Distance Protection with Parallel Compensation

Environmental and cost consciousness are forcing utilities to install more and more parallel lines. The close arrangement of the transmission lines leads to a higher fault rate and to influencing of the measuring results. The considerable influence exerted by parallel lines on the measuring results (of up to 30 % in distance protection) and the remedial actions are considered in this application example.

■ 1. Explanation of the term parallel line

1.1 Parallel lines with common positive and negative-sequence systems

The two parallel lines have the same infeed at both line ends.

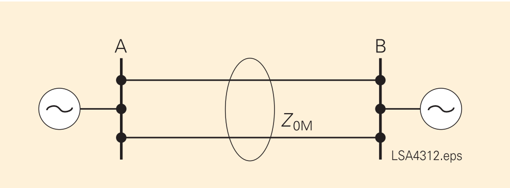

Fig. 1 Parallel lines with same infeed at both line ends

In this arrangement where both systems are connected with the same infeed, it is possible (for distance protection) to compensate the influence of the parallel line.

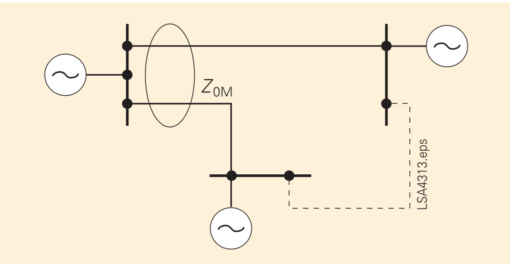

Fig. 2 Parallel line with only one common infeed

In this arrangement of parallel lines the effect can only be compensated on one side.

Fig. 3 Parallel lines over the Bosporus

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1.2 Parallel lines with common positive-sequence and independent zero-sequence system

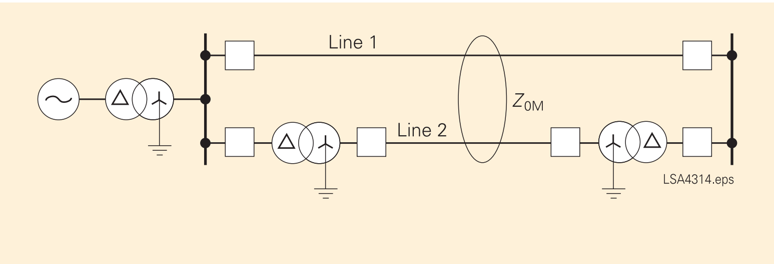


Fig. 4 Parallel line with common infeed at a common tower

This arrangement of parallel lines does not influence the distance measurement.

1.3 Parallel lines with isolated positive and zero-sequence systems

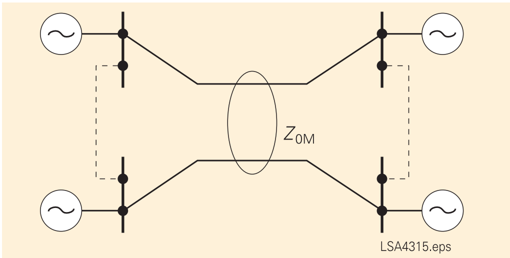


Fig. 5 Parallel lines with separate infeed

This is the most unfavorable arrangement for distance protection. Compensation of the inductive coupling of the circuits is not possible.

This arrangement causes a complicated fault voltage and current distribution due to the inductive coupling.

2. General

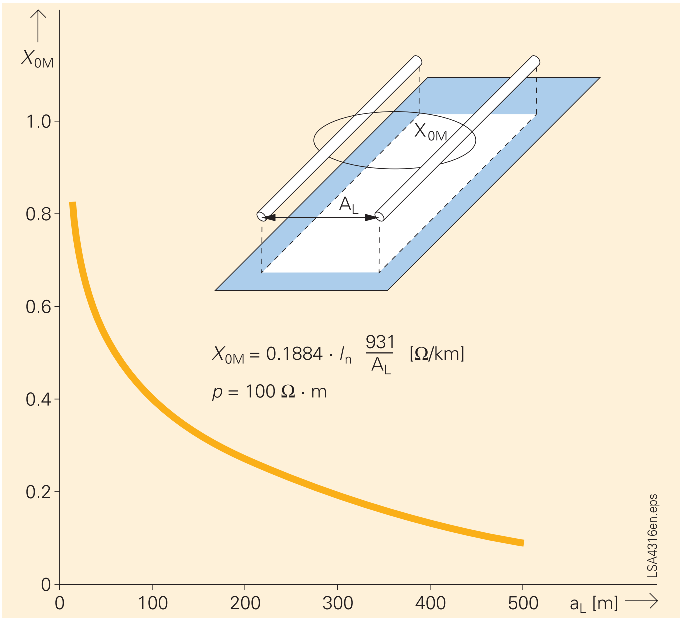


Fig. 6 Inductive coupling of parallel lines

When overhead lines follow parallel paths, a mutual, inductive coupling of the current paths exists. In the case of transposed lines, this effect in the positive and negative sequence system may be neglected for all practical purposes (mutual reactance less than 5 % of the self-impedance). This implies that during load conditions, and for all short-circuits without earth, the lines may be considered as independent.

During earth-faults, the phase currents do not add up to zero, but rather a summation current corresponding to the earth-current results. For this summated current, a fictitious summation conductor placed at the geometrical centre of the phase-conductors models the three-phase system. Two lines in parallel are modelled by two parallel single conductors with an earth return path, for which the mutual reactance must be calculated. In the case of lines with earth-wires, an additional coupling results, which must be considered in the calculations. The coupling impedance can be calculated as follows:

$$Z_M' = \frac{\pi \cdot \mu_0}{4} \cdot f + j_{\mu 0} \cdot f \cdot l_n \frac{\vartheta}{D_{ab}} \quad \left[\frac{\Omega}{km}\right]$$

$$\mu_0 = 4\pi \cdot 10^{-4} \quad \left[\Omega \cdot \frac{s}{km}\right]$$

$$\vartheta = 658\sqrt{\frac{\rho}{f}}$$

ϑ = Depth of penetration in ground
f = Frequency in Hz
ρ = Specific resistance in Ω / m
D_{ab} = Spacing in meters between the two conductors

For a typical value of the specific earth resistance of ρ = 100 Ω/m, a system frequency of 50 Hz, a conductor spacing of 20 m and an earth-fault of I_a = 1000 A, the following result is arrived at.

$$Z_M' = 0.05 + j\,0.24\ \Omega / km$$

Then the induced voltage in the parallel conductor can be calculated with $U_b = Z_M \cdot I_a$, and 250 V per km is obtained.
On a 100 km parallel line, this would give an induced voltage in the conductor of 25 kV.

