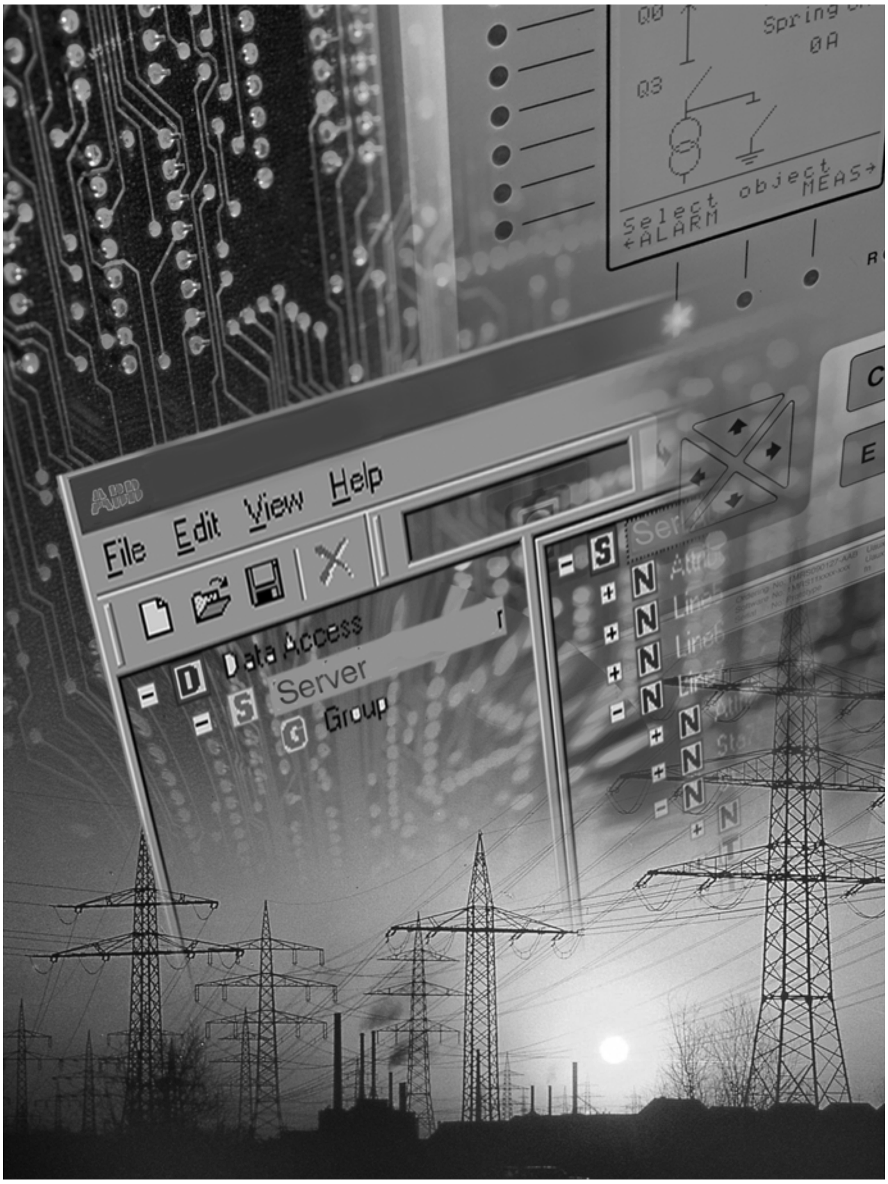
Distance Protection
REF 542*plus*

Application and Setting Guide



Contents:

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1. Scope

This document introduces the application of the distance protection function in the REF 542*plus* feeder terminal. The distance protection function is designed to provide selective power system feeder protection. The protection zone can be defined by applying line impedance and directional criteria. As a consequence, it enables fast and selective detection and isolation of faults in meshed medium voltage (MV) power systems.

The distance protection function can be implemented for MV power system protection regardless of the neutral earthing method used in the power system in question. It can be used in isolated neutral systems, in resonant earthed systems, i.e. systems where the neutral is earthed with an inductance (also known as arc suppression coil or Petersen coil) and in systems with low-resistance or reactance grounding.

The optimum operation time is about 30 to 35 milliseconds. This time setting shall be applied to avoid trip delays caused by possible saturation of current transformers (CTs). The distance protection features three impedance zones, each of which can be used either in the forward or backward direction. Additionally one directional and one non-directional backup zone are available. When auto-reclosing is used together with distance protection, the first impedance zone can be extended to handle faults on the entire length of the line.

The fault impedance is calculated by the distance protection. The value can be displayed and used to determine the fault location. Therefore the fault locator is an integral part of the distance protection function. Once the distance protection has provided a trip signal, the value of the fault impedance is displayed in ohms or in kilometers on the feeder terminal's HMI.

KEYWORDS: *feeder protection*, *selectivity*, *distance protection*, *backup protection*, *fault locator*

2. Introduction

The distance protection comprises the following ancillary functions:

- Fault detection start function
- Impedance calculation function
- Direction determination function with voltage memory
- Tripping logic

The purpose of the start function is to check the system for presence of system failures and to identify the type of fault that has occurred. The appropriate quantities to be measured for determining the impedance and the direction of the fault are selected on the basis of the type of system fault. Once the direction and the zone of a system fault have been determined, the tripping logic determines the trip time from the set impedance time characteristic.

A unit-type signal comparison protection scheme, which enables very short lines to be protected selectively, is also integrated in the distance protection. The comparison protection scheme requires a pilot wire link to be available for signal exchange between the distance protection units at both ends of the line.

To limit and repair possible damage, and to restore network operation, it is important to localize and isolate a fault as soon as possible. Because medium voltage networks usually cover wide areas, fault-location information expressed in kilometres or ohms reactive value is desired. The fault locator implemented in the distance protection is capable of determining the distance to the fault spot from the measured fault impedance, by calculating, based on the known nominal value of the cable reactance, the distance in kilometres to the fault spot.

Note
To assure the proper function of the distance protection the current transformers have to fulfil the requirements described in Section 4.2. Checking of CT requirements. Otherwise the correct function cannot be guaranteed. Besides, the fault locator would not either be able to calculate the correct value of the fault impedance.

Once a system fault has been detected and isolated, the system operator should be able to analyze the fault from data captured by a disturbance recorder and the sequence of appearance of the signalling events. Therefore, the use of the fault recorder function block in REF 542*plus* is to be recommended. The fault recorder function can be started either by an external control signal (via a binary input) or an internal signal obtained from the distance protection. Either the general start or the general trip signal can be used for starting the fault recorder. However, the fault reactance can only be calculated correctly, if the fault is located in the first impedance zone. Therefore, the fault recorder is preferably started with the trip signal of the protection. .

The distance protection measures the phase currents and phase voltages. Consequently, a measurement supervision scheme is needed to monitor the condition of the currents and the voltages measured.

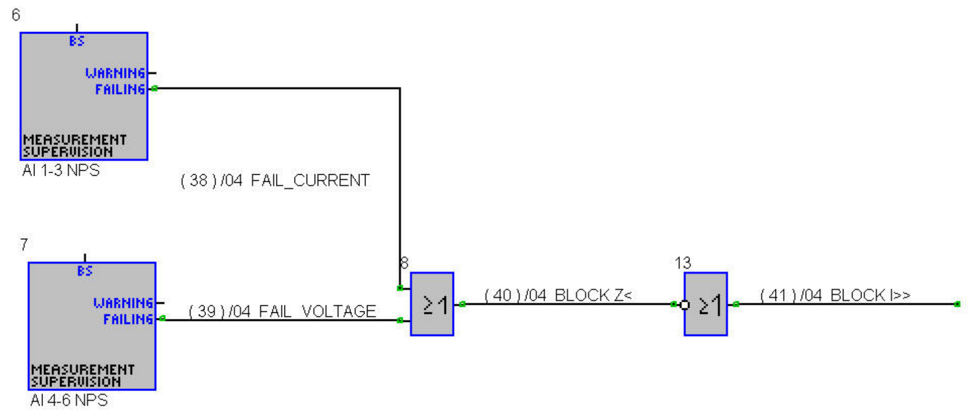

Fig. 2.-1 Supervision of currents and voltages measured

Fig. 2.-1 shows the measurement supervision scheme of the FUPLA (FUnction plan Programming LAnguage). Both the currents connected to the analog input channels 1 to 3, and the voltages connected to the analog input channels 4 to 6, are supervised through continuous calculation of the negative phase sequence. Should, for example, a fuse failure occur, the supervision of the negative phase sequence voltage will start. When the delay time, which is normally to be set in the range of 5 to 10 s, has expired, a high signal to block the distance protection will be generated. At the same time the blocking of the overcurrent protection is deactivated and the overcurrent protection can assume the function of local emergency back-up protection.

When the VT returns to normal condition, the blocking of the distance protection will be deactivated, i.e. the distance protection returns to normal operation and, consequently, the overcurrent protection operating as emergency back-up protection will no longer be necessary. For this reason, a feeder protection scheme shall comprise a combined distance protection and overcurrent protection.

3. Technical implementation

The ancillary functions implemented in the distance protection realization of the REF 542*plus* will be described in the following sections.

3.1. Start function

The purpose of the start function of the distance protection is to detect system faults selectively and check that the distance protection operates properly in MV systems regardless of the system grounding method chosen. Hence, the system neutral can be connected to earth via a high-ohmic or low-ohmic resistor. In this context high-resistance grounding implies that the power system is operated with isolated neutral or the system is provided with a Petersen coil to compensate for the capacitive generation of earth-fault current. Low-resistance grounding means that the electrical power system is connected to earth through a resistor or reactor for limiting the fault current to about 1.5 kA during an earth fault.

Moreover, the start function must be capable of detecting system faults under varying short-circuit power conditions. During high-load operation conditions, the short-circuit power may be much higher than during low-load conditions. In some installation locations, the high-load current might even be greater than the low short-circuit current.

To ensure the proper function of the distance protection under any system fault condition, the start function includes an undervoltage-controlled overcurrent start element in addition to the overcurrent start element, as follows:

- Overcurrent I> starting element, OR
- Earth-fault current IN> starting element, OR
- Undervoltage UF< controlled overcurrent IF> starting element

The overcurrent I> starting element is used to monitor the line current level. Fig. 3.1.-1 shows the corresponding signal processing diagram.

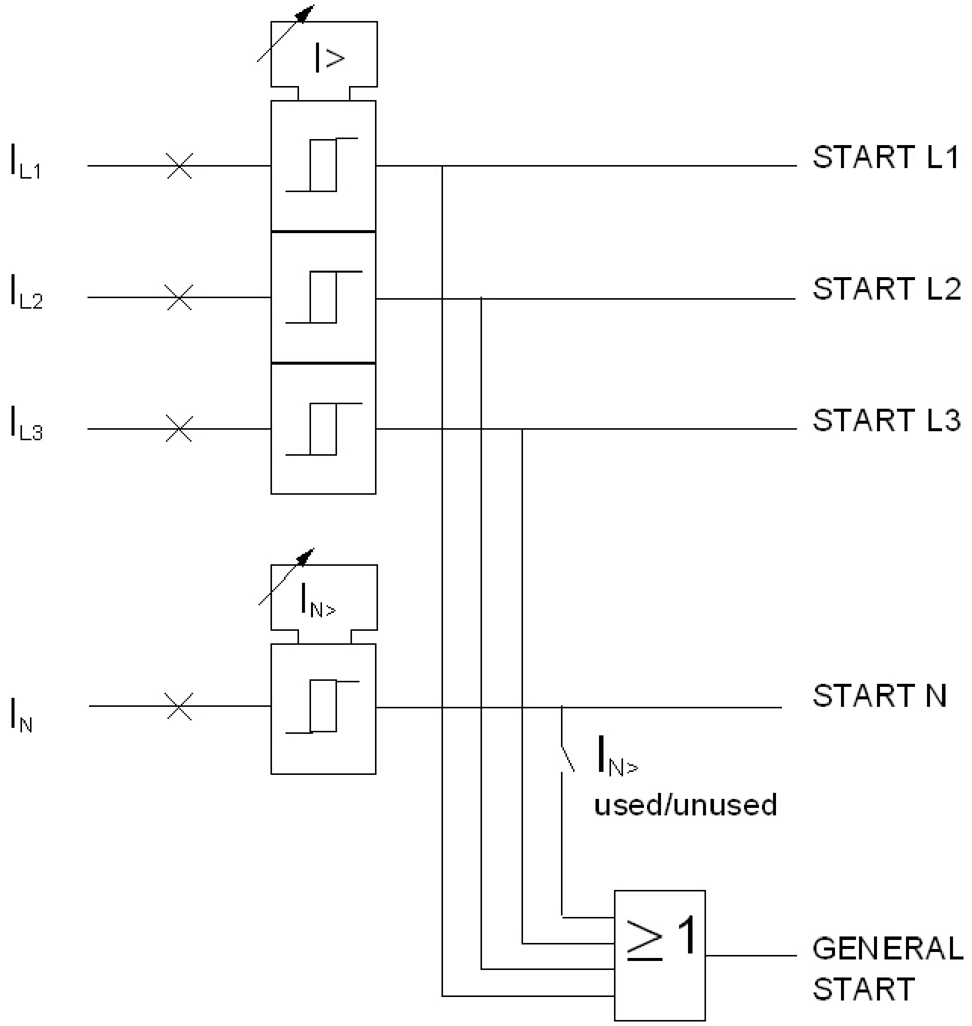

Fig. 3.1.-1 Logic diagram of the overcurrent and earth-fault start element

If an overcurrent threshold setting value is exceeded, a corresponding signal, i.e. Start L1, Start L2 or Start L3 indicating overcurrent on the related phase will be generated. The Start N signal is derived from the residual current calculated from the sum of the phase currents. The General Start signal is generated by the OR gate from all start signals, or optionally, by using the Start N signal.

