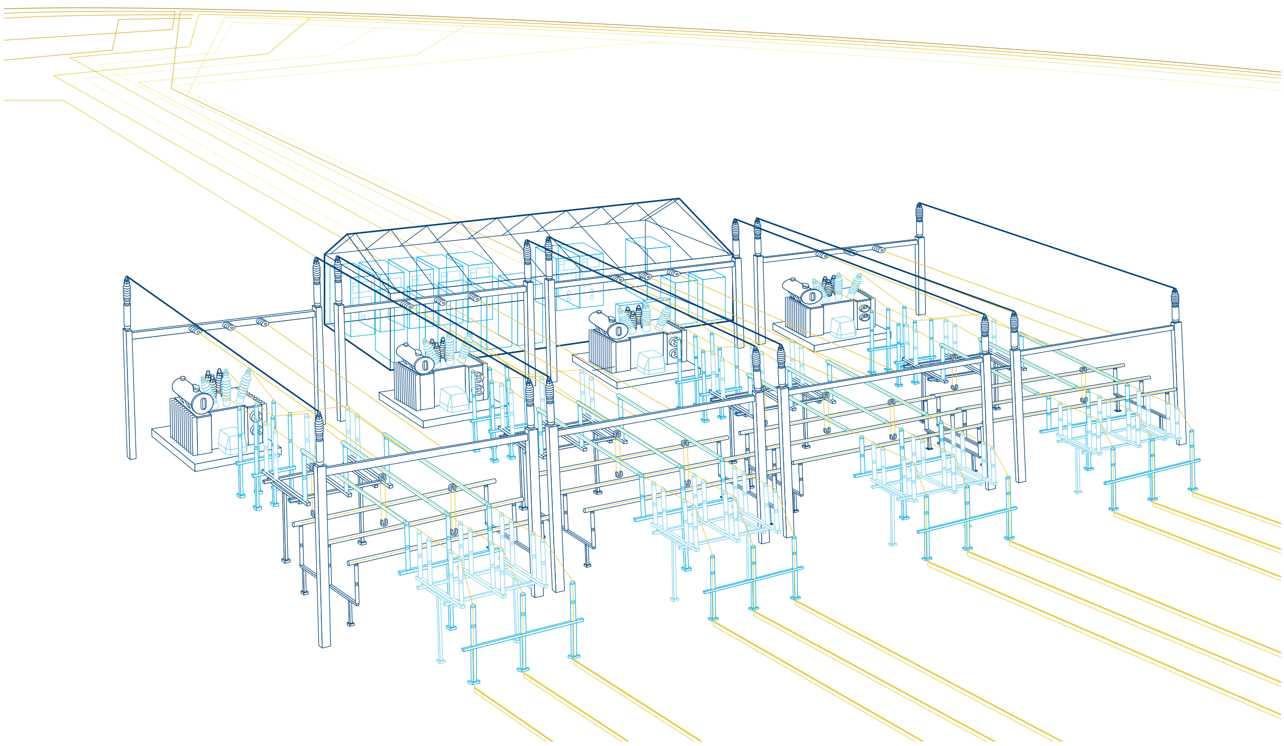
Distribution Automation Handbook

Section 8.8 Protection of Meshed Networks



Contents

8.8 Protection of Meshed Networks

The structure of modern distribution and sub-transmission networks is developing toward meshed and looped configurations. At the same time, the demand for maintaining high reliability and safety in operation is increasing. Due to these facts and the continuously increasing local generation, traditional protection schemes based on simple overcurrent functions cannot be applied anymore. Therefore, there is a need for more sophisticated protection schemes that must operate selectively and fast enough despite the changing network configurations due to daily operation. To fulfill these requirements, differential and distance protection functions have been introduced in modern IEDs as a solution.

8.8.1 Introduction

Distance protection determines the impedance to the fault point from the measured voltages and currents at the substation. In the simplest form, the calculated impedance is compared to the set impedance, which is obtained from the known impedance data of the protected line. If the calculated impedance is lower than the set impedance the distance function starts and finally trips the associated circuit breaker. The major advantage of the impedance-based operating principle is that the sensitivity of the protection is highly independent of the prevailing source conditions.

Differential protection compares the measured line end currents regarding both the magnitude and the phase angle. For the operation, there must be an interconnecting channel between the line end IEDs over which the interchange of current information is transferred. According to Kirchhoff's law, when the vectorial sum of these currents deviates from zero, it indicates a fault in the protected line. Current differential protection is the simplest form of line protection requiring very few settings to be entered in the IED regarding the characteristics of the protected line. Another major advantage is that it provides fast fault clearing and high sensitivity without compromising security.

This chapter brings forward the basic principles of these schemes in the distribution overhead line and cable protection.

8.8.2 Distance Protection

Distance protection is described in reference [8.8.1].

8.8.2.1 Impedance measurement

The impedance measurement is typically based on six *fault loops*: A-B, B-C, C-A, A-E, B-E and C-E. The algorithm performing the impedance measurement is also called the *measuring element* of the corresponding fault type. For two-phase short circuits and for single-phase earth faults, only one of these loops measures the correct impedance, whereas for other fault types there are several loops possible that produce the correct impedance. Table 8.8.1 makes a summary of this.

Table 8.8.1: Fault types and the corresponding loops for impedance measurement

Fault type	Phases involved	Fault loop for impedance measurement
Phase-to-earth fault	A-E	A-E

	B-E	B-E
	C-E	C-E
Phase-to-phase fault	A-B	A-B
	B-C	B-C
	C-A	C-A
Three-phase fault with or without earth	A-B-C(-E)	A-B or B-C or C-A or A-E or B-E or C-E
Two-phase-to-earth fault	A-B-E	A-B or A-E or B-E
	B-C-E	B-C or B-E or C-E
	C-A-E	C-A or C-E or A-E
Cross-country fault	A-E, B-E[1)]	A-E or B-E[2)]
	B-E, C-E[1)]	B-E or C-E[2)]
	C-E, A-E[1)]	C-E or A-E[2)]

1) Fault locations in different lines

2) Depending on the faulted line

In general form, the fault loop equations are given by (8.8.1), (8.8.2) and (8.8.3). For the phase-to-earth loop there are two alternative ways to calculate the impedance.

8.8.2.1.1 Phase-to-phase loop

The loop impedance calculation for $\underline{Z}_{Ph-Ph}$, Equation (8.8.1), provides the positive-sequence impedance $\underline{Z}_1$ to the fault point added by one half of the fault resistance between the phases.

$$\underline{Z}_{Ph-Ph} = \frac{\underline{U}_{Ph-Ph}}{\underline{I}_{Ph-Ph}} = \frac{\underline{U}_{PhX} - \underline{U}_{PhY}}{\underline{I}_{PhX} - \underline{I}_{PhY}} = \underline{Z}_1 + \frac{R_f}{2} \quad \textbf{(8.8.1)}$$

where the subscripts X and Y designate the faulted phases.

The loop model for phase-to-phase faults is shown in Figure 8.8.1. It should be noted that in case of a three-phase fault, the measured fault resistance is the total fault resistance per phase.

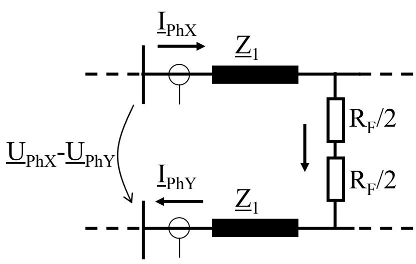


Figure 8.8.1: Phase-to-phase fault loop

8.8.2.1.2 Phase-to-earth loop

The loop impedance calculation for $\underline{Z}_{Ph-E}$, Equation (8.8.2), provides the sum of the positive-sequence impedance $\underline{Z}_1$ and the impedance of the earth return path $\underline{Z}_N$ to the fault point added by the *total* fault resistance between the faulted phase and earth. Alternative calculation by using the residual compensation factor, Equation (8.8.3), provides the positive-sequence impedance $\underline{Z}_1$ to the fault point added by the *total* fault resistance between the faulted phase and earth, but now the fault resistance term is affected by the residual compensation factor, $\underline{K}_N$.

$$\underline{Z}_{Ph-E} = \frac{\underline{U}_{PhX}}{\underline{I}_{PhX}} = \underline{Z}_1 + \underline{Z}_N + R_f \qquad \textbf{(8.8.2)}$$

or

$$\underline{Z}_{Ph-E} = \frac{\underline{U}_{PhX}}{\underline{I}_{PhX} + \underline{K}_N \underline{I}_N} = \underline{Z}_1 + \frac{R_f}{1 + \underline{K}_N} \qquad \textbf{(8.8.3)}$$

where the subscript *X* designates the faulted phase and

$\underline{K}_N$ is the residual compensation factor and

$\underline{I}_N$ is the residual current equal to the sum of the phase currents

The loop model for phase-to-earth faults is shown in Figure 8.8.2.

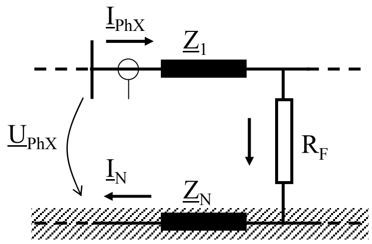


Figure 8.8.2: Phase-to-earth fault loop

The derivation of $\underline{K}_N$ and $\underline{Z}_N$ can be done with the aid of the zero-sequence impedance and phase-to-earth fault loop definitions. The determination of the zero-sequence impedance for a three-phase power line is shown in Figure 8.8.3. This measurement arrangement requires that the phase conductors are short-circuited and earthed at the end of the line, and a single-phase voltage at the point of measurement is injected as per Figure 8.8.3.

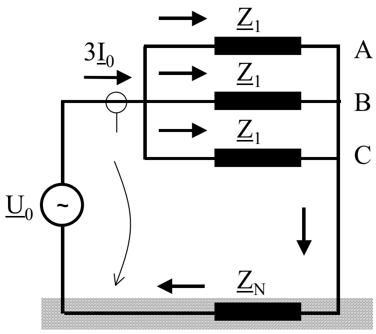


Figure 8.8.3: Measurement arrangement of the zero-sequence impedance for a three-phase power line

According to Figure 8.8.3, the following equations can be written.

$$\frac{\underline{Z}_0}{3} = \frac{\underline{U}_0}{3\underline{I}_0} = \frac{1}{3}\underline{Z}_1 + \underline{Z}_N \qquad \textbf{(8.8.4)}$$

and

$$\underline{Z}_N = \frac{\underline{Z}_0 - \underline{Z}_1}{3} \qquad \textbf{(8.8.5)}$$

where

U_0 is the injected zero-sequence voltage and

I_0 is the measured zero-sequence current

The derivation of Equation (8.8.3) can be done based on Figure 8.8.2. The following can be written.

$$\underline{U}_{PhX} = \underline{Z}_1 \underline{I}_{PhX} + \underline{Z}_N \underline{I}_N + R_f \underline{I}_N = \underline{Z}_1 \left(\underline{I}_{PhX} + \frac{\underline{Z}_N}{\underline{Z}_1} \underline{I}_N \right) + R_f \underline{I}_N \qquad \textbf{(8.8.6)}$$

Substitution of Equation (8.8.6) into Equation (8.8.3) results in

$$\underline{Z}_{Ph-E} = \frac{\underline{Z}_1 \left(\underline{I}_{PhX} + \frac{\underline{Z}_N}{\underline{Z}_1} \underline{I}_N \right) + R_f \underline{I}_N}{\underline{I}_{PhX} + \underline{K}_N \underline{I}_N} = \underline{Z}_1 + \frac{R_f}{\frac{\underline{I}_{PhX}}{\underline{I}_N} + \underline{K}_N} \qquad \textbf{(8.8.7)}$$

It is apparent from Equation (8.8.7) that

$$\underline{K}_N = \frac{\underline{Z}_N}{\underline{Z}_1} = \frac{\underline{Z}_0 - \underline{Z}_1}{3\underline{Z}_1} \qquad \textbf{(8.8.8)}$$

where

$\underline{Z}_1$	is the positive-sequence impedance of the line and
$\underline{Z}_0$	is the zero-sequence impedance of the line

In addition, if $\underline{I}_N$ is equal to $\underline{I}_{PhX}$, the result is exactly the same as indicated by Equation (8.8.3).

To illustrate the operation of the impedance measurement and especially the importance of selecting a correct loop equation for the impedance calculation, the following example is given. It can be seen that for a reliable and selective operation of the protection, the fault type must first be identified, and then based on this information the corresponding fault loop impedance is selected for making the trip decision. In the example, equations for all loops are presented in case of phase-to-earth (A-E) and phase-to-phase (B-C) fault. The results are also presented in the corresponding RX-diagrams of Figure 8.8.4 and Figure 8.8.5 by using typical impedance data from 20 kV network. For the line type in question applies $\underline{Z}_N / \underline{Z}_1 = 1.5\angle 38°$. In the equations, the fault resistance and the load has been neglected for the sake of simplicity. However, the effect of increasing the fault resistance has been shown in the corresponding RX- diagrams with dashed line phasors.

