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Directional Ground-Fault Protection

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SIPROTEC 5 Application

Directional ground-fault protection

APN-052, Edition 4

Content

1 Directional ground-fault protection Direction definition, connection variants, testing

1.1 Introduction

This practice-oriented paper shows, in addition to the illustrative explanation of the basis of ground fault parameters in insulated and arc-suppression-coil-ground systems, the connection variants for determination of the ground fault direction in detail.

This paper places a focus on testing the primary transformers and the ground fault direction protection function during commissioning and/or revisions using 3 connection examples.

1.2 Ground fault values in isolated and arc-suppression-coil-ground systems

The following diagrams show the basic curve of the ground-fault currents in the event of a ground fault in the network. In isolated networks, the neutral point is free. If a ground fault occurs in a conductor, the fault location has a connection to ground. This shifts the phase-to-ground voltages and results in a current flow via the phase capacities of the 2 healthy conductors.

This scenario is displayed in Figure 1. The ground fault occurs in feeder A, line L1. The displacement voltage (U0) can be measured directly via the broken-delta winding or calculated from the phase-to-ground voltages. The zero-sequence current zero-sequence current (3I0) is measured as ground current in each feeder. The ground current measurement can be performed via Holmgreen connection (separate cores and return conductors) or core balance current transformer.

The resulting phasor parameters in the phasor diagram for the healthy feeder are displayed on the lower right. It shows not only the position of zero voltage but also that of zero-sequence current zero-sequence current. For the evaluation of the ground current direction, the phasor parameters for zero voltage and zero-sequence current zero-sequence current are displayed on the primary side for the 2 measuring points (feeders A and B).

The resulting phasor parameters in the phasor diagram for the healthy feeder are displayed on the lower right. The position of zero voltage as well as that of zero-sequence current zero is shown there. For the evaluation of the ground current direction, the phasor parameters for zero voltage and zero-sequence current zero-sequence current are displayed on the primary side for the 2 measuring points (feeders A and B).

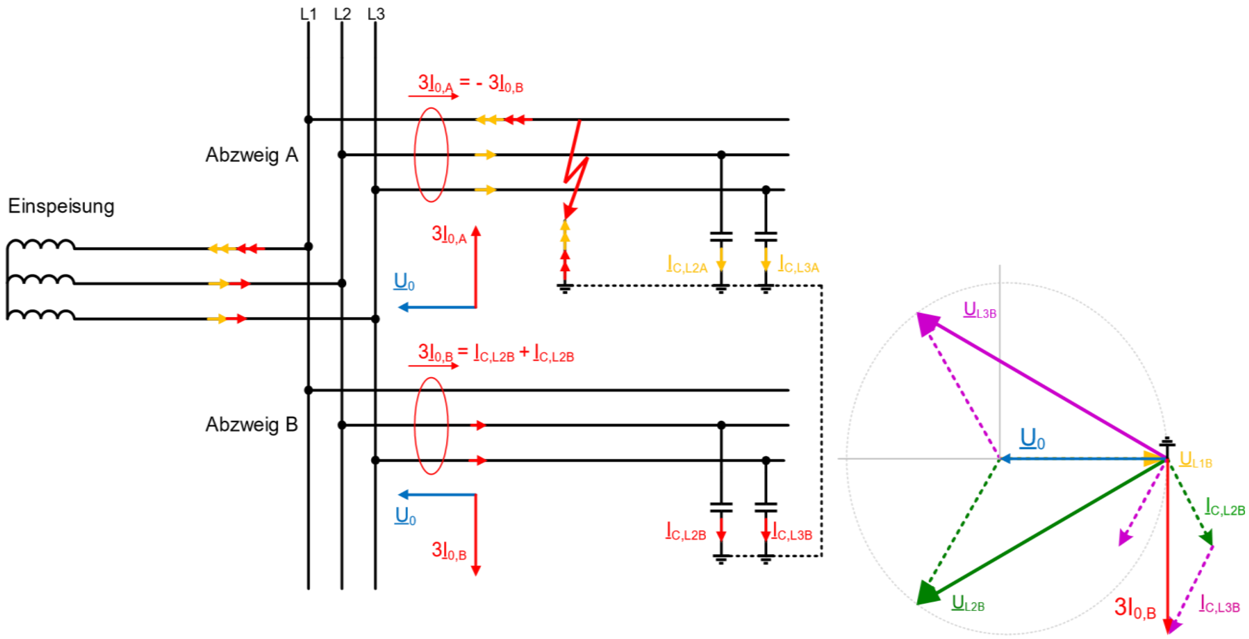


Figure 1: Measured variables for ground fault in an isolated network

Conclusions:

- The capacities of the faulty feeder lead to no measurable zero-sequence current zero-sequence current. This is canceled out at the measuring point (arrows in orange).
- The zero-sequence currents zero-sequence current of the healthy feeders determine the measurable zero-sequence current zero-sequence current in the faulty feeder (in the example, arrows in red).
- Between the healthy and faulty feeder, a phase angle rotation of 180° occurs in the zero-sequence current zero-sequence current.
- The reference system for determining direction is zero voltage. This results in the primary phasors illustrated above.
    - **Faulty feeder** $U_0 < 180°$, $3I_0 < +90°$
    - Healthy feeder $U_0 < 180°$, $3I_0 < -90°$

In compensated (resonant) systems, the capacitive ground fault current is practically canceled out at the error location. To achieve this, you switch an inductor (Arc-suppression coil) to ground. This can be done directly on the neutral point of the transformer's neutral winding, for example. Or you provide a separate neutral generator on the busbar. In case of a ground fault, the measured zero-sequence currents zero-sequence current change at the error location. The inductive current cancels the reactive current (compensates for it). Figure 2 shows the resulting measured variables. In the example, the Arc-suppression coil was configured with an additional residual watt-metric current increase in the transformer neutral point.
Displayed in green is the additional infeed resistive-inductive current I_Y in case of ground fault. The active current (residual watt-metric current) IR is also fed in to ensure reliable direction determination.

