Scott Transformer Application with Differential Protection

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SIPROTEC 5 Application

Scott Transformer Application with Differential Protection SIPROTEC 7UT85/86

APN-069, Edition 1

Content

1 Scott Transformer Application with Differential Protection SIPROTEC 7UT85/7UT86

1.1 Introduction

The application guideline describes the differential protection application for a Scott transformer. A standard differential protection relay for a 3phase application like the SIPROTEC 7UT8 with a 3-side application is recommended.

The theory of the application, the wiring, the setting and the testing is described in this document. An available user defined application template can be the basis for an individual application.

1.2 Principle of the Scott Transformer design

Scott transformers are converters between a three- and a two-phase system. The circuit was designed from Charles F. Scott in 1890 years. The applications are the power supply for two-phase furnaces, two phase motors and often used in traction substations.

Figure 1 shows the basic principle. The Scott transformer consists of two single-phase transformers with a three-phase input and a two-phase output. The connection distributes a balanced load between the 3 phases of the source.

The Scott circuit consists of a center-tapped "main" transformer T1 and a "teaser" transformer T2. T1 and T2 have respectively secondary windings. The center-tapped side of T1 is connected between two phases (in figure 1: phase A and phase C) of the three-phase system and T2 is connected on the remaining phase (in figure 1: phase B). Both secondary sides have the same secondary voltage and a phase shift of 90°. The secondary voltage of T2 is in phase with a primary phase to ground voltage and the secondary voltage of T1 is in phase with a primary phase-to-phase voltage. Figure 2 shows the drawing with the relevant winding ratios (N1 = primary winding and N2 = secondary winding). To get a balanced system the primary winding of the teaser transformer T2 has a reduced winding ratio of the factor $\sqrt{3}/2$ = 0,866. Figure 3 illustrates the phasor diagram for voltages and currents.

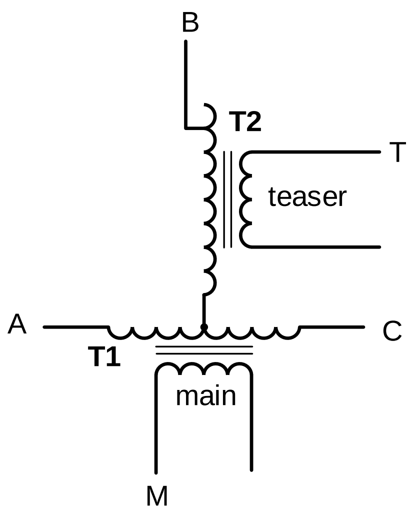

Figure 1: Principle design of Scott transformer

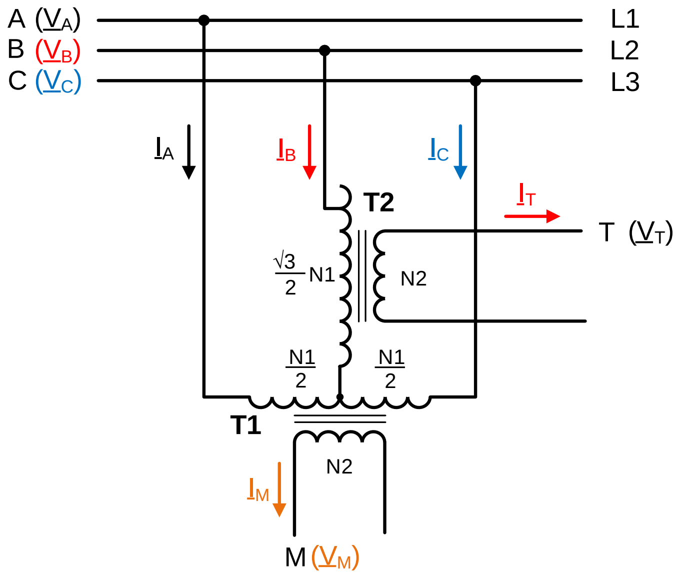

Figure 2: Scott transformer circuit connection with winding ratios

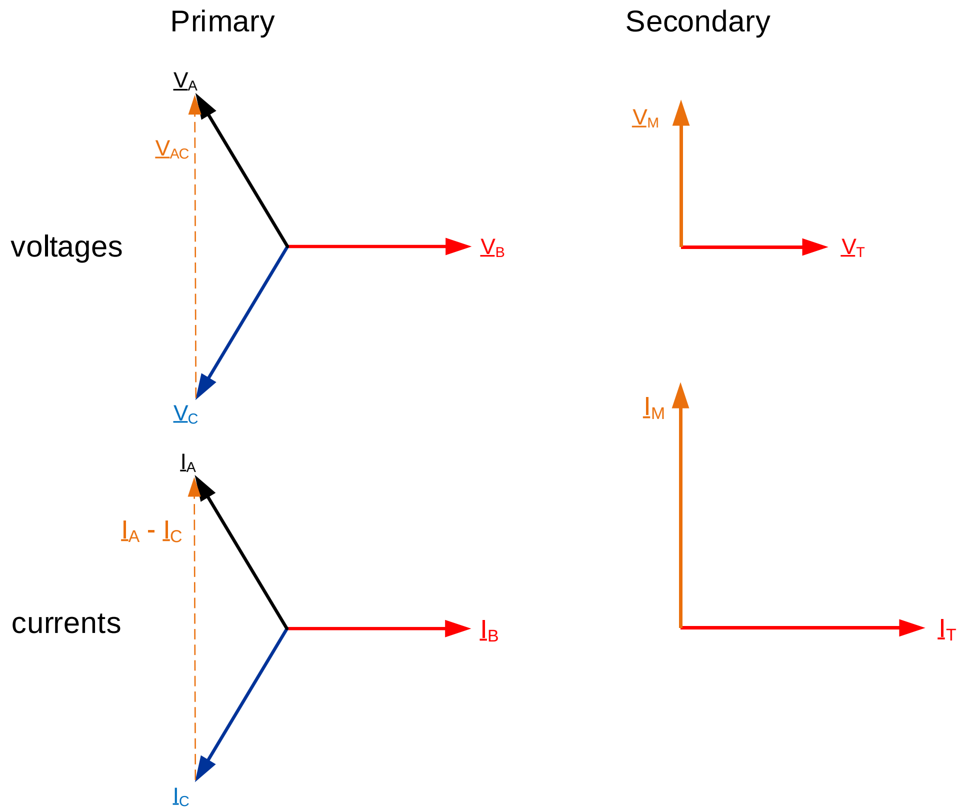

Figure 3: Phasor diagram for the voltages and currents

It shall be noted that a different design of the Scott transformer is possible. For example, the main transformer can be connected on phase A and B of the three-phase system and the teaser transformer uses phase C.