8.8.2.1.3 Example of impedance calculation

Impedance calculation of faulty and healthy loops in case of AE- and BC-fault is performed. The calculation uses typical impedance data from 20 kV network.

The following notations have been used:

$\underline{\boldsymbol{Z}}_1$	is the positive-sequence line impedance from the substation to the fault point
$\underline{\boldsymbol{Z}}_0$	is the zero-sequence line impedance from the substation to the fault point
$\underline{\boldsymbol{Z}}_{1source}$	is the positive-sequence source impedance
$\underline{\boldsymbol{Z}}_{0source}$	is the zero-sequence source impedance
$\underline{\boldsymbol{a}}$ and $\underline{\boldsymbol{a}}^2$	Are the complex numbers $-\frac{1}{2}+j\frac{\sqrt{3}}{2}$ and $-\frac{1}{2}-j\frac{\sqrt{3}}{2}$ respectively

8.8.2.1.4 A-E-fault, loop impedances

Using Equations Protection of Meshed Networks, (8.8.2) and (8.8.3) and the theory of symmetrical components, the following equations and the RX-diagram of Figure 8.8.4 can be derived.

AE-loop:

$$\underline{Z}_{AE} = \underline{Z}_1 + \underline{Z}_N$$
$$\underline{Z}_{AE}' = \underline{Z}_1 \qquad \textbf{(8.8.9)}$$

BE-loop:

$$\underline{Z}_{BE} = \infty$$
$$\underline{Z}_{BE}' = \underline{Z}_1 - j\frac{1}{\sqrt{3}}\frac{\underline{Z}_1 + \underline{Z}_{1source}}{\underline{K}_N} - (1-\underline{a}^2)\frac{\underline{Z}_0 + \underline{Z}_{0source}}{3\underline{K}_N} \quad \textbf{(8.8.10)}$$

CE-loop:

$$\underline{Z}_{CE} = \infty$$
$$\underline{Z}_{CE}' = \underline{Z}_1 + j\frac{1}{\sqrt{3}}\frac{\underline{Z}_1 + \underline{Z}_{1source}}{\underline{K}_N} - (1-\underline{a})\frac{\underline{Z}_0 + \underline{Z}_{0source}}{3\underline{K}_N} \quad \textbf{(8.8.11)}$$

AB-loop:

$$\underline{Z}_{AB} = \underline{Z}_1 + j\frac{\sqrt{3}}{3}(\underline{Z}_1 + \underline{Z}_{1source}) - \frac{(\underline{a}^2-1)}{3}(\underline{Z}_0 + \underline{Z}_{0source}) \quad \textbf{(8.8.12)}$$

BC-loop:

$$\underline{Z}_{BC} = \infty \quad \textbf{(8.8.13)}$$

CA-loop:

$$\underline{Z}_{CA} = \underline{Z}_1 - j\frac{\sqrt{3}}{3}(\underline{Z}_1 + \underline{Z}_{1source}) - \frac{(\underline{a}-1)}{3}(\underline{Z}_0 + \underline{Z}_{0source}) \quad \textbf{(8.8.14)}$$

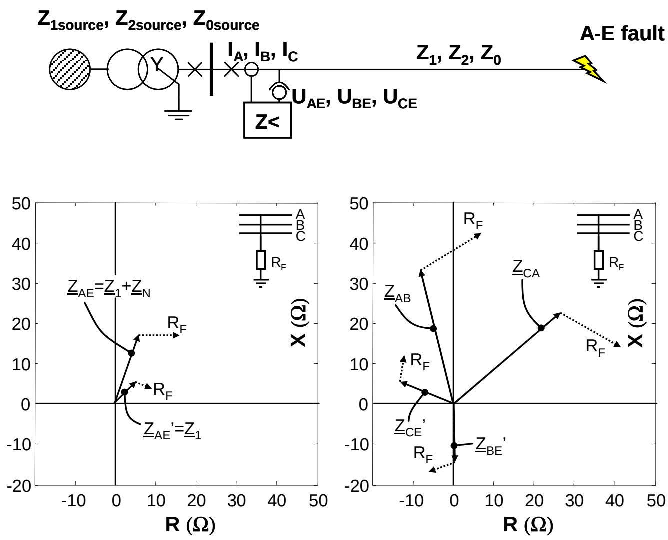


Figure 8.8.4: Measured loop impedances in case of AE-fault. Left: AE-loop, right: BE-, CE-, AB- and CA- loops

8.8.2.1.5 B-C-fault, loop impedances

Using Equations (8.8.1), (8.8.2) and (8.8.3) and the theory of symmetrical components, the following equations and the RX-diagram of Figure 8.8.5 can be derived.

BC-loop:

$$Z_{BC} = Z_1 \quad \textbf{(8.8.15)}$$

AB-loop:

$$\underline{Z}_{AB} = \underline{Z}_1 - j\sqrt{3}(\underline{Z}_1 + \underline{Z}_{1source}) \quad \textbf{(8.8.16)}$$

CA-loop:

$$\underline{Z}_{CA} = \underline{Z}_1 + j\sqrt{3}(\underline{Z}_1 + \underline{Z}_{1source}) \quad \textbf{(8.8.17)}$$

AE-loop:

$$\underline{Z}_{AE} = \underline{Z}_{AE'} = \infty \quad \textbf{(8.8.18)}$$

BE-loop:

$$\underline{Z}_{BE} = \underline{Z}_{BE'} = \underline{Z}_1 - j\frac{1}{\sqrt{3}}(\underline{Z}_1 + \underline{Z}_{1source}) \quad \textbf{(8.8.19)}$$

CE-loop:

$$\underline{Z}_{CE} = \underline{Z}_{CE'} = \underline{Z}_1 + j\frac{1}{\sqrt{3}}(\underline{Z}_1 + \underline{Z}_{1source}) \quad \textbf{(8.8.20)}$$

In case of phase-to-phase fault, both alternatives for calculating the phase-to-earth loops provide the same results because the sum of the phase currents equals to zero due to the fault type.

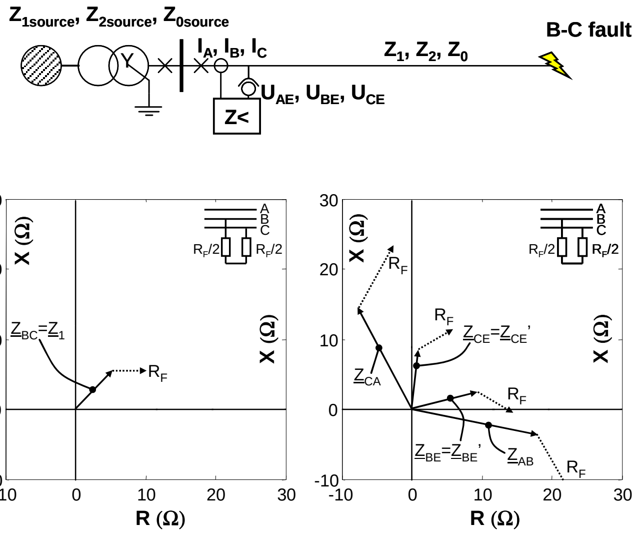


Figure 8.8.5: Measured loop impedances in case of BC-fault. Left: BC- loop, right: AB-, CA-, BE- and CE- loops

8.8.2.2 Zone characteristics

Ideally, the distance function can be set according to the known line impedance only. In practice, however, there are several other factors affecting the impedance measurement, which must also be taken into account in the setting considerations, such as:

- fault resistance
- impedances of the healthy loops during the fault
- impedance of the load
- load transfer
- intermediate in-feeds or out-feeds
- parallel lines
- line asymmetry
- inaccuracies in current and voltage measurement
- inaccuracies in line impedance data, especially in zero-sequence impedance
- the ratio between the source and line impedance (source impedance ratio, SIR)

In order to take these factors into account, a wide operating area in the RX-plane is actually needed. This operating area is known as the *zone characteristic* or *distance zone*, which has a certain *reach* based on the settings along the protected circuit. Faults occurring inside this zone are then detected and cleared by the function.

Typically, the characteristic is a geometric figure consisting of straight lines and/or circles. The most common shapes are:

- Directional quadrilateral or the quad characteristic

- Circular or the mho characteristic
- Non-directional circular or the offset-mho characteristic
- Non-directional quad characteristic
- Combination of the circular and quad characteristic, called the bullet characteristic

Examples of these characteristics are given in Figure 8.8.6.

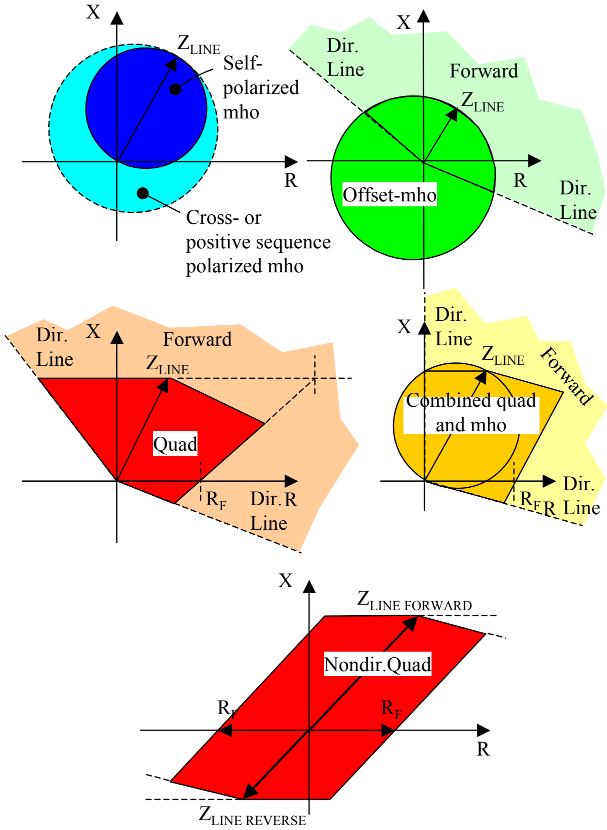


Figure 8.8.6: Typical zone characteristics used in distribution and sub-transmission networks

The quad characteristic has always a fixed shape in the RX-plane. The mho characteristic, on the other hand, can be made to adjust its size automatically in relation to the source impedance during the fault. This requires a so-called cross- or positive-sequence polarization (see chapter 'Directional function'). The expanding feature of the characteristic gives automatically a larger operating margin in the RX-plane and thus, a larger coverage for the fault resistance can be obtained. By using a so-called self-polarization (see chapter 'Directional function'), the shape of the mho characteristic becomes fixed in the RX-plane.

The mid-point of the offset-mho characteristic can be placed freely in the RX-plane, but typically the origin is inside the circle. To provide directionality, the directional lines, which are part of the quad characteristic, can be applied additionally. With the non-directional quad characteristic the reach in forward and reverse direction can be separately set. Typically, the non-directional characteristic is used for delayed backup protection purposes.

The distance protection function with quadrilateral characteristic is usually implemented using the impedance-mapping approach. This means that the impedance estimate is first calculated and then the result is compared in the impedance plane to the operation zone boundaries. On the other hand, the circular characteristic has traditionally been accomplished by torque-like algorithms and angle comparators. However, in modern IEDs, also circular characteristic can be implemented with the same impedance-mapping approach [8.8.10]. This solution reduces the computational burden in the IED as the fault loop impedances can be calculated centrally, and they can be utilized in zone boundary comparisons for both quadrilateral and circular characteristic. This is advantageous as short circuit and earth-fault measuring elements can have different zone characteristics. Also the post-fault analysis of the measuring element behavior becomes more straightforward and simple as all characteristics can be studied similarly in the impedance domain.

8.8.2.3 Starting function

During the healthy condition, all impedance loops (A-B, B-C, etc.) measure the impedance corresponding to the load impedance seen in each of the phases. After the fault inception, each of the fault loops measure different impedances depending on the fault type in question as seen in the example of Figure 8.8.4 and Figure 8.8.5. It is therefore mandatory that the fault type is first reliably identified before individual impedance-measuring loops are given the possibility to make a trip decision, that is, which measuring loops are *released* for measuring. This task is performed by the *starting function*.

In order to perform a valid fault loop selection, the starting function must first determine whether the fault is a short circuit or an earth fault. This is done by a special *earth fault detection logic*. Additionally, in high-impedance earthed networks, a separate logic is needed to identify if the fault is a cross-country fault (that is, a double earth fault) where the individual earth faults are located in different lines and phases. In such case, a so-called *phase preference logic* is used to select the 'preferred' earth-fault measuring loop. As a result, only the other faulted line is tripped and the fault is transformed back to an ordinary earth fault, which is then cleared or alarmed by the dedicated earth-fault protection. In high-impedance earthed networks, when the fault is identified as an earth fault without the activation of the cross-country fault detection logic, the operation of the distance protection becomes typically blocked by the phase preference logic.

