10.0 %
10P		3.0 %	_	≤ 10 %	1.50	5.0 %	15.0 %
TPX		0.5 %	± 30 min	ϵ ≤ 10 %	1.50	1.0 %	15.0 %
TPY		1.0 %	± 30 min	ϵ ≤ 10 %	1.50	3.0 %	15.0 %
TPZ		1.0 %	180 min ± 18 min	ϵ ≤ 10 % (only I ≈)	1.50	6.0 %	20.0 %
PX	IEC 60044-1 BS: Class X				1.50	3.0 %	10.0 %
C100 to C800	ANSI				1.50	5.0 %	15.0 %

Table 2 – Setting recommendations for CT errors (Manual 7SL87)

Influence of tap changers or voltage controls

If the transformer has voltage control, the deviation in the ratio caused by the stepping switch position can be accounted for like an additional "CT error", because the error is current-proportional. This compensation is only applied on the controlled side of the transformer. The considered deviation due to the voltage control refers to the mean current at rated apparent power.

The 220kV side of the 220 MVA transformer has a voltage control range of ± 10%.

This means, the following relationship is valid for the currents at rated apparent power:

$$I_{nT} = \frac{S_{nT}}{\sqrt{3} \times U_{nT}} = \frac{220MVA}{\sqrt{3} \times 220kV} = 577A \quad (8)$$

The minimum current flows at the highest stepping switch position:

$$I_{min} = \frac{S_{nT}}{\sqrt{3} \times U_{nT} \times 1.1} = \frac{220MVA}{\sqrt{3} \times 242kV} = 525A \quad (9)$$

The maximum current flows at the lowest stepping switch position:

$$I_{max} = \frac{S_{nT}}{\sqrt{3} \times U_{nT} \times 0.9} = \frac{220MVA}{\sqrt{3} \times 198kV} = 642A \quad (10)$$

The mean current value of the controlled transformer side therefore results in:

$$I_{mean} = \frac{I_{min} + I_{max}}{2} = \frac{525A + 642A}{2} = 583A \quad (11)$$

The maximum deviation from this mean current is:

$$\delta_{max} = \frac{I_{max} - I_{mean}}{I_{mean}} = \frac{642A - 583.5A}{583.5A} = 0.10 = 10\% \quad (12)$$

The maximum deviation is then added to CT errors A and B.

This results theoretically in a CT error A of 15% and a CT error B of 25% for the 220 kV side.

The transformer settings are made under the Power system Function group à Measuring point I-3ph à Transformer.

CT phases

11.931.8881.101	Rated primary current:	600.0	A
11.931.8881.102	Rated secondary current:	1 A	
11.931.8881.117	Current range:	100 x IR	
11.931.8881.118	Internal CT type:	CT protection	
11.931.8881.116	Neutr.point in dir.of ref.obj:	yes	
11.931.8881.114	Inverted phases:	none	
11.931.8881.107	CT error changeover:	1.50	
11.931.8881.108	CT error A:	15.0	%
11.931.8881.109	CT error B:	25.0	%

Figure 7 – Primary winding: Settings à Power system à Meas.point I-3ph à CT phases

CT phases

11.931.8881.101	Rated primary current:	1200.0	A
11.931.8881.102	Rated secondary current:	1 A	
11.931.8881.117	Current range:	100 x IR	
11.931.8881.118	Internal CT type:	CT protection	
11.931.8881.116	Neutr.point in dir.of ref.obj:	yes	
11.931.8881.114	Inverted phases:	none	
11.931.8881.107	CT error changeover:	1.50	
11.931.8881.108	CT error A:	5.0	%
11.931.8881.109	CT error B:	15.0	%

Figure 8 - Secondary winding: Settings à Power system à Meas.point I-3ph à CT phases

CT phases

11.931.8881.101	Rated primary current:	800.0	A
11.931.8881.102	Rated secondary current:	1 A	
11.931.8881.117	Current range:	100 x IR	
11.931.8881.118	Internal CT type:	CT protection	
11.931.8881.116	Neutr.point in dir.of ref.obj:	yes	
11.931.8881.114	Inverted phases:	none	
11.931.8881.107	CT error changeover:	1.50	
11.931.8881.108	CT error A:	5.0	%
11.931.8881.109	CT error B:	15.0	%

Figure 9 - Tertiary winding: Settings à Power system à Meas.point I-3ph à CT phases

Process monitor

Some SIPROTEC 5 functions offer the opportunity to make targeted settings for switch-on without having to use a setting group changeover. This example assumes that only the line differential protection really uses this function.