The undervoltage-controlled overcurrent starting element is defined by the logical combination of the current threshold value IF> and the setting value of the undervoltage UF<, as shown in Fig. 3.1.-2. Hereby, the related phase or line voltages must be below the undervoltage UF< setting value and the corresponding phase current must be below the current threshold value IF>.

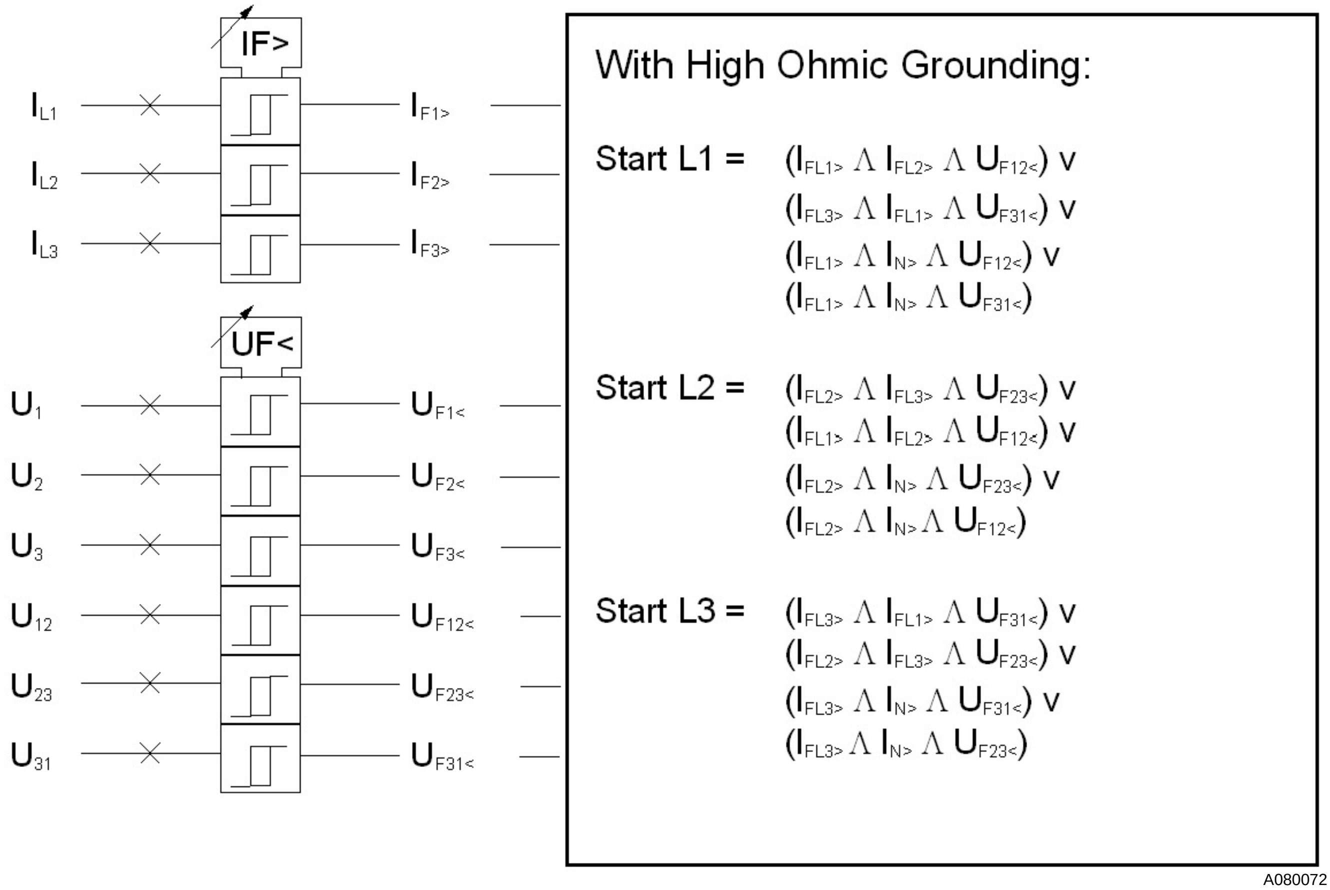

Fig. 3.1.-2 Undervoltage-controlled overcurrent starting element for application in high-resistance grounded power systems.

The start signals for two-phase or three-phase faults are derived from the combination of the concerned two-phase currents and the corresponding line voltage. If the current threshold value IF> is exceeded on two phases and the undervoltage condition of the corresponding line voltage is true, a start signal will appear. As an example, the generation of the overcurrent start signal for phase L1 is shown in the following equation (1):

$$
\begin{aligned}
\text{START L1} = \;& (\text{IFL1>} \;\Lambda\; \text{IFL2>} \;\Lambda\; \text{UF12<})\; V \\
& (\text{IFL3>} \;\Lambda\; \text{IFL1>} \;\Lambda\; \text{UF31<})\; V \\
& (\text{IFL1>} \;\Lambda\; \text{IN>} \;\Lambda\; \text{UF12<})\; V \\
& (\text{IFL1>} \;\Lambda\; \text{IN>} \;\Lambda\; \text{UF31<})
\end{aligned}
\tag{1}
$$

V: ORGate

Λ: AND Gate

The first two lines of the above equation are used to detect a system fault between two phases. Both the currents on phase L1 and L2 and on phase L3 and L1 are combined with their related line voltages U12 and U31. The next two lines are dedicated to cross-country faults involving two earth faults located on different phases and in different geographical locations. While line 3 of the equation is applied to check for cross-country faults on phases 1 and 2, line 4 is used for detecting cross-country faults on phases 3 and 1. A precondition is that a residual overcurrent IN> condition is prevailing during the cross-country fault. The logical scheme of the start element for the other two phases can be derived similarly, as shown below:

$$
\begin{aligned}
\text{START L2} = \; & (\text{IFL2>} \wedge \text{IFL3>} \wedge \text{UF23<}) \vee \\
& (\text{IFL1>} \wedge \text{IFL2>} \wedge \text{UF12<}) \vee \\
& (\text{IFL2>} \wedge \text{IN>} \wedge \text{UF23<}) \vee \\
& (\text{IFL2>} \wedge \text{IN>} \wedge \text{UF12<})
\end{aligned} \tag{2}
$$

$$
\begin{aligned}
\text{START L3} = \; & (\text{IFL3>} \wedge \text{IFL1>} \wedge \text{UF31<}) \vee \\
& (\text{IFL2>} \wedge \text{IFL3>} \wedge \text{UF23<}) \vee \\
& (\text{IFL3>} \wedge \text{IN>} \wedge \text{UF31<}) \vee \\
& (\text{IFL3>} \wedge \text{IN>} \wedge \text{UF23<})
\end{aligned} \tag{3}
$$

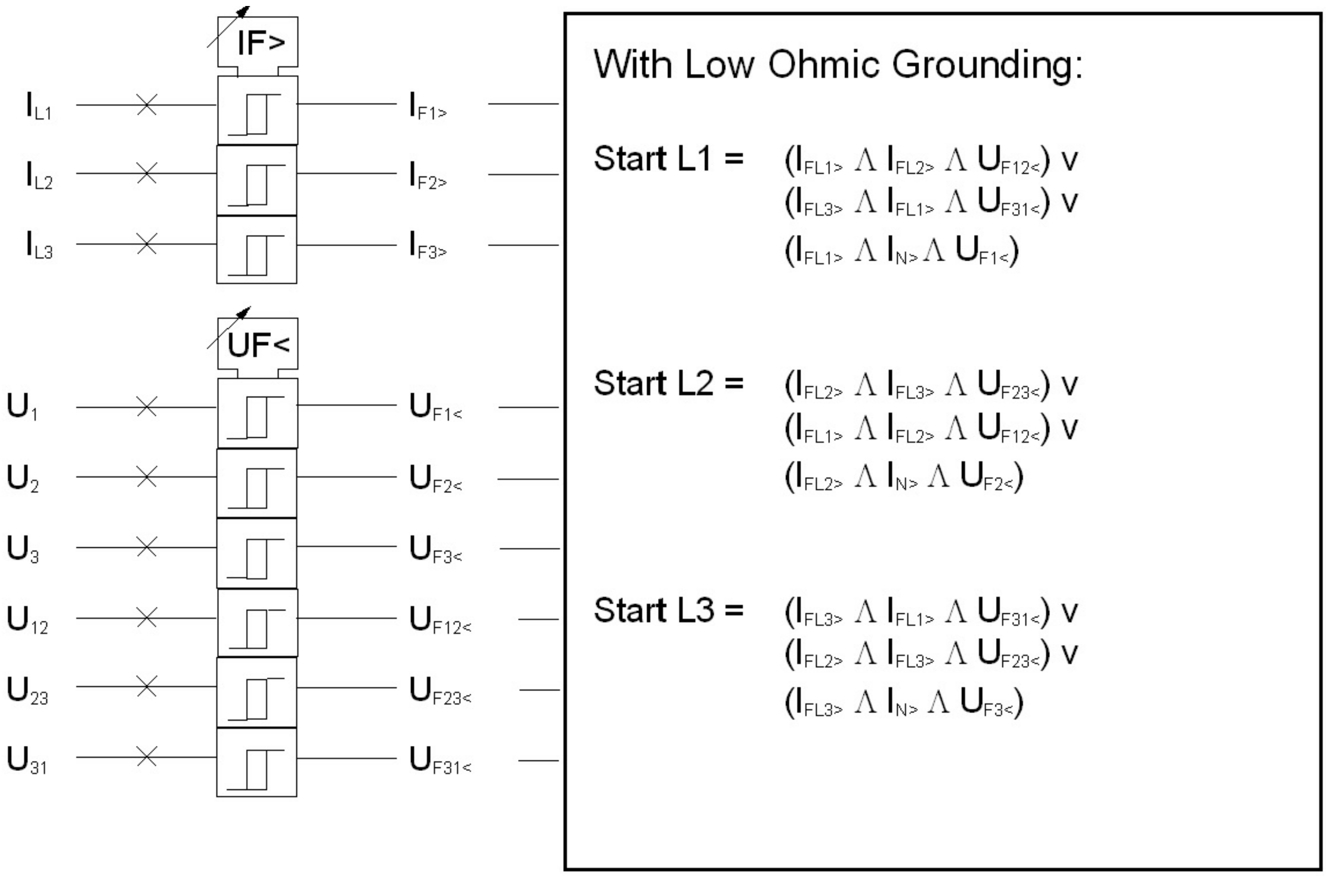

Fig. 3.1.-3 Undervoltage-controlled overcurrent starting for application in low-resistance grounded power system

The detection of 2-phase faults and 3-phase faults in a system with low-resistance earthing functions in the same way as shown in Fig. 3.1.-3. Because an earth fault must be isolated rapidly, it is not necessary to detect cross-country faults separately as in a system with high-resistance grounding. The signal of the residual current is logically combined with the signals of the phase voltages under consideration of the residual current condition. The equations for fault detection are as follows:

$$\begin{aligned} \text{START L1} = \; & (IFL1> \wedge IFL2> \wedge UF12<) \vee \\ & (IFL3> \wedge IFL1> \wedge UF31<) \vee \\ & (IFL1> \wedge IN> \wedge UF1<) \end{aligned} \tag{4}$$

$$\begin{aligned} \text{START L2} = \; & (\text{IFL2}> \wedge \text{IFL3}> \wedge \text{UF23}<) \vee \\ & (\text{IFL1}> \wedge \text{IFL2}> \wedge \text{UF12}<) \vee \\ & (\text{IFL2}> \wedge \text{IN}> \wedge \text{UF2}<) \end{aligned} \tag{5}$$

$$\begin{aligned} \text{START L3} = \; & (\text{IFL3}> \wedge \text{IFL1}> \wedge \text{UF31}<) \vee \\ & (\text{IFL2}> \wedge \text{IFL3}> \wedge \text{UF23}<) \vee \\ & (\text{IFL3}> \wedge \text{IN}> \wedge \text{UF3}<) \end{aligned} \tag{6}$$

3.2. Phase selection

An isolated neutral or resonant earthed neutral MV system can be operated with a prevailing earth-fault. Since an earth fault does not necessarily lead to immediate disconnection of the faulty line sections, this grounding concept is preferred by most utilities in the German speaking countries. However, if the earth fault develops into a cross-country fault, one of the two faulty line sections has to be disconnected selectively.