3. Calculation of the measuring error of the distance protection caused by a parallel line in the event of an earth fault

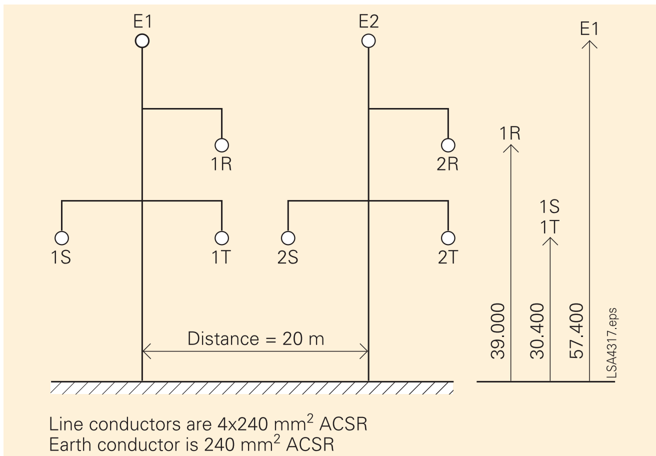


Fig. 7 Tower diagrams

	Earth resistance 100 Ω/ m
Positive impedance (Ω / km)	0.032 + j 0.254
Zero impedance (Ω / km)	0.139 + j 0.906
Coupling impedance (Ω / km)	0.107 + j 0.488

$R1$ = 0.032 Ω / km
$X1$ = 0.254 Ω /km
R_0 = 0.139 Ω / km
X_0 = 0.906 Ω / km
R_{0M} = 0.107 Ω / km
X_{0M} = 0.488 Ω / km

$$\frac{\underline{Z}_E}{\underline{Z}_L} = \frac{\underline{Z}_0 - \underline{Z}_1}{3 \cdot \underline{Z}_1} = 0.86$$

$$\frac{\underline{Z}_M}{\underline{Z}_L} = \frac{\underline{Z}_0 - \underline{Z}_1}{3 \cdot \underline{Z}_1} = 0.65$$

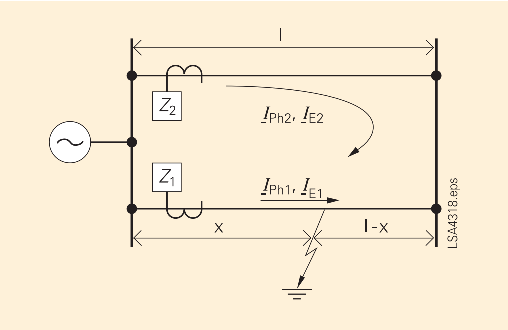


Fig. 8 Parallel line with an infeed without parallel line compensation

Phase current :
$I_{LA} = I_{A1}+I_{A2}+I_{A0}$ $\quad$ $I_{LB} = I_{B1}+I_{B2}+I_{B0}$

Earth current:
$I_{EA} = 3\ I_{A0}$ $\quad$ $I_{EB} = 3\ I_{B0}$

$K_0 = (Z_{Lo} - Z_{L1}) / 3\ Z_{L1}$
$K_{0M} = Z_{0M} / 3\ Z_{L1}$
$I_{C0} / I_{A0} = x / 2\text{-}x$

For measured impedance Z_A for the distance relay Z_1 is

$$\underline{Z}_1 = \frac{x}{l} \cdot \underline{Z}_L + \frac{x}{l} \cdot \underline{Z}_L \underbrace{\frac{\frac{\underline{Z}_{0M}}{3 \cdot \underline{Z}_L} \cdot \frac{x}{2l - x}}{1 + \frac{\underline{Z}_E}{\underline{Z}_L}}}_{\text{Measuring error}}$$

The measured impedance Z_B for the distance relay Z_2 is

$$\underline{Z}_2 = (2 \cdot l - x) \cdot \underline{Z}_L + \underbrace{\frac{x \cdot \frac{\underline{Z}_{0M}}{3 \cdot \underline{Z}_L}}{1 + \frac{\underline{Z}_E}{\underline{Z}_L}}}_{\text{Measuring error}}$$

By placing the values in the equations we can calculate the measuring errors for this double-circuit line with single-end infeed.
The results are shown in the diagram below:

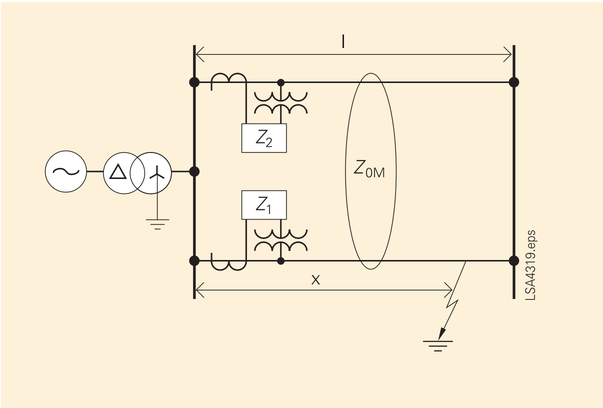


Fig. 9 Double-circuit line with single-end infeed

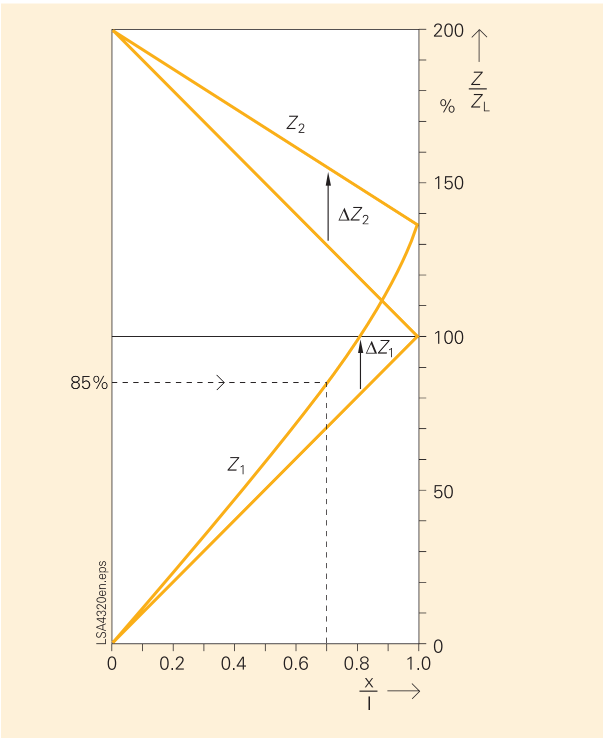


Fig. 10 Distance measuring error on a double-circuit line with single-end infeed

The greatest measuring deviation (35 %) occurs in the event of a fault at the end of the line, because the coupled length up to the fault position is at maximum.

This example shows that the zone reach needs to be reduced to 70 % to avoid overreaching in the event of earth faults.

3.1 Result

- The fault is proportional to $K_{0M} = Z_{0M} / 3\ Z_{L1}$
- The fault increases with the ratio of the earth current of the parallel line I_{EP} to the earth-fault current of the relay
- The relay has an underreach when the earth-fault current of the parallel line and the earth current of the relay are in phase (same direction)
- The relay has an overreach when the earth-fault current of the parallel line and the earth current of the relay have opposite phase (opposite direction).