Inrush currents of large transformers can flow over a longer period of time until the core material is magnetized. Measuring the exact duration is difficult in most cases. These values can be approximated during commissioning.

To do this, the *Inrush detection Function block* in the *Process monitor Function* is used. The operating mode (_:4681:101) must be determined depending on the mode and the available signals. This example assumes that the circuit breaker feedback and the "Manual Closure" switch feedback are available. It is also assumed that inrush currents are significantly below the rated transformer currents after 5s. This setting is selected for all three sides.

Closure detec.

21.1131.4681.101	Operating mode:	CB, Iopen, ManCl	
21.1131.4681.102	Action time after closure:	5.00	s
21.1131.4681.103	Min. time feeder open:	0.25	s

Figure 10 – Setting à Line à Process monitor à Closure detection

1.3.3 Settings of the line protection

Transformer Function block

Instantiating the *Transformer Function block* in the *Line differential protection Function* enables the transformer configuration. The transformation of the currents causes an angle rotation of the currents and voltages. This is indicated by the vector group by the manufacturer of the manufacturer. The vector group must be set identically for current and voltage unless the current vector group is not adapted by external measures. For this case, the current vector group can be set to 0. The voltage vector group has to be set to the vector group given on the type plate in order to enable the correct display of voltages and power data. In this example, there is no external adaption of the vector group.

At least one neutral point of the transformer is earthed in this example (on the 220kV side as well as on the 110kV side), it is therefore recommended to activate the Residual current elimination (_.3541.105) *on these sides*.

Transformer

21.821.3541.101	Rated apparent power:	220.0	MVA
21.821.3541.103	Voltage vector group nb.:	0	
21.821.3541.104	Current vector group nb.:	0	
21.821.3541.105	Residual curr. elimination:	yes	

Figure 11 - Primary winding: Setting à Line à 87 Line diff. Prot. à Transformer

Transformer

21.821.3541.101	Rated apparent power:	220.0	MVA
21.821.3541.103	Voltage vector group nb.:	6	
21.821.3541.104	Current vector group nb.:	6	
21.821.3541.105	Residual curr. elimination:	yes	

Figure 12 - Secondary winding: Settings à Line à 87 Line diff. Prot. à Transformer

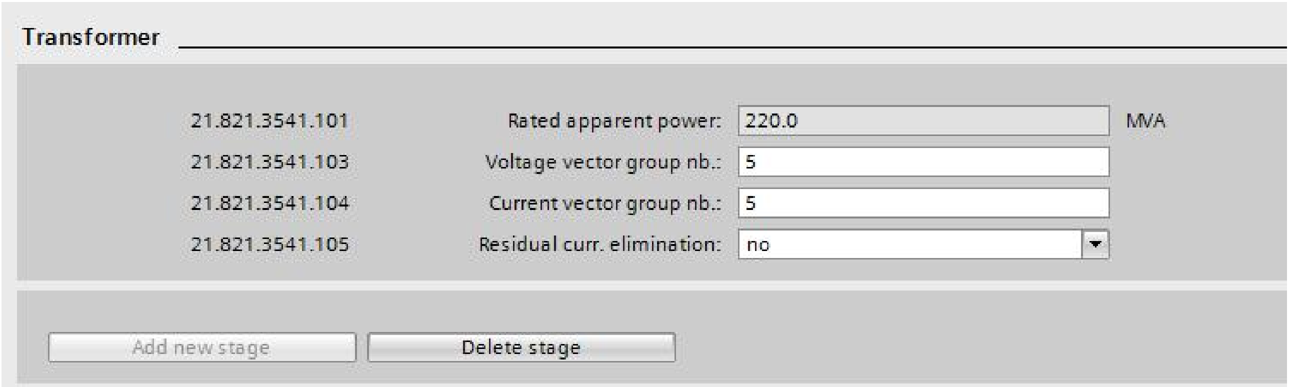


Figure 13 - Tertiary winding: Settings à Line à 87 Line diff. Prot. à Transformer

Function block I-DIFF

The threshold (_:3451:3) of the sensitive stage I-DIFF of the line differential protection should be set to at least the 2.5-fold value of the sum of load currents and the transformer losses.