To coordinate the disconnection of the concerned line section, an appropriate logic for the phase selection has to be incorporated into the distance protection function. This logic enables the distance protection to disconnect the concerned line section accordingly. The following phase selection setting is provided:

Normal acycle:	L3 before L1 before L2
Normal cycle:	L1 before L2 before L3 before L1
Inverse acyle:	L1 before L3 before L2
Inverse cycle:	L1 before L3 before L2 before L1

If, in a cross-country fault involving two earth faults L3-N and L1-N, the normal acyclic setting L3 before L1 before L2 is selected, the line section with the earth fault L3-N will be disconnected. The earth fault L1-N will still remain until disconnected by the power system control centre after reconfiguration of the MV power system.

Note
To enable disconnection of one specific line section in a cross-country fault, the distance protection systems of the entire MV power system must be configured with the same phase selection.

3.3. Calculation of the impedance

Once the starting element has detected the fault properly, the fault impedance can be calculated. The fault impedance is calculated by applying the discrete Fourier transformation (DFT) algorithm. The DFT algorithm is applied to filter out transient type disturbance and high orders of harmonics. The DFT algorithm allows the disturbance to be effectively eliminated and the fault impedance to be calculated with sufficient accuracy.

The following equation (7) is used to calculate the fault impedance in the case of a fault between two specific phases with no ground connection. The equation is used both for 2-phase faults and for 3-phase faults. Because there is no earth fault, no residual current will be involved.

$$\underline{Z}_{LL} = \frac{\underline{U}_{LL}}{\underline{I}_{LL}} \tag{7}$$

$\underline{Z}_{LL}$ is the impedance of the fault between the two phases to be determined. $\underline{U}_{LL}$ and $\underline{I}_{LL}$ are the corresponding line voltage and the calculated line current variable.

In the case of an earth fault or a two-phase-to-ground fault, the following equation (8) is used:

$$\underline{Z}_{LL} = \frac{\underline{U}_{LE}}{\underline{I}_{L} + \underline{k} \cdot \underline{I}_{N}} \tag{8}$$

$\underline{Z}_{LE}$ is the fault impedance to be determined. $\underline{U}_{LE}$ and $\underline{I}_{L}$ are the corresponding voltage or current measurement quantities of the relevant phase and $\underline{I}_{N}$ is the neutral current or the residual current obtained from the sum of all phase currents.

$$\underline{I}_{N} = \underline{I}_{L1} + \underline{I}_{L2} + \underline{I}_{L3} \tag{9}$$

However, to be able to finally calculate the impedance, the residual current must be corrected with the so called earth factor $\underline{k}$ as follows:

$$\underline{k} = \frac{1}{3} \cdot \left(\frac{\underline{Z}_{O}}{\underline{Z}_{L}} - 1\right) = \frac{1}{3} \cdot \left(\frac{\underline{Z}_{O} - \underline{Z}_{L}}{\underline{Z}_{L}}\right) \tag{10}$$

In this case $\underline{Z}_{0}$ is the impedance of the zero-sequence component and $\underline{Z}_{L}$ is the impedance of the positive-sequence component. The positive-sequence, negative-sequence and zero-sequence components are defined according to the method of symmetrical components.

To handle all types of fault correctly, six impedance loops must be calculated, that is, three for faults between phases and three for faults between phase and earth.

Because of various influencing quantities the fault impedance may deviate from the theoretical impedance value of the line unit. A typical example is an arcing fault, where the fault impedance is superposed with the non-linear arc resistance. To ensure tripping by the distance protection, a trip zone has to be defined. In general, distance protection relays of today have a polygonal tripping characteristic. If the calculated fault impedance falls within the polygonal trip zone, a trip command will be issued. Figure 3.3-1 below shows the polygon tripping characteristic of the distance protection function in REF 542*plus*.

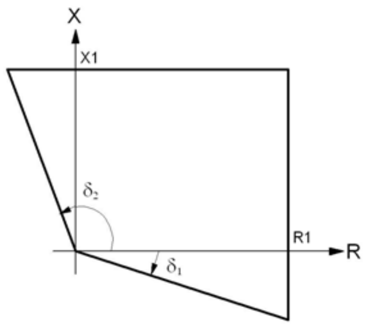

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Fig. 3.3.-1 Tripping characteristic for the distance protection

The first quadrant of the tripping characteristic is defined by the horizontal R-axis and the vertical X-axis. The reactance setting X1 defines the value of the horizontal limit and the resistance setting R1 for the vertical limit of the polygonal characteristic. The tripping area is finally closed by another two lines in the second and the fourth quadrants. The variable angle rotation for the line is δ_2 in the second quadrant and δ_1 in the fourth quadrant.

3.4. Direction detection with voltage memory

The direction toward a fault spot is normally derived from the result of the fault impedance calculation. The voltage related to the fault is used to determine the direction. However, if the fault occurs in the close-up area, where the VT or the voltage sensors are installed, the determination of the direction to the fault spot can be affected negatively by the low level of voltage. For this reason a voltage memory is always used to enable the determination of the direction at close-up faults.

The voltage memory will be activated if the voltage measured drops below about 10% of the rated voltage *U*n. All voltages (phase and line voltages) measured prior to the fault are saved in the voltage memory. At close-up faults, where the voltage drops close to zero, the memorized voltage measured before the fault is used for the determination of the direction. The memory function enables the function block to operate up to 300 seconds after a total loss of voltage. The prevailing voltage is applied again as soon as it exceeds 10% *U*n for at least 100 ms. The memorized voltage is also discarded if the measured voltage stays below 0.1 x Un for more than 300 seconds.

Note
When a fault occurs, a phase displacement with an angle of approximately up to 30° between the corresponding phase voltages before and after the fault occurrence may take place. This may happen, for example, when the fault situation develops into a cross-country fault. This fact should be taken into account when the directional characteristic is to be set too close to the tripping area of the distance protection.

The tripping characteristic should be set as follows to obtain a permanent optimal determination of the direction:

In the 2nd quadrant:

$$\delta_2 = 90° + 30° = 120°$$

and the 4th quadrant:

$$\delta_1 = 0° - 30° = -30°$$

3.5. Tripping logic

The tripping logic is generated by fault impedance calculation and direction determination, in logical combination with the impedance time characteristics. In total, the protection comprises three impedance zones, one directional zone, and one non-directional zone, including the corresponding five timer functions.

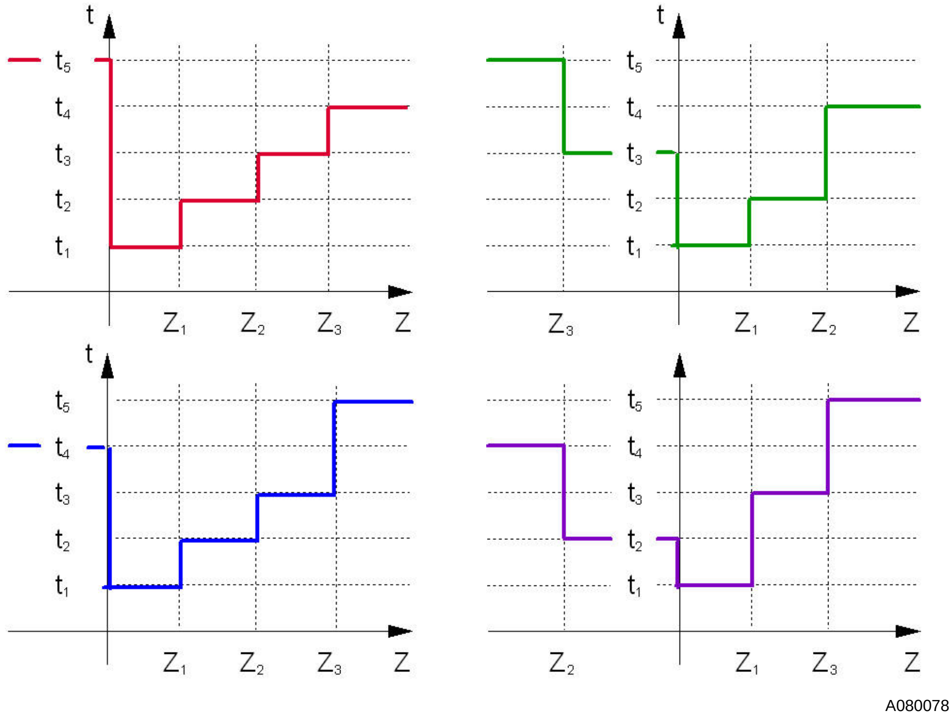


Fig. 3.5.-1 Impedance-time characteristics

As shown in Fig. 3.5.-1, every impedance zone and the directional zone can be directed either forwards or backwards. The timer functions are assigned as follows:

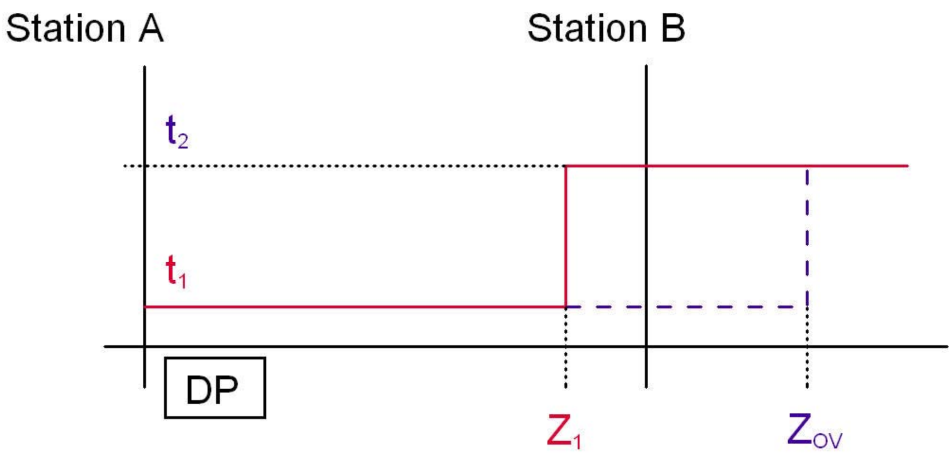
- Time t1 to impedance zone Z1,
- Time t2 to impedance zone Z2,
- Time t3 to impedance zone Z3,
- Time t4 to the directional zone as directional backup zone and
- Time t5 to the non-directional backup zone.

Every single zone can be activated or deactivated. The impedance zone characteristics to be selected depend on the network topology and the coordination of the protection scheme of the system.

Further, the tripping logic provides an interface to the auto-reclose (AR) function block, to the signal comparison scheme and to the switching-onto-fault scheme. For this reason, the function of the first impedance zone Z_1 is superposed by two other special zones, the "overreach zone" and the auto-reclose blocking zone. The corresponding setting parameters must be adapted accordingly.

3.6. Adaptation to auto-reclose function

Fig. 3.6.-1 illustrates the principle of the impedance-time diagram in conjunction with the auto-reclose function. The line to be protected interconnects stations A and B. The distance protection (DP) of station A includes auto-reclose functions, and its impedance-time diagram is shown in Fig. 3.6.-1.



DP	Distance Protection
Z_1	First impedance zone
Z_{OV}	Overreach zone

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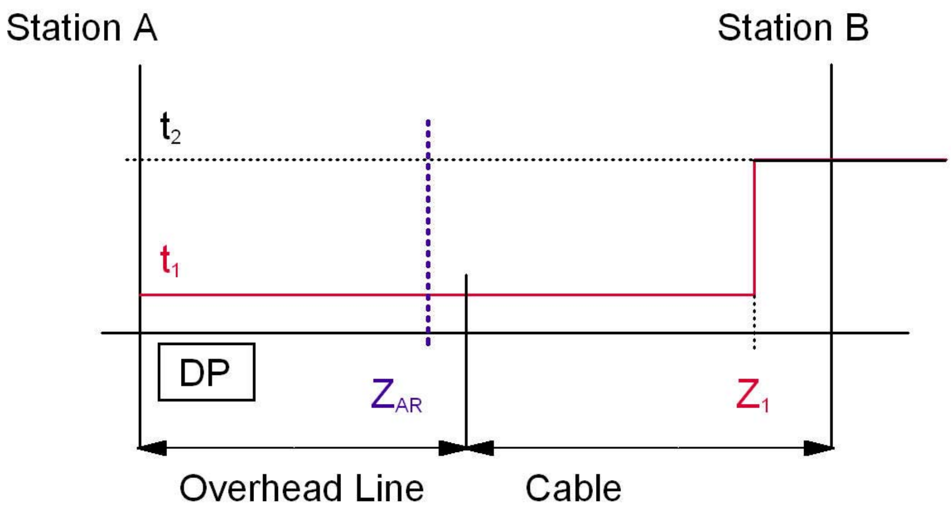
Fig. 3.6.-1 Zone characteristics for auto-reclosing on an overhead line

In an overhead line MV system the overreach zone Z_{OV} is generally set in the range between 120 and 150% of the line impedance in order to cover the whole length of the line and a small part of the line behind station B. In this case, the timer shall be given the same setting as t1 of the first impedance zone Z_1.