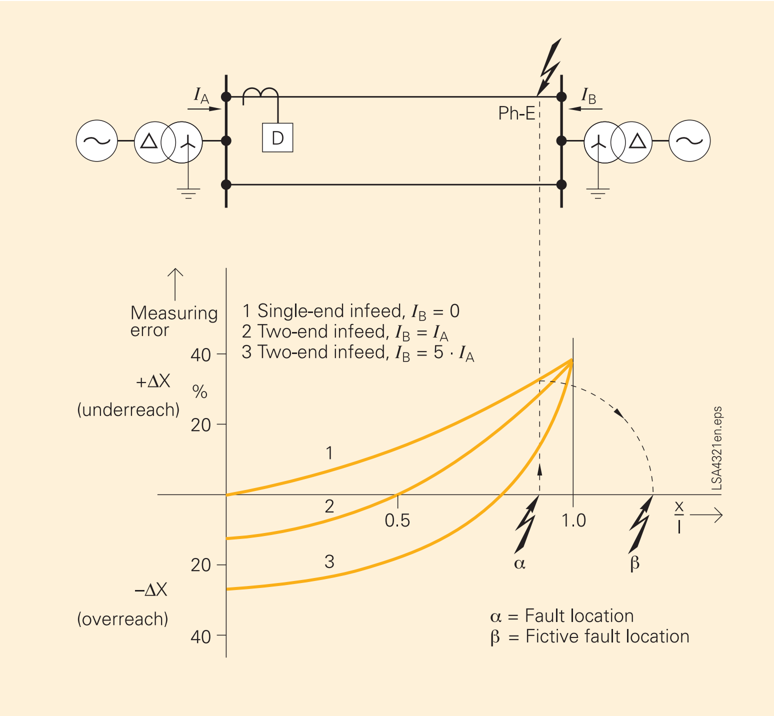


Fig. 11 Earth fault on a double-circuit line with two-end infeed

The measuring error of the relay on the faulty line with two-end infeed is shown in the above diagram. It can be seen that the fault becomes negative in the case of faults in the first 50 % of the line under the same infeed conditions. This is exactly the reach where the earth current on the parallel line flows in the opposite direction.

The following figures show that the parallel line influence changes strongly with the switching state of the parallel line. The reason is the different earth-current distribution.

$$\underline{Z}_{ph-E} = \frac{\underline{U}_{ph-E}}{\underline{I}_{ph-E} + \underline{k}_E \cdot \underline{I}_E + \underline{k}_{EM} \cdot \underline{I}_{Ep}}$$

with $\underline{k}_{EM} = \dfrac{\underline{Z}_{0M}}{3 \cdot \underline{Z}_{1L}}$

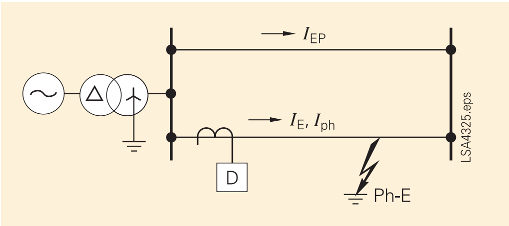


Fig. 12 Fault at the line end

$$\Delta Z = \frac{k_{EM}}{1 + k_E} \cdot Z_L \triangleq 24\ \%\ \text{von}\ Z_L$$

Fault at the line end (Fig. 12):
Infeed sources for positive-sequence and zero-sequence system at the line end

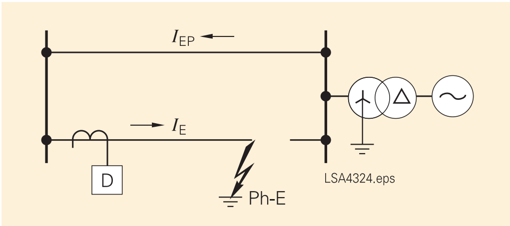


Fig. 13 Fault at the line end with open circuit-breaker

$$\Delta Z = -\frac{k_{EM}}{1 + k_E} \cdot Z_L \triangleq 24\ \%\ \text{von}\ Z_L$$

Fault at the line end (Fig. 13):
One switch open, star-point earthing and relay at opposite ends.

$$\Delta Z = \frac{3 \cdot k_{EM}}{1 + k_E} \cdot Z_L = \frac{Z_{0M}}{Z_0} \cdot Z_L \triangleq 40\ \%\ \text{of}\ Z_L$$

Fault at line end (Fig. 14):

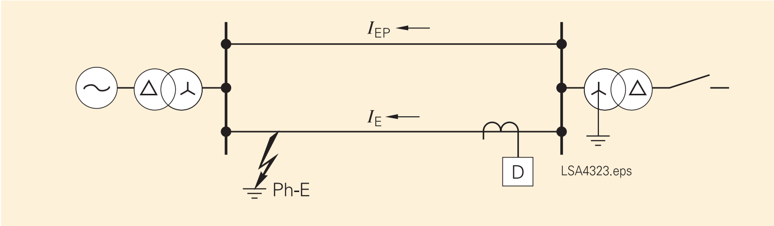


Fig. 14 Infeed sources of the positive and zero-sequence systems at opposite line ends

$$\Delta Z = -Z_L \cdot \frac{k_{EM} \cdot \frac{Z_{0M}}{Z_{0L}}}{1 + k_E} \triangleq -10\ \%\ \text{of}\ Z_L$$

Fault at line end (Fig. 15):

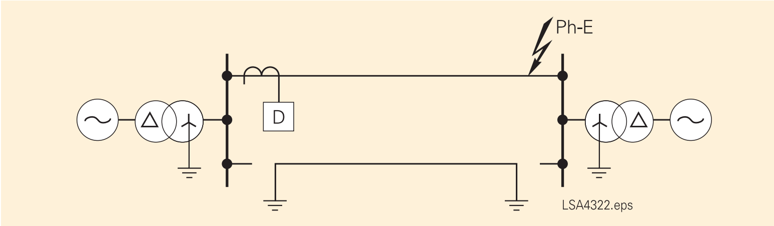


Fig. 15 Parallel line disconnected and earthed at both ends

4. Parallel line compensation

In order for the distance protection to be able to operate with parallel line compensation, it is assumed that it receives I_{EP} of the parallel line as a measuring variable.

$$\underline{Z}_A = \frac{\underline{U}_A}{\underline{I}_{ph} + \underline{k}_E \cdot \underline{I}_E}$$

$$= \frac{\underline{Z}_{1L}\left(\underline{I}_{ph} + \frac{\underline{Z}_{EL}}{\underline{Z}_{1L}} \cdot \underline{I}_E + \frac{\underline{Z}_{0M}}{3 \cdot \underline{Z}_{1L}} \cdot \underline{I}_{Ep}\right)}{\underline{I}_{ph} + \underline{k}_E \cdot \underline{I}_E}$$

As can bee seen from the equation the fault impedance is measured correctly when we add the term $\frac{\underline{Z}_{0M}}{3 \cdot \underline{Z}_{1L}} \cdot \underline{I}_{EP}$ in the denominator. With the normal setting $\underline{k}_E = \underline{Z}_E / \underline{Z}_L$ the denominator is then reduced against the bracketed expression in the counter and $\underline{Z}_{1L}$ is produced as measured result.

The distance protection has another measuring input to which the earth current of the parallel line is connected. The addition is numeric. It should be noted that the relay on the healthy line sees the fault at too short a distance due to coupling of the earth current of the parallel line. If zone 1 of the line without a fault is set to 85 %, the distance protection would lead to an overreach through the fed parallel fault. The distance protection would still see faults on the parallel line at up to 55 % line length in zone 1.