In general, the preset threshold of 30% of the rated side current is sufficient. This results in the following settings of the I-DIFF threshold for the configuration in secondary values:

$$IDIFF_{220} = 0.3 \times \frac{220MVA}{\sqrt{3} \times 217.8kV} \times \frac{1A}{600A} = 0.29A\ sec \tag{13}$$

$$IDIFF_{110} = 0.3 \times \frac{220MVA}{\sqrt{3} \times 110kV} \times \frac{1A}{1200A} = 0.29A\ sec \tag{14}$$

$$IDIFF_{33} = 0.3 \times \frac{220MVA}{\sqrt{3} \times 33kV} \times \frac{1A}{800A} = 1.44A\ sec \tag{15}$$

In general, the threshold at switch onto fault (_:3451:101) can be set to the same value.

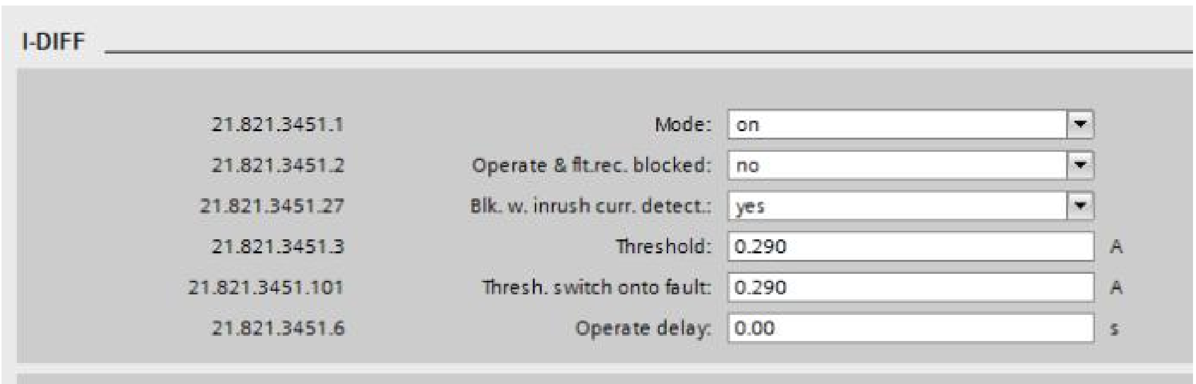


Figure 14 - Primary winding: Settings à Line à 87 Line diff. Prot. à I-DIFF

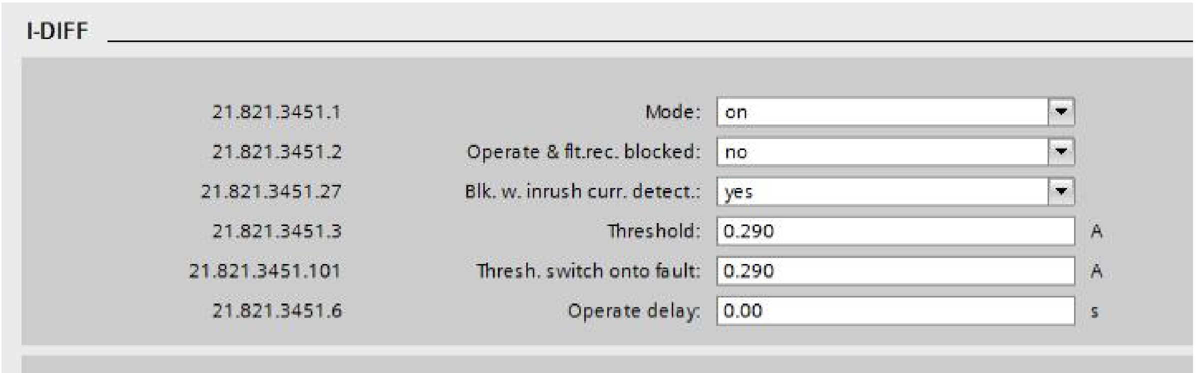


Figure 15 - Secondary winding: Settings à Line à 87 Line diff. Prot. à I-DIFF

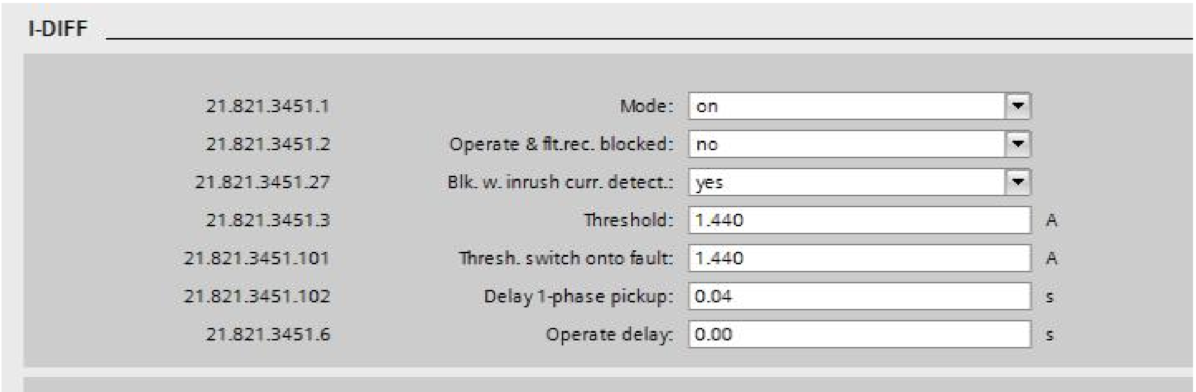


Figure 16 - Tertiary winding: Settings à Line à 87 Line diff. Prot. à I-DIFF

I-DIFF fast 2 Function block

The fast stage I-DIFF fast 2 of the line differential protection eliminates high-current errors in a very short time. The threshold values should be set so that inrush currents cannot cause unwanted tripping. For this, it is helpful to set the two threshold values for normal operation (_:18211:3) and switch-on (_:18211:101) differently. The threshold value upon switch-on (_:18211:101) is set to a value above the maximum inrush current. The maximum inrush current can be approximated with the following formula.