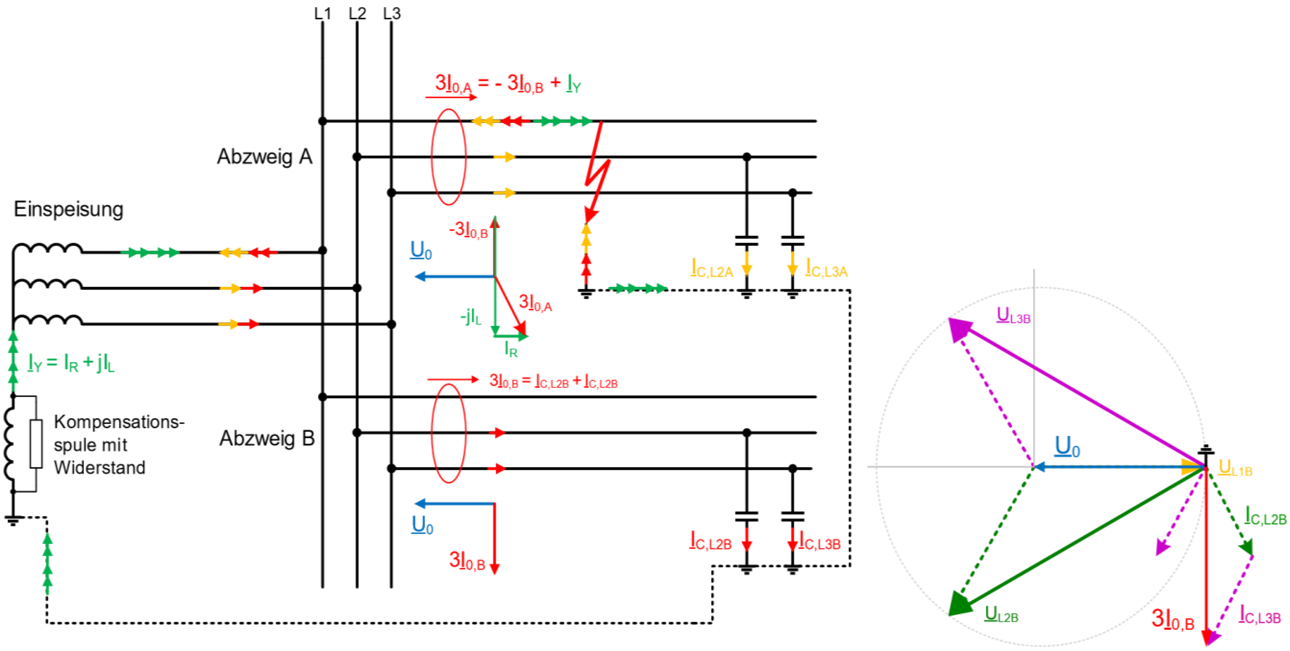


Figure 2: Measured variables for ground fault in compensated systems

Conclusions:

- At the error location, the inductive and reactive current compensate one another (see feeder A)
- On feeder A, there is an overlap of current $\underline{I}_Y$ and the reactive current of the healthy feeder ($-3\underline{I}_{0,B}$). This means that the ground current phasor $3\underline{I}_{0,A}$ is rotated compared to the illustration in the isolated system.
- On the healthy feeder, the phasor parameters do not change.
- The following picture results:
  - **Faulty feeder** $U_0 < 180°$, $3I_0 < -90°$
  - Healthy feeder $U_0 < 180°$, $3I_0 < -90°$

1.3 Determining ground fault direction (sin φ and cos φ methods)

To determine the ground fault direction, the secondary zero voltage and the secondary zero-sequence current are evaluated by the protection devices. The protection functions are defined with regard to the direction determination in such a way that the zero current measurement is related to the current input (I_N, I_{Ns}= SIP5 and I_E, I_{EE} = SIP4). Through the node definition (see chapter 3) a phase angle rotation of 180° ($-3\underline{I}_0$) takes place. Thus, zero currents in figure 1 and 2 rotate by 180° at the respective measuring point.

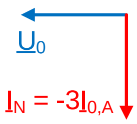
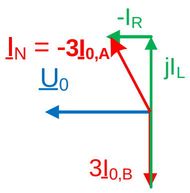
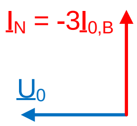
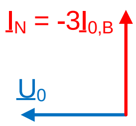
	Isoliertes Netz	Kompensiertes Netz
Abzweig A (Erdschluss)		
Abzweig B (fehlerfrei)		

Figure 3: Secondary phasors for zero voltage and zero-sequence current at the measuring point

For the insulated system, the phase angle difference between zero voltage and zero-sequence current is 90° under ideal conditions. The minor phase angle rotation due to the leakage losses was negligible. Due to the virtually 90° phase angle difference, the **sinφ** method is used (sin90° = 1). A limit line is in phase with zero voltage. If you take a minimum pickup current into account in addition, a tolerance band is the result.

For compensated systems, the **cos φ** method is applied. The zero voltage and the active share of the zero-sequence current are evaluated. For the faulty feeder, it is in phase with zero voltage (cos0° = 1). The limit line is now perpendicular to zero voltage. Here, you also need a certain band of tolerance. On the one hand, it is determined by the minimal pickup current and on the other hand, erroneous decisions caused by the angle fault of the current transformer are intended to be avoided. The angle error leads to a rotation of the secondary zero-sequence current phasor. The rotation occurs primarily mathematically positive and the zero-sequence current phasor in feeder B (Figure 3) turns towards the left. The protection installation calculates an active current that does not exist on the primary side.

Figure 4 shows the direction definitions (secondary side) in SIPROTEC protection devices. The agreement is that the "forward" direction points in direction of the faulty piece of equipment (wire, cable, motor, and generator). The zero voltage was placed into the real axis compared to Figure 3 (all phasors from Figure 3 are rotated by 180°). Moreover, the zero-sequence currents of feeders A and B were included into the drawing. The faulty Feeder A is defined as forward. The solid line describes the limit line. The dotted circle symbolizes that the protection function works above a certain minimum zero-sequence current and minimum zero voltage.

Due to the small effective currents in the cos φ method, the current setting is performed more sensitively. For the cos φ method, it is recommended to slightly tilt the directional characteristic due to the angle error in the zero-sequence current transformation. As already mentioned above, a rotation of the zero-sequence current phasor $3\underline{I}_{0,B}$ by a few degrees for this feeder can lead to a wrong determination of direction.

The respective setup parameters and setup recommendations can be found in the SIPROTEC manuals and are not discussed here.