For further explanations in this document the drawing of figure 2 (main transformer is connected on phase A and C; teaser transformer on phase B) is used.

1.3 Protection scheme and main setting values

According figure 2 and 3 there are two single phase differential protection designs for the application necessary. For transformer T2 the phase currents of phase B and phase T must be compared. The currents are in phase (positive definition of currents flow through). For transformer T1 the primary phase currents of phase A and phase C must be subtract ($\underline{I}_A - \underline{I}_C$). The resulting current is in phase with the current of phase M.

For the application a 3phase transformer differential relay can be used. Therefore, a special wiring is necessary. A device with 3 sides and 4 measuring points is basis for the application. To avoid CT impacts due to a parallel connection (subtraction via external antiparallel wiring) a subtraction inside the relay is recommended. Therefore 4 measuring points are used. As mentioned before there is no phase angle correction between the primary and secondary side necessary. The vector group correction can be set to zero (0°) and the zero-sequence elimination must be switched off. In that case the protection device uses the standard transformation matrix.

$$\begin{pmatrix} \underline{I}_A^* \\ \underline{I}_B^* \\ \underline{I}_C^* \end{pmatrix} = k \bullet \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \bullet \begin{pmatrix} \underline{I}_A \\ \underline{I}_B \\ \underline{I}_C \end{pmatrix}$$

With:	$\underline{I}_{A, B, C}$	input currents of each side
	$\underline{I}^*_{A, B, C}$	output currents of each side
	k	CT-mismatching correction factor

For transformer T2 the phase input A (I1) from the device is used. Two sides are necessary. For transformer T1 the phase input C (I3) from the device is used. There are 2 sides and 3 measuring points due to the subtraction of the currents $\underline{I}_A - \underline{I}_C$ necessary. The subtraction is realized via routing the measuring point 4 (phase C) inverted to transformer side 3 of the differential protection function (see chapter 1.4). The phase input B (I2) is not used for all measuring points. The secondary windings (2phase side of the Scott transformer) are the reference side and must be connected to function group Transformer side 1.

The proposed wiring is shown in figure 4.

For an accurate CT-mismatching the internal calculation of the relay must be considered. The protection function calculates for each transformer side a correction factor. Input values are the primary CT current ($I_{CT,prim}$), the set voltage of at each side (V_{Side}) and maximum of the apparent power (S_{Max}). In the application the 3phase (primary) side has the highest apparent power. With the following equation the correction factor k can be calculated.

$$k = \frac{I_{CT,prim}}{\dfrac{S_{Max}}{\sqrt{3} \cdot V_{Side}}}$$

For the calculation of the correct voltage the winding ratio of the Scott transformer must be considered. Table 1 summarizes the calculation. The drawing from figure 4 is the reference.

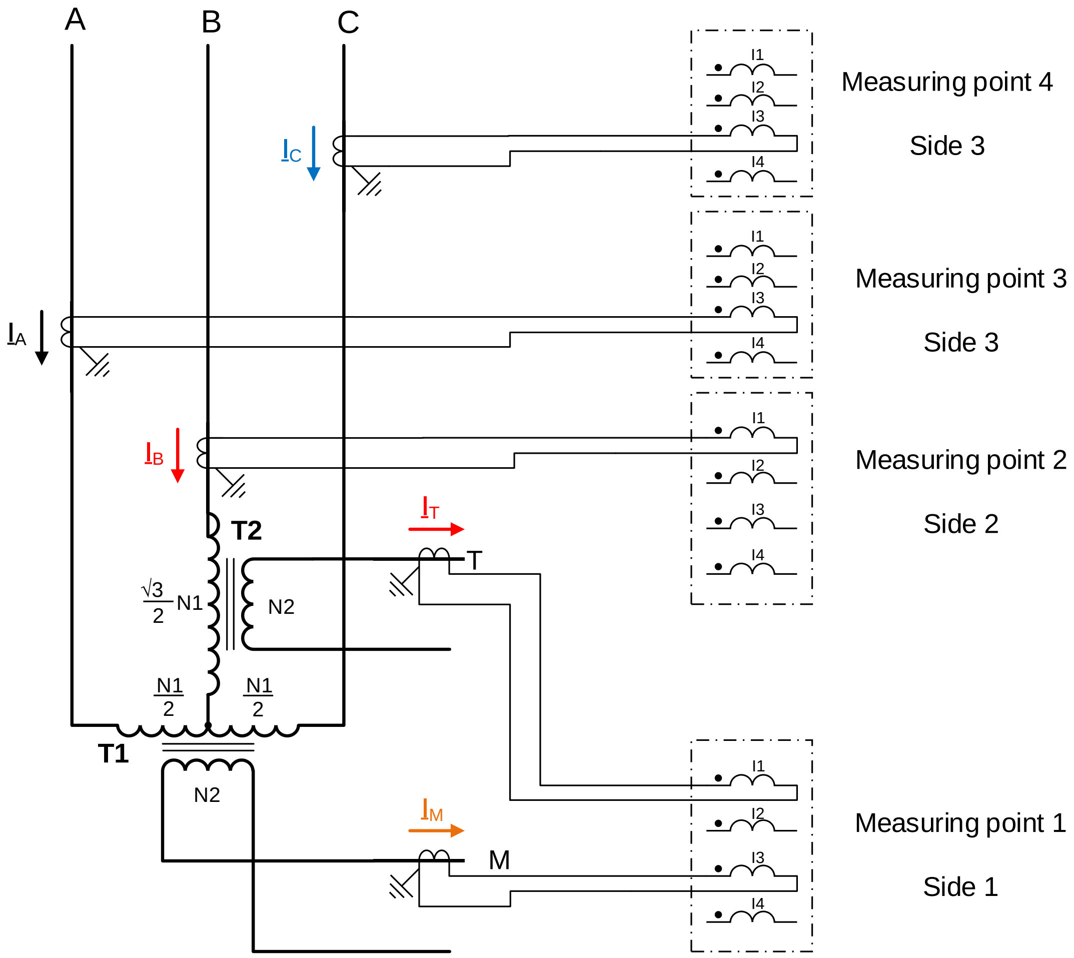

Figure 4: Wiring of the differential protection relay

	Side 1	Side 2	Side 3
V_{Side}	$V_M = V_T$	$= \frac{\sqrt{3}}{2} \cdot V_{ph-ph,prim}$	$= \frac{1}{2} \cdot V_{ph-ph,prim}$