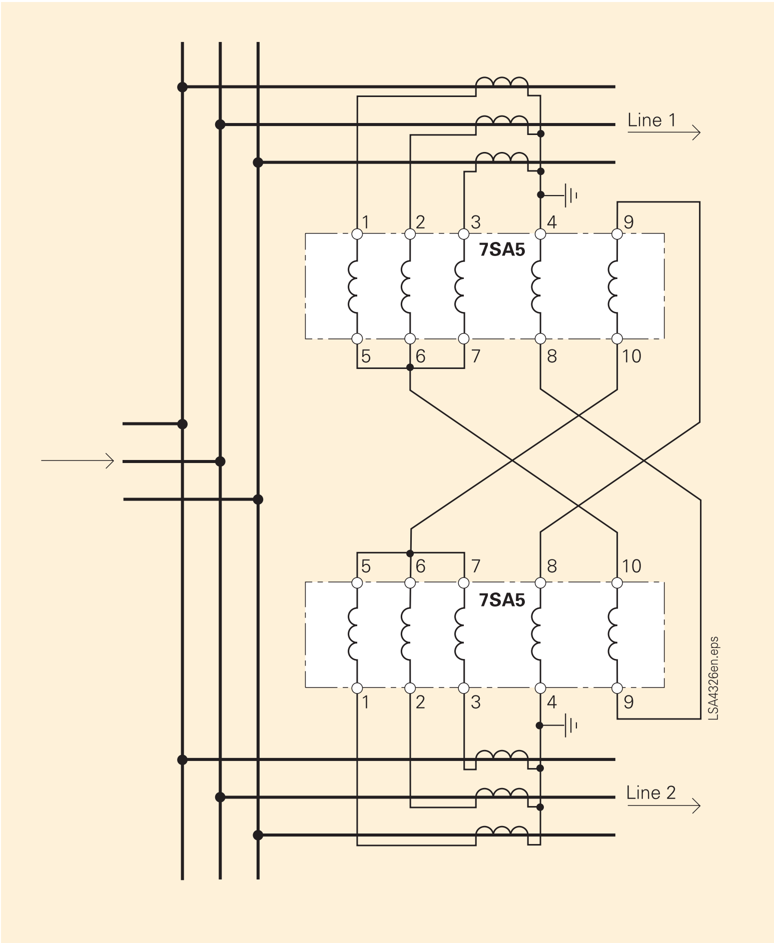


Fig. 16 Connection of the parallel line compensation

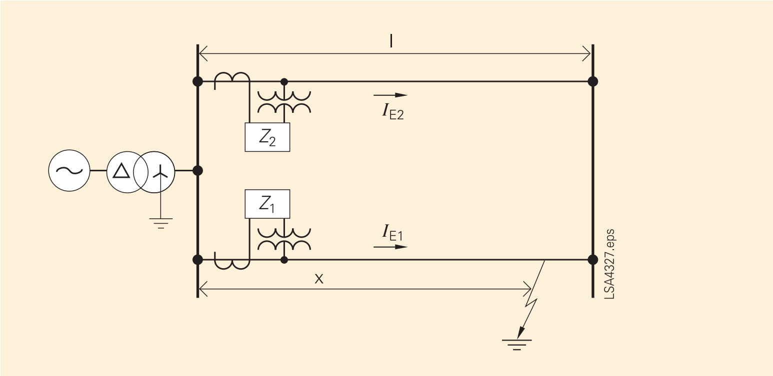


Fig. 17 Distance measurement with parallel line compensation

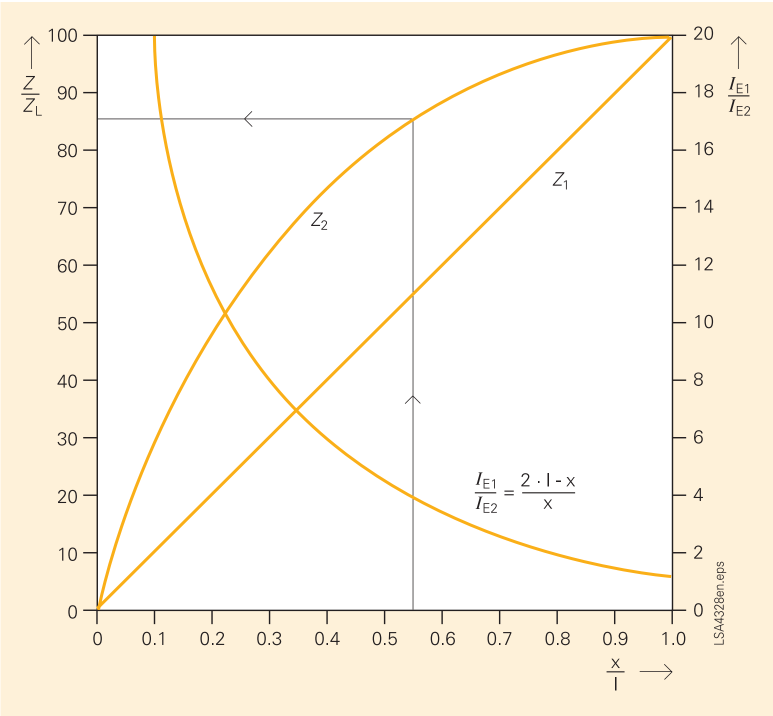


Fig. 18 Effect of the parallel line compensation

$$\left(\frac{Z_E}{Z_L} = 0.86 \,/\, \frac{Z_{0M}}{3 \cdot Z_L} = 0.65 \right)$$

Z_L = line impedance

The so-called earth-current balance is used to prevent this overfunction. It compares the earth currents of both line systems and blocks the parallel line compensation when the earth current of the parallel line exceeds the earth current of the own line by a settable factor.

$$\frac{I_{E1}}{I_{E2}} = \frac{2 \cdot l - x}{x} = \frac{2 - \frac{x}{l}}{\frac{x}{l}}$$

At a setting of x/l of 85 %, the parallel line compensation is effective for faults on the own line and for a further 15 % into the parallel line. This results in a factor of $I_{E1} / I_{E2} = 1.35$ as a standard value for the earth-current balance.

Setting instructions for the parallel line compensation

- The compensation is only possible where both lines end in the same station.
- In the distance protection the compensation is only used where no sufficient backup zone is possible without compensation (When the double-circuit line is followed by short lines).

Example:

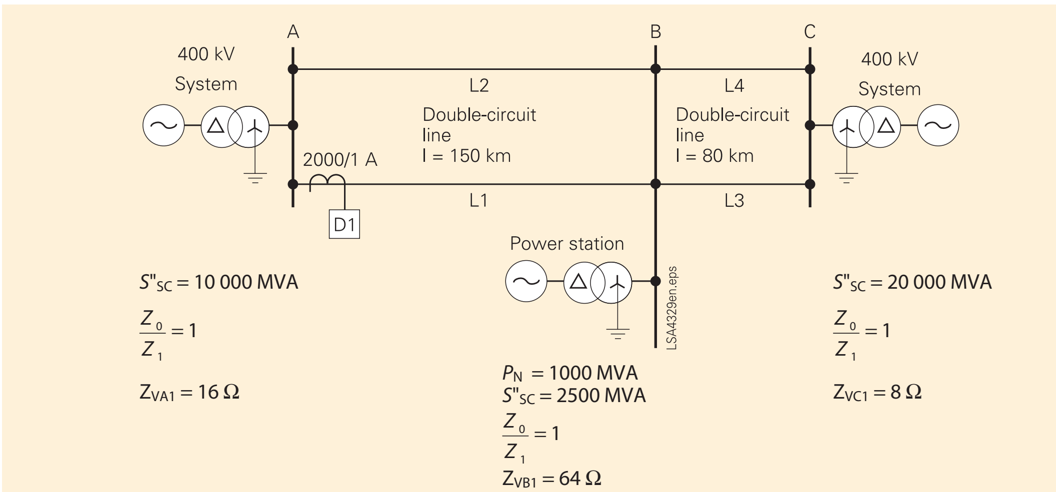


Fig. 19
Example of a double-circuit line station

5. Calculation examples

The procedure for setting a normal single-circuit line is explained in the available manuals. Special applications are dealt with here.