$$I_{Inrush,max} = \frac{I_{nT}}{u_{kr}[\%]} \tag{16}$$

The following maximum levels result from this for the three sides:

$$I_{Inrush,max,220} = \frac{220MVA}{\sqrt{3} \times 220kV} \times \frac{1}{0.17} = 3394A\ prim \tag{17}$$

$$I_{Inrush,max,110} = \frac{200MVA}{\sqrt{3} \times 110kV} \times \frac{1}{0.15} = 7000A\ prim \tag{18}$$

$$I_{Inrush,max,220} = \frac{40\ MVA}{\sqrt{3} \times 33kV} \times \frac{1}{0.15} = 4667A\ prim \tag{19}$$

The following secondary values result for the threshold at switch onto fault (_:18211:101):

$$IDIFF\_schn.2_{220} = 3394A \times \frac{1A}{600A} = 5.66A\ sec \tag{20}$$

$$IDIFF\_schn.2_{110} = 7000A \times \frac{1A}{1200A} = 5.83A\,sec \tag{21}$$

$$IDIFF\_schn.2_{33} = 4667A \times \frac{1A}{800A} = 5.83A\,sec \tag{22}$$

The duration of the inrush detection selected above causes the threshold at switch onto fault (_:18211:101) to be maintained until the inrush currents have mostly died down. This means that a sensitive value can be set for the threshold (_:18211:3) for normal operation. It is important to make sure that functions also accessing *Inrush detection* are not influenced negatively!

The threshold value (_:18211:3) can be set to the rated side current.

$$IDIFF_{220} = 1.0 \times \frac{220MVA}{\sqrt{3} \times 217.8kV} \times \frac{1A}{600A} = 0.97A\,sec \tag{23}$$

$$IDIFF_{110} = 1.0 \times \frac{220MVA}{\sqrt{3} \times 110kV} \times \frac{1A}{1200A} = 0.96A\,sec \tag{24}$$

$$IDIFF_{33} = 1.0 \times \frac{220MVA}{\sqrt{3} \times 33kV} \times \frac{1A}{800A} = 4.81A\,sec \tag{25}$$