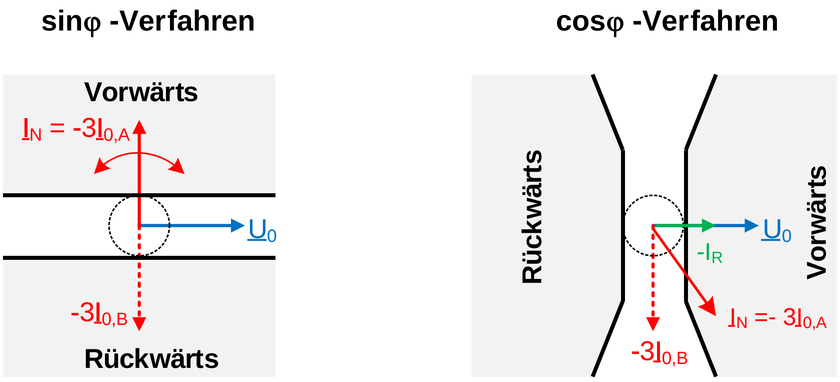


Figure 4: Direction definition and position of the limit line ($3\underline{I}_{0A}$ ground fault-prone feeder; $3\underline{I}_{0B}$ ground fault-free feeder)

Particularly for generator protection applications in busbar switching, it is customary to provide for a loading device. The generator is connected to an isolated system. By means of the loading device, an additional active current is fed in. As a result, the zero-sequence current phasor rotates in the direction of zero voltage. In this application, the limit line is adapted accordingly (rotation by - 45°). Figure 5 displays this application. It was assumed that in Figure 1 on Feeder A, a generator is connected and the loading device (grounding transformer with load impedance in the delta winding) is installed on the busbar.

Forward means that the ground fault is on the generator side. In this application, there is a shutdown and no notification as with system protection applications.

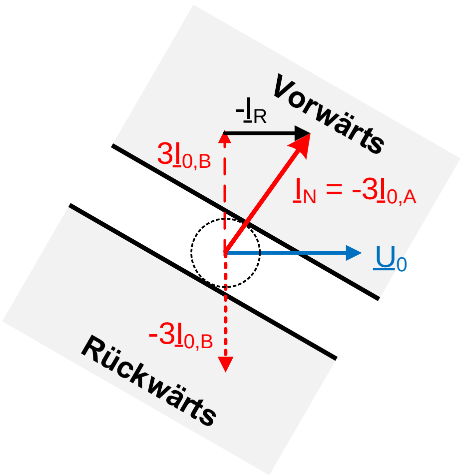


Figure 5: Rotation of the limit line for generator protection applications (I_R – current of the loading device)

1.4 Connection variants

SIPROTEC protection devices are based on the agreement that all currents to nodes are defined as positive. This definition has no influence on the wiring of the devices' internal current inputs. The following definitions apply:

$\underline{I}_{L1} + \underline{I}_{L2} * \underline{I}_{L3} + \underline{I}_{N} = 0$

$\underline{I}_{L1} + \underline{I}_{L2} * \underline{I}_{L3} = 3\underline{I}_{0}$

This means: $\mathbf{\underline{I}_{N} = -3\underline{I}_{0}}$

For the easiest form of ground current measurement, the return conductor I_N can be used. For the 4th current input (I4), the above definition leads to the connection according to Figure 6.

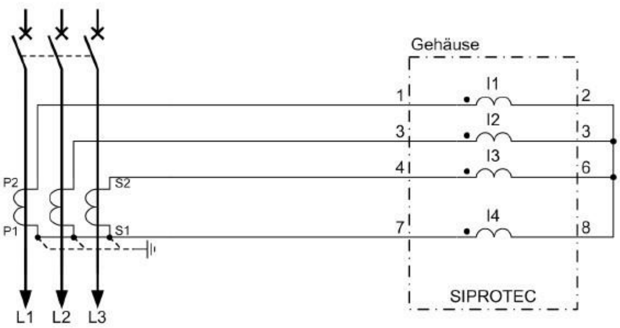


Figure 6: Ground current measurement by means of current in the return conductor
(Measurement method is also referred to as Holmgreen connection)

The dot depicted serves as direction orientation. In case the dot should be missing, it is still possible to remember the principle that the odd terminal designation corresponds to the dot. The terminal numbers depicted in Figure 6 correspond to the current measuring block of SIPROTEC 5.
If the ground current measurement is carried out via a core balance current transformer, the above node definition also applies and has influence on the wiring of I4 (see Figure 7). In this version, I4 is typically a sensitive current input.
An alternative application is the use of a separate converter core for zero-sequence current measurement. This connection is displayed in Figure 8.

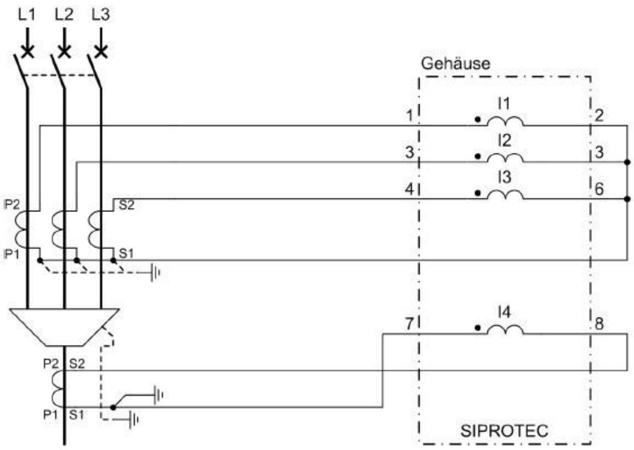


Figure 7: Ground current measurement by means of core balance current transformer

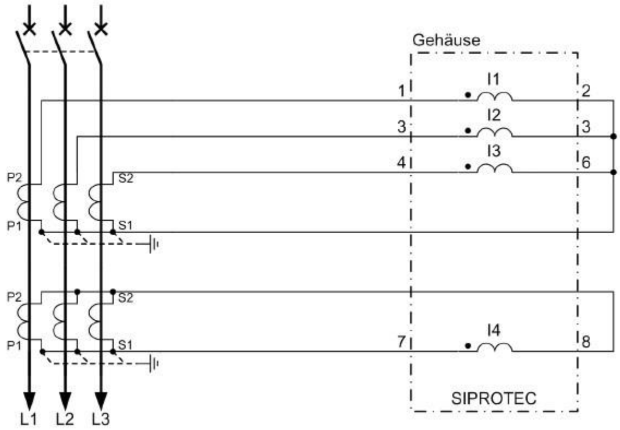


Figure 8: Ground current measurement by means of separate core in Holmgreen connection
(the 3 cores must be compensated in order to ensure a sensitive measurement)

In Figures 6 to 8, the neutral point of the 3-phase current transformer points in the direction of the "protected object ", this in our example is the faulty feeder. It can also occur, however, that the neutral point of the 3-phase current transformer points in the direction of the busbar. As the positive definition is in the direction of the protected object, internally the protection device rotates the currents by 180° for this connection (multiplication with -1 → carried out according to setup parameters for neutral point direction). As a result, the current input I4 is automatically rotated as well.

