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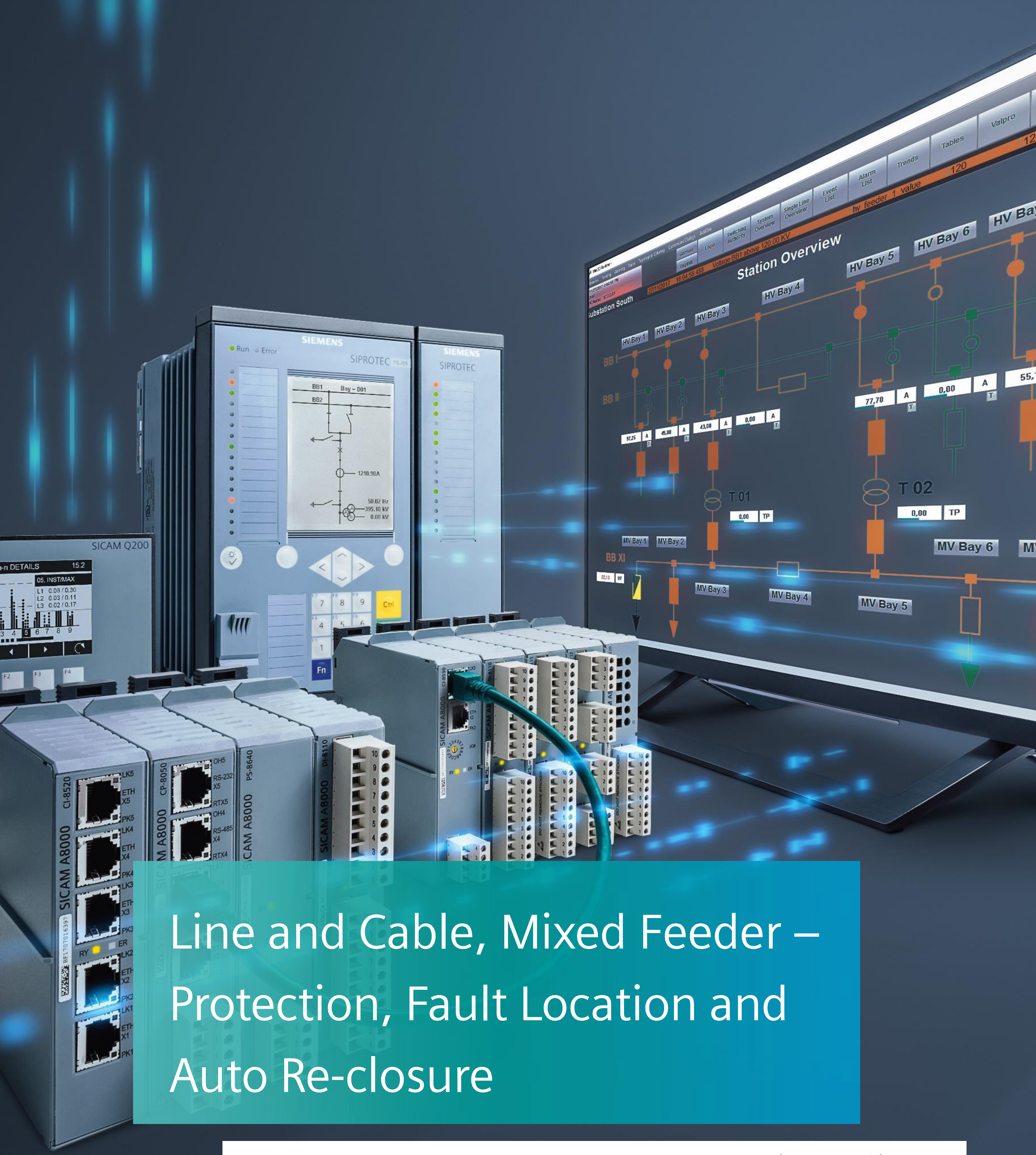

Line and Cable, Mixed Feeder – Protection, Fault Location and Auto Re-closure

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SIPROTEC 5 Application

Line and Cable, Mixed Feeder – Protection, Fault Location and Auto Re-closure

APN-081, Edition 1

Content

1 Line and Cable, Mixed Feeder – Protection, Fault Location and Auto-Re-closure

1.1 Introduction

In some situations, the overhead feeder includes a section of cable or other enclosed conductor (gas insulated line). For applications with such mixed sections of overhead line and cable the SIPROTEC5 devices provide special features. This application note will cover the following aspects when applied to mixed feeder:

a) Line differential protection (87L)
b) Distance protection (21)
c) Fault Location (Fault Locator Plus)
d) Auto re-closure (plus optional secondary arc detection)

General device configuration parameters are not covered in this application description. Only the special aspects relating to the mixed fixed feeder configuration.