When cooperating with the distance protection function, the auto-reclose (AR) function shall preferably be set in the Start and Trip controlled mode. If a general start signal is received, the specified time of the AR function will start. In consequence, the specified time of the AR function must be longer than the time t_{ov} of the overreach zone. If the operation time of the distance protection is longer than the specified time, the AR function will be stopped. Only for tripping within this specified time, the AR function is able to continue circuit breaker (CB) re-closing.

Once the specified time has expired, the overreach zone Z_{OV} will be deactivated again. If the system fault still persists, it will be handled by the protection scheme of the system in accordance with the set time coordination.

In the case of a mixed line comprising both cable and overhead lines the auto-reclose function is allowed to operate exclusively at faults within the overhead line section. From the distance protection point of view, if the line starts with an overhead line section and ends with a cable line section, the same setting as above with the standard AR will, in principle, be applicable. Only the AR zone Z_{AR} should now be set to approximately 90% of the impedance of the overhead line of the first section. Fig. 3.6.-2 shows the corresponding zone characteristic.



DP Distance Protection

Z_1 First impedance zone

Z_{AR} AR zone to release or block the AR function

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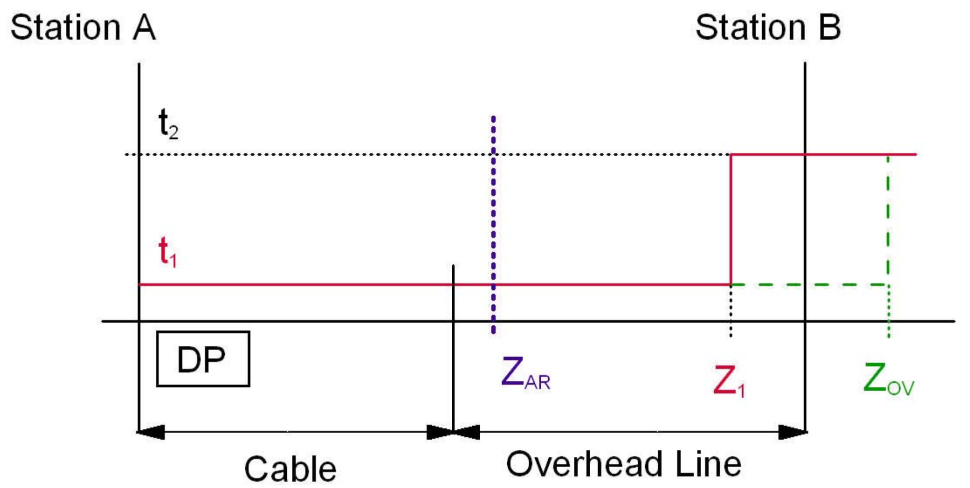
Fig. 3.6.-2 Zone setting for AR on mixed line starting with an overhead line section and ending with a cable line section

In this case, faults within the AR blocking zone release the AR function. If, on the other hand, a fault occurs in the cable section, the AR function will be blocked.



DP	Distance Protection
Z_1	First impedance zone
Z_{AR}	AR zone to release or block the AR function
Z_{OV}	AR overreach zone

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Fig. 3.6.-3 Zone setting for AR on mixed line starting with a cable line section and ending with an overhead line section

From the distance protection point of view, if the first section of the line is a cable and the second is an overhead line, the AR blocking zone Z_{AR} shall be used to block the AR function at system faults occurring in the first section, i.e. the cable section. Fig. 3.6.-3 shows the impedance-time characteristic to be programmed. A fault on the cable section, which is detected by the AR zone Z_{AR}, must block the AR function. Due to possible CT and VT measurement errors, the AR zone Z_{AR}, shall be set to approximately 110% of the cable impedance. The reach of the overreach zone Z_{OV} with the associated time defines the range for the activation of the AR function on the overhead line section, as mentioned above.

3.7. Switch onto faults

The distance protection incorporates the function "switch onto faults". By means of the following setting parameter, the tripping behaviour of the distance protection at local and remote closing of the CB can be defined.

Note
If the switch-onto fault function shall be used, the distance protection must use an output channel defined as a direct channel to a 2-2 switch object applied to simulate the CB. Otherwise the distance protection cannot recognize the closing of the CB.

3.7.1. Normal behaviour

When this setting is used, the distance protection does not check the CB closing command. A fault will always be cleared in accordance with the set impedance time characteristic. The distance protection will trip according to the impedance characteristic should a system fault occur after the line has been energized by closing the CB.

3.7.2. Overreach zone used

When this setting parameter is selected, the overreach zone will be activated for a time period of about 200 ms after closing of the circuit breaker. The protection zone is defined by the setting of the overreach zone Z_{OV}, which is normally about 120 to 150% of the first zone setting. Tripping will be performed within the time t_{OV}, which normally should be set equal to the time t_1 of the first impedance zone Z_1.

3.7.3. Trip after occurrence of general start

This setting will trip the CB immediately, if the general start signal is issued within 50 ms after a local or remote closing of the circuit breaker. Impedance measurement will not be involved at all.

4. Setting example

The setting of the distance protection requires detailed knowledge of the MV system. To achieve all the data needed, a comprehensive network analysis is recommended. Any possible power system configuration should be analyzed and the short-circuit currents for every possible fault condition should be calculated.

At least, the maximum short-circuit current is needed for dimensioning the CTs and the minimum short-circuit current including the minimum residual current for setting the starting element. The reach of the impedance zones can be derived from the impedance of the protected cable or overhead line.

The analysis of the power system will not be described in this example. The distance protection is assumed to operate under the following system conditions:

- 20 kV MV resonant earthed system
- Maximum busbar short-circuit current I_{MAX} 25 kA
- Network time constant for the decaying DC component 45 ms.
- Maximum load current 400 A
- Minimum short-circuit current I_{MIN} = 200 A
- Minimum residual current I_{RESID} = 100 A

Measurement transformer ratings:

- CT: 300 A/1 A
- VT: 20 kV/100 V

The impedance of the overhead line to be protected by the distance protection is:

- $\underline{Z}_L = 0.3\ \Omega + j\ 0.8\ \Omega$. In this example the calculation of the settings of just the first impedance zone will be explained. The calculations for the other zones are performed in the same way.
- The reactance of the overhead line is 0.4 Ω/km. This value is needed for the calculation of the fault distance as seen from to the fault locator.
- The zero sequence impedance will then be:

$\underline{Z}_0 = 1.4\ \Omega + j\ 4.0\ \Omega$

In general, it can be said that there is no special requirement for the VTs. The accuracy of the VTs should be equal to or better than class 1. On the other hand, the CTs have to be carefully dimensioned to avoid saturation. The dimensioning of the CTs will be explained and discussed in the following section.

4.1. Setting of the analogue inputs

For proper operation of the distance protection menu terminals/analogue inputs shall be provided for three phase current transformers, three voltage transformers and one current transformer for the residual current. The setting window is shown in Figure 4.1-1.

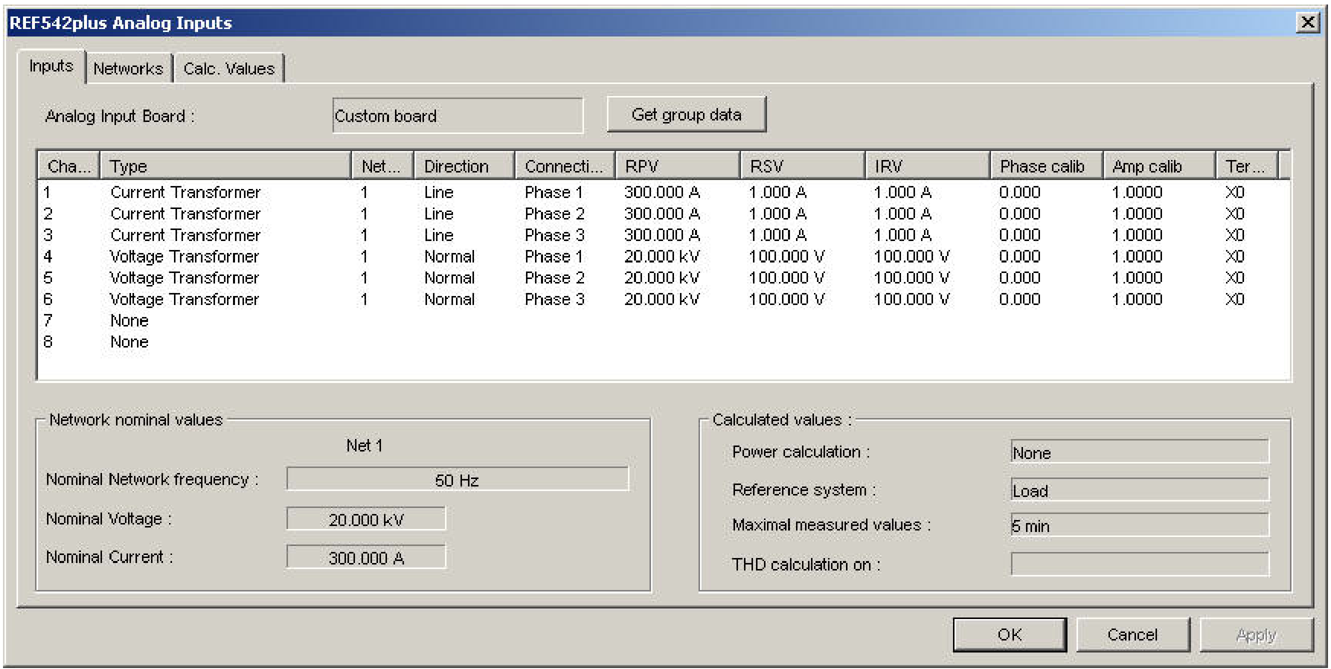

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Fig. 4.1.-1 Setting window of the terminal/analogue inputs

Note

If the rated secondary voltage of the voltage transformer is 110 VAC instead of 100 VAC, the RSV (Rated Secondary Voltage) value has to be changed accordingly. The IRV (Input Rated Value) value shall remain 100 VAC.

4.2. Checking of CT requirements

The behaviour of the distance protection depends on the quality of the currents measured. In the case of CT saturation, the current waveform might be distorted in such a manner that the proper operation of the distance protection might be jeopardized. CT saturation may be caused by a slowly decaying DC component which will be the case if a system fault is initiated at or close to the zero crossing point of the system voltage. Consequently, the CT has to meet the specific requirements for operation with distance protection to enable the distance protection to generate the fast tripping required. Then, after the trip signal has been issued, the CT may be allowed to saturate. However, it should be considered that in such a case the accuracy of the fault impedance calculation in the fault locator will be strongly affected by the saturation of the CT.

In principle, the distance protection of REF 542*plus* has been made insensitive to CT saturation by design. With the implemented algorithm based on the Discrete Fourier Transformation unwanted tripping is unlikely to happen. On the other hand, the tripping time can be delayed in such a manner that the overall selectivity of the system might be endangered. When saturation of the current transformer cannot be avoided, a response time setting of 30 ms is recommended for the first impedance zone. This setting strategy is necessary to lower the requirements on CTs as much as possible. With the above setting the CTs need to correctly reproduce the short-circuit current only for about the initial 25 ms.

For the selection of CTs it must be assumed that the fault is located in the middle of the first impedance zone of the distance protection. The CT must be able to reproduce the symmetrical short-circuit current without saturating during the initial 25 ms. Under this condition, the distance protection would still generate a CB trip signal within 30 ms. This rule has been derived from the result of a computer simulation study shown in Fig. 4.2.-1.

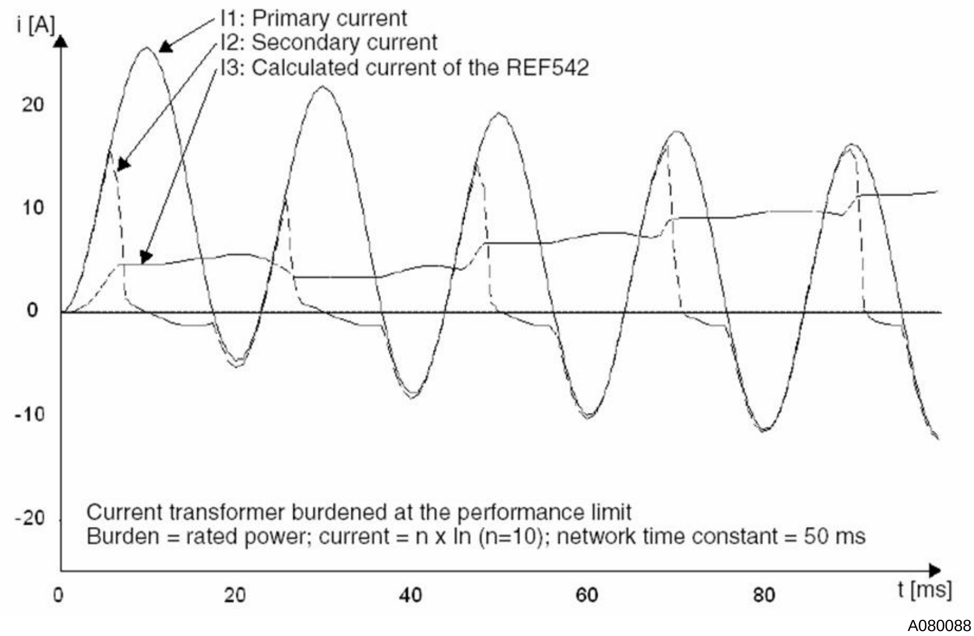


Fig. 4.2.-1 CB behaviour recorded in computer simulation

In Fig. 4.2.-1, the curve I1 denotes the primary current, I2 the CT secondary current and I3 the current calculated using an algorithm based on the Discrete Fourier Transformation. Due to CT saturation occurring already during the first half period, the result of the current calculation will amount to just 35% of the real short-circuit current. The consequence will be that the determined distance to the fault spot is inaccurate. The fault appears to be located about 3 times (100%/35%) farther away and consequently the trip command of the protection will be delayed.