Examples of typical phase preference logic schemes are given in Table 8.8.2, which shows the released loop for the measurement in the case when two phases are identified being faulty by the starting function.

Table 8.8.2: Examples of different phase preference logic schemes used in high-impedance earthed networks. Other phase combinations/orders are also possible. XC_FLT means the activation of the cross-country fault detection logic.

Phase preference logic	**AB-E-fault**	**BC-E-fault**	**CA-E-fault**
	AND fault detection in		
	A&B&*XC_FLT*	B&C&*XC_FLT*	C&A&*XC_FLT*
	Released loop for measurement		
Cyclic A-B-C-A	AE	BE	CE
Acyclic A-B-C	AE	BE	AE

In low-impedance earthed networks, the cross-country fault does not require any special treatment. However, the two-phase-to-earth-fault is often handled with a special logic called the *faulted loop selection logic*. It is needed due to the fact that in this fault type typically both phase-to-earth loops and the phase-to-phase loop is identified being faulty. It is then necessary to decide by the logic which loops or loop the tripping decision is based on. The intention is typically to prevent the leading phase-to-earth loop from overreaching as it may see the fault closer than it actually is. The most common starting/phase selection methods are

- Overcurrent (I>)
- Overcurrent/undervoltage (I> *AND* U<)
- Underimpedance (Z<)

The simplest method is based on overcurrent. It can be used in applications where the fault current magnitude in the furthest point of the network is higher than the highest expected load current despite the possible changes in the network configuration and the fault type. The principle of the overcurrent starting logic is illustrated in Table 8.8.3.

Table 8.8.3: Typical phase selection logic scheme based on overcurrent. EARTH_FLT means the activation of the earth fault detection logic

Fault type	Starting condition	Released loop for measurement
Phase-to-earth	I_A>&*EARTH_FLT*	AE
	I_B>&*EARTH_FLT*	BE
	I_C>&*EARTH_FLT*	CE
Phase-to-phase	I_A>&I_B>	AB
	I_B>&I_C>	BC
	I_C>&I_A>	CA
Two-phase-to-earth	I_A>&I_B>&*EARTH_FLT*	AE, BE, AB
	I_B>&I_C>&*EARTH_FLT*	BE, CE, BC
	I_C>&I_A>&*EARTH_FLT*	CE, AE, CA
Three-phase	I_A>& I_B>&I_C>	AB or BC or CA

It should be noted that in case of an earth fault the phase current magnitude must exceed the setting in order to ensure the correct phase selection. Therefore, the magnitude of the earth-fault current must also be sufficient to enable the phase overcurrent starting and dependable operation of the distance protection. This is important especially in solidly and low-impedance earthed networks, where the operation of the distance protection in earth faults is desired.

In networks where the fault current magnitude is too low for a dependable overcurrent starting, the starting/phase selection can be based either on the combined overcurrent and undervoltage criterion or directly on the underimpedance criterion. The advantage of the underimpedance criterion is that the reach on the protected circuit is independent of the source impedance. These starting methods are typically needed in applications where the source impedance is high or it is changing frequently, or where the fault current can be split between parallel paths like in meshed or ring type networks and lines or where the earth fault current is limited by a resistance or reactance.

The principal logic based on the combined overcurrent and undervoltage starting is that during an undervoltage condition, a lower current threshold, $I_{Ph} >$, is used to increase the sensitivity of the fault detection. If the undervoltage criterion is not fulfilled, the higher current threshold $I_{Ph} >>$ is valid. The logic is illustrated in Table 8.8.4.

Table 8.8.4: Typical phase selection logic scheme based on overcurrent and undervoltage. EARTH_FLT means the activation of the earth fault detection logic

Fault type	Starting condition	Released loop for measurement
Phase-to-earth	I_A>&U_A<&EARTH_FLT	AE
	I_B>&U_B<&EARTH_FLT	BE
	I_C>&U_C<&EARTH_FLT	CE
Phase-to-phase	I_A>&I_B>&U_{AB}<	AB
	I_B>&I_C>&U_{BC}<	BC
	I_C>&I_A>&U_{CA}<	CA
Two-phase-to-earth	I_A>&I_B>&U_{AB}<& EARTH_FLT	AE, BE, AB
	I_B>&I_C>&U_{BC}<& EARTH_FLT	BE, CE, BC
	I_C>&I_A>&U_{CA}<& EARTH_FLT	CE, AE, CA
Three-phase	I_A>& I_B>&I_C>&U_{AB}<& U_{BC}<&U_{CA}<	AB or BC or CA

Figure 8.8.7 shows a typical operating characteristic of an overcurrent/undervoltage starter. This kind of operating characteristic can also be converted to the RX-plane with fixed source impedance. The result is a group of circles.

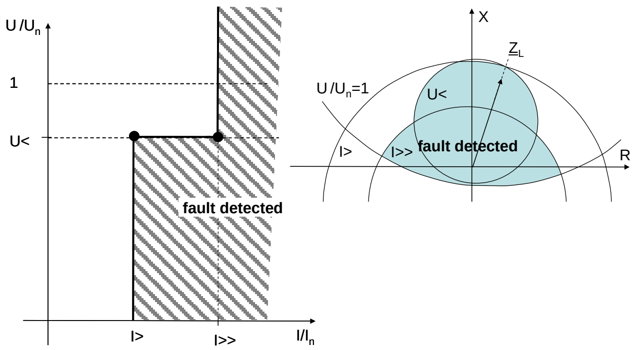


Figure 8.8.7: Typical operating characteristic of an overcurrent/undervoltage starter. Right: I/U-plane, left: RX-plane.

The principal starting logic based on underimpedance is shown in Table 8.8.5. Depending on the reach setting of the starter, it is, however, possible that more than one loop impedance enters the characteristic during a fault condition. In this case, additional measures such as comparisons of the loop impedance values for ensuring the correct loop selection can be used, or alternatively the final fault classification and trip decision is left to the actual distance zone

Table 8.8.5: Typical phase selection logic scheme based on underimpedance. EARTH_FLT means the activation of the earth fault detection logic

Fault type	Starting condition	Released loop for measurement
Phase-to-earth	Z_{AE}<&EARTH_FLT	AE
	Z_{BE}<&EARTH_FLT	BE
	Z_{CE}<&EARTH_FLT	CE
Phase-to-phase	Z_{AB}<	AB
	Z_{BC}<	BC
	Z_{CA}<	CA
Two-phase-to-earth	Z_{AB}<&EARTH_FLT	AE, BE, AB
	Z_{BC}<&EARTH_FLT	BE, CE, BC
	Z_{CA}<&EARTH_FLT	CE, AE, CA
Three-phase	Z_{AB}<&Z_{BC}<&Z_{CA}<	AB or BC or CA

As the load increases, the impedance presented by it decreases accordingly. It is therefore possible that the load impedance may move inside the zone characteristic resulting in a false operation of the protection. This can be avoided by reserving a sector in the zone characteristic for load. Such functionality is called the *load encroachment logic*. The reach of the distance zone must exclude the load impedance area to avoid false operation. This logic can easily be implemented directly in the RX-plane when the underimpedance criterion is being used for starting. Figure 8.8.8 shows typical examples of an underimpedance starter characteristic where the load encroachment logic is in use. It can be seen that if the measured impedance lies in the load area defined by the settings of the underimpedance starter, no release or tripping signals are given even if the measured impedance were also inside the corresponding zone characteristic.

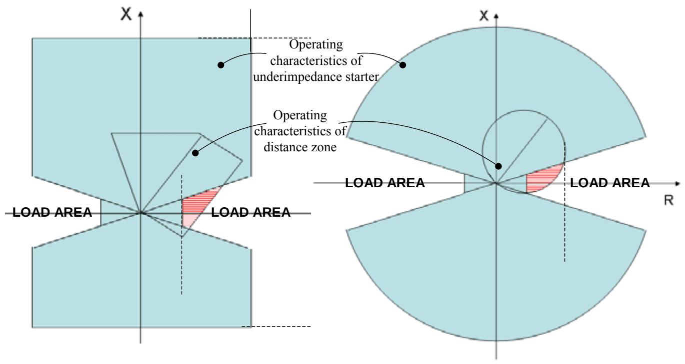


Figure 8.8.8: Examples of underimpedance starters with load encroachment logic in use. Left: quad, right: mho

8.8.2.4 Directional function

In applications with double-end infeed, it is of paramount importance that the protection is able to determine whether the fault is in the *forward* or in *reverse* direction. The determination of direction in a distance protection is typically based on the calculation of impedance with a selected *polarizing voltage*, and comparing this to the dedicated directional characteristic or directly to the boundaries of the distance zone. In the former method, the directional characteristic consists typically of directional lines, Figure 8.8.6, which are inherently a part of the quad characteristic, whereas the latter method is used with the mho characteristic. The mho characteristic can also be completed with additional directional lines. This is useful especially when the directional lines are combined with the offset/non-directional mho characteristic. This way, the resistive coverage can be improved in close-in faults and still maintain a dependable directional measurement.

The most commonly applied polarization methods are *self-, cross- and positive-sequence polarization*. For example, in case of AB-fault the direction is judged by the current $\underline{I}_{AB}$ and the voltage $\underline{U}_{AB}$ (self-polarization) or with the voltage $\underline{U}_{BC} - \underline{U}_{CA}$ rotated by –90 degrees (cross-polarization) or with the positive-sequence voltage $\underline{U}_{1AB}$ rotated by 30 degrees (positive-sequence polarization). In the first method the disadvantage is that in close-in faults the measured voltage may be too low for a dependable directional measurement. Such condition is avoided with the cross- or positive-sequence polarization, as healthy phases are utilized. Only in case of a close-in three-phase fault, where no healthy phases are available, the directionality must be secured with a special logic. This logic uses *memory voltage*, that is, a voltage prior to the fault inception for directional decision. Typically, memory voltage is activated when the voltage magnitude drops below a certain limit, for example 5 to 15% of the rated voltage. Theoretically with modern IEDs the memory voltage is available as long as desired, but practically because of possible frequency deviations the memory voltage is valid for a limited time only. After this time has elapsed, all start signals are frozen until the fault becomes cleared.

The only condition where the voltage memory cannot be applied is when the CB is closed onto fault. If the VTs are located on the line side of the CB, no memory voltage is available. In this case, the immediate non-directional tripping is ensured by a dedicated *switch-onto-fault logic*, which can be automatically enabled prior to the closing of the CB.

8.8.2.5 Basic coordination and application of multiple zones

To obtain a good and reliable selectivity and to fulfill the operating speed requirements of the protection, several distance zones are often needed. A typical example of this is presented in Figure 8.8.9, which shows the zones set for a 5-stage distance protection IED for a line between stations A and B. The zones Z_2 and Z_3 are set for time-grading in the forward direction, which means that they reach into the protection areas of the following distance protection IEDs in the protection chain, that is, the zones are *overreaching*, also providing inherent backup protection. The zone Z_1 does not reach into the protection zone of the next distance protection IED in the chain, that is, zone Z_1 is *underreaching*. This means that no time-grading is needed and the zone Z_1 can operate according to the fastest possible operating time. The zones 4 and 5 designated as Z_{AR1} and Z_{AR2} are dedicated only for controlling the autorecloser function. The purpose of the zone Z_{AR1} is to determine if the fault is on the cable section of the protected line or not. This means that in the station A the starting of this zone will block all autoreclosing attempts, whereas in the station B the starting of this zone will release autoreclosing. As the non-delayed fault clearing is not possible for the whole line length, faults located outside the reach of the underreaching zone Z_1 are cleared by the time-delayed overreaching zone Z_2. By applying a so-called *zone extension* or *local acceleration logic* controlled by the autorecloser (AR) function, the entire length of the protected line is possible to be covered by fast tripping without the use of a communication channel. The logic allows the zone Z_{AR2} with the desired overreach characteristic to trip non-delayed and to initiate the first shot of the AR-sequence. It should be noted that only the first trip of the AR-sequence is accelerated by the zone extension logic. If the fault is still persisting, further shots can be initiated by the other zones with different reach characteristics and time delays. The final trip ending the sequence is always performed by the normal time-graded protection (Z_1, Z_2 or Z_3), and the selective operation of the protection can be obtained. With the aid of this feature, flexibility in the setting of the reach characteristic and time delay for the initiation of the AR shots can be achieved.