The single line diagram of the mixed configuration used in this application is shown below in Figure 1. The relevant data of the application is provided under Data of applied Example.

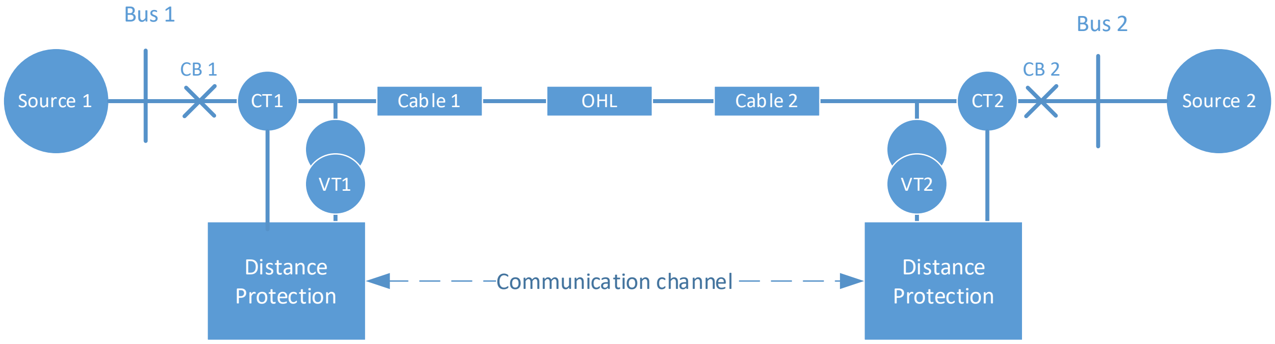


Figure 1: Single line diagram of application

1.2 Overview of the applied functions

Under separate headings the parameters of the covered functions are determined. Each section is largely independent of the other. Focus is placed on aspects that are special to the mixed feeder. The section on distance protection is therefore much longer than that of differential protection due to several parameters that require special consideration in the distance protection.

It is also possible to only look at the fault location and auto re-closure aspect of the application. The test results will focus on ground fault as these are most relevant to the applied functions.

1.2.1 Line differential protection (87L)

If a suitable communication channel is available, the 87L protection is ideal. The mixed feeder does not introduce serious application constraints for 87L.

1.2.2 Distance protection (21)

The distance protection can be adapted to the mixed feeder with zone specific compensation factors. This requires detailed calculation at the internal zone 1 boundary. Overreaching zones may be set with the impedance of the combined sections. Particular attention is therefore given to the calculation of the ground fault factors Kr and Kx.

1.2.3 Fault Location (Fault Locator Plus)

The fault locator is configured with parameters of each segment. This ensures accurate response over the entire length of the feeder. If a protection interface (with or without differential protection) is available, the fault locator will apply the 2-ended method as well as the single ended method. The auto re-close can be blocked by the fault locator when the fault is on the cable segment of the feeder. No detailed calculations are required as the section parameters can be applied directly.

1.2.4 Automatic Re-closure (ARC), optional Secondary Arc Detection (SAD)

Most of the feeder faults will be on the overhead line section as cable faults are rare in comparison with over-head line faults. The application of single pole tripping and auto re-close will improve the availability of the feeder. To minimize the damage and improve the quality of supply there should be no ARC attempt for faults on the cable section of the feeder. For this purpose, the ARC coordinates with the fault locator plus and is configured to only re-close for faults on the OHL section of the feeder. If the secondary arc detection function is applied, reclosure onto permanent ground faults can be eliminated entirely. The application of the SAD option is described.

1.3 Data of applied Example

The system parameters for the used example shown in Figure 1 are listed in the table below. Based on the system parameters and the shown distance protection reach settings the relevant values for determining the settings are calculated. The formulae for the calculation are provided. The applied calculations are done in an Excel spreadsheet that accompanies the application example.

Table 1: Source impedance data

	Source 1		Source 2	
Nominal Voltage	380 kV		380 kV	
	Mag [Ω]	**Ang**	**Mag [Ω]**	**Ang**
Z1	20,965	82,930	13,026	82,101
Z0	20,965	82,930	5,178	78,776

The source impedance data provided in Table 1 is checked in the model by comparing the calculated and model output short circuit currents for faults on Bus 1 and Bus 2:

Table 2: Busbar fault current magnitudes in kA

	Bus 1		**Bus 2**	
Fault	Calculated	Simulated	Calculated	Simulated
3 ph [kA]	10,46	10,25	16,84	16,50
1 ph [kA]	10,46	10,25	21,08	20,65

The small difference between calculated and simulated fault current is due to load modelling by the simulation resulting in small variation of source voltage magnitude.

The feeder impedances are provided in Table 3 below.