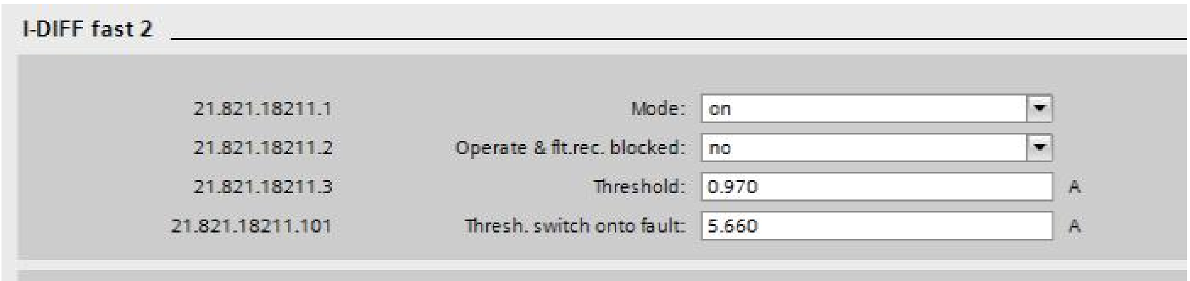


Figure 17 - Primary winding: Settings à Line à 87 Line diff. Prot. à I-DIFF 2

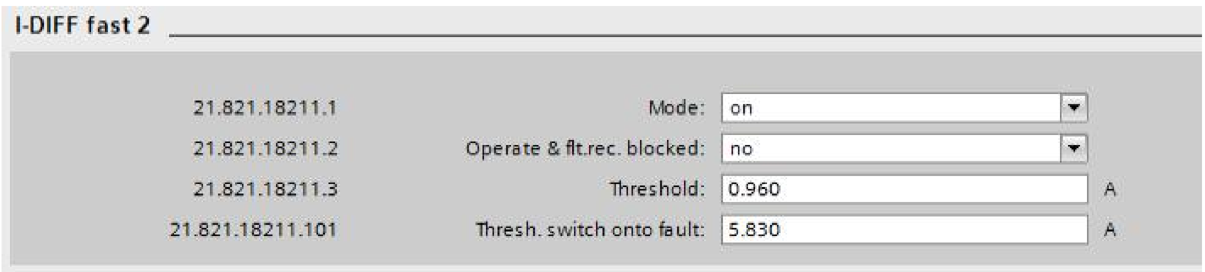


Figure 18 - Secondary winding: Settings à Line à 87 Line diff. Prot. à I-DIFF 2

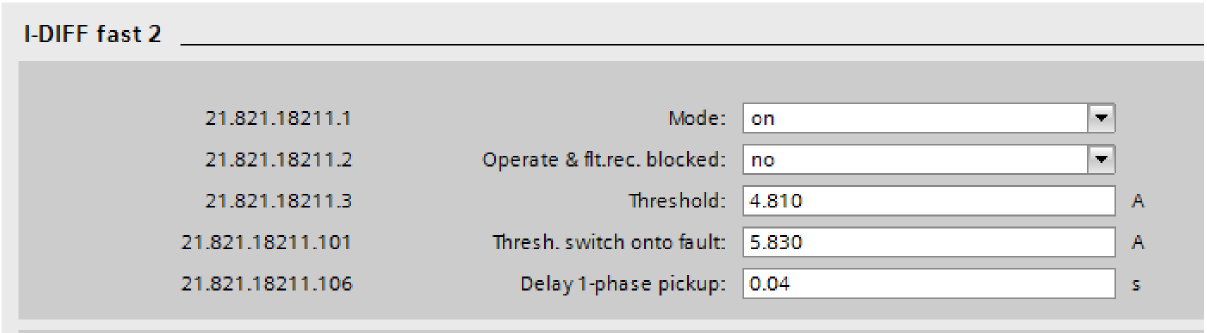


Figure 19 - Tertiary winding: Settings à Line à 87 Line diff. Prot. à I-DIFF 2

1.3.4 Further protection functions

Additional protection functions like frequency protection, voltage protection, etc., can be set for the individual voltage levels. These are not discussed here.

1.4 Summary

The line differential protection is a form of selective short-circuits protection for overhead lines, cables and busbars supplied from one or more end(s) in radial, looped or meshed systems. The instantiation of the optional *Transformer Function block* enables the protection of a transformer in the protection range. It ensures the right analysis of amplitude and phase angle of the measured currents at the related line ends with few additional transformer parameters like rated apparent power, primary voltage, vector groups and possibly available neutral point earthing. The application template *"DIFF overhead line with transformer"* for this application can be selected in DIGSI 5 and can easily be adapted to the requirements.

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