Table 1: Calculation of the reference voltage

Example:

Scott transformer:

Voltages: V_{prim} = 154 kV, $V_{sec} = V_M = V_T$ = 55kV

Apparent power: 80 MVA/40MVA/40MVA

CT-primary side (3phase): 400A/1A

CT-secondary side (2phase): 800A/1A

The rated load current on the 3phase and 2phase side of the Scott transformer is the following.

$$I_{rated,prim} = \frac{S_{prim}}{\sqrt{3} \cdot V_{prim}} = \frac{80MVA}{\sqrt{3} \cdot 154kV} = 299.9A$$

$$I_{rated,prim} = \frac{S_{\sec}}{V_{\sec}} = \frac{40MVA}{55kV} = 727.27A$$

Table 2 summarizes the set values for voltages and shows additional the correction factor for CT-mismatching.

	Side 1	Side 2	Side 3
V_{Side}	$V_M = V_T = 55kV$	$= \frac{\sqrt{3}}{2} \cdot 154kV = 133.4kV$	$= \frac{1}{2} \cdot 154kV = 77kV$
k	$\frac{800A}{\frac{80MVA}{\sqrt{3} \cdot 55kV}} = 0.953$	$\frac{400A}{\frac{80MVA}{\sqrt{3} \cdot 133.4kV}} = 1.155$	$\frac{400A}{\frac{80MVA}{\sqrt{3} \cdot 77kV}} = 0.667$

Table 2: Setting values for reference voltage and internal calculated correction factors *k*

If the maximum load current flows, the device measures the currents on the CT secondary side according table 3. The multiplication with the correction factor *k* gives the adapted current *I** for each measuring point. With these currents the differential and restraint current are calculated.

	Side 1 (phase A, C)	Side 2 (phase A)	Side 3 (phase C)
CT_{sec}	727.3A/800 = 0.91A	299.9A/400 = 0.75A	299.9A/400 = 0.75A 0.75A*√3 = 1.299A)*
*I**	*0.91A*0,953 =* ***0.867A***	*0.75A*1,155 =* ***0.866A***	*1.299*0,667 =* ***0.866A***

Table 3: Secondary CT currents at full load, adapted currents

) * Due the used difference of primary currents $\underline{I}_A - \underline{I}_C$ the phase current is multiplied by √3

Table 3 shows clearly a differential current of zero.

Transformer T1: $I_{diff} = I^*_{A,\ Side\ 1} - I^*_{A,Side\ 2} =$ 0,867A -0.866A =0.001A ≈ 0A

Transformer T2: $I_{diff} = I^*_{C,\ Side\ 1} - I^*_{C,Side\ 3} =$ 0,867A -0.866A =0.001A ≈ 0A

1.4 Protection design with SIPROTEC 7UT85/7UT86

The application can be realized with a transformer differential relay 7UT85 or 7UT86 [1]. Please order for the 7UT85 the necessary number of function points (minimum 70) for a 3-side application. The basic design of 7UT86 is a 3-side transformer. In the application four measuring points are used. The differential protection function is designed for a 3phase system. As mentioned in the chapter 1.3 the Scott transformer needs a special connection of the currents. The device is wired according the drawing in figure 4 (compare the current input numbers).

Scott Transformer Application with Differential Protection

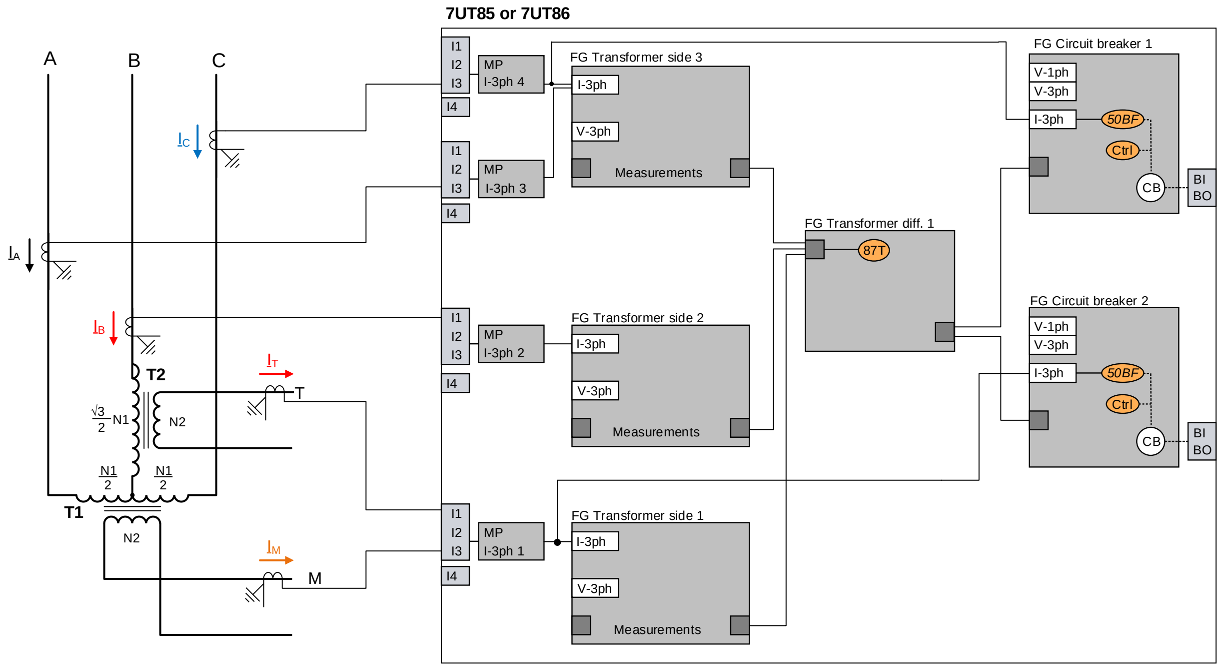

Figure 5: Structure of differential protection function

In Transformer side 3 the subtraction of the currents ($I_A - I_C$) is in the routing matrix of measuring points (MP) to function groups (FG) realized. Instead the cross (x) the letter (I) must be routed. That means the input current is multiplied by -1. The following figure 6 shows the routings.