Table 3: Feeder Impedance (primary)

	Cable 1		**OHL 2**		**Cable 2**		**Sum**	
	R	X	R	X	R	X	R	X
Z1	0,272	4,020	2,980	25,900	0,204	3,015	3,456	32,935
Z0	2,230	7,236	13,410	82,880	1,673	5,427	17,313	95,543

1.4 Line Differential Protection Settings (87L)

For the 87L function the settings at both sides are essentially the same. The individual sections of the feeder do not have to be considered in detail. It is sufficient to consider the charging current of all sections together.

Based on the total capacitance of all 3 sections the total charging current is calculated:

$$I_{tot\_charge} = 2 \cdot \pi \cdot f \cdot C_{tot} \cdot \frac{V_N}{\sqrt{3}} = 2 \cdot \pi \cdot 50Hz \cdot 9.468\mu F \cdot \frac{380kV}{\sqrt{3}} = 653A$$

Based on this a charging current compensation can be applied or the setting of 87L can be set to approximately 2.5 times the charging current.

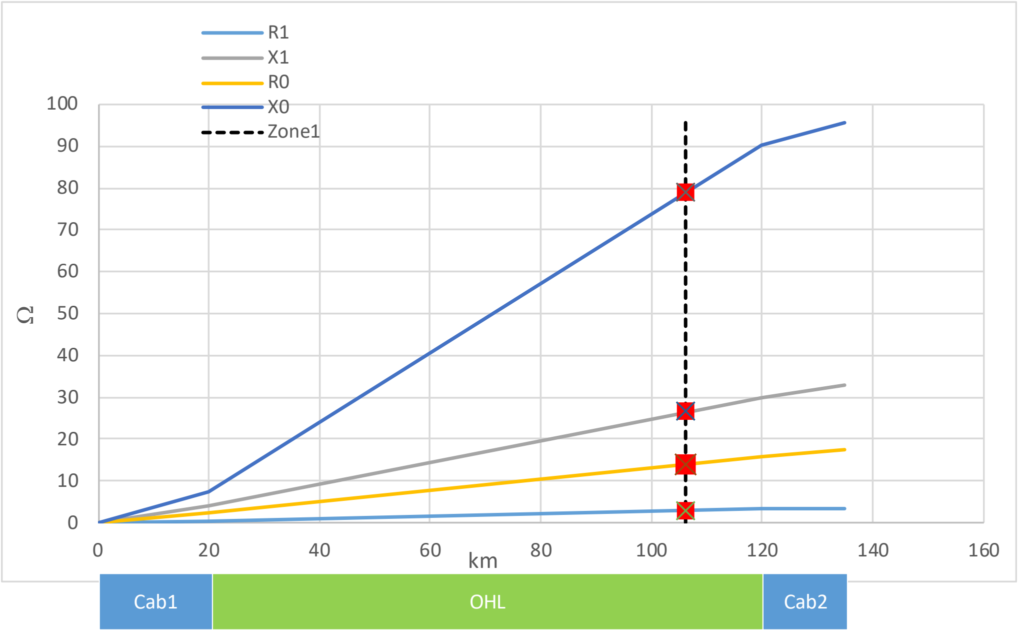
1.5 Distance Protection Settings (relay at Bus 1 side)

In this section the calculation of settings that need special measures on mixed feeders are addressed. The zone boundaries for the distance protection are defined as follows (these are general values without consideration of adjacent feeders or other system components):

Table 4: Zone reach definitions

	Reach	Time delay[ms]	Function
Zone1	80%	0	Instantaneous trip for fault on feeder; 20% safety margin
Zone2	120%	300	Overreach for 100% feeder coverage; 20% safety margin, 300ms time grading
Zone 3	150%	600	Overreach zone for POTT and remote backup,
Zone 4	-80%%	600	Reverse zone for POTT (Echo and weak in-feed); remote backup,

As the impedance is not uniform across all sections of the line, the compensation parameters must be calculated at the zone boundary of Zone 1. It is possible to set zone specific values for all zones. In this example however, the overreach and reverse reach zones are set based on the impedance values of all sections (sum total). The diagram below shows the profile of the various impedances across the 3 sections of the feeder.



The zone 1 boundary values marked in red above are calculated and used in the next paragraph as follows:

Boundary X1	26,348 Ω
Boundary R1	2,841 Ω
Boundary X0	78,686 Ω
Boundary R0	13,791 Ω

1.5.1 Zone 1 parameters

The distance protection setting, requiring special measures for Zone 1, are calculated as follows with the system conditions defined for this example application:

1.5.1.1 X reach

The X reach for Zone 1 is calculated using the total reactance of the mixed configuration.

$$X_{Zone1} = X_{sum} \cdot zone1_{reach} = 32{,}935 \cdot 80\% = 26{,}348\ \Omega$$

1.5.1.2 Zone 1 Physical Boundary (km or %)

The calculated X-reach of Zone 1 is used to determine the location of this physical boundary (km) inside the mixed configuration:

If XZone1 < XCab1 then the boundary is on Cab1.
If (XZone1 - XCab1) < XOHL then the boundary on OHL.
If XZone1 > XCab1+ XOHL then the boundary on Cab2.