If the neutral point of the 3-phase current transformer points towards the busbar and if the ground CT
current transformer remains in the existing installation position in Figures 7 and 8, the connections to input I4 must be exchanged.

The zero voltage is directly measured on the broken-delta winding or calculated from the 3 phase-to-ground voltages. Figure 9 shows the connection in principle. The dot is intended for direction orientation (exceptions are possible, e.g. 7SJ82).

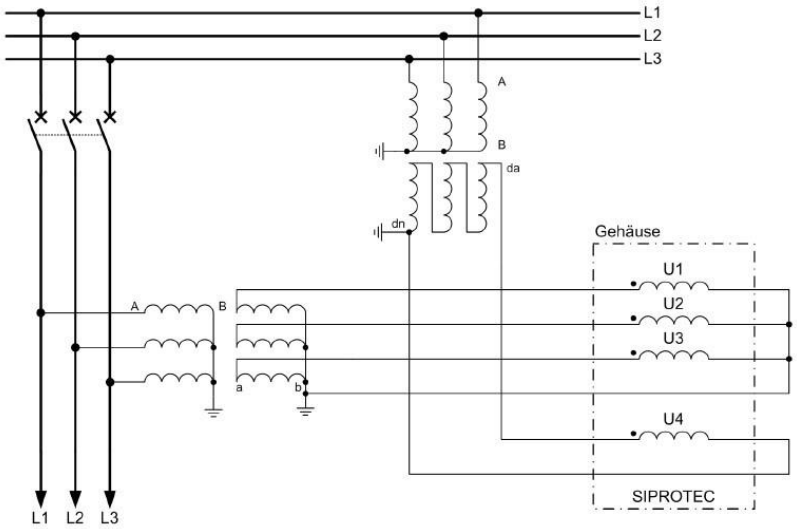


Figure 9: Detection of the zero voltage (Direct measurement via U4 or calculation from U1 to U3)

With the directional ground-fault detection, there is also a connection variant where the ground-current input is used, decoupled from the 3-phase current transformers. This means that its neutral point direction has no influence on the ground current detection. Based on the forward direction definition, the ground current direction of forward requires the connection according to Figure 10. This type of connection can be found in SIPROTEC 4 with 7UM6 as well as with SIPROTEC 5, if a 1-phase function group (voltage-current-1-phase) or on the 7UM85 the function group “Generator stator” (90% SES MS-1ph.) is used.

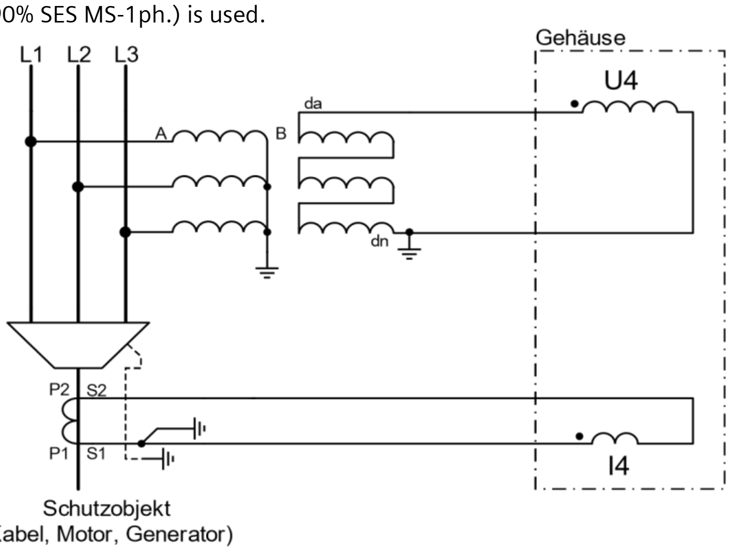


Figure 10: Connection with 1-phase measurement or 1-phase function group in SIPROTEC 5
(Dot corresponds again to an odd terminal number)

1.5 Testing of the ground fault direction

Based on the above remarks, in addition to the wiring, the protection setting also has an influence on the proper determination of direction. For this reason, testing of the system is an absolute necessity.

For a generation protection application, the generator itself is used for the primary testing. Relevant testing instructions are described in the manual of the 7UM85 under function testing stator ground-fault protection 90% in chapter 10.7.3. Busbar switching. That is why generator protection applications are not handled in greater detail at this time.

1.6 Evaluation of the primary converter

A prerequisite for the concrete direction determination is the proper installation as well as the wiring of the voltage and current transformers. Testing them is the first step. The section below looks at selected test items that are the prerequisite for a proper direction determination.

All tests are only allowed to be carried out by
electrically **qualified personnel and the electro technical safety rules have to be observed.**

a) Current transformer connection

- *Connection of primary current transformer according to Figure 6 (ground current measurement with return conductors)*
  For this type of connection, the phase sequence, and the position of the neutral point have to be checked.

- *Connection of primary current transformer according to Figure 7 (ground current measurement by means of core balance current transformer)*
  As the position of the neutral point of the 3-phase current transformer has an influence on the handling of ground current by the protection device, the correct installation, and connection has to be checked. For the core balance current transformer, the installation position (e.g. P1 or K pointing towards the protected object) has to be checked. Moreover, it is necessary to firmly seal both halves of the core balance current transformer and to lead the grounding line through the core balance current transformer (see Figure 11). The carrying iron for the sealing end must be insulated against the framework so that the ground current flows back via the grounding line. The proper installation (no gap between halves) has to be inspected by means of a 3-phase symmetrical current feed. The secondary current measured should be very low (e.g. < 2 mA when connecting a 3-phase cable). This value has to be checked again under full load.

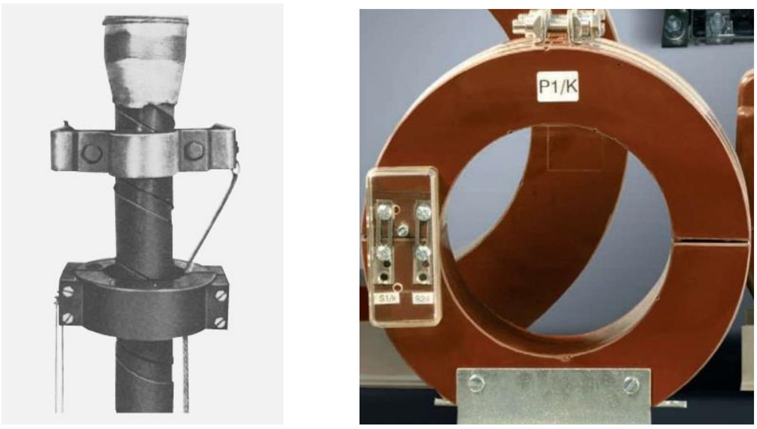


Figure 11: Connection of core balance current transformer, latest version (Ritz company)

- *Connection of primary current transformer according to Figure 8 (ground current measurement by means of separate core in Holmgreen connection)*
  The special feature of this type of connection is the ground current measurement via a separate core. Here as well, the position of the neutral point of the 3-phase current transformer has an influence on the ground current. The proper installation and connection of the converter cores has to be checked. In addition to the visual inspection, the infeed of a primary current provides the necessary certainty. A 1-phase check is sufficient, as the position of the current phasor has to be inspected.
  According to the converter connection and testing connection in Figure 12, the phase current and the zero-sequence current zero-sequence current must be in opposite phase (phase rotation 180°). Based on the transformation ratio, the amplitudes may vary. Due to the smaller transformation ratio, the measured zero-sequence current zero-sequence current will be larger.