To ensure proper operation of the distance protection and consequently the selectivity of the whole protection scheme of the electrical system, a comprehensive system analysis including short-circuit calculation has to be done. The maximum magnitude of the short-circuit current and the corresponding network time constant on every CT installation place shall be determined.

In this setting example, the maximum short-circuit current is assumed to be 25 kA. According to the related IEC 60255 standard, the thermal withstand current of the current input is 100 In (nominal current). Therefore, the lowest possible CT rated current must not fall below 25 kA / 100 = 250 A. Consequently, the selection of the primary rated current of 300 A is correct.

As mentioned above, a comprehensive power system analysis is needed. At first the impedance angle φ_s of the current and voltage quantities under short-circuit conditions shall be calculated. In this example, the impedance angle can be calculated from the given value of the network time constant τ = 45 ms for the decaying DC component of the short-circuit current. Due to the relation:

$$\tau = \frac{Xs}{\omega Rs} \qquad (11)$$

and

$$\tan\varphi s = \frac{Xs}{Rs} \qquad (12)$$

the impedance angle can be determined by combining equation and as follows:

$$\varphi s = arc\tan\omega t = arc\tan(2\pi 50Hz 45ms) = 85.95° \qquad (13)$$

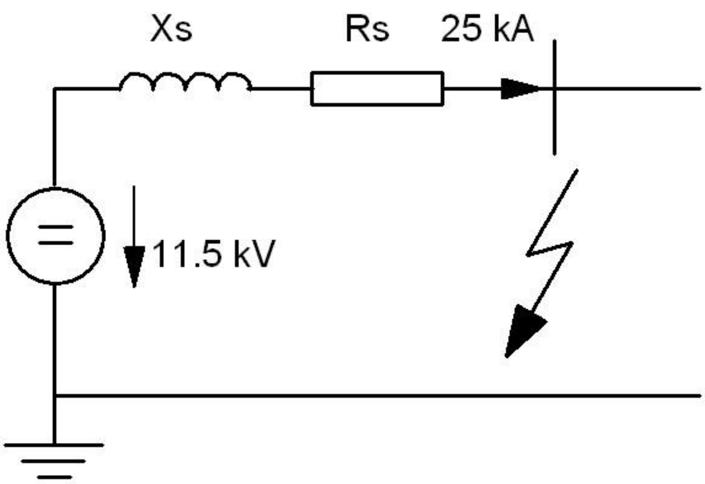
Then the source impedance of the incomer is to be estimated using the maximum short-circuit current on the busbar as follows:

$$Zs = \frac{Ur}{\sqrt{3}Isc} = \frac{20kV}{\sqrt{3}25kA} = 0.46\Omega \qquad (14)$$

Based on the impedance angle in equation (13) the reactance Xs and the resistance Rs can be estimated as follows:

$$Xs = Zs\sin\varphi s = 0.458\Omega$$
$$Rs = Zs\sin\varphi s = 0.0032\ \Omega \qquad (15)$$

The equivalent diagram for the incomer as shown in Fig. 4.2.-2 can be used for further calculations.



A080090

Fig. 4.2.-2 Equivalent diagram of the feeder

As already mentioned, the short-circuit current in the middle of the protected line and the related time constant must be determined to be able to continue the dimensioning of the CT. In Fig. 4.2.-3 the equivalent diagram for the calculation of the fault current If can be seen.

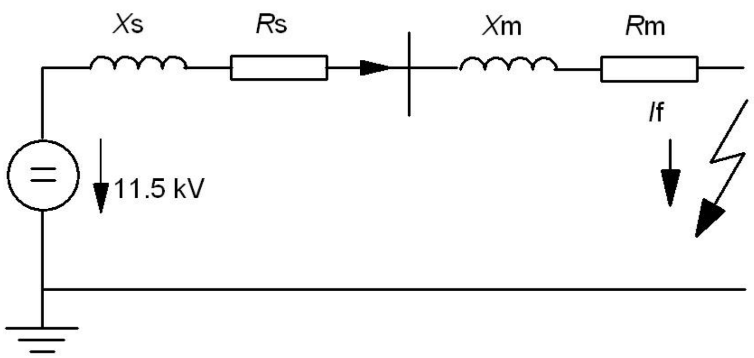


Fig. 4.2.-3 Equivalent diagram for the calculation of the fault current

The total fault reactance Xf and resistance Rf are:

$$Xf = (0.458 + 0.40)\Omega = 0.858\Omega$$
$$Rf = (0.032 + 0.15)\Omega = 0.182\Omega \qquad (16)$$

The short-circuit current If is

$$I_f = \frac{Ur}{\sqrt{3}\sqrt{(0.858^2 + 0.182^2)}} = 13.2kA \qquad (17)$$

and the related time constant τf is

$$\tau_f = \frac{0.858}{0.182\omega} = 15ms \qquad (18)$$

The calculation of the accuracy limit factor of the CTs is described in Reference [1]. To secure selectivity and fast tripping of the distance protection, the CT must be able to correctly reproduce the fault current containing a DC component during the first 25 ms. The diagram illustrated in Fig. 4.2.-4 shows the oversize factor K(ct) as a function of the network time constant for the decaying DC component, needed to avoid the CT saturation during the initial 25 ms.

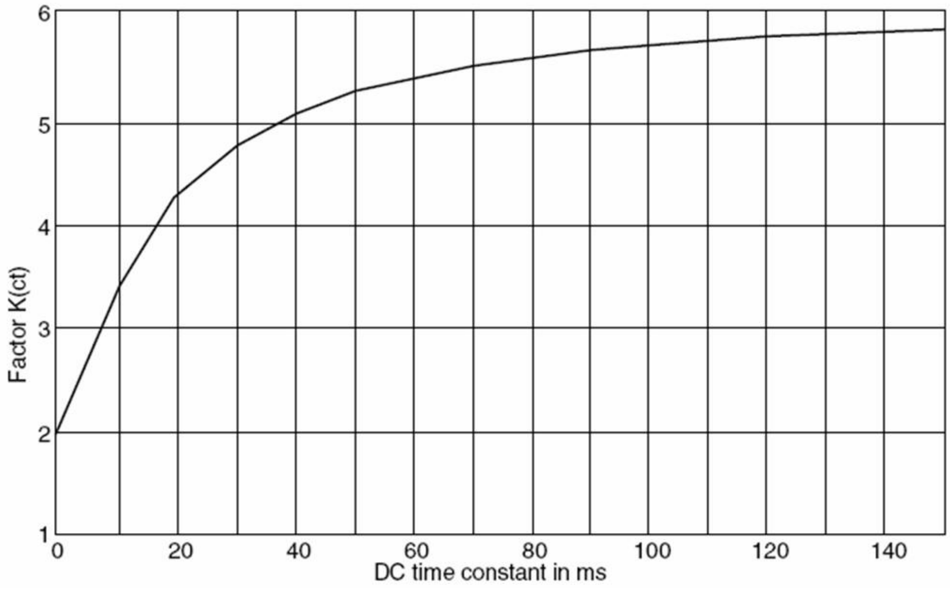


Fig. 4.2.-4 Oversize factor K(ct) needed to avoid CT saturation during the first 25 ms.

As shown by the diagram in Fig. 4.2.-4 an additional oversize factor K(ct) of about 3.8 is needed. This means that the CT must have an actual accuracy limit factor of

$$F_A = \frac{13.2kA}{300A}3.8 = 167 \tag{19}$$

This accuracy limit factor is required to ensure that the distance protection is able to trip in 30 ms as set. If this condition cannot be fulfilled, the operation time may be delayed by at least 5 times the time constant. In this example, the operation time of the first impedance zone could be delayed up to 75 ms, but then the accuracy limit factor FMIN must be at least greater than

$$F_{MIN} \geq \frac{13.2kA}{300A} \geq 44 \tag{20}$$

In this example, the internal burden of the 300/1 A CT is assumed to be 2.0 VA and the resistance of the wiring including the input transformer of the REF 542*plus* is assumed to be about 0.5 Ω, i.e. an actual burden of 0.5 VA.

The equation for calculating the actual accuracy limit factor in [1] is as follows:

$$F_A = F_N \frac{S_{IN} + S_n}{S_{IN} + S_A} \tag{21}$$

F_n	rated accuracy limit factor
F_A	actual accuracy limit factor
S_{IN}	internal burden of CT secondary coil
S_n	rated burden of CT
S_A	actual burden of CT

If a CT with a rated accuracy limit factor of 20 is to be used, the rated burden of the CT must be at least

$$S_n = \frac{F_A}{F_n}(S_{IN} + S_A) - S_{IN}$$
$$= \left[\frac{167}{20}(2.0 + 0.5) - 0.5\right] VA = 20.4 VA \tag{22}$$

To ensure the correct operation of the distance protection a CT with the following technical specifications is recommended:

300 A /1 A, 20 VA, 5P20

If the rated power of the CT has to be reduced, a higher rated primary current must be selected.

4.3. Setting for the system adaptation

First of all the system adaptation has to be defined. In this example the distance protection will operate in a resonant earthed MV power system. Therefore the **high omic** radio button high ohmic in the **net type** field is selected, as shown in Figure 4.3-1.

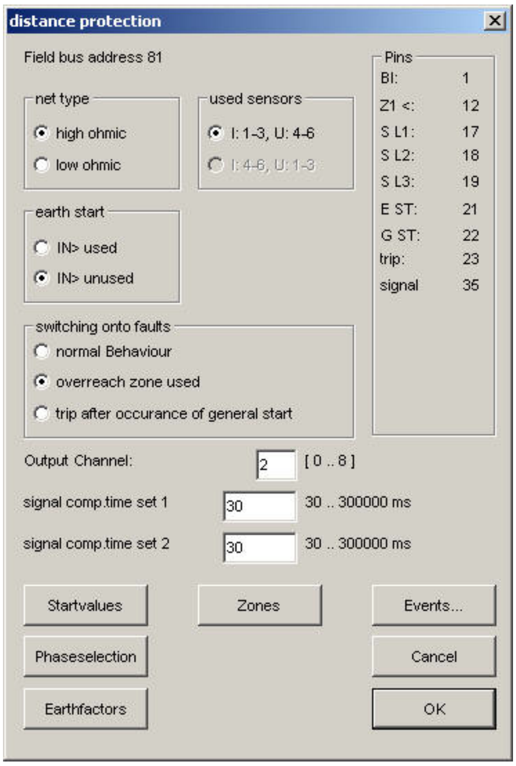


Fig. 4.3.-1 General settings for system adaptation

Because the start of the residual current starting element alone must not operate the distance protection, the radio button **IN> unused** in the **earth start** box is checked.

In the case of a switching-onto-fault condition, the overreach zone of the distance protection shall be applied in order to cover faults along the whole length of the line. Consequently, the radio button **overreach zone used** in the **switching onto fault** box is to be activated.

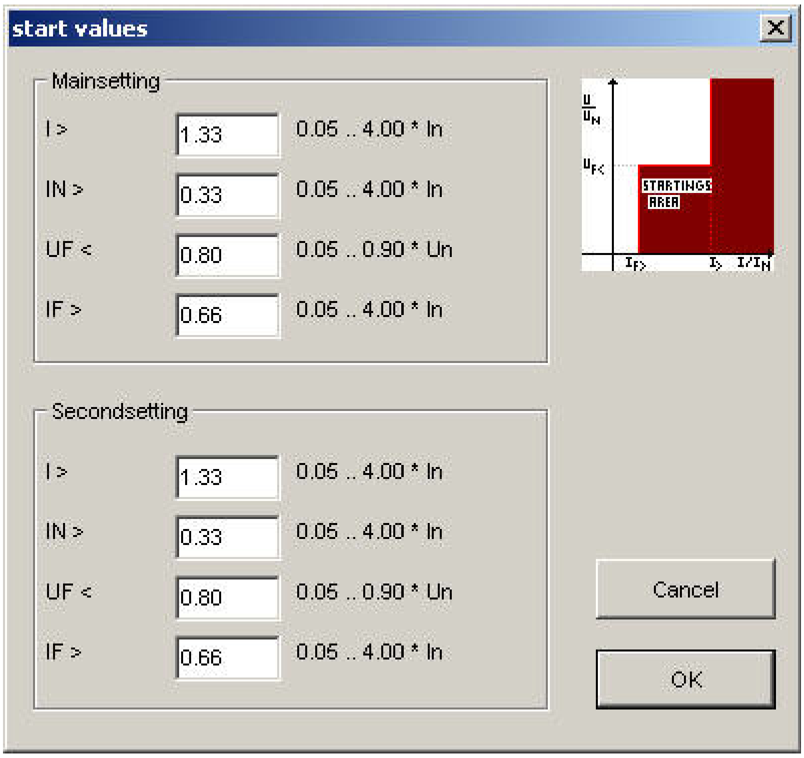
4.4. Starting element setting

According to the result of the system analysis, the minimum short-circuit current I_{MIN} is 200 A and the minimum residual current I_{RESID} is 100 A. The maximum load current is about I_{MAX} 400 A. Since the rated primary current of the CT is 300 A, the setting values referring to the rated value of the measurement transformers have to be set as below:

- Overcurrent starting element I> = 400 A/300 A = 1.33
- Undervoltage controlled overcurrent IF> = 200 A/300 A = 0.66
- Residual current IN> = 100 A/300 A = 0.33

The undervoltage criterion is used to detect power system faults with low level short-circuit currents. Besides, the undervoltage criterion is used for the detection of two-phase faults and cross-country faults. To improve sensitivity the undervoltage threshold setting for controlling the overcurrent starting element is to be set below the tolerance band for the system voltage operation of 0.85 *U*n. In this example the value 0.8 is used.