$X_{Zone1} - X_{Cab1} = 26{,}348 - 4{,}02 = 22{,}328\ \Omega$ $X_{OHL} = 25{,}9\Omega$

The Zone 1 boundary is therefore on the OHL section of the mixed feeder configuration. The physical location of the boundary (in km along the OHL) is determined as follows:

$$Zone1_{Boundary_{OHL}} = \frac{X_{Zone1} - X_{Cab1}}{X_{OHL}} \cdot Length_{OHL} = \frac{22{,}328\ \Omega}{25{,}9\Omega} \cdot 100km = 86{,}21\ km$$

It is more practical for the calculation to express the above physical boundary as percentage reach into the OHL section.

$$Zone1_{Boundary_{OHL}} = \frac{X_{Zone1} - X_{Cab1}}{X_{OHL}} \cdot Length_{OHL} = \frac{22{,}328\ \Omega}{25{,}9\Omega} = 86{,}21\ \%$$

1.5.1.3 Zone 1 compensation parameters (Kr, Kx, and Line Angle)

This boundary is applied to the following calculations.

Impedance upto Zone 1 Boundary	Equation	Value	Result
$R1_{Zone1}$	$= R1_{Cab1} + R1_{OHL} \cdot Zone1_{Boundary_{OHL}}$	$= 0{,}272 + 2{,}98 \cdot 86{,}21\%$	$= 2{,}841\Omega$
$X1_{Zone1}$	$= X1_{Cab1} + X1_{OHL} \cdot Zone1_{Boundary_{OHL}}$	$= 4{,}02 + 25{,}9 \cdot 86{,}21\%$	$= 26{,}348\Omega$
$R0_{Zone1}$	$= R0_{Cab1} + R0_{OHL} \cdot Zone1_{Boundary_{OHL}}$	$= 2{,}23 + 13{,}41 \cdot 86{,}21\%$	$= 13{,}791\Omega$
$X0_{Zone1}$	$= X0_{Cab1} + X0_{OHL} \cdot Zone1_{Boundary_{OHL}}$	$= 7{,}236 + 82{,}88 \cdot 86{,}21\%$	$= 78{,}686\Omega$

The results in the above table can now be applied to calculate the compensation factors (Kr and Kx) and the line angle at the zone 1 boundary. This ensures best possible accuracy at the zone boundary and therefore optimal zone selectivity.

$$Kr_{Zone1} = \left(\frac{R0_{Zone1}}{R1_{Zone1}} - 1\right) \cdot \frac{1}{3} = \left(\frac{13{,}791\ \Omega}{2{,}841\ \Omega} - 1\right) \cdot \frac{1}{3} = 1{,}34$$

$$Kx_{Zone1} = \left(\frac{X0_{Zone1}}{X1_{Zone1}} - 1\right) \cdot \frac{1}{3} = \left(\frac{78{,}686\ \Omega}{26{,}348\ \Omega} - 1\right) \cdot \frac{1}{3} = 0{,}63$$

$$Line\_angle_{Zone1} = arctan\left(\frac{X1_{Zone1}}{R1_{Zone1}}\right) = \left(\frac{26{,}348\ \Omega}{2{,}841\ \Omega}\right) = 83{,}85°$$

These settings are applied as Zone Specific settings to Zone 1.

1.5.2 Zone 2, 3 and 4 parameters

For Zone 2, 3 and 4 the settings will be calculated based on the overall (sum) of the feeder impedance:

1.5.2.1 X reach

The X reach for Zone 2, 3, and 4 are calculated using the total reactance of the mixed configuration.

$$X_{Zone2} = X_{sum} \cdot zone2_{reach} = 32{,}935 \cdot 120\% = 39{,}522\ \Omega$$

$$X_{Zone3} = X_{sum} \cdot zone3_{reach} = 32{,}935 \cdot 150\% = 49{,}403\ \Omega$$

$$X_{Zone4} = X_{sum} \cdot zone4_{reach} = 32{,}935 \cdot 40\% = 26{,}348\ \Omega$$

1.5.2.2 Zone 2, 3 and 4 compensation parameters (Kr, Kx, and Line Angle)

These are calculated with the total feeder impedance.