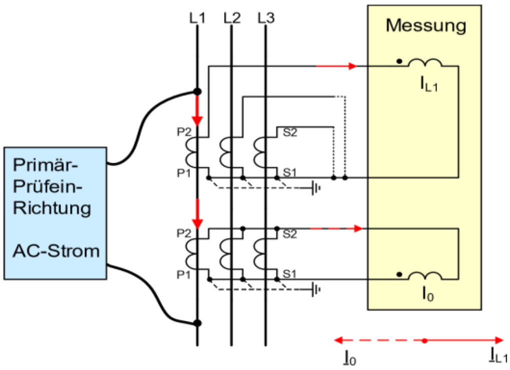


Figure 12: Primary inspection for ground current measurement by means of separate core in Holmgreen connection

b) Voltage transformer connection

- *Zero voltage measurement by means of broken-delta winding*
  Here the correct transformation ratio and the proper wiring of the broken delta connection have to be inspected. The "da" connection is the required voltage measuring input cable head for the protection device and the return conductor is "dn". As a reference parameter on the secondary side, at least one 1-phase phase-to-ground voltage is required. The optimal connection is made according to Figure 9.

- The primary inspection can be carried out with a 1-phase testing installation. This test connection is displayed in Figure 13. If the rated phase-to-ground voltage ($U_{LL}/\sqrt{3}$) is fed in as the test voltage, then the secondary rated voltage (typically 100 V) is measured on the broken delta connection. For smaller test voltages, conversion must be made according to the transformation ratio.

  To check the proper terminal connections, the phasor parameters are evaluated on the secondary side. As the infeed is co-phasal in all 3 phases, the phase-to-ground voltages and the voltage on the broken-delta winding must be in phase if installation and wiring have been carried out properly. In Figure 13, the voltage drops for line L1 are displayed. Voltages are transformed co-phasal via the voltage transformer.

- *Calculation of zero voltage from the phase-to-ground voltages*
  The primary test is identical to the above test according to Figure 13. Here, the broken delta connection is the reference parameter. As preparation, the wiring of the cables has to be checked to ensure the proper phase. To do so, the phase-to-ground voltage is fed in cyclically and the secondary voltage value is evaluated. In doing so, the transformation ratio is also checked at the same time.
  The calculated zero voltage is in phase with the phase-to-ground voltages and has the amplitude of a phase-to-ground voltage. Due to the leg conversion ($U_{prim}/\sqrt{3}$ / $U_{sec}/\sqrt{3}$ / $U_{sec}/3$), the voltage must be higher by a factor of $\sqrt{3}$ at the broken delta connection.

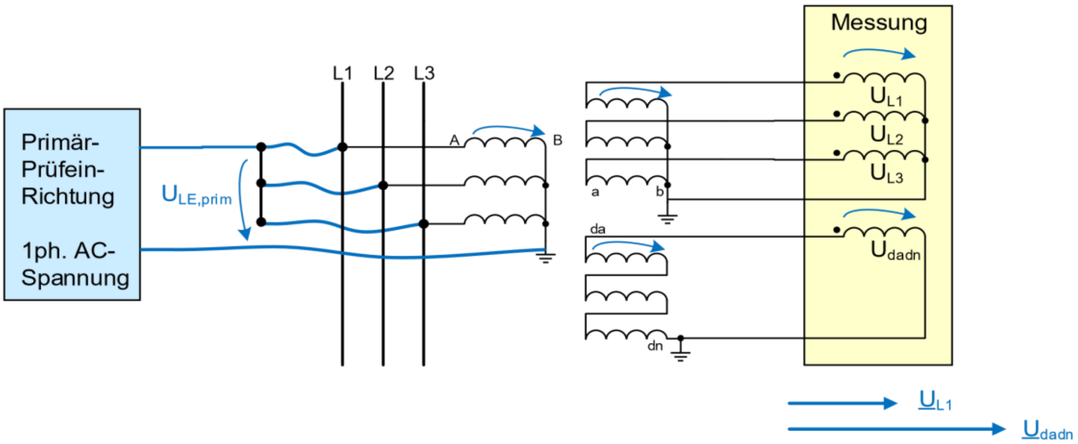


Figure 13: Testing of voltage transformer

1.7 Testing the ground fault direction protection

Below, the three connections with respect to ground current measurement are explained. The zero voltage can selectively be taken from the 3 phase-to-ground voltages or via the broken–delta winding. The testing parameters are fed in from the converter terminals. A ground fault is assumed in line L1 of the feeder to be tested. It is tested for forward direction. This means, the ground fault is in the direction of the protected object.

The direction of the ground-fault protection is set to “forward”. As a test result, the function must detect “forward”. In addition, the conduct for a ground-fault-free feeder should be evaluated. For an isolated system, "backwards" must be indicated. For compensated systems and assumed "ideal" conditions, the direction is indefinite (see Figure 4, cos φ, current $-3I_{0,B}$).

- **Ground current measurement via return conductor**
  This test connection, along with the test parameters, is shown in Figure 14. Table 1 shows the test parameters for the insulated and compensated system. For the compensated system, a pure active current (ideal conditions) is fed in.
  If "forward" is not recognized in the test, the test configuration, the infeed of testing parameters and the protection setting (in particular, the neutral point setting of the 3-phase current transformer) have to be checked. If the result continues to be negative, there is a wiring fault (presumably in the ground current connection).