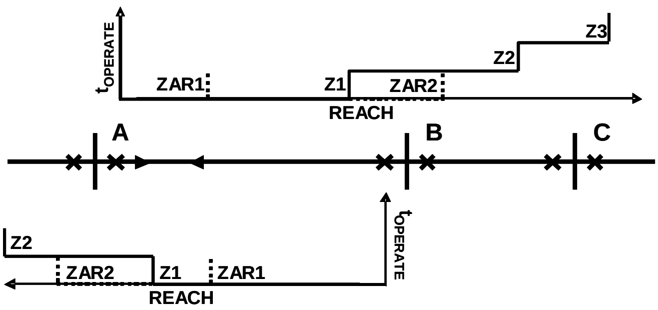


Figure 8.8.9: Example of typical distance zone application and coordination in distribution and sub-transmission networks

8.8.2.6 Scheme communication logic

In practice, a fast tripping with the underreaching zone Z_1 cannot be applied to cover 100% of the line length. This is due to the error sources and inaccuracies affecting the impedance measurement. Typically this leads to a security margin of 10 to 15% of the line length, where faults are cleared with a delayed tripping. If a fast tripping for the whole line length is required, this can be accomplished with the *scheme communication logic*. Such functionality is also needed in case of extremely short lines where difficulties arise with the minimum zone-setting limits.

The idea with the scheme communication logic is to exchange information between the line ends via a communication channel. Typically, at least one communication channel capable of transmitting a binary signal is required in each direction.

Scheme communication logics can be divided broadly into two categories. These are *blocking* and *permissive* schemes. The characteristics of the communication channel (for example speed and security against false or lost signals) will influence the choice of the scheme. A permissive scheme depends on the received signal, so its dependability is typically lower than that of a blocking scheme. To overcome the lower dependability of the permissive schemes, the *unblocking* scheme may be used instead.

In the *directional comparison blocking* or the *DCB*-scheme, Figure 8.8.10, a block signal is sent to the remote end if the local terminal detects a reverse fault. At the remote terminal, the overreaching zone Z_2 is allowed to operate after a coordinating time delay if it is not blocked by the arrival of the blocking signal. The coordination time must allow for the transmission of the blocking signal with a certain margin to prevent a false trip. For sending the blocking signal, a reverse or non-directional zone controlled by the operation of the forward zone can be used.

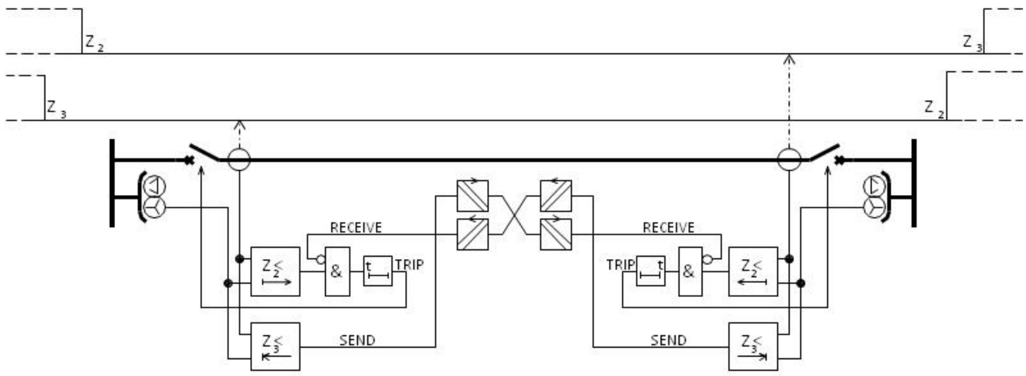


Figure 8.8.10: Simplified schematics of the DCB-scheme with principal zone reaches.

The *direct underreaching transfer trip* or the *DUTT*-scheme uses an instantaneous zone Z_1 to trip the local breaker and to transfer the trip signal to the remote end. The remote terminal operates immediately upon receipt of the transfer trip signal, without any additional conditions. This scheme is very simple but its security is low, as false signal results in malfunction.

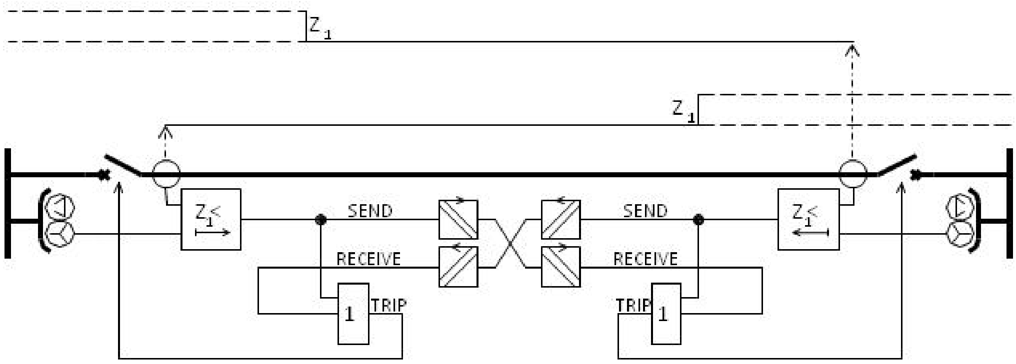


Figure 8.8.11: Simplified schematics of the DUTT-scheme with principal zone reaches.

In the permissive schemes a forward zone is used to issue a release signal. It indicates that the remote terminal has detected a fault in the forward direction on the line. The permissive scheme principle is further subdivided into *underreaching* and *overreaching* principles, where the names indicate that an *underreaching* or an *overreaching* zone issues the release signal.

The *permissive underreaching transfer trip* or the *PUTT*-scheme uses the underreaching zone Z_1 to trip the local breaker and sends a permissive trip signal to the remote terminal, Figure 8.8.12. The remote terminal breaker trips when it receives the permissive signal if its overreaching zone Z_2 detects simultaneously the fault. By using the overreaching zone for supervising the faulty condition, this scheme is more secure than the DUTT-scheme. Operation in case of faults outside the protected line is prohibited as an underreaching zone is used for signal transmission. Additionally, the PUTT-scheme does not require any additional logic to maintain security under current reversal conditions on parallel lines. The drawback is that several factors, for example parallel lines and infeeds, may cause underreach problems. The PUTT-scheme is also not applicable with weak infeed terminals.

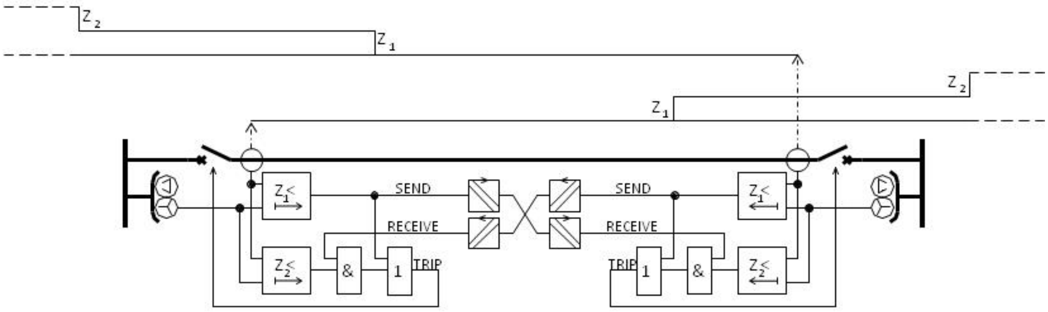


Figure 8.8.12: Simplified schematics of the PUTT-scheme with principal zone reaches

Permissive overreaching transfer trip or the *POTT*-scheme uses an overreaching zone Z_2 to send a permissive trip signal to the remote end, Figure 8.8.13. The remote terminal breaker trips when it receives the permissive signal if its overreaching zone is simultaneously detecting the fault. The POTT-scheme has the advantage that it is applicable to extremely short lines below the minimum zone-setting limit. There is also no problem with the impact of parallel line coupling. The drawback is that the distance zone and time coordination with the remote line end IEDs is necessary. The POTT-scheme may have to be complemented with a *weak end infeed* or *the WEI-logic*. The logic is needed at the station from which the short circuit power fed to the fault spot has decreased so much that the impedance can no longer be reliably measured. The weak end infeed logic enables the circuit breakers of both ends to be tripped also in these situations, and its function is based on echoing the trip permission signal (*ECHO*, Figure 8.8.13).

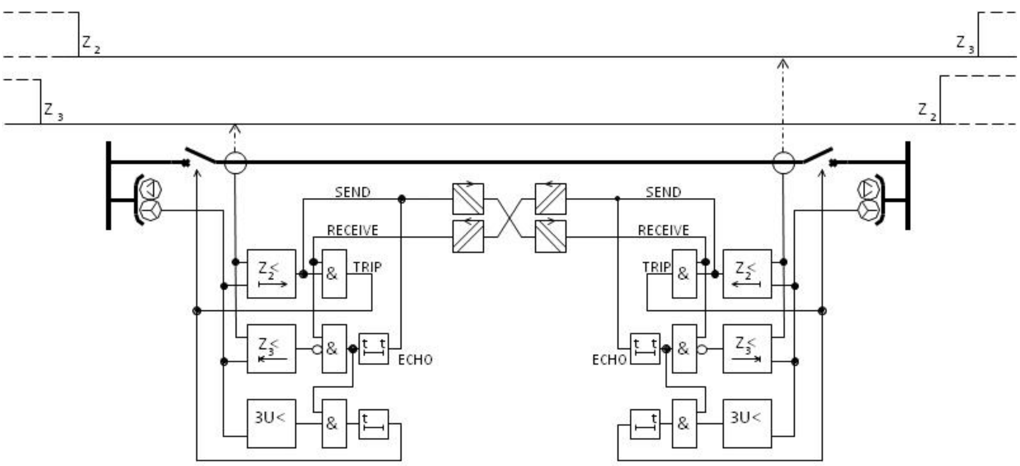


Figure 8.8.13: Simplified schematics of the POTT-scheme with principal zone reaches complemented with WEI-logic

When the permissive overreach scheme is applied in the protection of two parallel lines, the possible non-simultaneous tripping of the circuit breakers of the faulty line may cause a so-called change of direction of the fault current on the parallel healthy line immediately after the tripping of the first circuit breaker. This current may then cause a non-selective operation of the protection of the healthy line. To prevent this operation, a *current reversal logic* must be added to the basic logic, which blocks the protection for the short time during which a current reversal could occur.

In the *directional comparison unblocking* or the *DCUB*-scheme, a guard signal is continuously sent between the two ends of the line, Figure 8.8.14. If a fault is detected by the overreaching zone of the local terminal, the guard signal is changed to a permissive signal. This means that no trip delay is required to be waited for the blocking, which makes this scheme typically somewhat faster than the blocking scheme. The remote terminal detects the change in signals, and if it also detects a fault in overreaching zone, it trips. The DCUB-scheme also uses a logic that permits a trip if a loss-of-guard is detected and a fault in the overreaching zone is also detected, even if the permissive signal is not received.

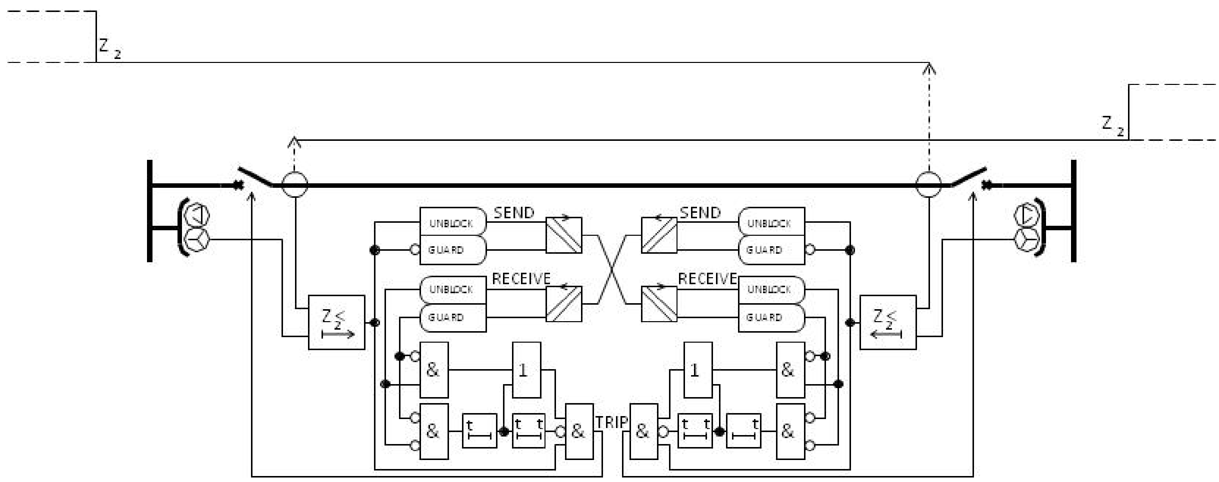


Figure 8.8.14: Simplified schematics of the DCUB-scheme with principal zone reaches

8.8.2.7 Example of using IEDs with distance protection in a meshed MV-network

Figure 8.8.15 shows a distribution network where distance protection is applied as the main protection for feeders and busses and as a backup protection for transformers.