Connect measuring points to function group

Measuring point	Transformer side 1	Transformer side 2	Transformer side 3	Circuit breaker 1	Circuit breaker 2
	I 3ph	I 3ph	I 3ph	I 3ph	I 3ph
(All)	(All)	(All)	(All)	(All)	(All)
Meas.point I-3ph 1 [ID 1]	X			X	
Meas.point I-3ph 2 [ID 2]		X			X
Meas.point I-3ph 3 [ID 3]			X		
Meas.point I-3ph 4 [ID 4]			I		

Figure 6: Inverting of Measuring point 4 (phase current I_C)

In the folder "power systems" for all measuring points the parameter of used CT's must be set. The MP1 is connected to the 2phase side of the Scott transformer and according the example the CT-ratio is 800A/1A. The CT-star point (see grounding symbol in figure 5) is connected towards to the Scott transformer. The 3phase side uses a 400A/1A CT's. For the MP2 to 4 the settings are identical. Figure 7 shows the setting screenshots.

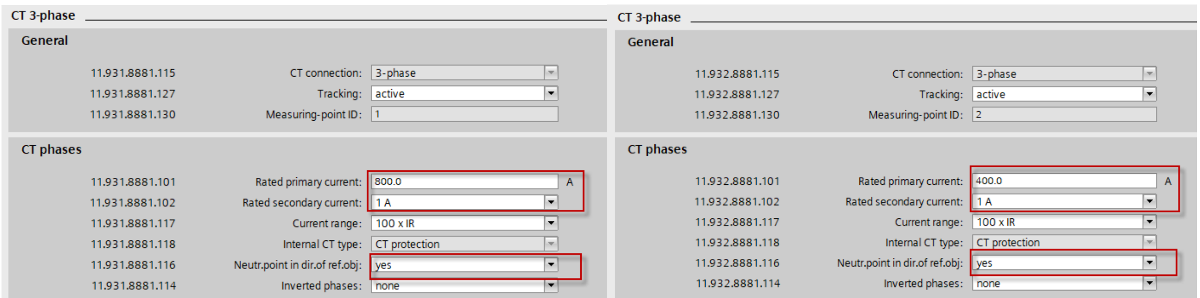

Figure 7: CT-settings (left 2phase side, right 3phase side of the Scott transformer)

In a next step in each function group under folder “general” the main primary data must be set. For these settings must be considered, that the device is designed for a 3phase system. With the apparent power and the voltage, the device calculates the rated current for each transformer side. The used equation is:

$$I_{rated,prim} = \frac{S_{prim}}{\sqrt{3} \cdot V_{prim}}$$

Therefore, for the 2phase side the apparent power must be multiplied by √3. Instead 40MVA from the example √3 * 40MVA must be set. Figure 8 is the screenshot of the settings. As can be seen in grey the calculated rated current (727.3A) is according the value from chapter 1.3. Regarding the discussion in chapter 1.3 due to the special design of the 3phase Scott transformer side different voltages must be set. For FG Transformer side 2 the rated voltage must be multiplied by the factor √3/2. Therefore, the setting value is √3/2 * 154kV = 133.40kV (see figure 9). For FG Transformer side 3 the setting value for the voltage is the half of the rated voltage ½ * 154kV = 77kV (see figure 10).