Total Impedance of feeder	Equation	Value	Result
R1 Total	$= R1_{Cab1} + R1_{OHL} + R1_{Cab2}$	$= 0{,}272 + 2{,}98 + 0{,}2014$	= 3,456Ω
X1 Total	$= \mathrm{X1}_{Cab1} + \mathrm{X1}_{OHL} \cdot + X_{Cab2}$	$= 4{,}02 + 25{,}9 + 3{,}015$	= 32,935Ω
R0 Total	$= R0_{Cab1} + R0_{OHL} + R0_{Cab2}$	$= 2{,}23 + 13{,}41 + 1{,}673\%$	= 17,313Ω
X0 Total	$= X0_{Cab1} + X0_{OHL} + X0_{Cab1}$	$= 7{,}236 + 82{,}88 + 5{,}427$	= 95,543Ω

The results in the above table can now be applied to calculate the compensation factors (Kr and Kx) and the line angle.

$$Kr_{gen} = \left(\frac{R0_{Zone1}}{R1_{Zone1}} - 1\right) \cdot \frac{1}{3} = \left(\frac{17{,}313\ \Omega}{3{,}456\ \Omega} - 1\right) \cdot \frac{1}{3} = 1{,}34$$

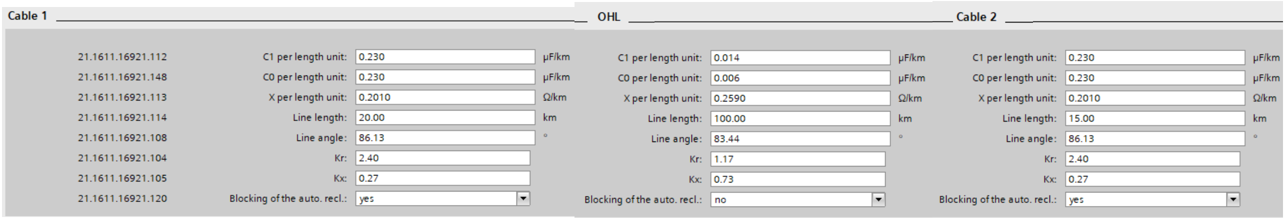
$$Kx_{gen} = \left(\frac{X0_{Zone1}}{X1_{Zone1}} - 1\right) \cdot \frac{1}{3} = \left(\frac{95{,}543\ \Omega}{32{,}935\ \Omega} - 1\right) \cdot \frac{1}{3} = 0{,}63$$

$$Line\_angle_{gen} = arctan\left(\frac{X1_{Zone1}}{R1_{Zone1}}\right) = \left(\frac{32{,}935\ \Omega}{3{,}456\ \Omega}\right) = 84{,}01°$$

These settings may be applied as general settings, or as Zone Specific settings to Zone 2, 3 and 4.

1.6 Fault Locator Plus

The Fault Locator Plus function can be applied effectively in this case because it makes allowance for the individual configuration of each segment of the feeder. In this example the parameters for Cable1, OHL and Cable2 are set as follows:



Cable 1

21.1611.16921.112 C1 per length unit: 0.230 μF/km
21.1611.16921.148 C0 per length unit: 0.230 μF/km
21.1611.16921.113 X per length unit: 0.2010 Ω/km
21.1611.16921.114 Line length: 20.00 km
21.1611.16921.108 Line angle: 86.13 °
21.1611.16921.104 Kr: 2.40
21.1611.16921.105 Kx: 0.27
21.1611.16921.120 Blocking of the auto. recl.: yes

OHL

C1 per length unit: 0.014 μF/km
C0 per length unit: 0.006 μF/km
X per length unit: 0.2590 Ω/km
Line length: 100.00 km
Line angle: 83.44 °
Kr: 1.17
Kx: 0.73
Blocking of the auto. recl.: no

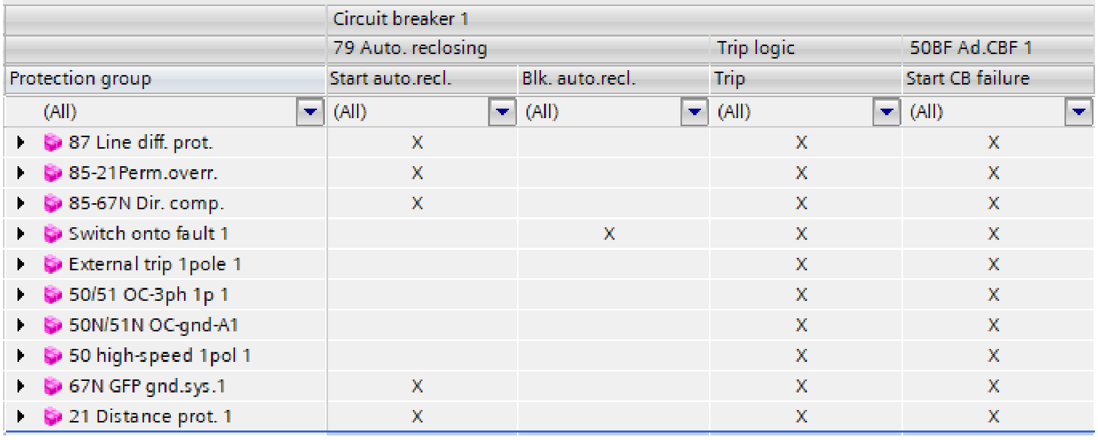
Cable 2

C1 per length unit: 0.230 μF/km
C0 per length unit: 0.230 μF/km
X per length unit: 0.2010 Ω/km
Line length: 15.00 km
Line angle: 86.13 °
Kr: 2.40
Kx: 0.27
Blocking of the auto. recl.: yes

To co-ordinate with the auto re-close, the “Blocking of the auto. Recl.” is set to “yes” on the cable segments and to “no” on the OHL segment.