5.1 Double-circuit line in earthed system

The coupling in the zero-sequence system requires detailed consideration of the zone setting for earth faults.

5.2 General procedure

It is recommended to first determine the grading of the distance zones for phase faults without taking into account the parallel line coupling. In the second step the zone reaches are then checked for earth faults and a suitable earth-current compensation factor selected.
The use of parallel line compensation must be considered so that an adequate remote backup protection can be ensured in the event of earth faults.

5.3 Grading of the distance zones for phase-to-phase short-circuits

The zones must be set according to the basic rules of grading plans. For the backup zones, the parabolic course of the impedance dependent on the fault location is important.
When double-circuit lines are connected in series there are also different reaches of the backup zones dependent on the switching state and the infeed at the opposite end.
Theoretically speaking, this results in relatively high effort for creating the grading plan of double-circuit lines.
The procedure is usually simpler in practice. Half the impedance of the following parallel line can be used for practical grading of the second zone (double-circuit line follows single-circuit line). This gives:

$$Z_{2A} = GF2 \cdot (Z_{A\text{-}B} + 0.5 \cdot Z_{B\text{-}C})$$

In the third zone, the grading should be performed according to the backup protection strategy. A selective grading for all switching states leads to relatively short third stages which hardly get any longer than the corresponding second stage. In the high and extra-high voltage system, an attempt will be made for the third stage to cover the following double-circuit line in normal parallel line mode. In this case the following step setting is derived:

$$Z_{3A} = 1.1 \cdot (Z_{A\text{-}B} + Z_{B\text{-}C})$$

In the pickup zone the following lines should be in the protected zone in the worst switching state (single line follows parallel line). The following setting should be set for this:

$$Z_{+AA} = 1.1 \cdot (Z_{A-B} + 2 \cdot Z_{B-C})$$

As a rule infeeds are available in the intermediate stations of the double-circuit line which have to be taken into account in the grading of the backup zones. This is demonstrated by the following example (see Fig. 19):

Double-circuit line.
Setting of the distance zones for phase-to-phase short-circuits

Given:
100 kV double-circuit line
Line data:
Configuration according to
l_1 and l_2 = 150 km, l_3 and l_4 = 80 km
Z_{1L}'= 0.0185 + j 0.3559 Ω/km
Z_{0L}'= 0.2539 + j 1.1108 Ω/km
Z_{0M}'= 0.2354 + j 0.6759 Ω/km
$P_{nat.}$ = 518 MW per line
Current transformer: 2000/1 A
Voltage transformer: 400/0.1 kV

Task:
Calculation of the zone setting for relay D1.

Solution:
Only X values are used in the short-circuit calculations, for the sake of simplicity:
$X_{L1} = X_{L2}$ = 0.3559 Ω/km · 150 km = 53.4 Ω
$X_{L3} = X_{L4}$ = 0.3559 Ω/km · 80 km = 28.5 Ω
We generally apply a grading factor (GF) of 85 %.
The zone reaches are calculated as follows:
X_1 = 0.85 · 53.4 Ω
For selective grading of the 2nd stage it is assumed that the parallel line L2 is open but that always at least half the short-circuit power is available from the intermediate infeed in B. Grading takes place selectively to the end of the 1st zone of the distance relays of the following lines 3 and 4. That means we can use about half the line impedance. This gives a simplified equivalent circuit. For a three-pole fault in C we calculate the short-circuit currents drawn in the figure.

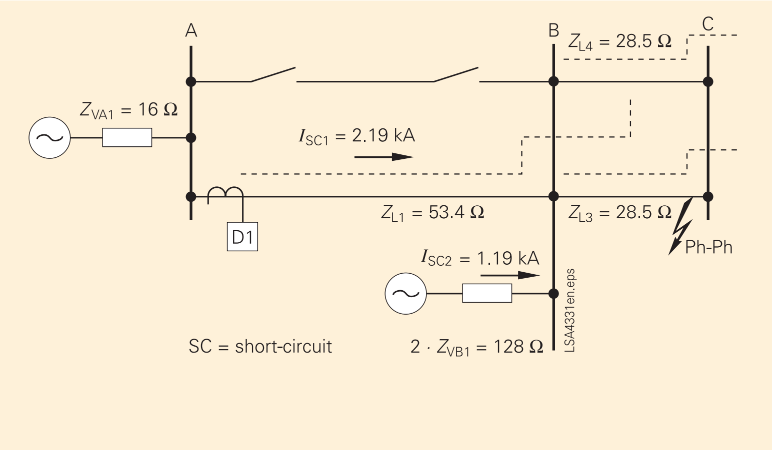


Fig. 20 Protection setting in double-circuit lines: System data for the calculation example

Under consideration of the intermediate infeed effect we get

$$X_2 = \left[53.4 + \frac{28.5}{2} \cdot \left(1 + \frac{1.19}{2.19}\right)\right] \cdot 0.85 =$$

$$64\ \Omega = 120\ \%\ X_{L1}$$

According to the above recommendation we get for zone 3

$$X_3 = (53.4 + 28.5) \cdot 1.1 = 90.1\ \Omega = 169\ \%\ X_{L1}$$

and for the pickup zone:

$$X_{+A} = (53.4 + 2 \cdot 28.5) \cdot 1.1 = 121\ \Omega = 226\ \%\ X_{L1}$$

we adapt the reach of the zones in R direction to the impedance of the natural power:

$$Z_{Nat.} = \frac{U_{N^2}}{P_{Nat.}} = \frac{400^2}{518} = 309\ \Omega$$

We assume that a new line has to transmit double the power temporarily and allow an additional safety margin of 30 %. This gives the maximum R reach of pickup as:

$$RA1 = 0.7 \cdot \frac{309}{2} = 108\ \Omega$$

We further select φ_A = 50° and
*RA*2 = 2 · RA1 = 208 Ω

An R/X ratio of 1 offers adequate compensation for fault resistance for the distance zones.

5.4 Zone reach during earth faults

The earth-current compensation factor $\underline{k}_E$ is decisive in the Ph-E measuring systems. For single-circuit lines this is set to the corresponding $\underline{Z}_F/\underline{Z}_L$ value. The protection then measures the same impedance for Ph-Ph and earth faults.
On double-circuit lines the zero-sequence system coupling produces a measuring error for earth faults. The measurement can be corrected with the parallel line compensation. This function is contained optionally in the relays 7SA. Only the earth current of the parallel line needs to be connected to the relay and the coupling impedance set. The earth-current balance may be left at the standard value x/l = 85 %. The earth-current factor must be adapted to the single-circuit line in this case.