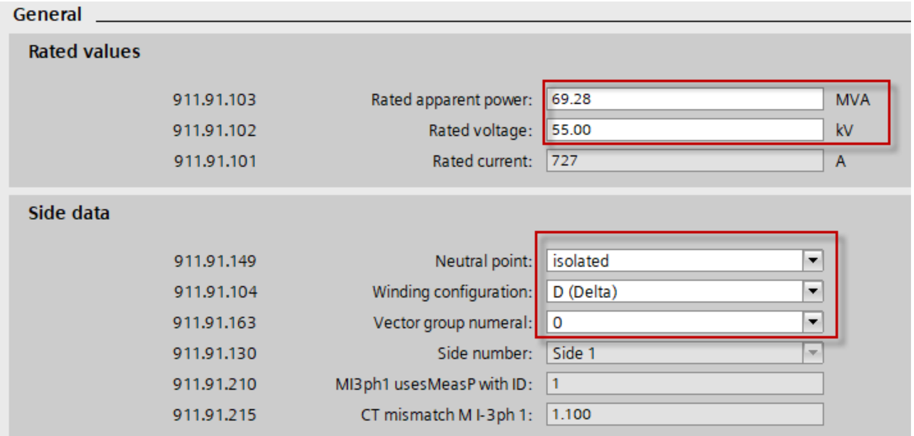

Figure 8: Settings under “general” of FG Transformer side 1

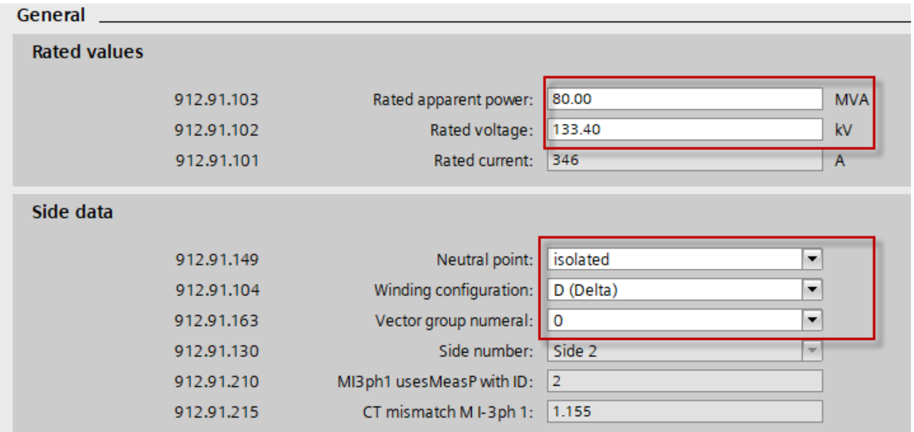

Figure 9: Settings under “general” of FG Transformer side 2

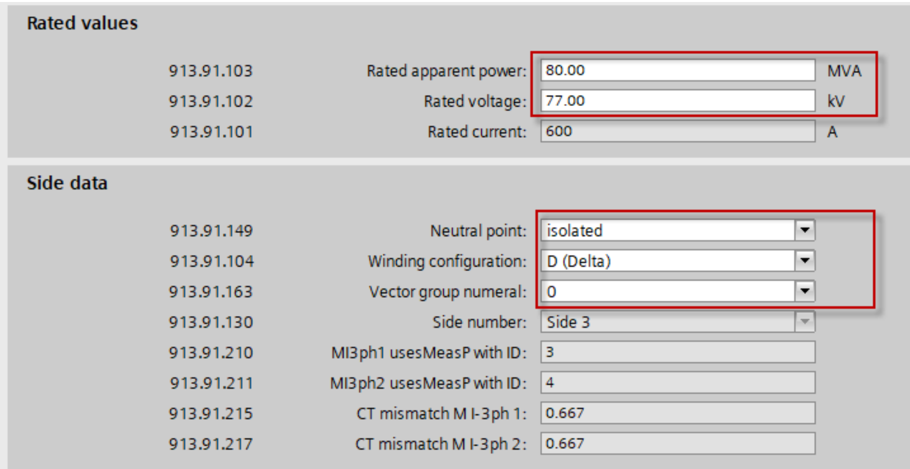

Figure 10: Settings under “general” of FG Transformer side 3

In the FG “Transformer diff.” under folder “general” the protection shows the calculated adaption factor for the correction of CT-mismatch (see figure 11). These values are identical with the calculated values from chapter 1.3, table 3.

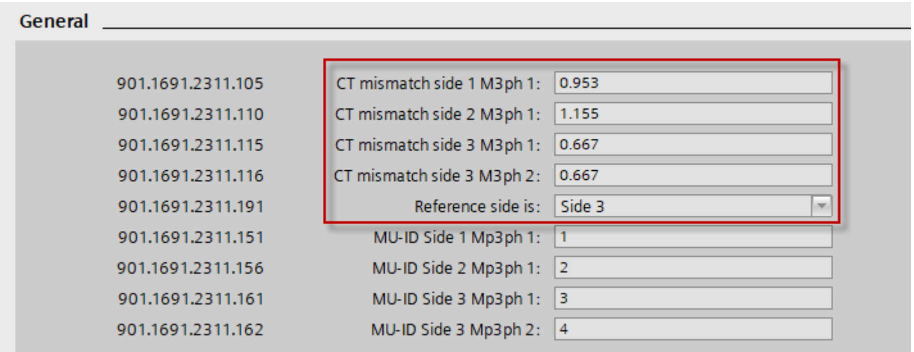

Figure 11: Correction factors for CT -mismatch

For setting the differential characteristic the default setting can be used (see figure 12). For blocking the inrush currents the second harmonic as well the CWA principle shall be active. Please use the standard setting as well for DC offset detection (handling of low fault current with DC offset). Figure 13 shows theses settings.

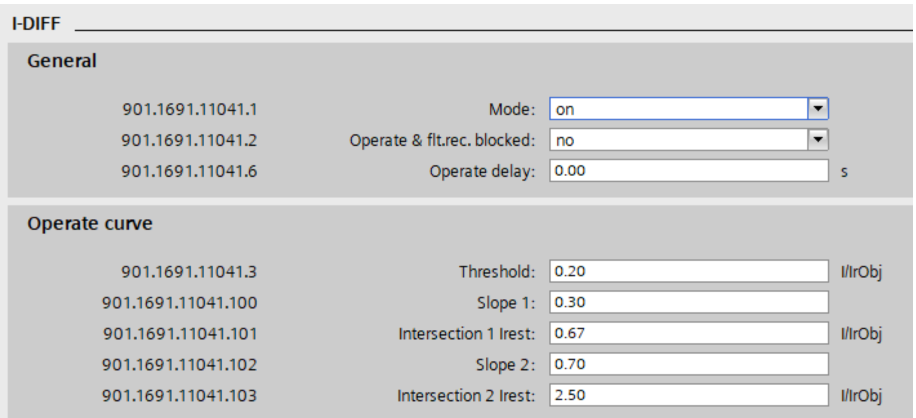

Figure 12: Setting values for the differential characteristic

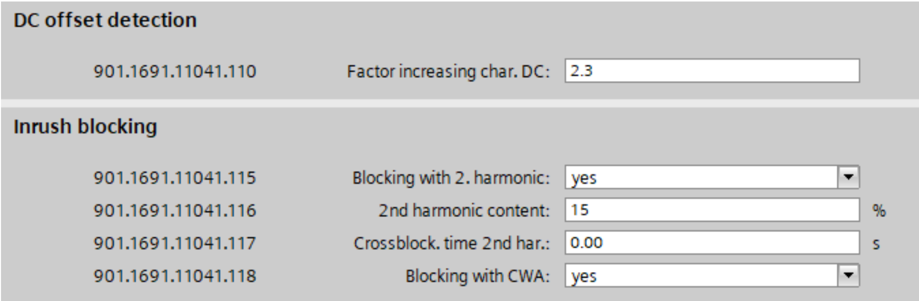

Figure 13: Setting values for inrush blocking

The rest of setting like routing of binary outputs, LEDs, communication protocol must be done project specific.

If you start the application with an individual device the user defined template "***Scott_transformer_7UT8_V750.uat***" can be used. This template is according the structure of figure 5.

1.5 Testing

The main goal of the test is the check of the correct wiring, the right settings and routings. This secondary test is done after cubicle building (factory site tests). For these tests a test equipment with 6 current inputs is necessary and an individual setting of the phase currents (magnitude and phase angle) shall be possible.

It's recommended to inject secondary currents which corresponds to the primary currents. For the first test a full load current flow is simulated. That means a flow through load current.

Due to the positive definition of the currents towards the Scott transformer (see CT star points) the currents of the 2phase are not according phasor diagram in figure 3. The currents $\underline{I}_T$ and $\underline{I}_M$ must be turned by 180°.

The following table 3 shows the set current in the test equipment.

	Primary currents		Secondary currents	
	Magnitude	angle	magnitude	angle
$\underline{I}_A$	299.9 A	+120°	0.75 A	+120°
$\underline{I}_B$	299.9 A	0°	0.75 A	0°
$\underline{I}_C$	299.9 A	-120°	0.75 A	-120°
$\underline{I}_T$	727.3 A	-180°	0.91 A	-180°
$\underline{I}_M$	727.3 A	-90°	0.91 A	-90°

Table 3: Test currents

The test results can be effective checked with DIGSI in the online mode. The test suit visualizes the relevant measured values. Figure 14 shows from all used measuring points the measured currents (view primary values). Unfortunately, the names of the phasors coming from the 3phase system. Please keep in mind the wiring according figure 4 and 5. For interpretation the phase angles consider that the software uses the first line as a reference and put the angle in the "zero axis" (0°). The first line is the current $\underline{I}_T$. To compare the values with table 3, the phase angles of table 3 must be add by +180°. This transformation is done in table 4.