8.8.2.7.1 Feeder Protection

In feeder protection (IEDs #4, #5, #9, #10 and #11, Figure 8.8.15), the underreaching zone Z_1 and the overreaching zone Z_2 is set in the forward direction, whereas the zone Z_3 can be applied in different ways. It can be used either as an overreaching backup protection in the forward direction or as a bus protection if set in the reverse direction. In the former application, bus faults are tripped by the overreaching zone Z_2 of the remote end IED first, whereas in the latter application bus faults are tripped by the reverse reaching zone Z_3 of the local end IED. As the zone Z_1 is underreaching the remote end substation, its operation time can be set to minimum.

The reach of the zone Z_2 must be such that it overreaches suitably the remote end substation but underreaches in the least favorable switching state the substation behind the remote end substation. On the other hand, the reach must not exceed the shortest zone Z_1 reach of any of the feeders connected to the remote end substation. For example, in Figure 8.8.15 the zone Z_2 of the IED #4 in the substation A must not see the faults in the substation C or in its outgoing feeders. A reach setting of 140% fulfills both the above setting considerations in this case. The operation of the zone Z_2 must be delayed as long as the grading margin in relation to the corresponding zone Z_1 operation time in the outgoing feeders of the remote end substation requires. For example, considering the zone Z_2 of the IED #4, its operation time must be such that it coordinates with the zones Z_1 of the IEDs #6, #7, #9 and #10 of the substation B.

When set in the forward direction, the reach of the zone Z_3 can be set so that it must not exceed the shortest zone Z_2 reach of any of the feeders connected to the remote end substation. This way the operation time delay of the remote backup protection can be set equal to the operation time of the zone Z_2 in question added by the required grading margin. Other possibility is that the zone Z_3 is set to reach as far as possible taking into account the maximum load conditions. This way, the coverage of the remote backup protection becomes as wide as possible, but the operation time must be set longer than the longest operation time of the protection of any of the feeders inside the reach of the zone Z_3. The zone Z_3 can also be used as a non-directional backup protection allowing different reaches in the forward and reverse direction. The reach of the zone Z_3 in the forward and reverse direction can be set in accordance with the above viewpoints.

Optionally the operation of the zone Z_1 and Z_2 can be complemented by an auxiliary communication channel for the use in the scheme communication logic. In this application the setting of the zone Z_2 can be set according to the guidelines given for the zone Z_3 above, but it must never exceed the shortest zone Z_2 reach of any of the feeders connected to the remote end substation. The reach of the zone Z_1 can be set similarly as above. The zone Z_3 can now be dedicated for the reverse-reaching bus protection. Its reach and operation time settings must coordinate with the settings of the zone Z_1 settings of the other feeders of the substation.

8.8.2.7.2 MV-incomer protection

In the MV-incomer protection (IEDs #3, #6 and #8, Figure 8.8.15), the zone Z_1 is set to underreach the HV-side transformer terminals, so it provides a fast backup protection for the transformer differential relay. The zone Z_2 is set to overreach suitably so that it covers the HV-side bus and some part of the incoming HV-lines (some not shown in Figure 8.8.15) providing a time-delayed backup protection for these parts of the circuit. The zone Z_2 can also be used as a non-directional time-delayed backup protection. The reverse-reaching zone Z_3 is used as a time-delayed bus protection and it also serves as an overreaching backup protection for the feeders within its reach. Depending on its reach, the operation time is set to coordinate with the corresponding zones of the outgoing feeder IEDs in the substation.

8.8.2.7.3 Transformer feeder protection

In the transformer feeder protection (IEDs #1, #2 and #7, Figure 8.8.15), the zone Z_1 is set to underreach the MV-side transformer terminals, so it provides a fast backup protection for the transformer differential relay. The zone Z_2 is set to overreach suitably so that it covers the MV-side bus and some part of the MV-feeders providing a time-delayed backup protection for these parts of the circuit. Depending on its reach, the operation time is set to coordinate with the corresponding zones of the outgoing MV-feeder IEDs in the substation. The reverse-reaching zone Z_3 can be used as a time-delayed bus protection serving also as an overreaching backup protection for the HV-lines within its reach. Alternatively, it can be used as a non-directional backup protection. Also in case of transformer feeder, the protection can optionally be complemented by an auxiliary communication channel for the use in the scheme communication logic, which enables a fast backup protection for the transformer differential relay.

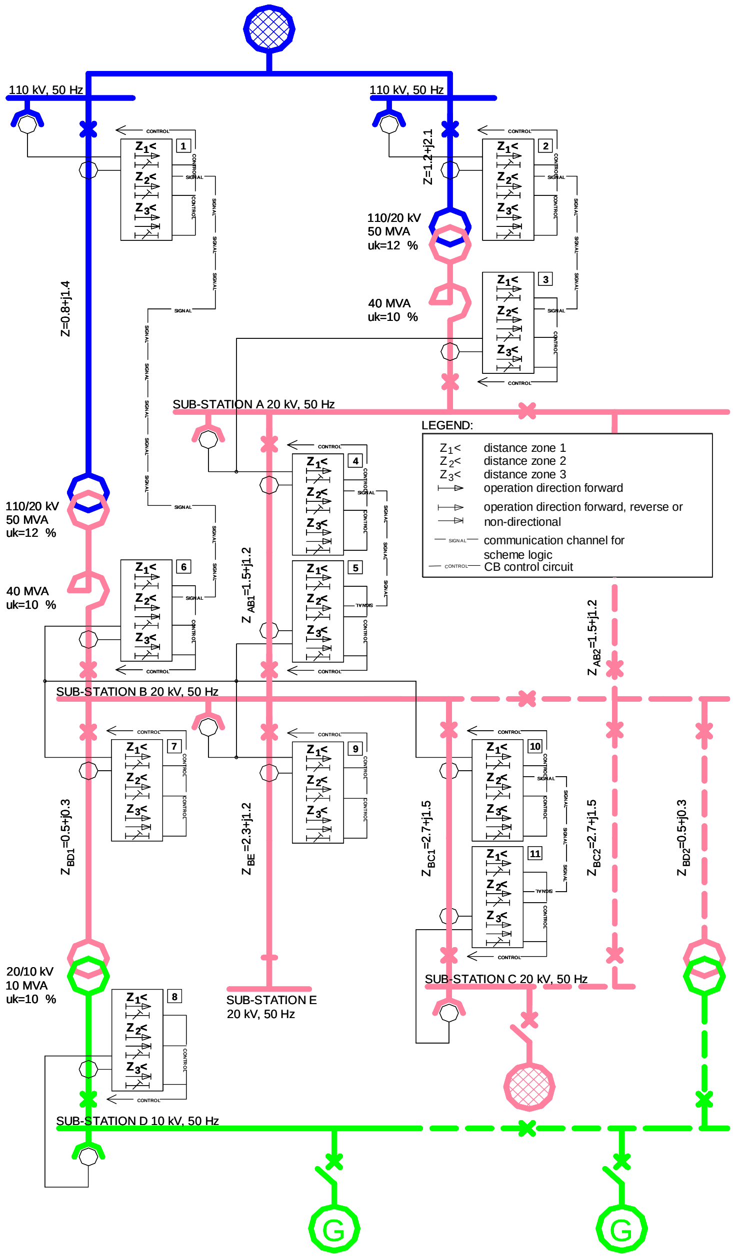


Figure 8.8.15: Example of using IEDs with distance protection in a meshed MV-network

8.8.2.8 Pros and cons of distance protection

In conclusion, distance protection is especially suitable for the main protection in ring and meshed systems with possible multiple supply points and changing network connections where a fast fault clearance is required.

Pros:

- The reach of the zones and selectivity is greatly independent of the magnitude of fault currents and network conditions.

- An auxiliary communication channel is not necessary for a fast fault clearance.
- Fast fault clearance of the zone Z_1 usually covers 80-90% of the line section.
- The rest of the line is always covered by the overreaching zone Z_2 with an operating time of approximately 150-200 ms (relaying time).
- Remote backup protection for lines is always available as time selectivity between successive feeder IEDs is also applied.
- Busbar protection can always be arranged by the forward-overreaching zone and/or by the dedicated reverse-reaching zone.
- Selection of setting values is quite easy as exact fault current calculations are typically not needed.
- In modern IEDs, multiple distance zones are typically included, and high flexibility in the zone parameterization and setting selection is a standard feature.

Cons:

- With short line applications due to setting limitations of the zone Z_1, an auxiliary communication channel is required in order to achieve selectivity and fast fault clearance.
- The sensitivity may not be adequate to detect earth faults in non-solidly earthed systems, and thus a separate earth-fault protection must be implemented
- Three-phase voltage measurement in the station is required

8.8.3 Differential Protection

8.8.3.1 Traditional restrained low-impedance schemes applying metallic pilot wires

Traditional implementations apply metallic pilot wires as interconnecting channel between the line ends. Typically, the pilot wire consists of a two-wire circuit of telephone line-type cable, which can be operated with 50 Hz secondary level signals, or it can be used as a communication channel where the current information is interchanged in the analog or digital format.

Two basic solution principles can be identified: *opposing voltage* and *circulating current*. In these solutions, the pilot wire is operated with a 50 Hz signal consisting of secondary-level phase currents. Despite the solution in question, the operating criterion is principally the same, which is given in the simplest form by the equation:

$$\left|\underline{I}_{OP}\right| \geq k \times \left|\underline{I}_{RES}\right| + I_B \qquad \textbf{(8.8.21)}$$

where

$\underline{I}_{OP}$	is the calculated operating current phasor
$\underline{I}_{RES}$	is the calculated restraint current phasor
k	is the characteristic slope setting
I_B	is the basic start current setting

The operating and restraint currents are also called the differential and stabilizing currents respectively. The operating criterion states that the higher the restraint current is, the higher the operating current which is required to operate the protection. The correspondence between these two current quantities is given by the slope setting *k*. Thanks to this *restrained characteristic,* a certain level of apparent operating current resulting from, for example, CT and other measuring errors that are proportional to the magnitude of the measured phase currents can be allowed without the risk of false operation.

In the *opposed voltage* principle, the current does not circulate through the pilot wires during normal operating conditions or during the ideal outside-fault conditions. Figure 8.8.16 shows this schematically. However, in the *circulating current* principle, the current circulates through the pilot wires during normal operating conditions and ideal outside-fault conditions. Figure 8.8.17 shows this schematically.

In both principles, the operation and restraint quantities are formed in each line end from the measured pilot wire currents I_{PL}, I_{PR} and the currents I_L and I_R, which are proportional to the primary line end currents, Figure 8.8.16 and Figure 8.8.17.

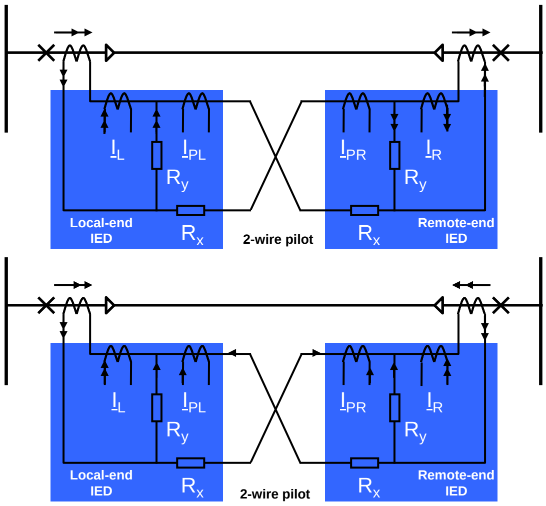


Figure 8.8.16: Current flow in the ‘opposed voltage’ principle, top: normal or outside fault conditions, bottom: inside fault conditions

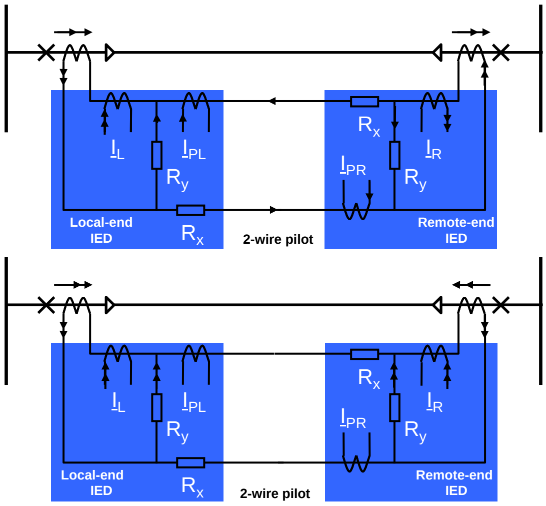


Figure 8.8.17: Current flow in the 'circulating current' principle, top: normal or outside fault conditions, bottom: inside fault conditions

In the opposed voltage principle, the operation and restraint currents for the local end IED are obtained from equations (8.8.22) and (8.8.23).

$$I_{OP\_L} = \left|\underline{I}_L + \underline{I}_R\right| = \left|2(1+\frac{R_x}{R_y})\underline{I}_{PL}\right| \qquad \textbf{(8.8.22)}$$

$$I_{RES\_L} = \frac{\left|\underline{I}_L\right| + \left|\underline{I}_R\right|}{2} = \frac{\left|\underline{I}_L\right| + \left|2(1+\frac{R_x}{R_y})\underline{I}_{PL} - \underline{I}_L\right|}{2} \qquad \textbf{(8.8.23)}$$

For the circulating current principle, similar equations can be written for the operation and restraint currents, equations (8.8.25) and (8.8.25).

$$I_{OP\_L} = \left|\underline{I}_L + \underline{I}_R\right| = \left|2(\underline{I}_L - \underline{I}_{PL}(1+\frac{R_x}{R_y}))\right| \qquad \textbf{(8.8.24)}$$

$$I_{RES\_L} = \frac{\left|\underline{I}_L\right| + \left|\underline{I}_R\right|}{2} = \frac{\left|\underline{I}_L\right| + \left|\underline{I}_L - 2(1+\frac{R_x}{R_y})\underline{I}_{PL}\right|}{2} \qquad \textbf{(8.8.25)}$$

where

$\underline{I}_L$	is the local-end current phasor
$\underline{I}_R$	is the remote-end current phasor
$\underline{I}_{PL}$	is the local-end pilot current phasor

$\underline{I}_{PR}$	is the remote-end pilot current phasor
R_x	is half of the pilot wire loop resistance added by a possible matching resistance of the IED
R_y	is the reference resistance of the IED

Similar equations apply to the remote end IED.