Fig. 4.4.-1 shows the setting parameters of the starting element:

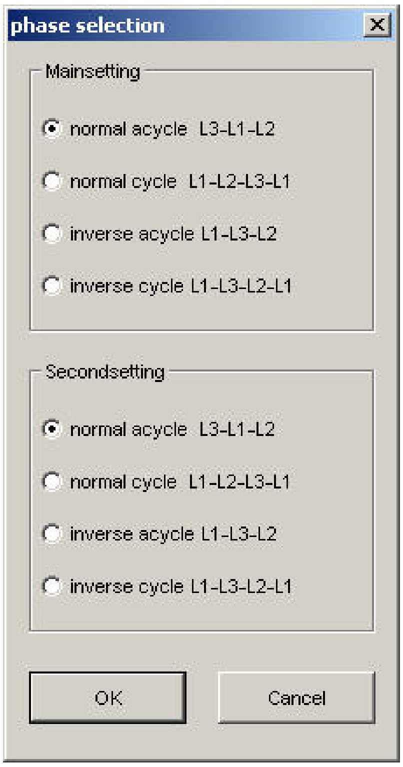


A080098

Fig. 4.4.-1 Settings of the starting system

4.5. Settings for phase selection

In the case of a cross-country fault in a resonant earthed MV system, only the faulted line section is to be isolated. For this reason all the protection devices installed in the system should have the same phase selection. An example of the commonly used phase selection is shown in Fig. 4.5.-1.

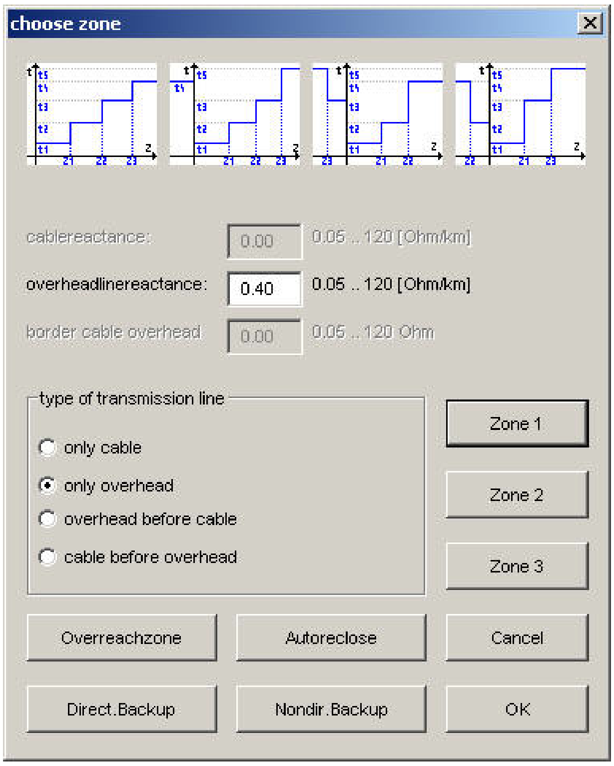


A080100

Fig. 4.5.-1 Phase selection normal acycle L3-L1-L2

By applying this setting a cross-country fault involving phases L1 and L2 will cause an isolation of the line section where the earth fault in phase L1 is located. Then the operation of the rest of the power system can continue, as the system is affected only by one earth fault.

4.6. Impedance zone setting



A080102

Fig. 4.6.-1 Zone setting

As shown in Fig. 4.6.-130, the primary value of the line reactance per kilometre must be entered at first. This value is needed for the relay to calculate the distance to the fault spot in kilometers. This way of calculating the distance is only possible if the line between the stations consists of one type of overhead line or one type of cable. If the connection comprises a mix of different overhead lines and/or cable types, the fault location can only be derived by an external calculation of the fault reactance.

In this example the reactance of the overhead line is 0.4 per km. In accordance with the line data, the primary impedance of the overhead line to be protected is:

$$\underline{Z}_L = 0.3\Omega + j0.8\Omega$$

The length of the line to be protected can be calculated accordingly:

Line length = (0.8 / 0.4) km = 2 km

Furthermore, in this example the primary zero impedance is assumed to be:

$$\underline{Z}_0 = 1.4\Omega + j4.0\Omega$$

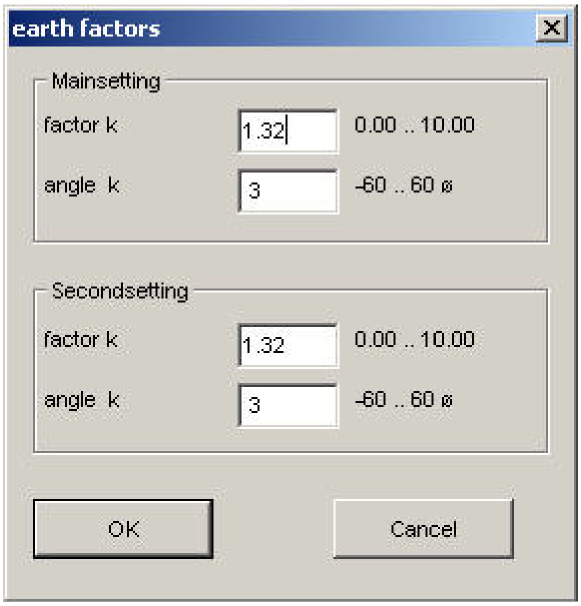
The earth factor can be estimated using equation (23):

$$\underline{k} = \frac{1}{3} \cdot \left(\frac{(1.4 - 0.3) + j(4.0 - 0.8)}{0.3 + j0.8}\right) = \frac{1.1 + j3.2}{0.3 + j0.8} \qquad (23)$$

Based on the above results the numerical value of the earth factor and the angle can be calculated as follows:

$$|\underline{k}| = \frac{3.38}{0.84} = 1.32$$

$$\varphi(\underline{k}) = 71° - 69° = 3° \quad (24)$$



A080104

Fig. 4.6.-2 Setting of the earth factor k

The setting mask for the earth factor is shown in Fig. 4.6.-2. Because selectivity is required for the first zone, the earth factor is set according to the line data of the first zone. The above calculation gives an earth factor setting of 1.32 and an angle setting of 3°.

4.6.1. Setting of zone 1

As appears from the data given in the setting example, the impedance of the line to be protected is

$$\underline{Z}_L = 0.3\Omega + j0.8\Omega$$

To avoid non-selective tripping due to the measurement error of class 3, the setting of zone 1 is limited to 0.95% of the line length

$$\underline{Z}_0 = 0.28\Omega + j0.76\Omega$$

The earth factor can be estimated using equation (10):

The tripping characteristic of zone 1, as shown in Fig. 3.3.-1, is to be limited by the reactance X_1 and the resistance R_1. The reactance X_1 is obtained directly from the line impedance

$$X_1 = 0.76\Omega$$

As the operating characteristic is to cover arcing faults and high-resistance faults too, the resistance limitation is selected to be about five time the resistance value.

$$R_1 = 1.4\Omega$$

To determine the setting of zone 1 of the distance protection it is necessary to calculate the setting value for the secondary side of the measurement transformer. For historical reasons the setting of the impedance zone refers to the secondary impedance expressed in ohm. This, as a matter of fact, is not quite correct. It is only true for a distance protection system connected to current transformers with a rated secondary value of 1 A.

The input transformer module of the REF 542*plus* is used to adapt the measured quantity to the signal processing. The intention is that the setting value can be related to the rated value of the measurement transformer. An overcurrent protection function, for example, can be set as a ratio of the rated current of the CTs. The same consideration also applies to the distance protection.

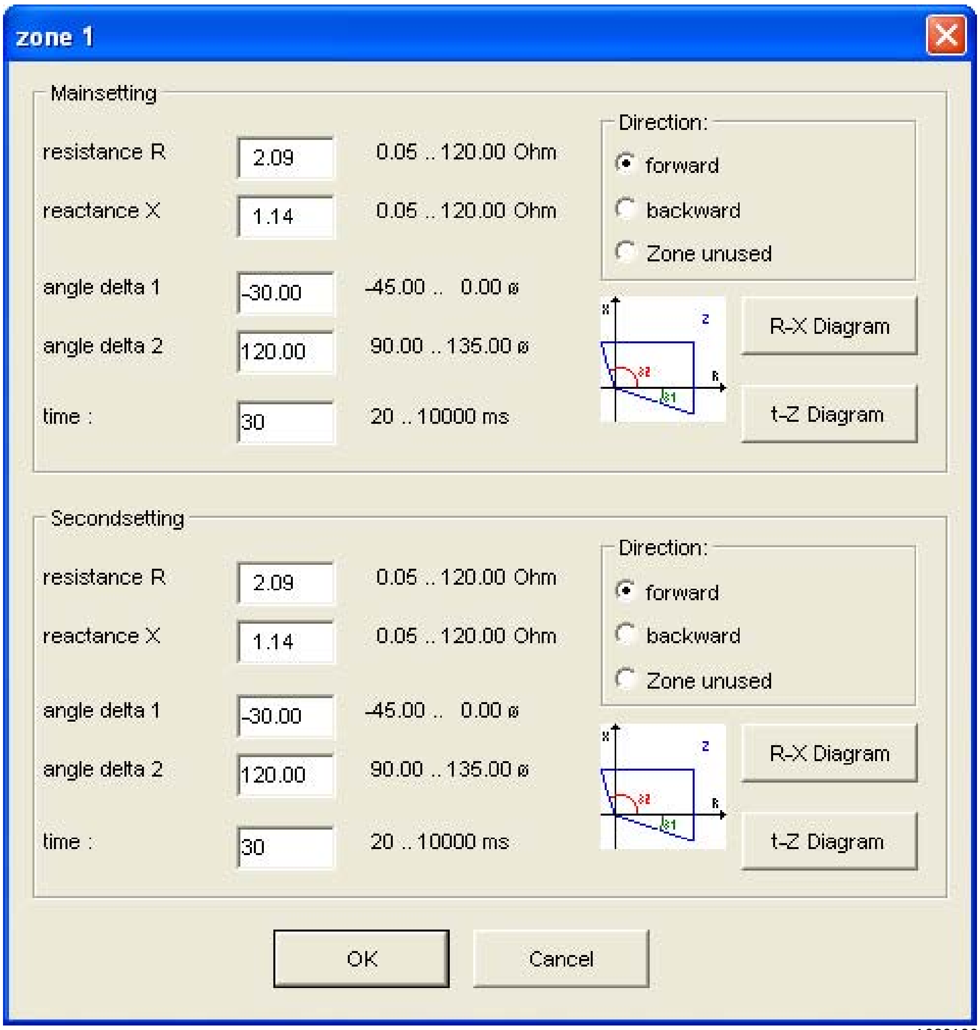
For this setting example the following reference impedance can be used.

Primary reference impedance: Z_P = 20 kV / 300 A = 66.67

Because the setting of the distance protection function of REF 542*plus* is calibrated in Ω, it must be considered that 100 Ω is equal to the rated secondary impedance. The setting for zone 1 can then be determined as follows:

$$\text{Setting for X} = (X_{1L}/Z_p)100\Omega = 1.14\Omega$$

$$\text{Setting for R} = (XR_{1L}/Z_p)100\Omega = 2.09\Omega$$



A080106

Fig. 4.6.1.-1 Setting of zone 1

Fig. 4.6.1.-1 shows the settings of zone 1. As mentioned above, the operation time shall be set to 30 ms. The distance protection operates in the forward direction.

4.6.2. Setting of overreach zone

The overreach zone can be set, if the auto-reclose function is used or if the **setting overreach zone** is used is selected for **switching onto fault function** as shown in Fig. 4.3.-1. The setting value can be based on the setting of zone 1 by multiplying the value by a factor between 1.1 and 1.5. Note that the overreach zone shall cover the whole length of the overhead line to be protected and even a small part of the line beyond the next station. For this setting example the factor shall be 1.2. The setting is shown in Fig. 4.6.2.-1 below.