5.5 Setting of the $\underline{k}_E$ factor (operation without parallel line compensation)

In the event that the parallel line compensation is not used, a $\underline{k}_E$ factor must be found which ensures adequate protection for the possible operating states of the double-circuit line (see Table 1).

a) This equation applies for $\frac{x}{l} \leq 1$

For $\frac{x}{l} > 1$ it applies that: $\dfrac{GF1(1+k_{XER}) + k_{XEM} \cdot \dfrac{X'_{0M}}{X'_{0L}}}{1+k_{XEL}}$

b) $k_{XEL} = \left(\dfrac{X'_{EL}}{X'_{1L}} \right)_{Line}$

c) $k_{XEM} = \left(\dfrac{X'_{0M}}{3 \cdot X'_{0L}} \right)_{Line}$

Adapting the setting to a particular operating state causes an overreach or underreach in the respective other states. GF1 in % is the selected grading factor for the 1st zone (reach for phase-to-phase faults). *x/l* in % then specifies how far the zone 1 (Ph- E loop) reaches in the event of earth faults, referred to the line length.

Determining of the relay setting value $\underline{k}_{ER}$ is demonstrated by the example of double-circuit line operation. For a fault at the distance *x*/*l*, the voltage at the relay location is:

$$\underline{U}_{Ph\text{-}E} = \frac{x}{l} \underline{Z}_L \cdot \underline{I}_{Ph} + \frac{x}{l} \underline{Z}_E \cdot \underline{I}_E + \frac{x}{l} \frac{\underline{Z}_{0M}}{3} \cdot \underline{I}_{EP}$$

Whereby with single-end infeed:

$$I_{Ph} = I_E \text{ and } I_{EP} = \frac{\frac{x}{l}}{2 - \frac{x}{l}} \cdot I_E$$

For the measurement on the Ph-E loop the result is

$$\underline{Z}_{Ph-E} = \frac{\underline{U}_{Ph\text{-}E}}{\underline{I}_{Ph} + \underline{k}_{ER} \cdot \underline{I}_E} = \frac{x}{l} \cdot \frac{\underline{Z}_L + \underline{Z}_E + \dfrac{\underline{Z}_{0M}}{3} \cdot \dfrac{\frac{x}{l}}{2 - \frac{x}{l}}}{1 + \underline{k}_{ER}}$$

$\underline{k}_{ER}$ is the complex earth-current compensation factor set at the relay.
X and R are calculated separately for the numerical relays 7SA. Simplified equations apply for this if phases and earth currents have the same phase relation.

This results in:

$$X_{Ph-E} = \frac{U_{Ph-E} \cdot \sin \varphi_{SC}}{I_{Ph} + \left(\dfrac{X_E}{X_L} \right)_R \cdot I_E} = \frac{x}{l} \cdot X_L \cdot \frac{1 + \dfrac{X_E}{X_L} + \dfrac{X_{0M}}{3 \cdot X_L} \cdot \dfrac{\frac{x}{l}}{2 - \frac{x}{l}}}{1 + \left(\dfrac{X_E}{X_L} \right)_R}$$

$$R_{Ph-E} = \frac{U_{Ph-E} \cdot \cos \varphi_{SC}}{I_{Ph} + \left(\dfrac{R_E}{R_L} \right)_R \cdot I_E} = \frac{x}{l} \cdot R_L \cdot \frac{1 + \dfrac{R_E}{R_L} + \dfrac{R_{0M}}{3 \cdot R_L} \cdot \dfrac{\frac{x}{l}}{2 - \frac{x}{l}}}{1 + \left(\dfrac{R_E}{R_L} \right)}$$

Initially, only the X value measured is of interest for the reach.

With $k_{XEL} = \dfrac{X_E}{X_L}$ and $k_{XEM} = \dfrac{X_{0M}}{3 \cdot X_L}$ this gives:

$$X_{Ph-E} = \frac{x}{l} X_L \cdot \frac{1 + k_{XEL} + k_{XEM} \cdot \dfrac{\frac{x}{l}}{2 - \frac{x}{l}}}{1 + k_{XER}}$$

The Ph-E measuring system and the Ph-Ph measuring system have the same impedance pickup value (common setting value Z1).
Therefore: $Z_{Ph\text{-}E} = Z_{Ph\text{-}Ph} = Z1 = GF1 \cdot Z_L$, applies, whereby GF1 is the grading factor of the first zone.
The following equation is finally arrived at for the earth-current compensation factor which must be set at the relay:

$$k_{XER} = \frac{1 + k_{XEL} + k_{XEM} \cdot \dfrac{\frac{x}{l}}{2 - \frac{x}{l}}}{GF1} \cdot \frac{x}{l} - 1$$

We can vary the reach of the Ph-E measuring systems of a given zone reach for phase faults (GF1 in % of Z_L) by adjusting the k_{XER} factor.
We can also solve the previous equation according to x/l and then arrive at the reach for a given k_{XER} setting.

$$\frac{x}{l} = \frac{[GF1 \cdot (1 + k_{XER}) + 2(1 + k_{XEL})] - \sqrt{[..]^2 - 8(1 + k_{XEL} - k_{XEM}) \cdot (1 + k_{XER}) \cdot GF1}}{2 \cdot (1 + k_{XEL} - k_{XEM})}$$

In the same way we derive the equations specified in Table 1 for the cases “parallel line open” and “parallel line open and earthed at both ends”.

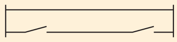
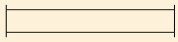
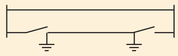
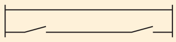
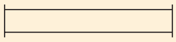
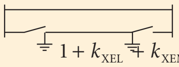
		Reach x/l at Ph-E short-circuits		
		 $\frac{x}{l} = GF1 \cdot \frac{1+k_{XER}}{1+k_{XEL}}$	 $\frac{x}{l}$ = See equation on previous page	 $\frac{x}{l} = \frac{(1+k_{XER}) \cdot GF1}{1+k_{XEL} - k_{XEM} \cdot \frac{X'_{0M}}{X_{0L}}}$ a)
k_{XER}-setting with: $\frac{x}{l} = 0.85$ GF1 = 0.85 $k_{XEL} = 0.71$ b) $k_{XEM} = 0.64$ c) $X'_{0M} = 0.72\ \Omega/km$ $X'_{0L} = 1.11\ \Omega/km$ $X'_{1L} = 0.356\ \Omega/km$	 $k_{ER} = \frac{1+k_{EL}}{GF1} \cdot \frac{x}{l} - 1 = 0.71\,(0.5)$	85 % (75 %)	71 % (64 %)	108 % (98 %)
	 $k_{XER} = \frac{1+k_{XEL} + k_{XEM} \cdot \frac{x/l}{2-x/l}}{GF1} - 1$ $k_{XER} = 1.18$	108 %	85 %	132 %
	 $k_{XER} = \frac{1+k_{XEL} + k_{XEM} \cdot \frac{X'_{0M}}{X'_{0L}}}{GF1} \cdot \frac{x}{l} - 1 = 0.31$	65 %	56 %	85 %

Table 1 Distance measurement in the event of earth faults: Reach (in X direction) dependent on the relay setting

$$k_{XER} = \left(\frac{X_E}{X_L}\right)_{Relay}$$ and the switching state

The choice of the setting of k_{XER} requires a compromise which takes all three cases of operation into account (Table 1)[1]. At a grading factor of GF1 = 85 %, adaptation to the single-circuit line usually offers an acceptable solution. The two-end disconnection of a line with earthing at both ends only occurs in maintenance work, so the brief overreach of 8 % is only rarely effective because overreaching is usually reduced by intermediate infeeds.

In operation with single-pole auto-reclosure, the overreach would only lead to excessive auto-reclosure and not to final disconnection, provided that a transient short-circuit is concerned (about 90 % of faults).