It can be seen that the pilot wire resistance and thus the ratio R_x/R_y defines the magnitude of the pilot current, which must be able to be measured by the IED with an adequate accuracy. This means that there is a maximum limit for the R_x/R_y –ratio, which is defined by the measurement accuracy requirement for the pilot current. This will in turn have an effect on the maximum length of the pilot wire and the protected line. Typically this distance is in order of 10 km.

Satisfactory operation of the schemes described above depends on the reliability of the pilot wire. The effect of a pilot wire short circuit and open circuit on the two principles presented above are opposite as Table 8.8.6 below shows. Where it is indicated that tripping will be caused, tripping requires that the load current magnitude will exceed the settings.

Table 8.8.6: Effect of pilot wire failures on the traditional pilot wire schemes

Principle	Effect of Shorts	Effect of Open Circuits
Opposed voltage	Cause tripping	Block tripping
Circulating current	Block tripping	Cause tripping

Therefore, a means for supervising the pilot wire against short circuits and open circuits must be incorporated. Also attention must be paid to the protection against overvoltages that can originate from mutual induction or earth potential rise during earth faults. Adequate voltage withstand is usually achieved by summation current transformers in each line end described below. However, if the insulation level does not become adequate in this way, additional isolation transformers must be included in the scheme.

In order to use only a 2-wire pilot, there must be a means for deriving a representative single-phase current from the phase and neutral currents. Therefore a suitable *summation current transformer* needs to be used, and the pilot currents I_{PL} and I_{PR} in Figure 8.8.16 and Figure 8.8.17 are actually outputs from these summation CTs. A summation CT derives a single-phase signal from a three-phase input in order to simplify and economize the differential protection IED and its measuring circuit. Figure 8.8.18 shows one arrangement where the output current I_M is proportional to the three-phase and neutral input currents.

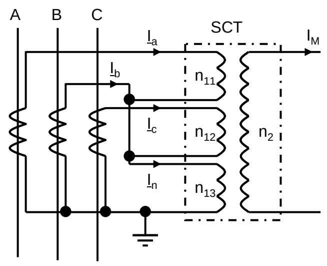


Figure 8.8.18: Example of a summation CT circuit

The current I_M is given by the phasor summation of the input currents taking into account the turns ratios of each winding.

$$\underline{I}_M = \underline{I}_a n_{11} / n_2 + \underline{I}_c n_{12} / n_2 + \underline{I}_n n_{13} / n_2 \quad \textbf{(8.8.26)}$$

For the sake of simplicity, if the turns ratio n_{12}/n_2 is taken as a reference and selected to be equal to 1, for example, then a typical choice for n_{11}/n_2 and n_{13}/n_2 would equal to 2 and 3 correspondingly. This means that the relative value of the output current I_M in relation to the phase current varies depending on which phases are involved in the fault. For example, if in a three-phase fault a current corresponding to the rated secondary current of the summation CT is required to operate the protection, then only 43% of this current is required in case of phase C earth fault.

8.8.3.2 Basic high-impedance scheme

The *high-impedance* scheme uses metallic pilot wires as an interconnecting channel between the line ends. The scheme is particularly easy to implement and set and has a high operational reliability. The basic operating principle is pretty much the same as in the circulating current principle by assuming that the ratio R_x/R_y approaches zero. This means that typically the resistor R_y is much higher than R_x. The former one is now called as the *stabilizing resistor*. The restraining of this scheme is performed with the aid of this resistor, and as the name implies it is employed for the prevention of false operations on the faults outside the area of protection. Such operations may be caused by the differential current arising from the non-simultaneous saturation of the current transformers. As the restraint current does not need to be calculated anymore, the operating current is simply the current that flows through the stabilizing resistor at each end of the line, Figure 8.8.19. This means that the implementation can now be done with a simple three-phase current- or voltage-measuring single-function relay located in each end of the line. Other possibility is to use three pieces of single-phase relays. The maximum length of the protected line depends mainly on the dimensioning of the CTs and lies typically around few kilometers. Due to this limitation, simplicity and moderate cost of the scheme it is suitable especially for short MV-cable networks. Another advantage is that this scheme can easily be implemented with modern IEDs offering also other required protection, control and monitoring functions for the local and remote line ends.

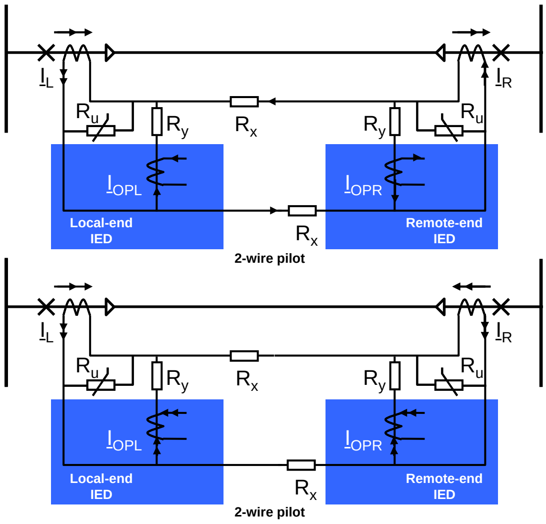


Figure 8.8.19: Current flow in the 'basic high-impedance' principle, top: normal or outside fault conditions, bottom: inside fault conditions. Single-phase presentation.

The design of the stabilization of the high-impedance scheme is based on the assumption that one of the current transformers of the protection fully saturates at faults outside the area of protection, while the rest of the current transformers do not saturate at all. The idea is to route the apparent differential current formed in the said way to flow through the saturated current transformer rather than through the IED. Because the impedance of the saturated current transformer is low, a high resistance, that is, the stabilizing resistor, is connected in series with the IED current input circuit. Now the entire differential current is forced to flow through the measuring circuit of the saturated current transformer. The voltage drop formed over the measuring circuit will then be the same as that over the secondary relaying circuit. This *stabilizing voltage* must not cause the protection to operate, and it is calculated simply as

$$U_S = (2 \times R_x + R_{2CT}) \times I_{k\max} / n \qquad \textbf{(8.8.27)}$$

where

$2 \cdot R_x$	is the total pilot wire loop resistance
R_{2CT}	is the resistance of the CT secondary winding
$I_{k\max}$	is the primary maximum through-fault current
n	is the turns ratio of the CTs

When the protection is implemented using a voltage-measuring function, the selected setting must be equal to or exceed the calculated stabilizing voltage. The value of the stabilizing resistor is determined according to this voltage setting. When the protection is implemented using a current-measuring function, the current value at which the function should operate must be determined first. By means of the stabilizing voltage and the current setting, the value of the stabilizing resistor is obtained. Typically, the stabilizing resistor must be separately installed and connected into the secondary relaying circuit.

The stabilizing resistor in each line end is calculated as:

$$R_S = \frac{U_S}{I_{OP} >} \quad \textbf{(8.8.28)}$$

where

$I_{OP} >$ is the selected operating current of the protection in each line end

When no saturation of the CTs occur in case of a through-fault, the IEDs in each end of the line measure an operating current proportional to $(R_x/R_y)/(1+R_x/R_y)\times I_k/n$ when neglecting the excitation current of the CTs. The false operating current forming in this way is typically much lower than the selected current setting $I_{OP} >$, which corresponds to the worst case in this respect.

On faults inside the area of protection, the current transformers attempt to feed a secondary current proportional to the short circuit current through the stabilization resistor and input circuits of the IEDs. But because the impedance of this circuit is high, the secondary voltage may exceed the ratings of the IED and the secondary wiring. For this reason, *voltage dependent resistors*, *VDRs*, (R_u in Figure 8.8.19) are needed to be connected in parallel with the IEDs in order to limit the voltage to a safe level. The importance of the VDRs is illustrated in Figure 8.8.20, which shows an example of the voltage rise in the secondary circuit in case of internal fault with fault current equal to 25 kA. In this case, a stabilizing resistor of 1000 Ω had been used. It can be seen that without the use of the VDRs, the peak value of the secondary voltage is around 6 kV. With the selected VDR type, this voltage can be reduced to 2 kV, which can be considered being safe for the IED and the wiring.

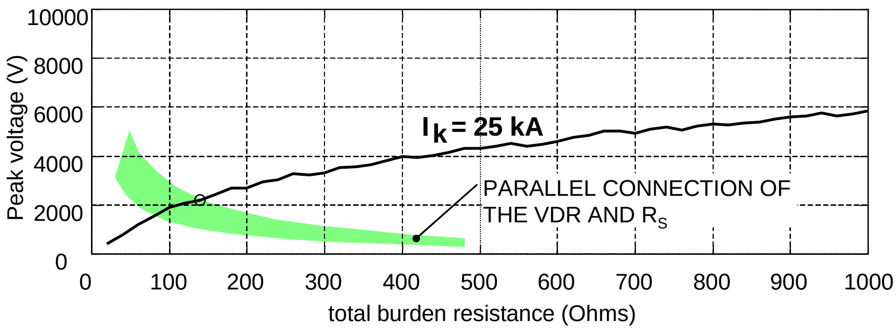


Figure 8.8.20: Example of voltage rise as a function of the total secondary-circuit resistance in case of internal fault

The current transformers used in the high-impedance protection applications must have an adequate accuracy limit factor to be capable of supplying enough current to the relaying circuit on faults inside the area of protection. This requirement is fulfilled if the knee point voltage of the current transformers is at least twice the chosen stabilizing voltage. In this way, the protection operates fast and reliably also for differential current levels just slightly exceeding the set value. The protection requires class X or PX current transformers according to BS 3938 or IEC 60044-1 respectively, the repetition capability of which is determined by the knee point voltage and the resistance of the secondary circuit. In the specification of class X or PX CTs, the magnetizing current corresponding to the knee point voltage is also given. This current value is needed for the calculation of the overall sensitivity of the protection. Furthermore, it should be noted that because the current transformer secondary circuits are galvanically interconnected, all the current transformers of the scheme should have the same transformation ratio.

8.8.3.3 Modern low impedance schemes applying digital communication media

The metallic pilot wire has a rather modest bandwidth that limits the transmission capacity, speed and the distance of the communication, whereas fiber optic cables as a communication medium offer practically an interference-free signal transmission with a very large capacity.

In the following, an example of a modern differential protection is introduced mainly for the use in MV-networks [8.8.2]. This IED features a fully numeric line differential protection with phasors which can operate according to a phase-segregated or combined sequence-based algorithm. The communication interface and link applies fast synchronous data communication and operates via dedicated fiber optic cables or twisted pair pilot wires or alternatively applies shared communication networks by using multiplexers.

Dedicated single-mode fibers offer a reach up to 50 km and multimode fibers up to 2 km. The reach of the dedicated twisted pairs depends on the type of the external communication accessories, for example the SHDSL bridge, wire quality and required transmission rate. The twisted pair communication channel can provide a reach up to 10 km in ideal circumstances.