1.7 Automatic Re-closure

The auto re-close function is started in the typical manner by means of the circuit breaker interaction. In this example the configuration is done as follows.



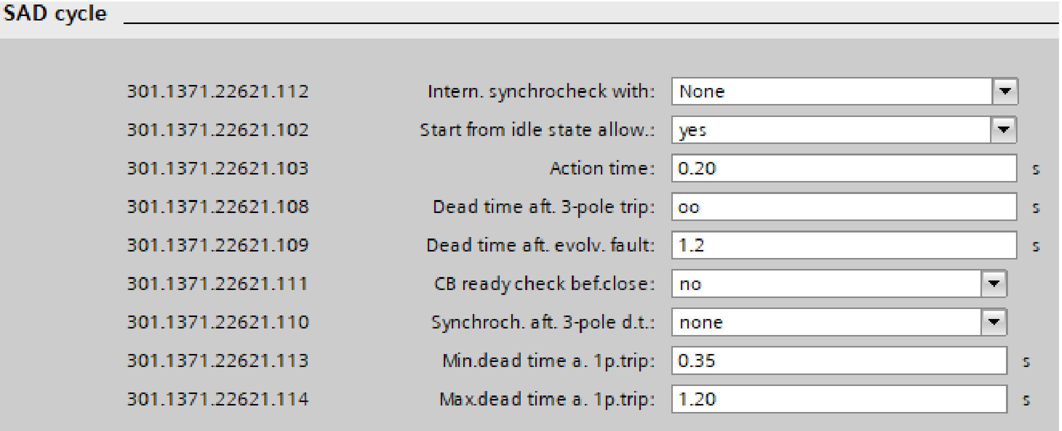
	Circuit breaker 1			
	79 Auto. reclosing		Trip logic	50BF Ad.CBF 1
Protection group	Start auto.recl.	Blk. auto.recl.	Trip	Start CB failure
(All)	(All)	(All)	(All)	(All)
87 Line diff. prot.	X		X	X
85-21Perm.overr.	X		X	X
85-67N Dir. comp.	X		X	X
Switch onto fault 1		X	X	X
External trip 1pole 1			X	X
50/51 OC-3ph 1p 1			X	X
50N/51N OC-gnd-A1			X	X
50 high-speed 1pol 1			X	X
67N GFP gnd.sys.1	X		X	X
21 Distance prot. 1	X		X	X

In the auto reclose the action time is used to prevent auto re-closure when tripping is with Zone 2 or slower.

1.7.1 Optional Secondary Arc Detection (SAD)

If the auto re-close is done with SAD, the re-closure onto permanent faults can be prevented. This is a very useful extension for OHL where it can prevent closure onto permanent (metallic) faults. In the mixed feeder application it provides an additional security measure to prevent closure for faults on the cable segments which will typically be metallic (permanent).

The 79 SAD is applied with only one stage in this example using the following settings:



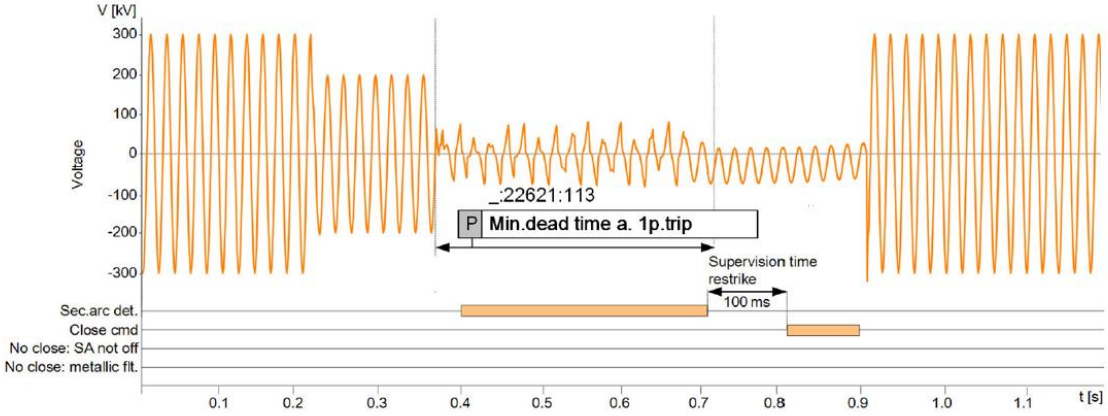
SAD cycle

301.1371.22621.112 Intern. synchrocheck with: None
301.1371.22621.102 Start from idle state allow.: yes
301.1371.22621.103 Action time: 0.20 s
301.1371.22621.108 Dead time aft. 3-pole trip: oo s
301.1371.22621.109 Dead time aft. evolv. fault: 1.2 s
301.1371.22621.111 CB ready check bef.close: no
301.1371.22621.110 Synchroch. aft. 3-pole d.t.: none
301.1371.22621.113 Min.dead time a. 1p.trip: 0.35 s
301.1371.22621.114 Max.dead time a. 1p.trip: 1.20 s

This ensures only re-closure on single pole trip (Dead time after 3-pole trip = ∞) with a minimum dead time of 350 ms when the secondary arc clears fast, alternatively a maximum dead time of 1.2 s when the secondary arc is slow to clear. If the secondary arc is permanent or the fault is metallic there is no re-closure.

1.7.2 Transient Fault (arc fault)

The recorded fault below shows the phase voltage during a ground fault. In this case the fault arc extinguishes approximately 30 ms after the breaker opens. This allows short dead time as the SAD detects disappearance of the secondary arc and the appearance of the capacitively coupled fundamental frequency voltage.



[dw_SAD-times_3-legend, 1, en_US]

Figure 2: Arc fault with secondary arc duration of 30 ms – ARC close with dead time of 500 ms

1.7.3 Permanent Fault (metallic)

A permanent fault (not arc fault) will produce a voltage as shown in the diagram below. The very small (near zero) voltage after the breaker opens is an indication that the fault is permanent and auto re-close would not be successful.

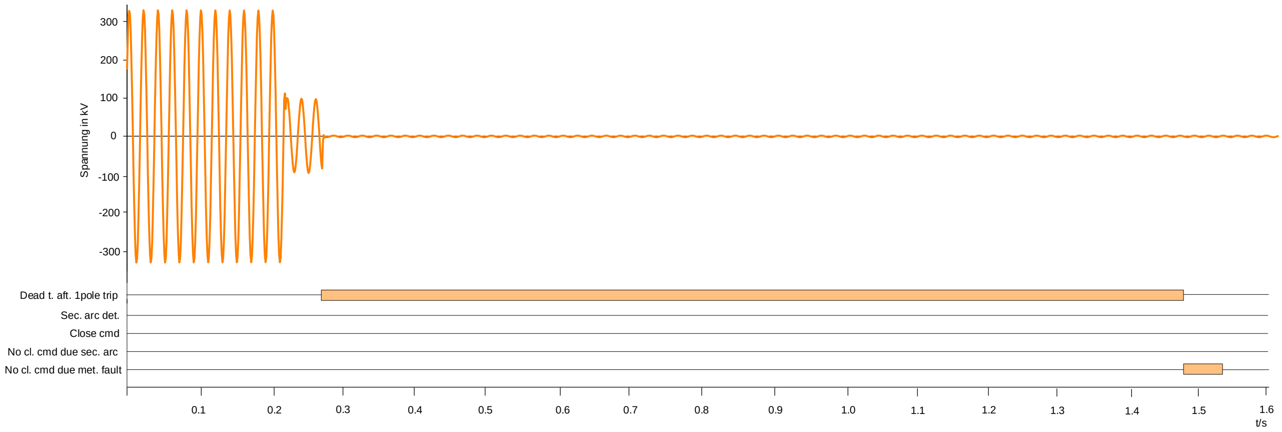


Figure 3: Metallic fault SAD blocks the auto re-close

As can be seen in the diagrams above the SAD function can re-close with very short dead times on transient faults while at the same time preventing re-closure on permanent faults.

1.8 Test Cases

To illustrate the effectiveness of the applied functions some test cases are used. Initially the 1-phase to ground faults are applied at various locations. Full load current (1700A) and fault resistance.