Alternatively, the reach can be reduced slightly for earth faults by setting a lower k_{XER} factor. If it were reduced from $k_{XER} = 0.71$ to $k_{XER} = 0.5$, overreach would just about be avoided in this example. The reach with both lines in service would then only be 64 %, taking into consideration that the parallel line coupling only takes full effect in the worst case of single-end infeed. In the normal case of two-end infeed the earth current on the parallel line is much lower in the event of faults close to the middle of the line, and the zone reach corresponds almost to the single-circuit line. In addition, the parallel line coupling at the other end of the line always has the opposite direction, i.e. the zone reach is increased. Reliable fast disconnection can always be ensured by intertripping. However, in reducing the k_{XER} factor it must be taken into account that the reach of the backup zones is also reduced accordingly in the event of earth faults. Zone reach reduction (e.g. GF1 = 0.8) should therefore also be considered instead of only reduction of the k_{XER} factor.

5.6 Setting the overreach zone

Zone Z_{1B} should be set to 120 – 130 % Z_L. This reach would also apply for earth faults in the case of operation with parallel line compensation.

1) The numeric values in Table 1 were calculated with the line layers of the previous example. For the sake of simplicity the complex factors $k_{EL} = 0.71 - j0.18$ and $k_{EM} = 0.64 - j0.18$ were only taken into account with their real components, which correspond to the values $k_{XEL} = X_E/X_L$ and $k_{XEm} = X_M/(3 \cdot X_L)$ in the first approximation. This gives sufficient accuracy for the extra high-voltage system.

Adapting the setting to an operating state causes an overreach or underreach in the respective other states. GF1 in % is the selected grading factor for the 1st zone (reach for Ph-Ph faults). *x*/*l* in % then specifies how far zone 1 (Ph-E loop) reaches in the event of earth faults, referred to the line length.

Determining of the relay setting value $\underline{k}_{ER}$ is demonstrated by the example of double-circuit line operation:

The voltage at the relay location for a fault at the distance *x*/*l* is:

$$\underline{U}_{\text{Ph-E}} = \frac{x}{l}\underline{Z}_L \cdot \underline{I}_{\text{Ph}} + \frac{x}{l}\underline{Z}_E \cdot \underline{I}_E + \frac{X}{l}\frac{\underline{Z}_{0M}}{3} \cdot \underline{I}_{EP}$$

with single-end infeed:

$$I_{\text{Ph}} = I_E \text{ and } I_{EP} = \frac{\frac{x}{l}}{2-\frac{x}{l}} \cdot I_E$$

for the measurement of the Ph-E loop the following is derived:

$$\underline{Z}_{\text{Ph-E}} = \frac{\underline{U}_{\text{Ph-E}}}{\underline{I}_{\text{Ph}} + \underline{k}_{ER} \cdot \underline{I}_E} = \frac{x}{l} \cdot \frac{\underline{Z}_L + \underline{Z}_E + \frac{\underline{Z}_{0M}}{3} \cdot \frac{\frac{x}{l}}{2-\frac{x}{l}}}{1 + \underline{k}_{ER}}$$

whereby $\underline{k}_{ER}$ is the complex earth current compensation factor set on the relay. X and R are calculated separately in the numerical relays 7SA. Simplified equations apply for this when phases and earth currents have the same phase angle. This results in

$$X_{\text{Ph-E}} = \frac{U_{\text{Ph-E}} \cdot \sin\varphi_{SC}}{I_{\text{Ph}} + \left(\frac{X_E}{X_L}\right)_R \cdot I_E} = \frac{x}{l} \cdot X_L \cdot \frac{1 + \frac{X_E}{X_L} + \frac{X_{0M}}{3 \cdot X_L} \cdot \frac{\frac{x}{l}}{2-\frac{x}{l}}}{1 + \left(\frac{X_E}{X_L}\right)_R}$$

$$R_{\text{Ph-E}} = \frac{U_{\text{Ph-E}} \cdot \cos\varphi_{SC}}{I_{\text{Ph}} + \left(\frac{R_E}{R_L}\right)_R \cdot I_E} = \frac{x}{l} \cdot R_L \cdot \frac{1 + \frac{R_E}{R_L} + \frac{R_{0M}}{3 \cdot R_L} \cdot \frac{\frac{x}{l}}{2-\frac{x}{l}}}{1 + \left(\frac{R_E}{R_L}\right)_R}$$

Only the measured value is initially for the reach:

With $k_{XEL} = \frac{X_E}{X_L}$ and $k_{XEM} = \frac{X_{0M}}{3 \cdot X_L}$ this gives:

$$X_{\text{Ph-E}} = \frac{x}{l} X_L \cdot \frac{1 + k_{XEL} + k_{XEM} \cdot \frac{\frac{x}{l}}{2-\frac{x}{l}}}{1 + k_{XER}}$$

The Ph-E measuring system and the Ph-Ph measuring system have the same impedance pickup value (common setting value Z_1).
Therefore: $Z_{\text{Ph-E}} = Z_{\text{Ph-Ph}} = Z_1 = GF1 \cdot Z_L$, applies, whereby GF1 is the grading factor of the first zone:

The following equation finally results for the earth-current compensation factor which must be set in the relay:

$$k_{XER} = \frac{1 + k_{XEL} + k_{XEM} \cdot \frac{\frac{x}{l}}{2-\frac{x}{l}}}{GF1} \cdot \frac{x}{l} - 1$$

Without parallel line compensation the 120 % reach must be dimensioned for the case of parallel line operation under consideration of the previously defined k_{XER} factor.

$$GF = \frac{1 + k_{XEL} + k_{XEM} \cdot \frac{\frac{x}{l}}{2-\frac{x}{l}}}{1 + k_{XER}} \cdot \frac{x}{l}$$

For a fault at the end of the line (*x*/*l* = 100 %) and a safety margin of 20 %, the following equation for the overreach zone is produced:

$$X1B = GF_{100\%} \cdot X_L \cdot \frac{120\%}{100}$$

$$= \frac{1 + k_{XEL} + k_{XEM}}{1 + k_{XER}} \cdot X_L \cdot 1.2$$

The selected $k_{XER} = 0.71$ produces
$X1B = 165\ \%\ X_L$.
Without parallel line compensation, the overreach zone must therefore be set very high, so that a safety margin of 20 % is ensured in double-circuit line operation.

5.7 Reach of the backup zones for earth faults

We observe the behavior of the distance measurement with and without parallel line compensation.