As can be seen from figure 14 the magnitudes and the phase angles are according the injected current. The wiring is correct.

	Primary		changed
	Magnitude	angle	angle
I_A	299.9 A	+120°	-60°
I_B	299.9 A	0°	-180°
I_C	299.9 A	-120°	+60°
I_T	727.3 A	-180°	0°
I_M	727.3 A	-90°	+90°

Table 4: Adapted phase angles for better comparison with figure 14

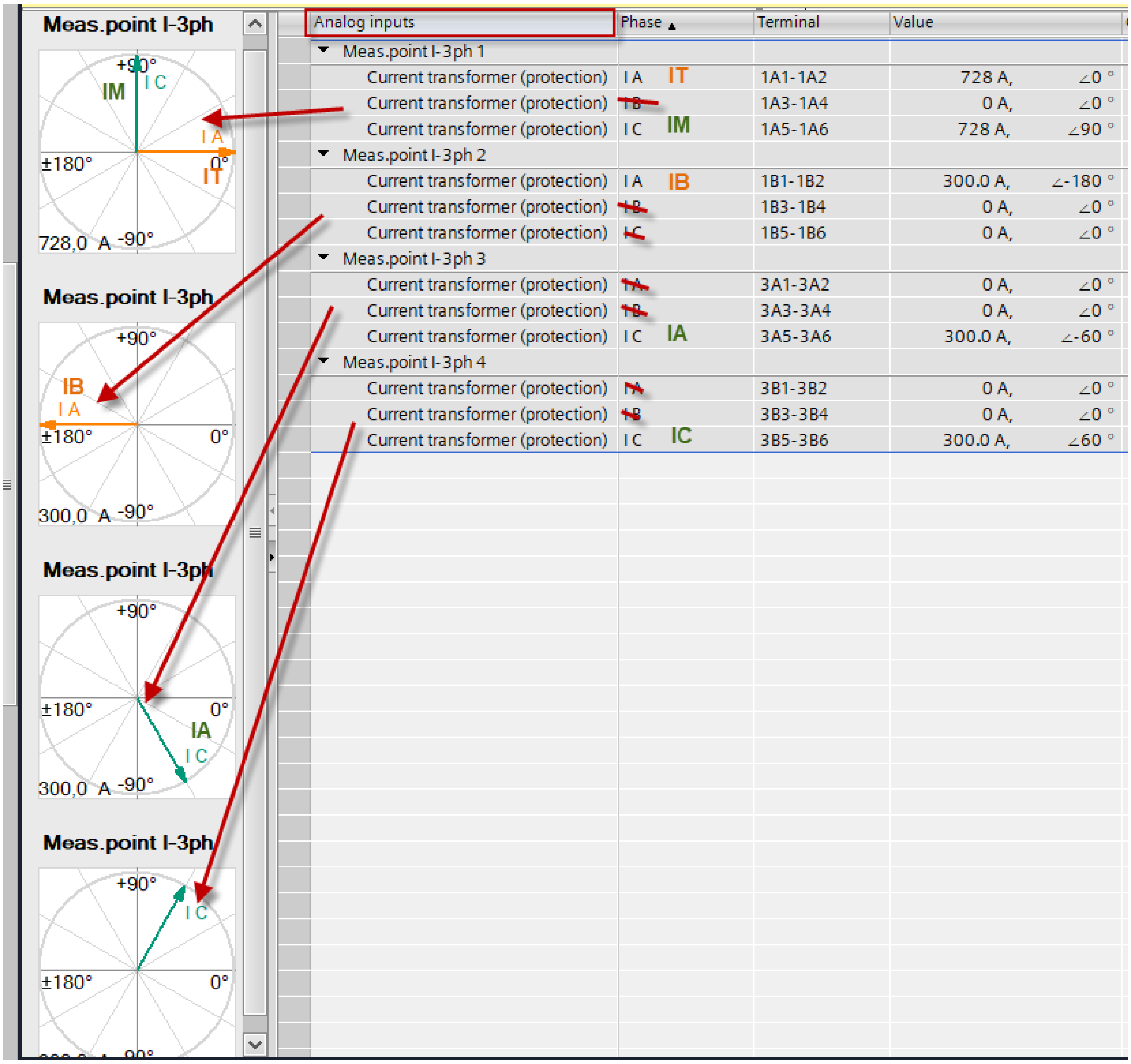

Figure 14: Wiring of the differential protection relay (in colors the connected currents)

The next step is the check of the differential and restraint current. Figure 15 shows the result as expected. The differential current under load must be zero and the restraint current according the adapted phase current. A restraint current of 0.867 I/IrObj is according the calculation from table 2. That means the wiring and setting of differential protection is okay.

Figure 16 shows a view from the device display during this test (is part of the user template). Relevant measured values are indicated.

For testing the internal failure, the injected currents from the 2phase side ($\underline{I}_T$, $\underline{I}_M$) are turned by 180°. That means an internal failure with sources from both sides of the Scott transformer. The differential current must be the double of the adapted phase current (2*0,867 I/IrObj = 1,734 I/IrObj). The restraint current is according the maximum of the phase current. The injected currents from both sides are the same. So, the restraint current must be 0.867 I/Obj. Figure 17 shows the expected results.

Function values | User-def. valu...