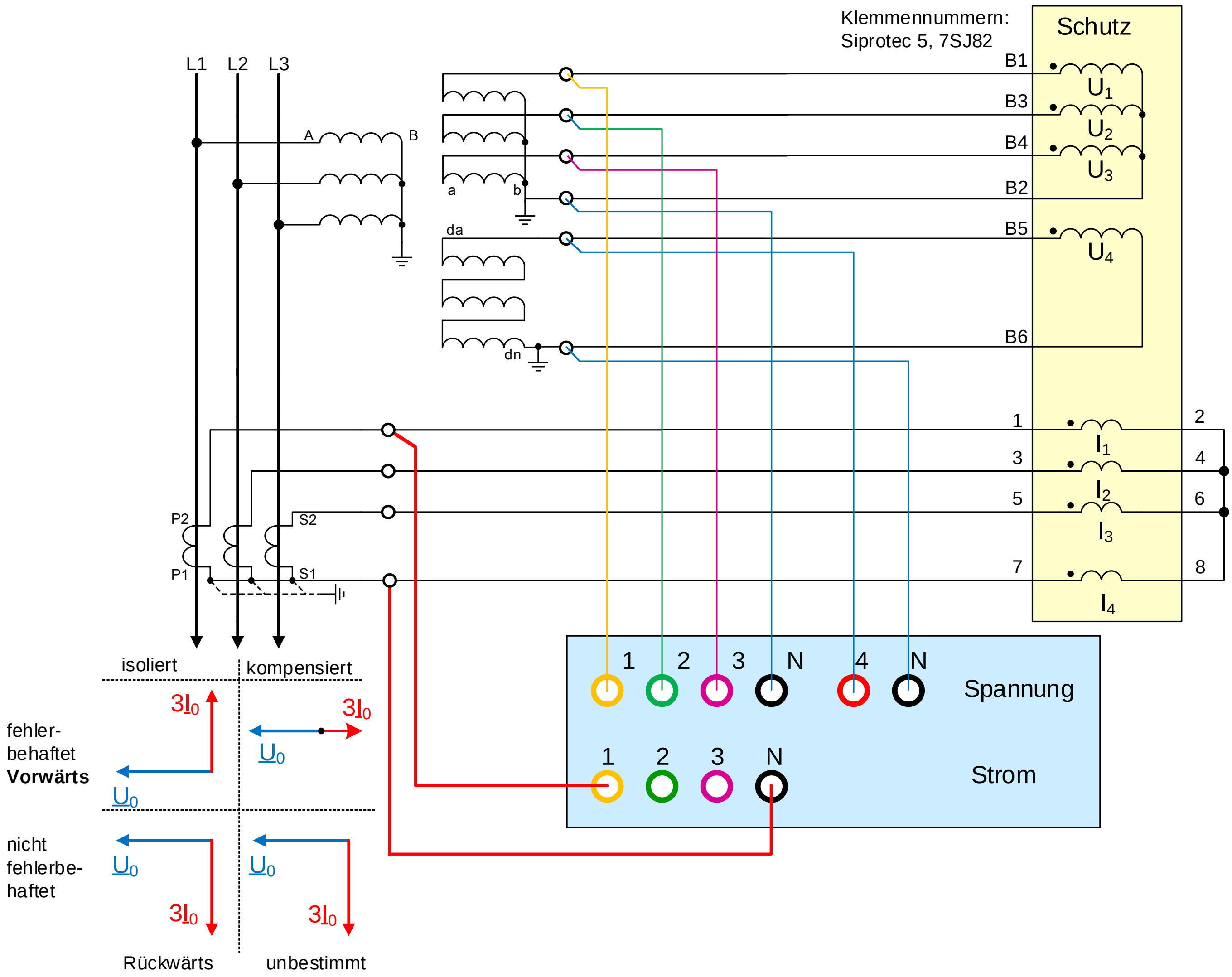


Figure 14: Test configuration, ground current measurement via return conductor

Table 1: Test parameters, secondary testing

	Isolated				Compensated			
	Forward		Reverse		Forward		not faulty	
$\underline{U}_{L1}$	0	0°	0	0°	0	0°	0	0°
$\underline{U}_{L2}$	100 V	-150°	100 V	-150°	100 V	-150°	100 V	-150°
$\underline{U}_{L2}$	100 V	+150°	100 V	+150°	100 V	+150°	100 V	+150°
$\underline{U}_{dadn}(U4)$	100 V	180°	100 V	180°	100 V	180°	100 V	180°
$\underline{I}_{L1}$ ($3\underline{I}_0$)	0.5 A	+90°	0.5 A	-90°	0.1 A	0°	0.5 A	-90°

- **Ground current measurement by means of core balance current transformer**
  This test connection, along with the test parameters, is displayed in Figure 15. For the core balance current transformer, the primary test is recommended. The ground current fed in has to be led through the core balance current transformer. The testing wire has to be led through the core balance current transformer in the direction of the protected object. A larger testing current can be achieved by looping it through several times. The primary testing current is the fed in current multiplied by the number of looped turns.

Table 2 shows the test parameters (assumption: 3 loops: primary current 3*2A =6A).