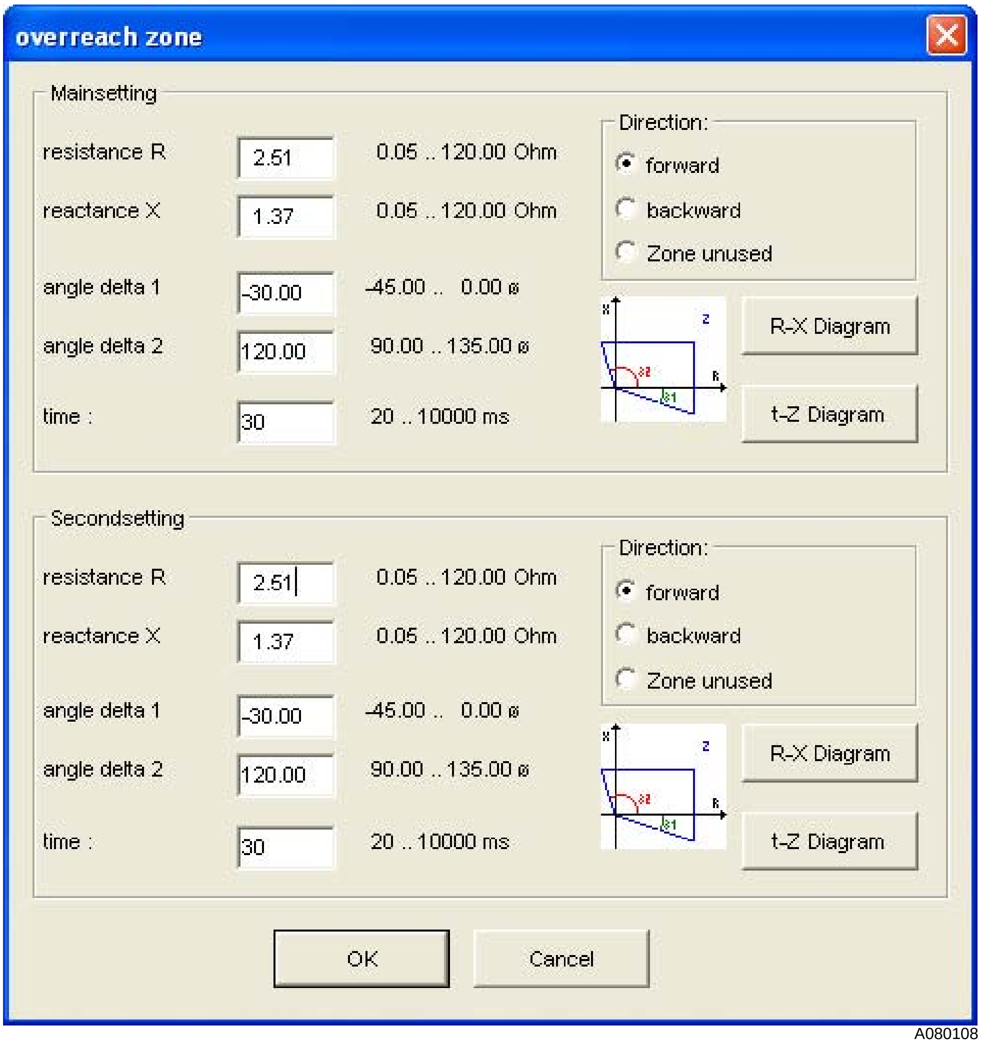


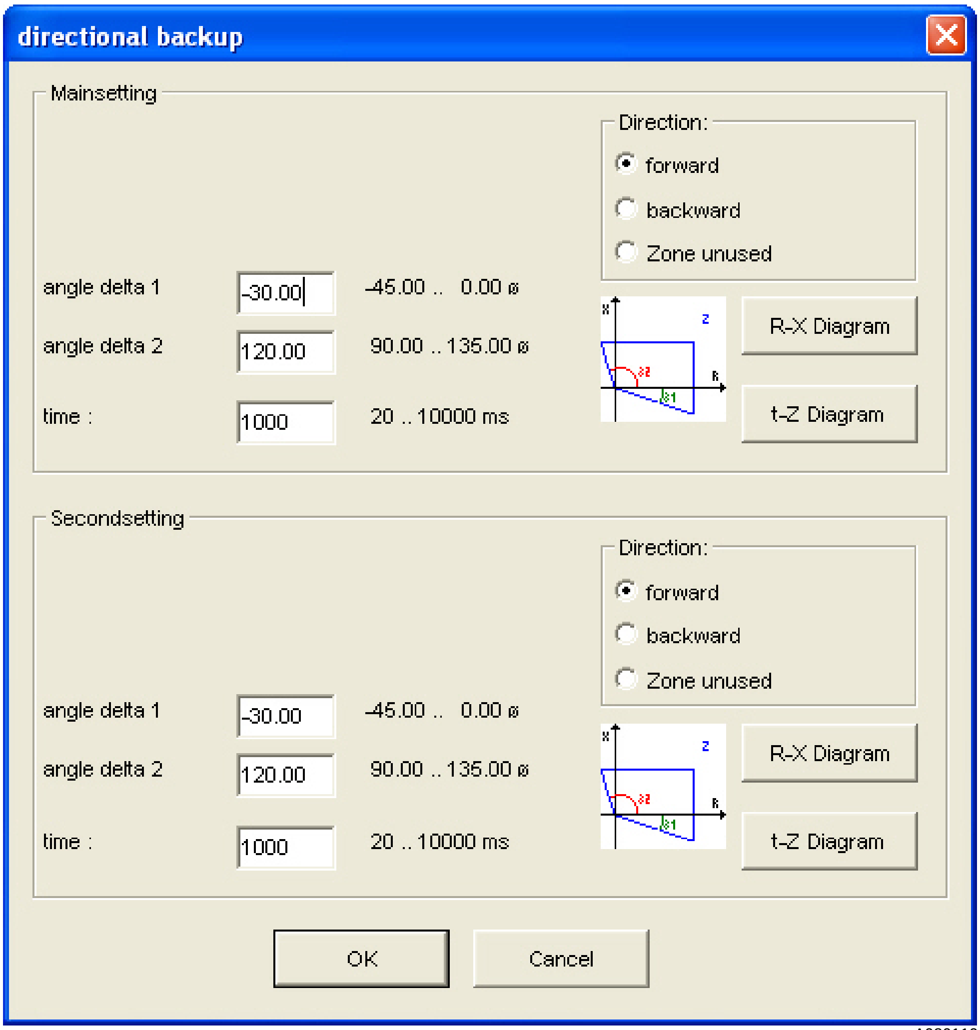
Fig. 4.6.2.-1 Setting of overreach zone

4.6.3. Setting of other zones

The impedance zones 2 and 3 can be set in the same way as described above. If zone 2 and 3 no longer are required, the radio button **zone unused** is selected, which sets the zone out of operation?

The settings of the **auto-reclose** function have already been explained in Section 3.6. Adaptation to auto-reclose function. If an overhead-before-cable case is to be set in the **choose zone** mask, see Fig. 4.6.-1. In this case the setting value will release the AR function for faults on the overhead section of the mixed line. On the other hand, if **cable-before-overhead** is selected, the AR will be blocked for faults on the cable section.

The zone for directional backup and non directional backup can be applied for back-up protection. The setting is shown in Fig. 4.6.3.-1 and Fig. 4.6.3.-2.



A080110

Fig. 4.6.3.-1 Setting of directional backup zone

The directional backup zone can be set in forward or in backward direction. If this zone is not needed for the application the zone can be set with the related radio button as Zone unused.

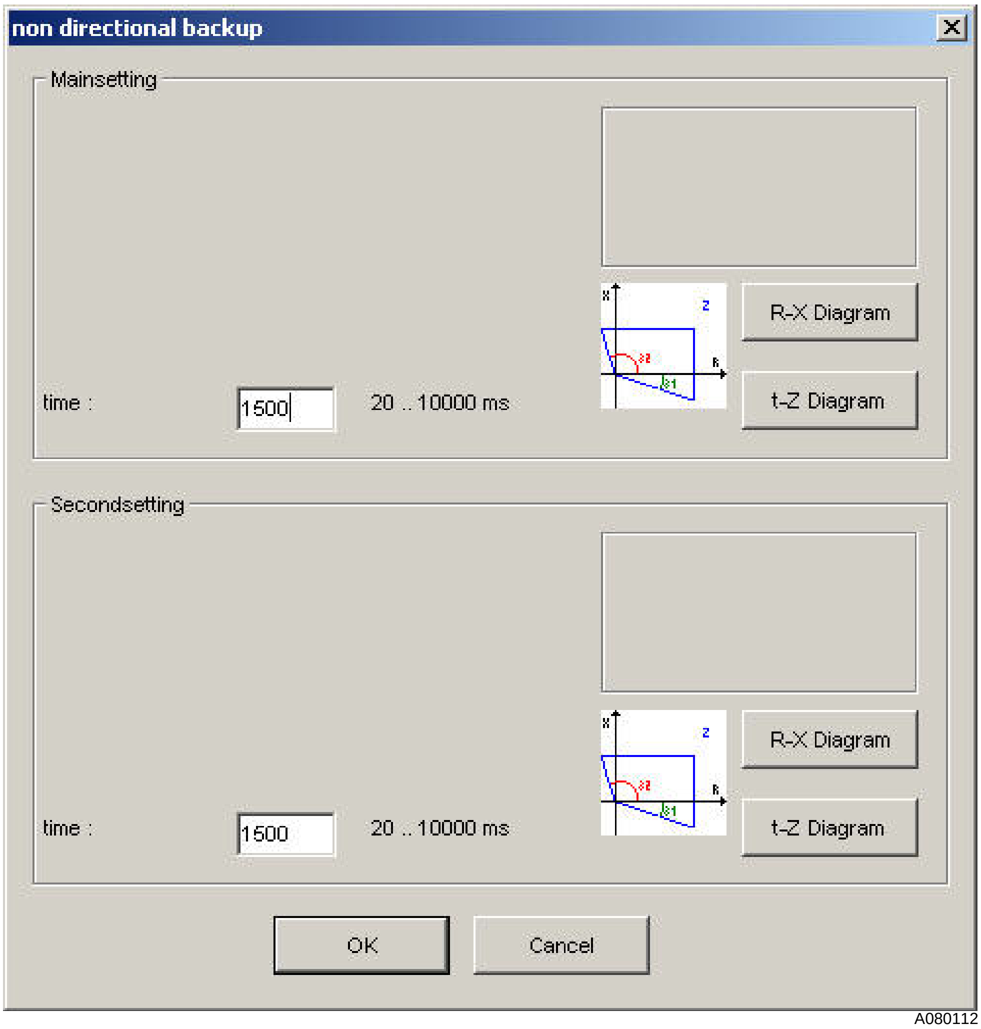


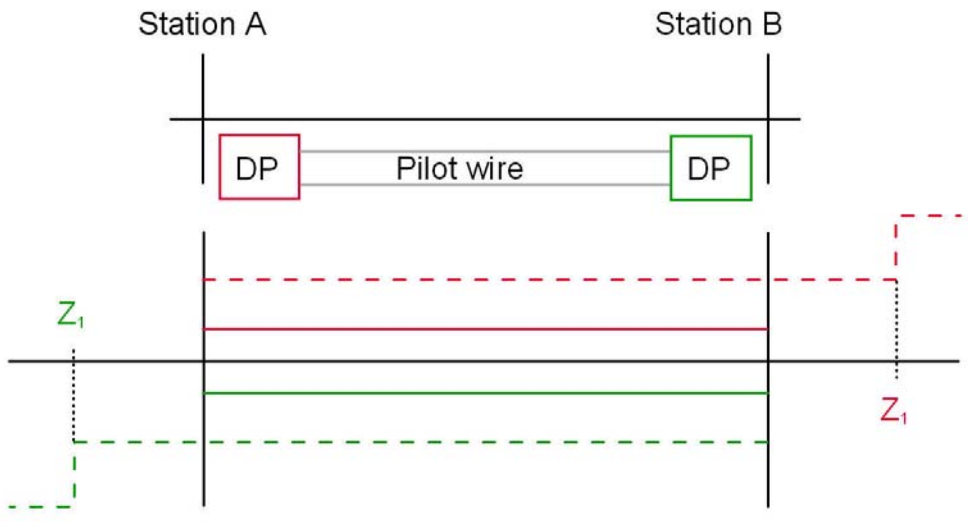
Fig. 4.6.3.-2 Setting of non-directional backup zone

The non-directional backup only features definite time operation characteristic as long as the starting condition is fulfilled.

4.7. Signal comparison scheme

If the reach of the protection zone is less than the smallest possible impedance setting value, the distance protection can be supplemented with a signal comparison scheme. This enables the reasonably selective time-graded protection to operate as absolute selective protection.

Provided with the signal comparison scheme, the distance protection turns into a protection system including a data communication link. However, there are no specific requirements on the signal connection and transmission as would be the case with the line differential protection. The distance protection will also operate properly without a communication link. Fig. 4.7.-1 below illustrates the principle of distance protection including a signal comparison scheme communication over a pair of pilot wires.