Measurements	Value	Quality	Number
▼ Function values			
▼ 87T diff. prot....			
I diff.:A	0 I/IrObj	good (process)	901.1691.2311.300
I restr.:A	0.867 I/IrObj	good (process)	901.1691.2311.301
I diff.:B	0 I/IrObj	good (process)	901.1691.2311.300
I restr.:B	0 I/IrObj	good (process)	901.1691.2311.301
I diff.:C	0.001 I/IrObj	good (process)	901.1691.2311.300
I restr.:C	0.867 I/IrObj	good (process)	901.1691.2311.301

Figure 15: Differential and restraint current during full load test

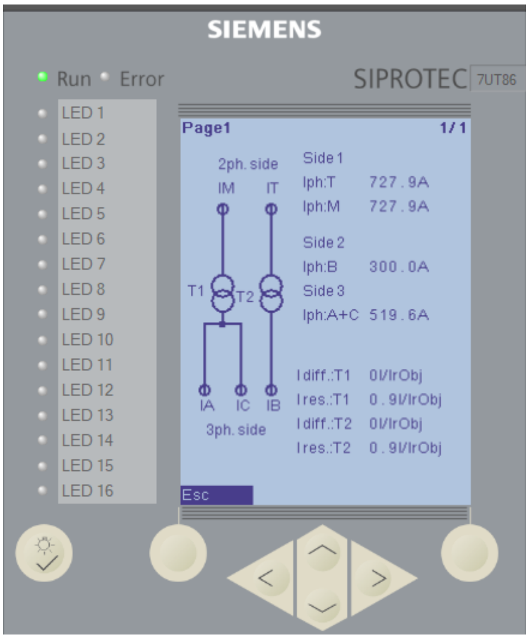

Figure 16: Indication on the device display during the full load test

Function values | User-def. valu...

Measurements	Value	Quality	Number
▼ Function values			
▼ 87T diff. prot....			
I diff.:A	1.734 I/IrObj	good (process)	901.1691.2311.300
I restr.:A	0.867 I/IrObj	good (process)	901.1691.2311.301
I diff.:B	0 I/IrObj	good (process)	901.1691.2311.300
I restr.:B	0 I/IrObj	good (process)	901.1691.2311.301
I diff.:C	1.733 I/IrObj	good (process)	901.1691.2311.300
I restr.:C	0.867 I/IrObj	good (process)	901.1691.2311.301

Figure 17: Differential and restraint current during internal failure with currents according full load

Additionally, the log file and the fault record shall be checked. Figure 18 shows the log file from the internal fault. The entries are as expected. Pickup of phase A (T2) and phase C (T1) is correct and as well the trip (operate) is visible.

Time stamp	Relative time	Fault number	Entry number	Functions structure	Name	Value
		(All)	(All)	(All)	(All)	(All)
09.11.2019 14:40:22.305 (29)		4		Fault log		
09.11.2019 14:40:22.305	00:00:00:00.000		1	Transformer diff. 1:87T diff. prot. 1:I-DIFF	Slope 1	0.30
09.11.2019 14:40:22.305	00:00:00:00.000		2	Recording:Fault recorder:Control	Fault number	4
09.11.2019 14:40:22.305	00:00:00:00.000		3	Transformer diff. 1:87T diff. prot. 1:I-DIFF	Pickup	phs A phs C
09.11.2019 14:40:22.305	00:00:00:00.000		4	Transformer diff. 1:87T diff. prot. 1:I-DIFF	Operate	phs A phs C
09.11.2019 14:40:22.305	00:00:00:00.000		5	Transformer diff. 1:87T diff. prot. 1:I-DIFF	CWA int. fault detected	on
09.11.2019 14:40:22.305	00:00:00:00.000		6	Circuit breaker 2:Circuit break.	Trip/open cmd.	on
09.11.2019 14:40:22.305	00:00:00:00.000		7	Circuit breaker 2:Circuit break.	Definitive trip	on
09.11.2019 14:40:22.305	00:00:00:00.000		8	Circuit breaker 1:Circuit break.	Trip/open cmd.	on
09.11.2019 14:40:22.305	00:00:00:00.000		9	Circuit breaker 1:Circuit break.	Definitive trip	on
09.11.2019 14:40:22.305	00:00:00:00.000		10	Transformer diff. 1:87T diff. prot. 1:General	I diff. operate phA	1.733 I/IrObj
09.11.2019 14:40:22.305	00:00:00:00.000		11	Transformer diff. 1:87T diff. prot. 1:General	I diff. operate phB	0 I/IrObj
09.11.2019 14:40:22.305	00:00:00:00.000		12	Transformer diff. 1:87T diff. prot. 1:General	I diff. operate phC	1.733 I/IrObj
09.11.2019 14:40:22.305	00:00:00:00.000		13	Transformer diff. 1:87T diff. prot. 1:General	I restr. operate phA	0.867 I/IrObj
09.11.2019 14:40:22.305	00:00:00:00.000		14	Transformer diff. 1:87T diff. prot. 1:General	I restr. operate phB	0 I/IrObj
09.11.2019 14:40:22.305	00:00:00:00.000		15	Transformer diff. 1:87T diff. prot. 1:General	I restr. operate phC	0.867 I/IrObj

Figure 18: Log during trip

For better comparison with the phase names used in chapter 1.3 the phase names in the "cfg"-file from the stored fault record are modified. Figure19 shows the instantaneous currents and additional the binary trip (operate) traces of the differential protection. Figure 20 is a screenshot of the phasor diagram and the differential characteristic with the calculated differential and restraint currents. As can be seen from the phasor diagram for the internal fault the currents ($\underline{I}_T$, $\underline{I}_B$) are in phase. The differential current is below the threshold and in the trip region.