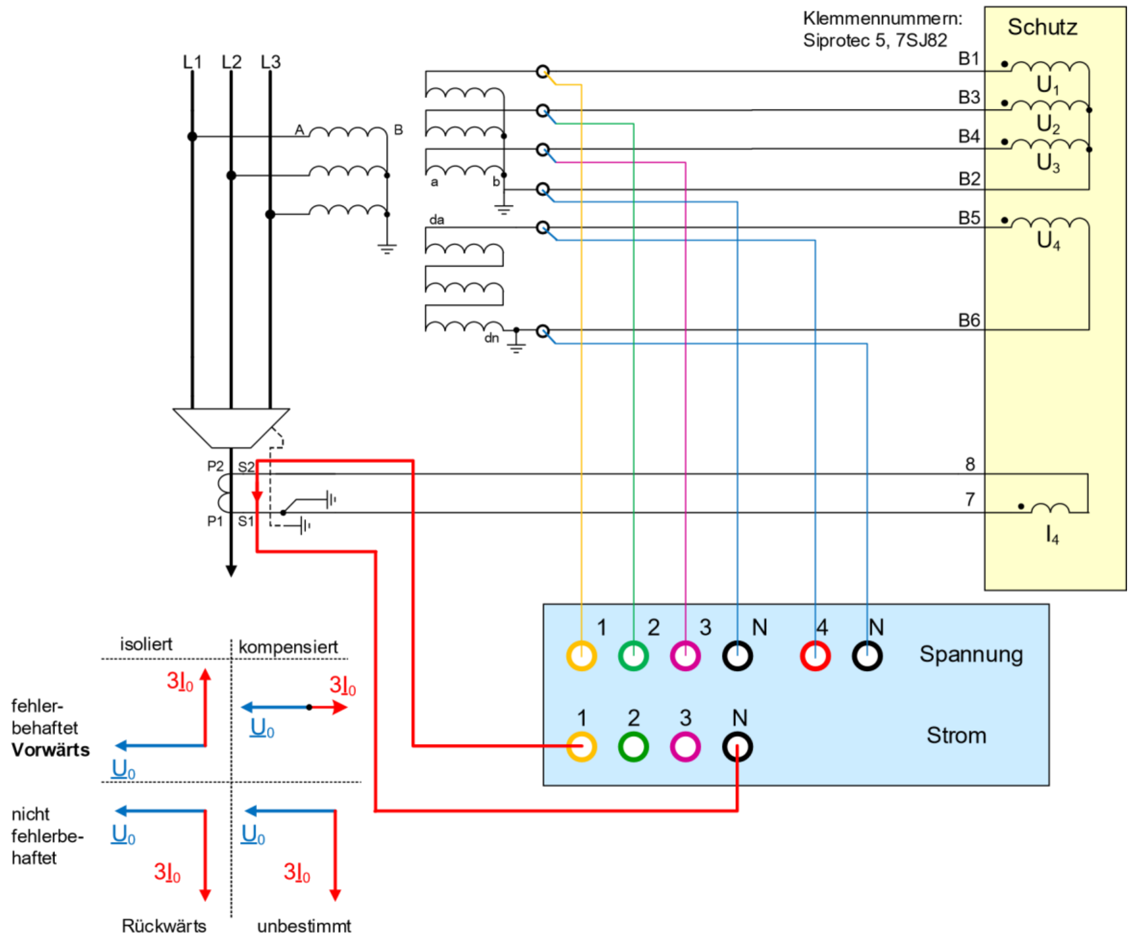


Figure 15: Test configuration, ground current measurement by means of core balance current transformer

Table 2: Test parameters, primary test (3 test loops through the core balance current transformer)

	Isolated				Compensated			
	Forward		Reverse		Forward		not faulty	
$\underline{U}_{L1}$	0	0°	0	0°	0	0°	0	0°
$\underline{U}_{L2}$	100 V	-150°	100 V	-150°	100 V	-150°	100 V	-150°
$\underline{U}_{L2}$	100 V	+150°	100 V	+150°	100 V	+150°	100 V	+150°
$\underline{U}_{dadn}(U4)$	100 V	180°	100 V	180°	100 V	180°	100 V	180°
$\underline{I}_{L1}$ ($3\underline{I}_0$)	2 A	+90°	2 A	-90°	1 A	0°	2 A	-90°

The test result can be documented with a fault record. The analysis is carried out with SIGRA. In the phasor diagram, the relevant parameters can be displayed. Figure 16 shows the test result of a cos φ measurement.

The calculated zero voltage $\underline{U}_0$ was set to the zero axis. The measured voltage $\underline{U}_{dadn}$ is in phase and √3 larger. The ground current (I_N) is in phase with zero voltage. According to the direction definition in Figure 4, the direction is forward. In addition, the phasors of the voltages $\underline{U}_{L2}$ and $\underline{U}_{L3}$ are displayed. They correspond to the phase-to-phase voltage.

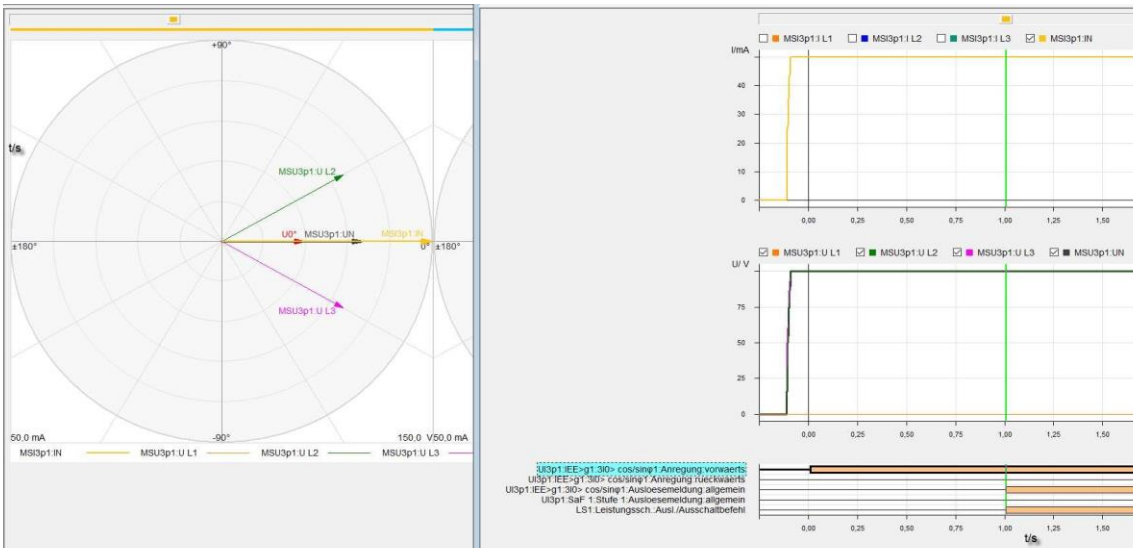


Figure 16: Test result documented in the fault record (compensated system = cos φ measurement)

- **Ground current measurement by means of separate core in Holmgreen connection**
  This test connection, along with the test parameters, is displayed in Figure 17. Secondary parameters are fed in and the test parameters from Table 1 are used.