DP Distance Protection

Z_1 First impedance zone of the corresponding distance protection

Fig. 4.7.-1 Zone 1 setting of a distance protection including a signal comparison scheme

As shown above, the line to be protected is so short, e.g. just some hundred meters, that the discrimination of the fault location by applying the first impedance zone Z1 cannot be guaranteed. Consequently, the zone setting can only be higher than the impedance of the entire line. To maintain the selectivity of the protection, the operation time of the first impedance zone must be set higher than the setting usually used for distance protection, for example about 200 ms, for the zone to operate as backup protection for the signal comparison scheme, if this fails due to a broken pilot wire or disturbances in the auxiliary voltage used for signalling.

The signal comparison scheme will ensure fast tripping. In this case, the t1 time of the first impedance zone, as mentioned above, has to be increased, for example, to 200 ms. The two distance protection units located in either end of the line are interconnected via a pilot wire pair. This scheme will enable the general-start and impedance Z_1< signals generated during the power system fault to be compared. Fig. 4.7.-2 below shows an example of how the signal comparison scheme functions when simple relay contact logic is used.

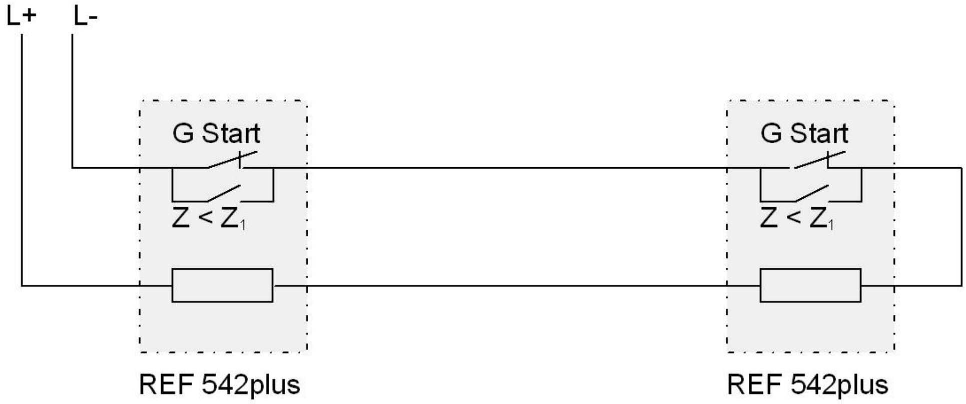


Fig. 4.7.-2 Principle of the distance protection with signal comparison scheme

As mentioned above, the two REF 542*plus* devices with distance protection are connected together via a pilot wire pair forming a loop including the two protection devices. An auxiliary voltage is applied at one end of the loop. The resistor of the loop shall be selected so as to allow a certain current of e.g. 1 mA, to flow through the loop continuously to enable loop supervision. The voltage drop over the resistor shall be used to activate the related binary input of the REF 542*plus* devices.

If the auxiliary voltage fails, an indication signal can be generated after the expiry of a selectable time delay of, say, 5 s. When necessary, this information can be forwarded to the higher-level control system. As already mentioned, also in the case of a failure in the pilot wire the line will still be protected by the distance protection, although with a slightly prolonged operation time.

The operation principle of the signal comparison scheme is as follows.

- If a fault occurs in the power system, both distance protection devices will be activated. Both of them will generate a general-start signal. The general-start signal is linked to a normally closed contact (N/C), which opens the pilot wire loop at both ends. Because the loop is only open for a short time, less than 5 s, a no loop disturbance indicating signal will appear.
- Tripping by the distance protection is only possible if both protection units acknowledge a fault within the first impedance zone Z1. In this case, signal Z1< appears and closes the signal comparison loop again. This closed loop condition now means that the fault is located within the protection zone of both distance protection devices, which will allow tripping of the distance protection. Should a fault arise outside of the protection zone, the loop will not be closed due to the missing Z1< signal. Consequently, there will be no tripping, but the fault will be selectively isolated by the related protection unit.

- The signal comparison protection will also operate properly, if the line is fed from just one end. If a fault occurs within the protection zone, the loop remains closed because the distance protection device at the far end remains idle. The trip signal will then be generated by the distance protection device at the feeding end, which originally started on detection of the system fault.

The signal comparison scheme enables a fault occurring within the protection zones to be isolated selectively and rapidly. However, when determining the settings, the propagation time of the signals to be transferred must be taken into account. To ensure that the loop is opened at the right time, it is important that the general start signal always appears before the Z1< signal. In addition, consideration must be taken to the fact that the signals required by the signal comparison protection are not always received simultaneously at the two line ends. Sufficient time delays must be defined for the binary inputs.

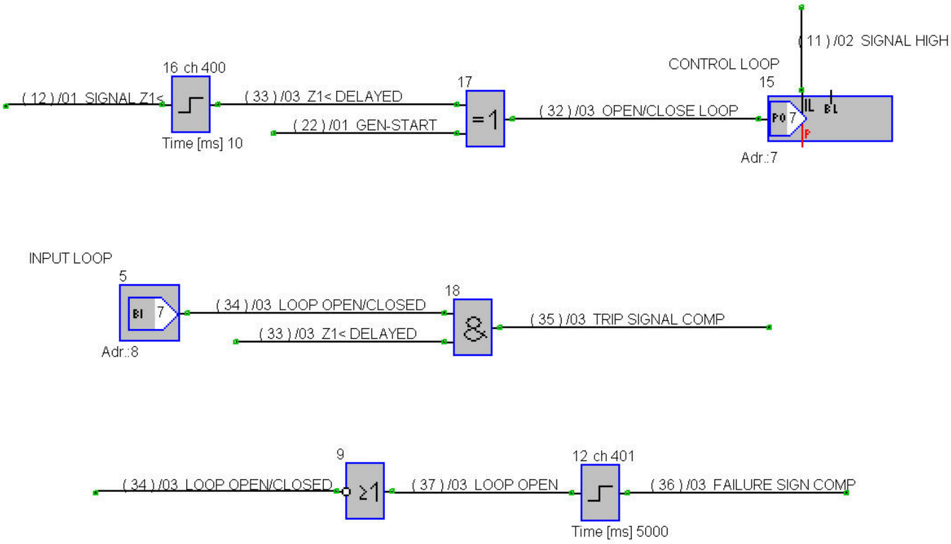


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Fig. 4.7.-3 Example of the configuration for the signal comparison scheme

Fig. 4.7.-3 shows an example of the logical scheme for configuring the signal comparison scheme in the FUPLA. The loop is controlled by the binary output of channel 7. If the general start signal appears the loop will be opened and closed again by the appearance of the Z< signal. For compensation of the propagation time the Z1< signal is delayed 10 ms. The binary input of channel 7 will recognize the loop condition. If the loop is closed and the delayed Z< signal exists, the trip will be initiated by connecting the output of the AND gate to the input SIGNAL COMP of the distance protection function block. To supervise the operation condition of the pilot wire connection a failure signal will be generated, if the loop remains opened for more than 5 seconds.

5. Summary

The operation principle of the distance protection is explained. The distance protection incorporates the following functions:

- Starting element of overcurrent and voltage controlled overcurrent scheme.
- Adaptation to the system grounding.
- Fault impedance calculation.
- Directional detection by using voltage memory.
- Trip logic for programming the different zones in combination with the fault direction.
- Trip logic for programming the auto-reclosure in mixed cable and overhead line.
- Switching onto fault scheme.
- Signal comparison scheme

In the setting example all the needed setting parameter are explained. Also the needed CT ratings are calculated.

6. References

[1] 1MRS755481: Calculation of the Current Transformer, Accuracy Limit Factor, ABB Application Note

[2] 1MRS755860: Protection Functions, Configuration and Settings

7. List of symbols

AR	Auto-reclosure
CB	Circuit breaker
CT	Current transformer
DP	Distance protection
FUPLA	Function Plan Programming Language
I>	Overcurrent (high set)
If	Fault current
IF>	Overcurrent (low set)
IL1,2,3	Current in phase 1,2 and/or 3
I_{LL}	Concatenate current
IN	Earth or residual current
IN>	Earth or residual overcurrent
k	Earth factor
MV	Medium voltage
Rf	Fault resistance
Rs	Source resistance
$t_{1,2,3,4,5}$	Time setting for the impedance time characteristic
U1,2,3	Phase voltage in phase 1,2 and/or 3
U12,23,31	Line voltages
UF<	Undervoltage to control IF>
U_{LE}	Phase voltage
U_{LL}	Concatenate or line voltage
VT	Voltage transformer
Xf	Fault reactance
Xs	Source reactance
Z_0	Zero sequence impedance
$Z_{1,2,3}$	Setting of the first, second or third impedance zone
Z_{AR}	Setting for controlling the AR operation
Zf	Fault impedance
Z_L	Line impedance
Z_{LE}	Impedance for phase to earth fault
Z_{LL}	Impedance for phase to phase fault
Z_{OV}	Setting for the overreach zone
Zs	Source impedance
τ	Network time constant

8. Connection diagram

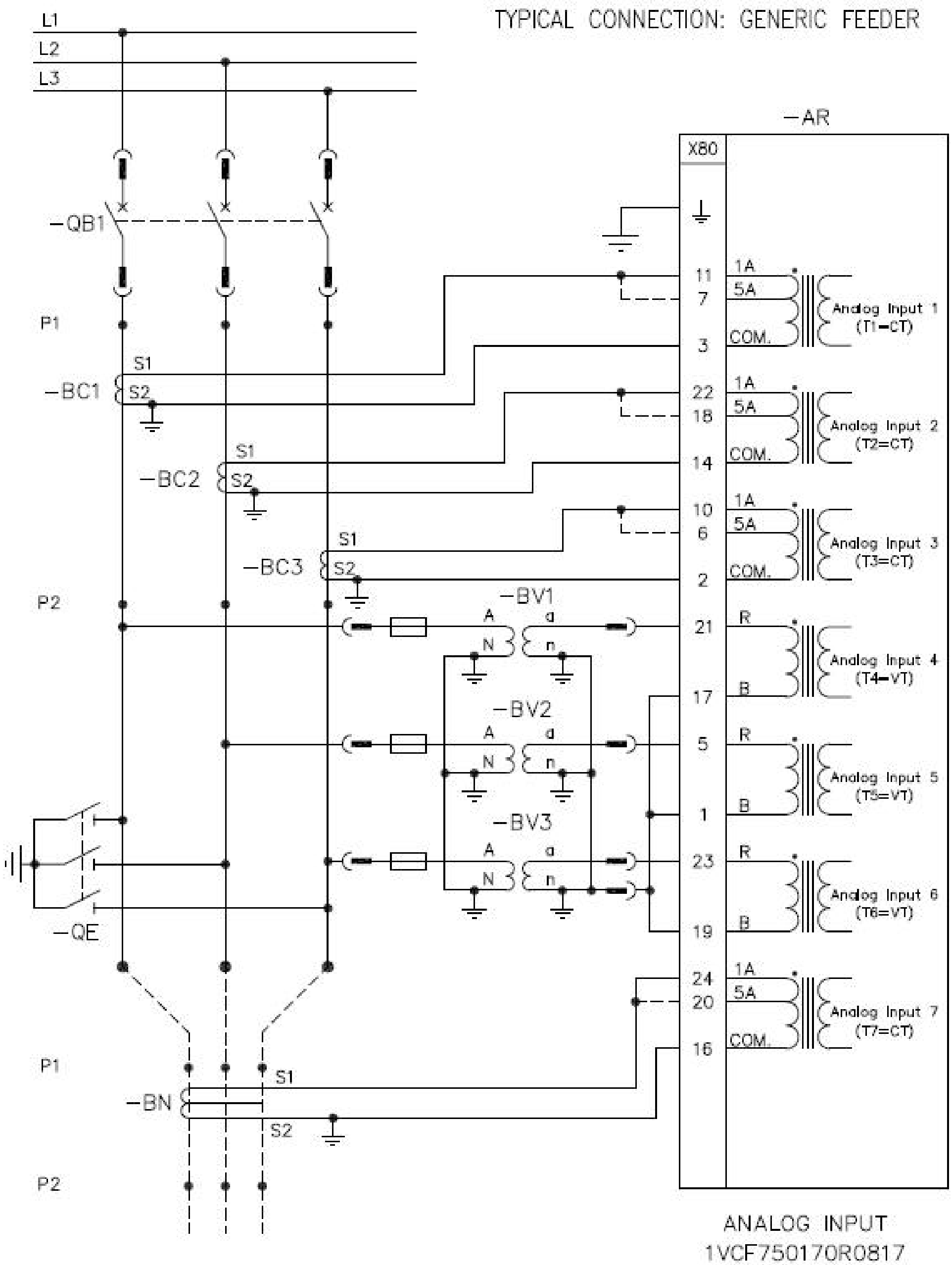

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ABB Oy
Distribution Automation
P.O. Box 699
FI-65101 Vaasa
FINLAND
Tel. +358 10 22 11
Fax. +358 10 224 1094
www.abb.com/substationautomation

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