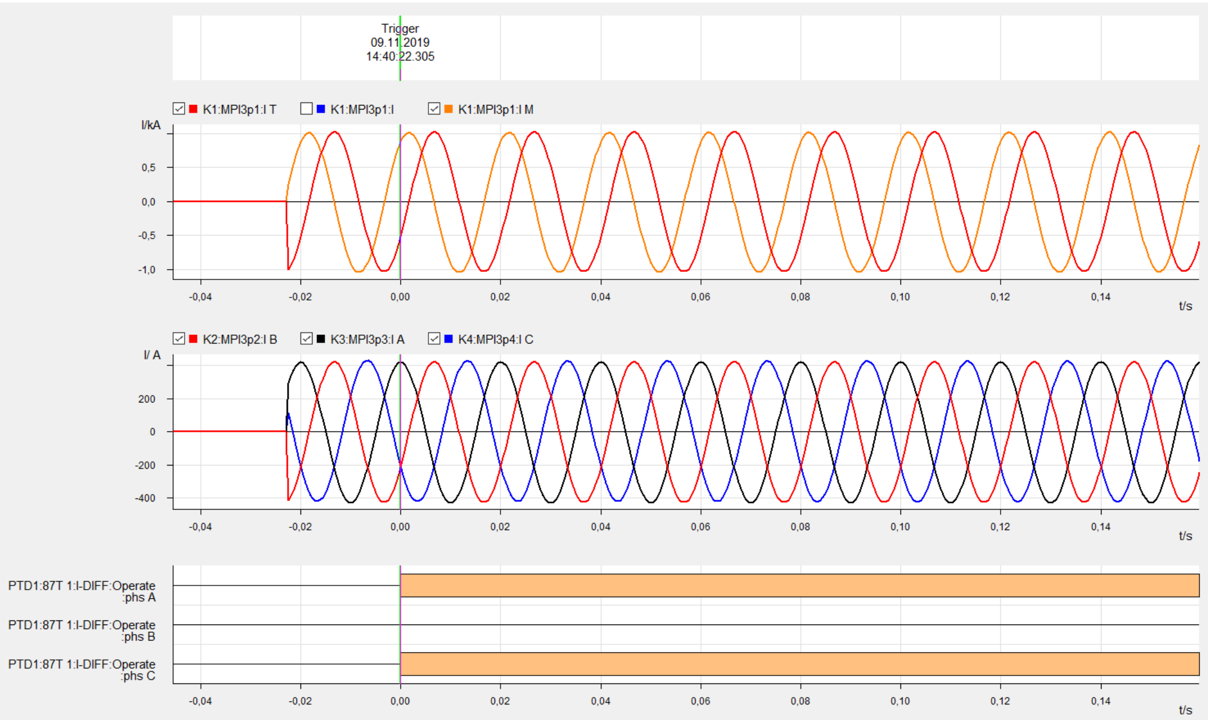

Figure 19: Internal fault: instantaneous currents and binary traces

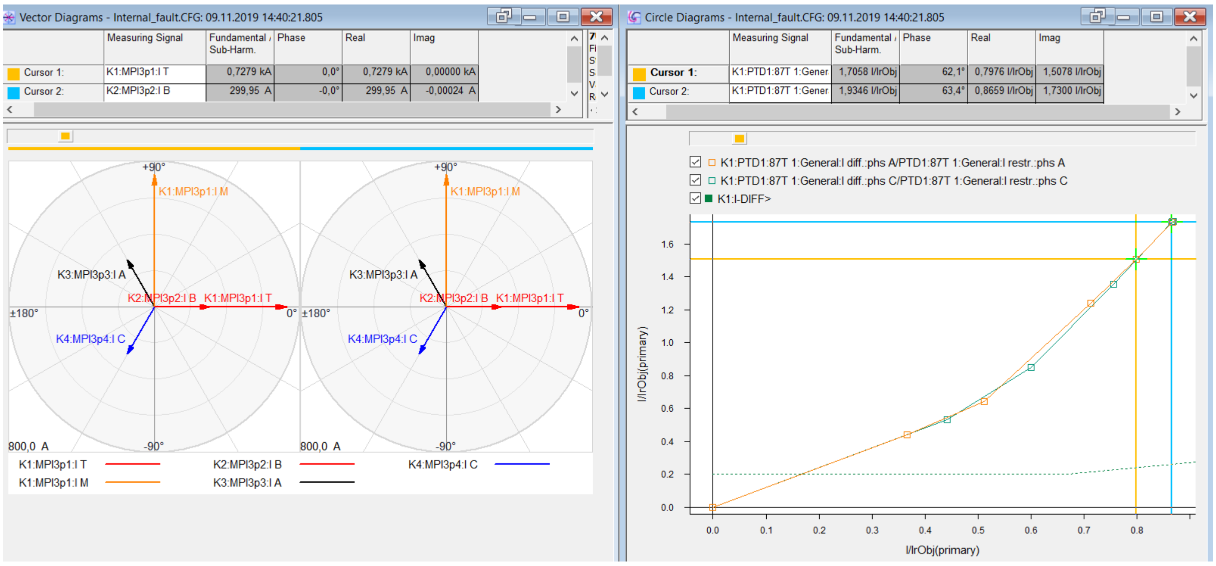

Figure 20: Internal fault: phasor diagram and differential characteristic

Primary Test:

After wiring the protection cubicle in the plant the correct wiring can be checked with a primary test. This test can be done with a low voltage 3phase transformer (e.g. 400V). This transformer is connected on the high voltage side (3phase side) of the Scott transformer. On the medium voltage (2phase side) an external short circuit between the phases is wired.

For example, a Scott transformer with a short circuit voltage (u_{SC}) of 12% is assumed. The rest of values are from the example. With the following calculation the expected test currents can be estimated.

$$ZTR_{154kV} = \frac{V^2_{r,HV} \cdot u_{SC}}{S_r} = \frac{154kV^2 \cdot 0{,}12}{80MVA} = 35.6\Omega$$

$$I_{HVprim} = \frac{V_{r,test}}{\sqrt{3} \cdot ZTR_{154kV}} = \frac{400V}{\sqrt{3} \cdot 35.5\Omega} = 6{,}5A$$

$$I_{HVsec} = \frac{I_{HVprim}}{CT_{ratio}} = \frac{6{,}5A}{400} = 0.016A$$

$$I_{MVsec} = \frac{I_{HVprim} \frac{\sqrt{3}}{2} \frac{V_{HV}}{V_{MV}}}{CT_{ratio}} = \frac{6{,}5A \cdot \frac{\sqrt{3}}{2} \frac{154kV}{55kV}}{800} = 0.0197A$$

These small currents are enough for the wiring test. The differential current must be zero and restraint current according the injected phase current. With correction of CT-mismatching the expect restraint current at Transformer side 1 (MV side = 2phase side) is 0.0197A*0.91 = 0.018A → 0,018I/IrObj.

If this test is not possible after a conventional wiring test the differential protection shall be checked under load conditions. The differential protection trip must be blocked, but a backup overcurrent protection is in service. Under load condition the measured values must be checked. The differential current must be zero and the restraint current according the load current (see for comparison figure 15).

1.6 Conclusion

The application guideline describes the differential protection application for a Scott transformer. A standard differential protection relay for a 3phase application can be used. A 7UT8-device with a 3-side application is recommended. Due to the relay design and the design of the Scott transformer a special wiring is necessary.

The theory of the application, the wiring, the setting and the testing is described in this document. An available user defined application template can be the basis for an individual application.

1.7 Literature

[1] SIPROTEC 5 Transformer differential protection 7UT82, 7UT85, 7UT86, 7UT87; V7.80 and higher, Manual C53000-G5040-C016-9, Edition 06.2018

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