The point-to-point communication channel between the local and remote end terminals is a dedicated link used only for the line differential protection in this case. This link can be established by fiber optic cables that are directly connected between the terminals or by Ethernet bridging [8.8.3], where the long-distance data transmission is performed over the metallic wires modulated by the DSL technology-based modems [8.8.4] as presented in Figure 8.8.21. The SHDSL technology presents the symmetrical and high-speed transmission methods for signals on twisted-pair copper wires, making it excellently suitable for retrofit installations with already existing pilot wires. The modem can also be directly integrated inside the IED, which simplifies the connections.

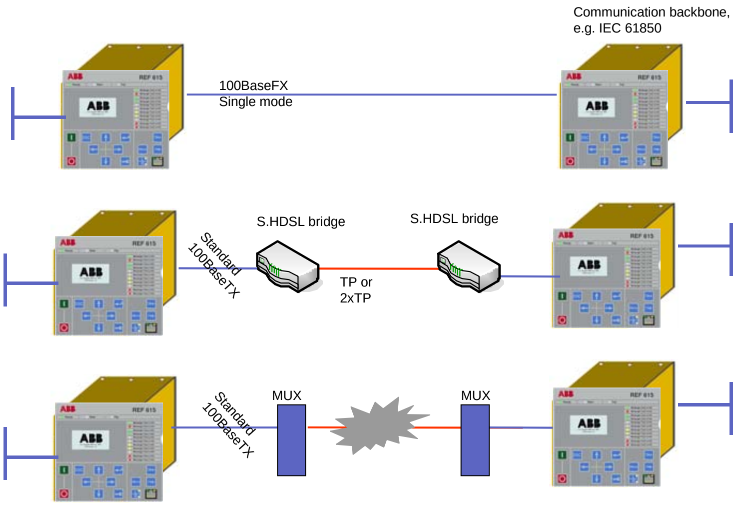


Figure 8.8.21: Example of a modern differential relay with different communication arrangements between the local and remote terminals

Multiplexing as an alternative solution offers a more efficient way of utilizing the arranged communication link between the substations. Multiplexer is a device that combines several input information signals into one output signal which carries several communication channels, by means of some multiplexing technique. Line differential protection application reserves typically only a few communication channels from the multiplexer and the rest are available for other application needs. For example, if one channel can carry data 64 kbit/s and the protection communication requires 384 kbit/s, the protection would then reserve 6 channels from the multiplexer to its use.

The currently applied 1st version of the Substation Automation standard, IEC 61850, does not yet define the methods for changing communication signals between substations. The standard is still based on the Ethernet LAN, and the scope of the standard is further to be extended. However, there is a group of specialists already working for the substation-to-substation section (IEC 61850 90-1) of the standard, so further developments in the area of protection communication in accordance with this standard is to be expected [8.8.6].

8.8.3.3.1 Communication protocols and methods

As the differential protection applications in the MV-area consist typically of two terminals, the master-master communication method is utilized. In this method, both terminals share an equal position in the communication hierarchy and both terminals send sampled and processed measurement values to the other terminal, execute the differential protection algorithm and evaluate the tripping condition. The tripping conditions are also transferred as binary signals between the terminals to implement the direct inter-tripping functions in both directions. To enable this basic functionality and to fulfill the requirements set on the differential protection, a communication channel with the following general considerations must be incorporated:

- Bandwidth: Required communication channel bandwidth capable of transmitting the specified protection information.
  - How much and how frequently information between the terminals must be interchanged?
- Speed: Propagation delay of the communication channel.
  - How fast the differential protection must operate?
- Reliability: Required reliability from a single protection telegram transmission.
  - Single vs. multiple transmission of a protection telegram?
- Accuracy: Differential delay of the communication channel due to asymmetry in the go-and-return communication paths.
  - Echo-method vs. external clock synchronization?

Figure 8.8.22 illustrates the protocol layers used in the communication arrangement between the terminals. Ethernet is a frame-based technology for local area networks (LANs) communication, and standardized as IEEE 802.3, which covers the physical and data link layers of the OSI model [8.8.7]. Physical layer of the Ethernet encompasses several methods for physical links, depending on the speed and medium: 100BASE-TX runs Ethernet over CAT5 copper cabling with two twisted pairs, whereas 100BASE-FX uses different line coding and is used with fiber optic cables (single or multimode). The SHDSL technology as such is out of the Ethernet standard but may easily be connected to the Ethernet either internally or via external connection, Figure 8.8.22, and it utilizes twisted-pair cables similar to telephone lines or equivalent as transmission media.

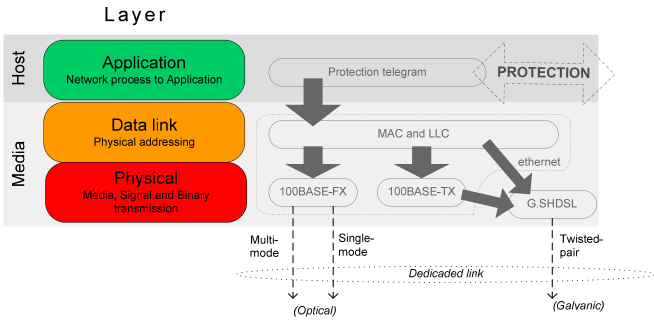


Figure 8.8.22: Line differential protection communication layers

The functionality of the different protocol layers, Figure 8.8.22, is the following:

- Line differential application data is coded and transferred inside the protection telegrams. Protection telegrams include analog measurement data with the needed protection synchronization information and application binary status data, such as circuit breaker position. Also communication quality indications may be exchanged between terminals.
- The data link layer provides data transfer over the physical link. The Media Access Control (MAC) and Logical Link Control (LLC) are sub-layers of the data link layer.
  - MAC layer provides physical addressing mechanism into the medium by providing the MAC address or Ethernet Hardware address. The address is unique and 48 bits (6 bytes) long.
  - LLC layer provides flow and error control and makes the multiplexing of the different upper level protocols (IP, ARP, GOOSE, etc.) over the MAC layer possible. Integrity of the data is ensured by this layer by the error control and dropping out of the corrupted data packets.
- Physical layer makes the raw bit transfer between the network nodes.

So although the basic motivation for the data transmission arrangement is the need to transfer analog measurement data between the substations, this alone is insufficient for constructing an end-to-end, stable, flexible and accurate communication arrangement for the line differential protection application. A solution principle that fulfills the above requirements is presented in the following.

Depending on the impact on the protection application of losing one protection telegram, redundancy must be considered in the sending. Here is presented a transmission method where protection telegrams include analog raw samples among other data and are interchanged only two times per fundamental frequency (ff) cycle, Figure 8.8.23, left. In this method, losing of a single protection telegram would increase the operation time of the protection in case of an internal fault more than one ff-cycle. Therefore, a multiple transmission of the same protection telegram is preferred. Whereas in the transmission method illustrated in Figure 8.8.23, right, the transmission of preprocessed FFT-samples, that is, phasors, is performed eight times per ff-cycle. As a consequence, losing a single protection telegram is not as critical when considering the operation time. The appropriate method should be selected primarily based on the protection-scheduling tasking interval. As in this case, the task is expected to be executed eight times per FFT-cycle; thus the method 2 of Figure 8.8.23 is preferred.

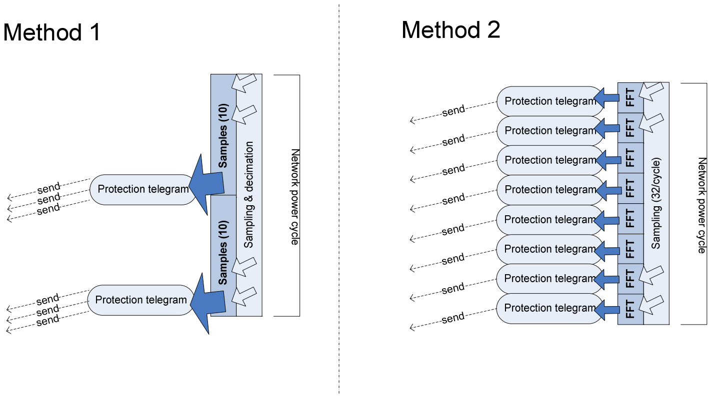


Figure 8.8.23: Transmission methods. Left: multiple sending of raw samples 2 times per ff-cycle, Right: single sending of preprocessed FFT-samples 8 times per ff-cycle. FFT stands for the discrete Fourier transformation of the analog measurement data.

8.8.3.3.2 Synchronization of analog samples

If the sampling of the measurement data is performed centrally by one terminal, which is typically the approach in the transformer differential protection, the calculations of operation and restraint currents can simply be arranged directly from the analog samples of the measured signals. In the case of line differential protection, the accurate synchronization of the local and remote analog samples becomes a challenge. Only after adequate synchronization, the protection algorithm is capable of performing reliable and accurate operation and restraint current calculations. In the line differential protection, the sampling is performed decentrally by at least two terminals in different locations with a substantial distance from each other. The sampling is scheduled by the internal clocks of these two terminals, not synchronized with each other in any way, Figure 8.8.24.

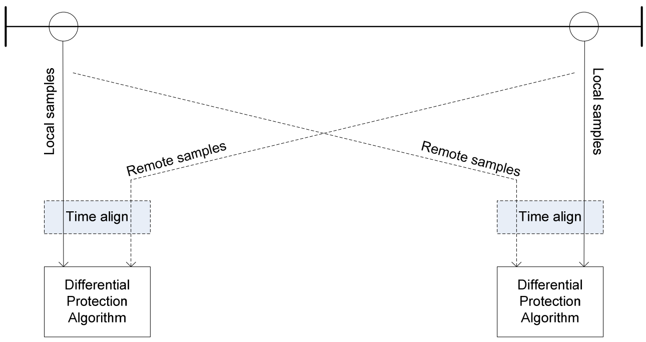


Figure 8.8.24: Time-aligning of the local and remote end samples

Before the time alignment of the local and remote samples can be done, the sampling time difference, that is, the sample latency, needs to be solved by some means. The sampling latency originates from the signal propagation delay depending on the implementation of the digital communication link between the line ends together with the internal delays of the corresponding terminals.

The synchronization can be implemented accurately by using external clock reference arranged by the help of modern GPS technology, if such is available in both line ends. However, arranging this may not be economically or technically feasible. Another possibility is to use a so-called echo method, where the terminals create their own time reference between each other over the protection communication link. This can be used when the external time synchronization is not possible but the propagation delay is symmetrical in both directions and the differential delay of the propagation is small, that is, the propagation delay stays constant. The principle of the echo-method is presented in Figure 8.8.25.

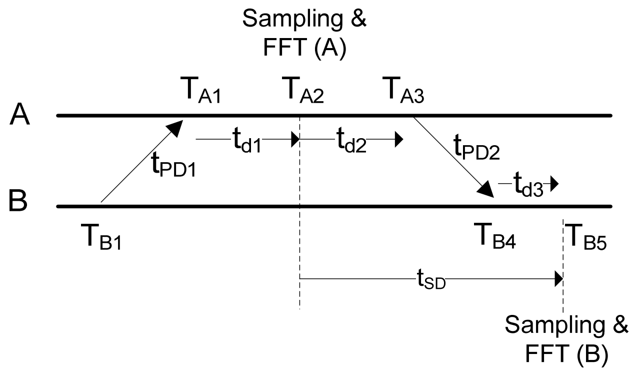


Figure 8.8.25: Forming of the channel propagation delay and the principle of the echo method algorithm

According to Figure 8.8.25, the terminal B transmits its protection telegram at T_{B1} (based on terminal B time concept), and the terminal A receives it at T_{A1} (based on terminal A time concept). At T_{A2}, the terminal A performs its sampling and FFT-calculations. The time differences t_{d1} ($T_{A1} \rightarrow T_{A2}$) and t_{d2} ($T_{A2} \rightarrow T_{A3}$) are measured by the terminal A and sent within the protection telegram, including also the analog phasor data from T_{A2}. The protection telegram enters the network at T_{A3} and is received by the terminal B at T_{B4}. At T_{B5} the terminal B performs its protection calculations. The terminal B measures the time difference t_{d3} ($T_{B4} \rightarrow T_{B5}$) and can now accurately calculate the sample latency t_{SD}, that is, the application-to-application delay time that is further needed in the time alignment of the local and remote analog phasors.