5.8 Distance measurement without parallel line compensation

For the simple case that the parallel line is followed by a single-circuit line (Fig. 21, line 4 disconnected), the measured impedance can be determined as follows:

Voltage at the relay location:

$$\underline{U}_{\text{Ph-E}} = \underline{Z}_{\text{L1}} \cdot \underline{I}_{\text{Ph1}} + \underline{Z}_{\text{E1}} \cdot \underline{I}_{\text{E1}} + \frac{\underline{Z}_{\text{0M 1-2}}}{3} \cdot \underline{I}_{\text{E2}}$$

$$+ \frac{x}{l_2} \underline{Z}_{\text{L2}} \cdot \underline{I}_{\text{Ph3}} + \frac{x}{l_2} \underline{Z}_{\text{E2}} \cdot \underline{I}_{\text{E3}}$$

With $\underline{I}_{\text{Ph1}} = \underline{I}_{\text{E1}} = \underline{I}_{\text{E2}} = \underline{I}_{\text{SC}}$ and $\underline{I}_{\text{Ph3}} = \underline{I}_{\text{E3}} = 2 \cdot \underline{I}_{\text{SC}}$ we get for the relay reactance:

$$X_{\text{Ph-E}} = \frac{U_{\text{Ph-E}} \cdot \sin\varphi_{\text{SC}}}{I_{\text{Ph1}} + k_{\text{XER}} \cdot I_{\text{E1}}} =$$

$$\frac{1 + k_{\text{XEL1}} + k_{\text{XEM1-2}}}{1 + k_{\text{XER}}} \cdot X_{\text{L1}} + 2 \cdot \frac{x}{l_2} \cdot \frac{1 + k_{\text{XEL3}}}{1 + k_{\text{XER}}} \cdot X_{\text{L2}}$$

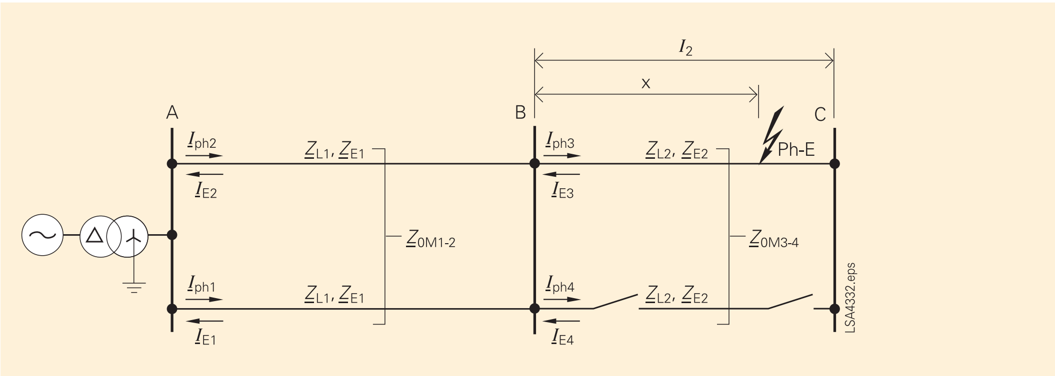


Fig. 21 Distance measurement on double-circuit lines: Fault on a following line

If we set $x/l = 0$ we arrive at the measured reactance in the event of a fault at the opposite station. For the calculated example this gives the value

$$X_{\text{Ph-E}} = \frac{1 + 0.71 + 0.64}{0.71} = 1.37 \cdot X_{\text{L1}}$$

This shows that in the case at hand the backup zones only reach beyond the next station when they are set greater than 137 % Z_{L1}. This does not apply for the 2nd zone at the selected setting.

At the grading (120 %) selected on the basis of the phase-to-phase short-circuits, the 2nd zone would only reach up to 91 % Z_{L1} in the parallel line state in the event of an earth fault.

This problem is particularly pronounced when the downstream line, according to which the second zone has to be graded, is substantially shorter than the protected line, and when only a short intermediate infeed is present.

$$\underline{U}_{\text{Ph-E}} = \underline{Z}_{\text{L1}} \cdot \underline{I}_{\text{Ph1}} + \underline{Z}_{\text{E1}} \cdot \underline{I}_{\text{E1}} + \frac{\underline{Z}_{\text{0M1-2}}}{3} \cdot \underline{I}_{\text{E2}} + \frac{x}{l_2} \underline{Z}_{\text{L2}} \cdot \underline{I}_{\text{Ph3}} + \frac{x}{l_2} \underline{Z}_{\text{E2}} \cdot \underline{I}_{\text{E3}} + \frac{x}{l_2} \frac{\underline{Z}_{\text{0M3-4}}}{3} \cdot \underline{I}_{\text{E4}}$$

With $\underline{I}_{\text{Ph1}} = \underline{I}_{\text{E1}} = \underline{I}_{\text{E2}} = \underline{I}_{\text{SC}}$ and

$\underline{I}_{\text{Ph3}} = \underline{I}_{\text{E3}} = \left(2 - \frac{x}{l_2}\right) \cdot \underline{I}_{\text{SC}}$ and $\underline{I}_{\text{E4}} = \frac{x}{l_2} \cdot \underline{I}_{\text{SC}}$

we get:

$$X_{\text{Ph-E}} = \frac{1 + k_{\text{XEL1}} + k_{\text{XEM1-2}}}{1 + k_{\text{XER}}} \cdot X_{\text{L1}} + \frac{\frac{x}{l_2}\left(2 - \frac{x}{l_2}\right) \cdot (1 + k_{\text{XEL2}}) + \left(\frac{x}{l_2}\right)^2 \cdot k_{\text{XEM3-4}}}{1 + k_{\text{XER}}} \cdot X_{\text{L2}}$$

Resolution according to x/l_2 produces again the equation for the reaches of the zones:

$$\frac{x}{l_2} = \frac{2(1 + k_{\text{XEL2}}) - \sqrt{4(1 + k_{\text{XEL2}})^2 - 4(1 + k_{\text{XEL2}} - k_{\text{XEM3-4}}) \cdot \Delta}}{2 \cdot (1 + k_{\text{XEL2}} - k_{\text{XEM3-4}})}$$

with

$$\Delta = \frac{X_{\text{L1}}}{X_{\text{L2}}} \cdot \left[(1 + k_{\text{XER}}) \cdot \frac{X_{\text{Zone}}}{X_{\text{L1}}} - (1 + k_{\text{XEL1}} + k_{\text{XEM1-2}})\right]$$

For zone 3 (169 % X_{L1}) we get $x/l_2 = 33$ %, i.e. only slightly more than for the single-circuit line. For the pickup zone (226 % X_{L1}) the expression under the root is negative because the zone only reaches to just past the next substation.
The limit (root = 0) is at 223 % X_{L1}.

5.9 Distance measurement with parallel line compensation

With parallel line compensation, faults on the own line are measured in the correct distance. For faults beyond the next substation the zones are extended by the factor:

$$k = \frac{1 + k_{\text{XER}} + k_{\text{XEMR}}}{1 + k_{\text{XER}}}$$

according to the compensation factors set at the relay.
The term $1 + k_{\text{XER}}$ must be replaced in the equations on pages 12 and 13 by $1 + k_{\text{XER}} + k_{\text{XEMR}}$.

This gives us a reach of up to 71 % Z_{L2} for the 2nd zone, i.e. the zone reaches up to just before the end of the first zone of the following line which is set to 85 % Z_{L2}.

Taking account of the intermediate infeed in station B, there will be a further reduction of the 2^{nd} stage so that the safety margin is increased. The 3^{rd} zone (169 %Z_{L1}) just reaches with parallel line compensation and the pickup zone (226 % Z_{L1}) comfortably reaches over the next station but one (C) (A fault in C would correspond to 162 % Z_{L1}). For the final definition of the setting, the intermediate infeed again has to be taken into account.

6. Summary

The zone setting can be estimated for the double-circuit lines based on the arithmetic procedures and the derived equations shown here. In practice the intermediate infeeds must be taken into account, so that the second zone can be graded safely past the next station (whilst retaining the selectivity and reliably detecting busbar faults).

If the line lengths do not differ, an acceptable compromise for the relay setting can usually be found without parallel line compensation. For short following lines, parallel compensation must however be taken into account.

Computer programs are nowadays available for the relatively complex testing of the backup zones and the pickup.