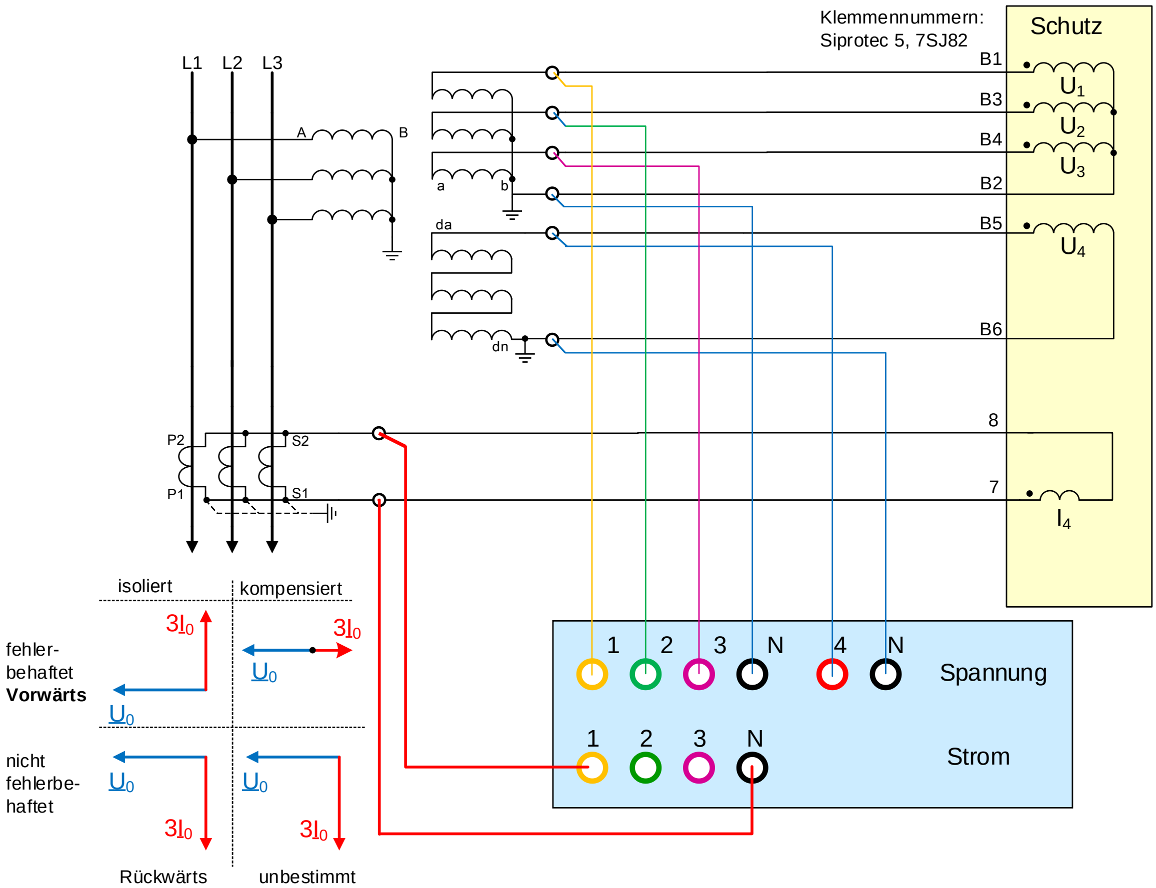


Figure 17: Test configuration, ground current measurement by means of separate core in Holmgreen connection

- **Test for pure 1-phase measurement**
  If the ground current is processed decoupled from the 3-phase current transformers and the displacement voltage is measured directly, the test is simplified. The displacement voltage and the ground current are fed in.
  The test is carried out on the system layout shown in Figure 10. Due to the use of a core balance current transformer, the test is recommended using primary current. This test connection is displayed in Figure 18. The test parameters can be obtained from Table 2 – the last 2 lines.
  In case "forward" is not detected in the forward test, there must be a wiring fault (presumably in the power connection).

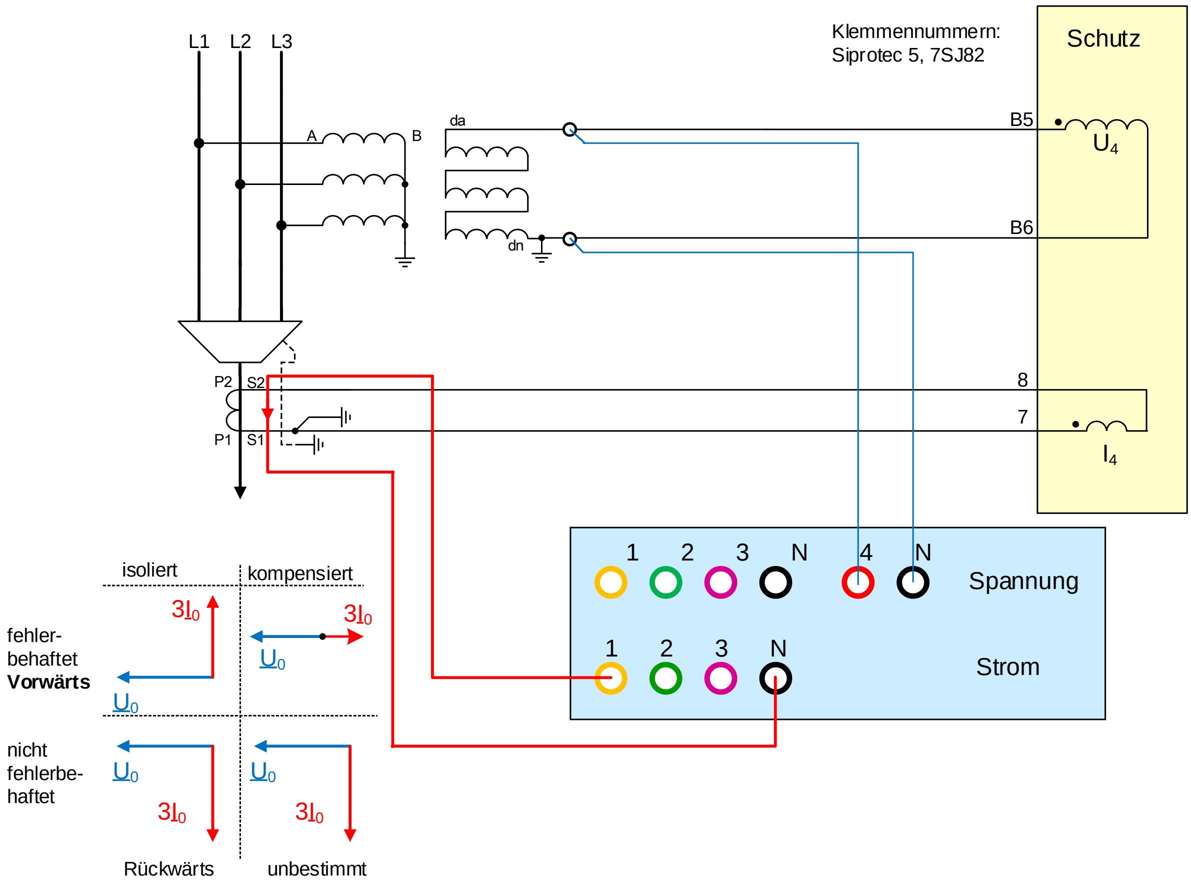


Figure 18: Test configuration, ground current measurement by means of core balance current transformer (1-phase test parameters)

1.8 Summary

This hands-on application paper – together with the basic description – provides a guideline for connecting and testing the directional ground fault function in isolated and compensated systems.

With examples, various switching variants are vividly explained, thus offering assistance for commissioning tests.

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