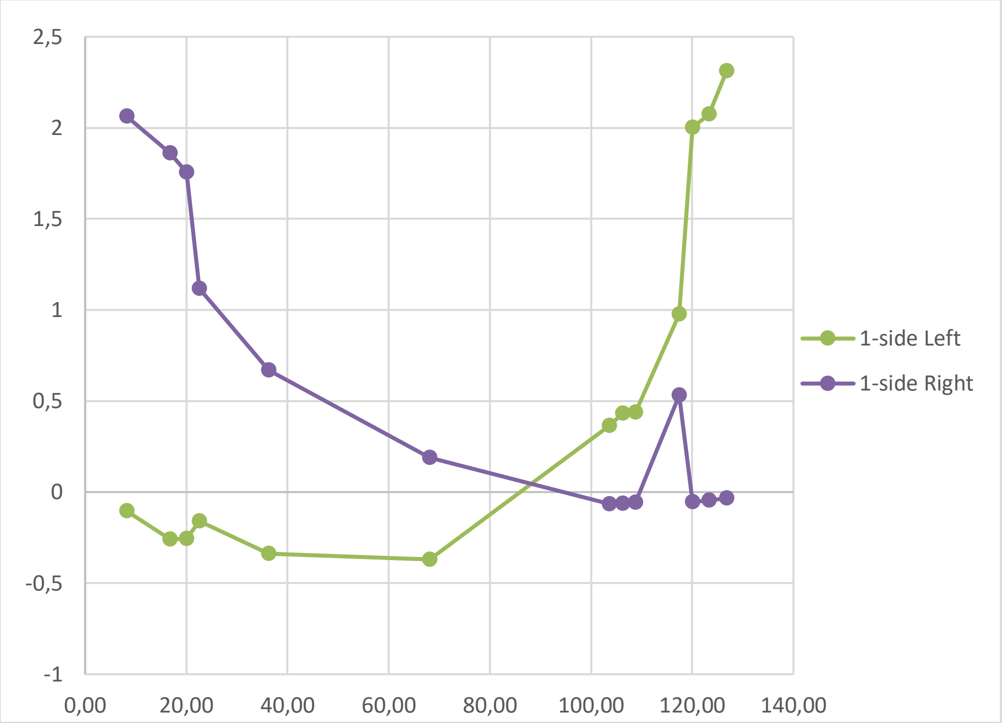


Figure 4: Fault location 1-sided

It is apparent that the single sided fault location is very accurate for faults up to approximately 80% of the feeder; tolerance less than 500 m. It is therefore better to use the result of the side that is closer to the fault.

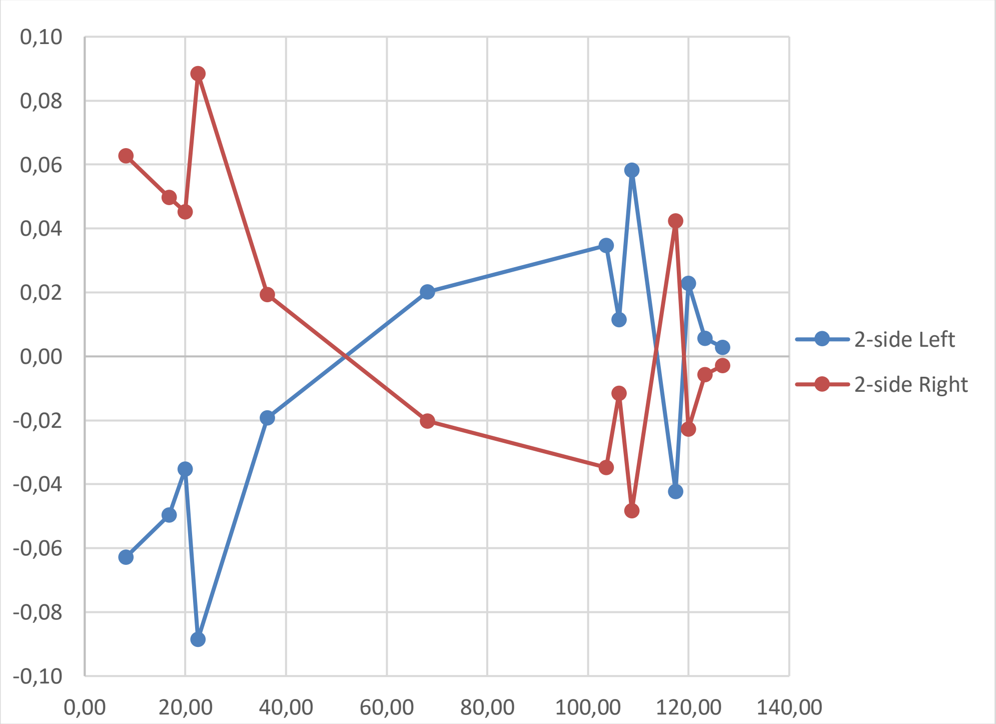


Figure 5: Fault location 2-sided

When the communication is available, the 2-sided fault location provides very good results for all fault locations with tolerance less than 100 m.

The selective protection response of both 87L and 21 was also proven with the tests. The accuracy of the fault locator effectively controlled the auto reclose so that there were no re-close for faults on the cable sections.

1.9 Conclusion

The protection and auto reclosure on mixed feeders are effectively done with the SIPROTEC5 devices. The standard functionality along with some special features ensures a transparent solution with clear reporting of the operation.

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For the U.S. published by
Siemens Industry Inc.

100 Technology Drive
Alpharetta, GA 30005
United States

For more information, please
contact our Customer Support
Center.

Tel.: +49 180 524 70 00
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