Propagation delay t_{PD} and sample latency t_{SD} are constantly calculated and this is done for each received protection telegram separately and on both terminals:

$$t_{PD} = \frac{(T_{B4} - T_{B1}) - (t_{d1} + t_{d2})}{2} \qquad \textbf{(8.8.29)}$$

$$t_{SD} = t_{PD} + t_{d2} + t_{d3} \qquad \textbf{(8.8.30)}$$

The quantity $(T_{B4} - T_{B1})$ presented in Equation (8.8.29) can also be referred to as the round-trip time, whereas $(t_{d1} + t_{d2})$ is the turnaround time. Propagation delay can be simplified, Equation (8.8.31), in case of symmetrical communication channel.

$$t_{PD} = t_{PD1} = t_{PD2} \qquad \textbf{(8.8.31)}$$

The protection algorithm execution scheduling is synchronized with the sampling and FFT-calculation. Depending on the CPU capacity, the task that runs the actual protection application may be executed, for example, once for every 4th sample (eight times per fundamental frequency cycle). By increasing the task cycle frequency even more, the operation time of the protection can be made even shorter. The sample latency in the equations above expects that the protection algorithm at the terminal B is executed at time T_{B5}, and thus it affects also the operation time of the protection.

Since the sampling is not synchronized between the line ends, the local and remote analog phasors must be time-aligned and this is done by selecting the nearest local analog phasor available from the short history memory that matches closest to the calculated sample latency in time, Figure 8.8.26.

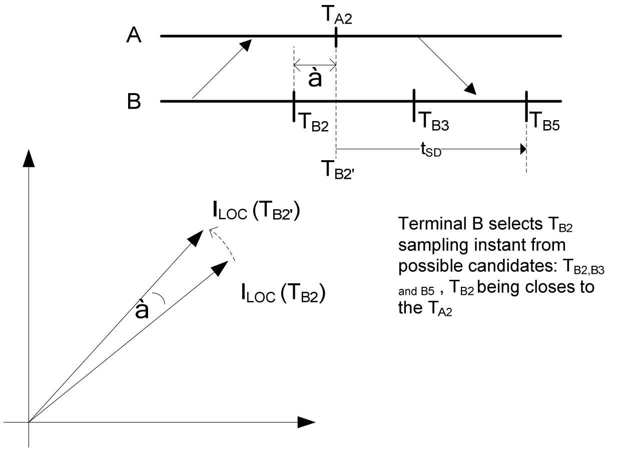


Figure 8.8.26: Rotating of the local phasor to make it exact in time with the remote phasor that is used in the restraint and differential current calculations

The error caused by the nearest local sampling instant difference to the remote sampling instant is further compensated by rotating the local or remote phasor to make them match exactly in time:

$$\alpha = \frac{T_{B2} - T_{B2'}}{T_P} \times 360° \qquad \textbf{(8.8.32)}$$

where

T_P is the fundamental frequency (ff) cycle time

T_{B2} is the time of the closest sampling instant

$T_{B2'}$ is the ideal sampling instant time

The error in the achieved sample latency measurement is directly seen as the apparent differential current caused by the error in the angle, Figure 8.8.26. As an example, an inaccuracy of 0.1 ms in the 50 Hz system gives a maximum amplitude error of around 3%, while an inaccuracy of 1 ms gives a maximum amplitude error of approximately 31%. The corresponding values in the 60 Hz system are 4% and 38% respectively.

The error is totally caused by the possible asymmetry of the communication channel, but when the symmetrical communication channel is used, these can practically be disregarded.

When the external clock reference (GPS) is used [8.8.8], the analog samples are time-stamp-tagged by the terminals before sending. Since the terminals share a common global time reference, time stamps are directly comparative on both ends and the sample latency can be based on the simple difference calculation of these two time stamps. Depending on the accuracy of the freewheeling internal real-time clocks of the terminals, the use of the common time reference is still possible for some time, even in case the GPS signal has been suddenly lost for a short time. After a longer period without a new clock synchronization message, a decision needs to be made by the line differential protection to block its operation since the accuracy of the sample latency and as a consequence the accuracy of the calculated differential current become worse within time. It is still also possible to try to switch back to the echo method before issuing the blocking signal. This procedure is illustrated in Figure 8.8.27.

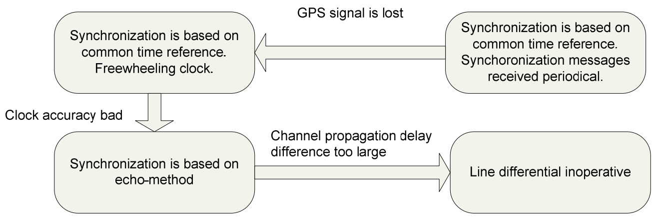


Figure 8.8.27: Operation during the loss of GPS signal.

8.8.3.3.3 Binary signal interchange

Together with the analog measurement data, also binary data can be exchanged by the local and remote terminals. The use of the binary data is typically application-specific, which also sets speed requirements for the data transmission. Especially when the binary data is used as blocking signals of the protection, the transfer speed must be extremely high. Typical applications of binary signal interchange are the following:

- Remote circuit breaker or disconnector status indications, Figure 8.8.28
- Direct inter-tripping of the circuit breakers on both line ends
- Blocking of the line differential protection, for example during switching inrush condition or current circuit supervision failure, Figure 8.8.28
- Protection schemes that apply scheme communication logic used to complement the differential protection, for example earth-fault protection
- Autoreclose sequence coordination
- Remote alarming

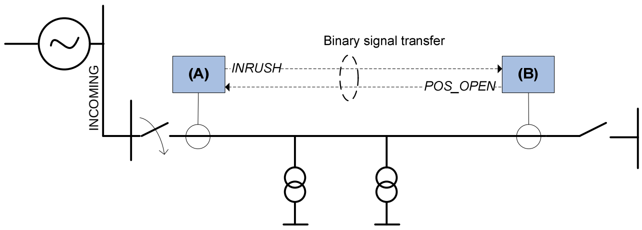


Figure 8.8.28: Binary signal transfer application example in a line with tapped loads

Figure 8.8.28 shows one example of the binary signal interchange applications. According to Figure 8.8.28, the relay B transfers its breaker open status to the relay A and this information is then used to lower the setting of the non-restrained high-set stage suitably prior to the closing command of the breaker controlled by the relay A to allow a fast switch-on-to-fault protection. On the other hand, during the breaker closing only the relay A would detect the transformer inrush current and the 2^{nd} harmonic content of it, but both relays would see differential current as a consequence. The relay A signals the relay B to block its low-set stage to prevent possible false tripping.

8.8.3.3.4 Supervision of the communication channel

Line differential protection is vulnerable to errors in the communication channel. Communication interference/ interruptions lasting longer than allowed prolongs the operation time of the protection. Therefore, the channel needs to be supervised in adequate manner. Typically, the line differential protection includes a backup protection functionality, for example overcurrent protection, whose operation is not dependent on the operation of the communication channel. These may even be out of use during the normal operation of the differential protection and its communication channel. The backup functions are then released during a communication failure, ensuring always a certain degree of protection.

Often the communication-related disturbances are random, relatively short in duration and disappear by themselves. The reason for these can be, for example, the loss of protection telegrams due to checksum errors. Depending on the expected error rate of the communication channel, the protection telegram loss can still be an unavoidable event in digital communication networks in the long term. Despite this, the terminals cope with these situations without issuing an alarm for the operator or jeopardizing the safety of operation. This is done by the automatic scheme switching between the differential protection and its backup protection during short-term communication interference. The probability of automatic recovery decreases as the interruption time increases. Delayed alarming, in addition to the switching between the main and backup protection, is performed in case of communication interruptions lasting longer than typical short term disturbances. The alarm is an indication of a more permanent failure in the protection communication that typically is not self-clearing.

Switching back from the backup protection to the line differential protection may include a reset time characteristic. This operates as hysteresis for the scheme switching, securing on the other hand also the proper operation of the backup protection during the short-term communication interference. Figure 8.8.29 shows the basic operation principle of the scheme switching during communication disturbances.

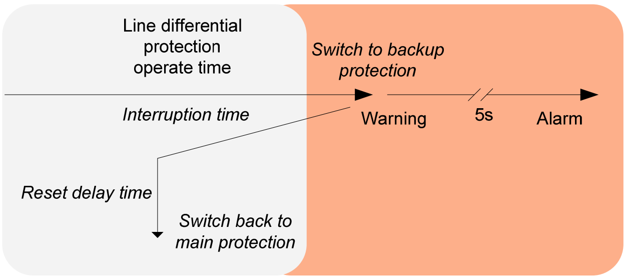


Figure 8.8.29: Line differential protection operation during communication disturbances

The requirement for quickly reacting communication supervision originates from the fact that the operation and restraint current calculation is fully dependent on the continuity of receiving new analog phasors from the remote end terminal, Figure 8.8.30. The incoming protection telegram operates as a trigger for the calculations where the effect of the sample latency t_{SD} must be taken into account. This means that the latest received remote end phasor and the local end phasor closest to it from the history memory is used for updating the current quantities, Figure 8.8.26 and Figure 8.8.30.

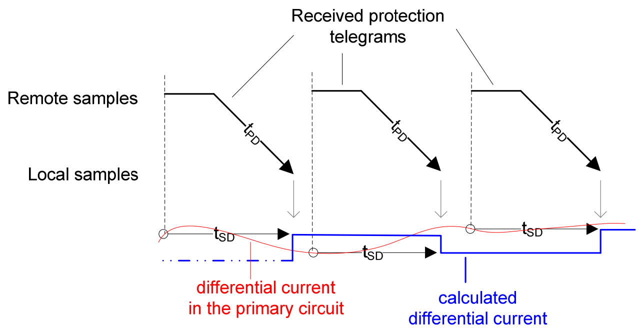


Figure 8.8.30: Differential current calculation timing characteristic

As the update of the differential and restraint current calculations is only possible when a new protection telegram is received, missing telegrams do not endanger the stability of the protection due to load or through-fault currents. However, to prevent the drastic consequences of communication failures on the operation speed of the protection, the concept of protection telegram income guarding is used for the supervision. This is illustrated in Figure 8.8.31, where communication interference takes place at the most unfavorable moment, that is, just prior to an internal fault.

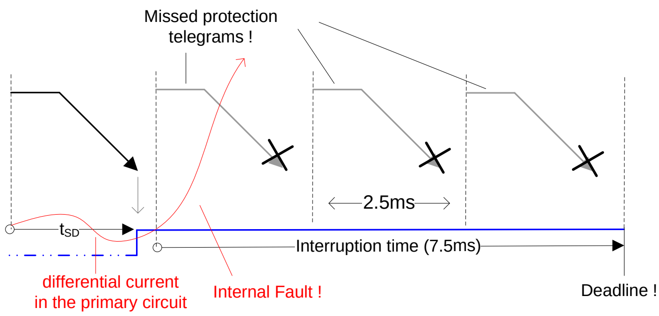


Figure 8.8.31: Protection communication supervision during internal fault

In the protection telegram income guarding, the reception of a new protection telegram always starts a deadline timer, which is then reset by the arrival of a new protection telegram. If an interruption is detected and is lasting longer than allowed, for example 7.5 ms, presented in Figure 8.8.31, the protection communication supervision issues a blocking signal for the differential protection. As a result, the backup protection is released and it finally operates to clear the fault. If the interruption disappears before the deadline timer elapses, the differential protection operates but there will be an additional operation time delay which depends on the deadline timer setting.

Communication quality information is also continuously exchanged between the line ends within the protection telegrams. This ensures that the protection scheme switching is done coordinately between the line ends. Even in case the interference would only be detected on the other line end terminal, the consequence is a simultaneous blocking of both line end terminals.

8.8.3.3.5 Phase-segregated scheme

In the phase-segregated scheme, differential protective functions are implemented on per phase current basis. The phase current differential computations determine whether a fault has occurred and identify which phase or phases are involved in the fault. The differential (operation) quantity in the current differential function is the magnitude of the phasor summation of the local and remote current. Thus, the operation quantity is equal to the total fault current for internal faults and equal to 0 (neglecting line-distributed capacitance-charging currents) for external faults:

$$I_{OPphA} = \left| \underline{I}_{LphA} + \underline{I}_{RphA} \right| \qquad \textbf{(8.8.33)}$$

The stabilizing (restraint) current is calculated as the amplitude of the phasor difference:

$$I_{RESphA} = \frac{\left| \underline{I}_{LphA} - \underline{I}_{RphA} \right|}{2} \qquad \textbf{(8.8.34)}$$

where

$\underline{I}_{LphA}$ is the local end phasor presenting the phase current A and

$\underline{I}_{RphAC}$ is the remote end phasor presenting the phase current A

Equations (8.8.33) and (8.8.34) assume positive current direction from the busbar towards the line in both line ends. Similar equations apply for phases B and C. Alternatively, the restraint current can be calculated based on the sum of amplitudes of the local and remote end current phasors.

A typical operating characteristic is shown below, where the settings are

P is the minimum operating current

$S1$ is slope 1

$S2$ is slope 2

I_{KNEE1} is slope intersection 1

I_{KNEE2}	is slope intersection 2
$IRES_{SAT}$	is the CT saturation restraint
IOP_{SAT}	is the CT saturation operation

The detection of CT saturation desensitizes the operation as described in Figure 8.8.32.

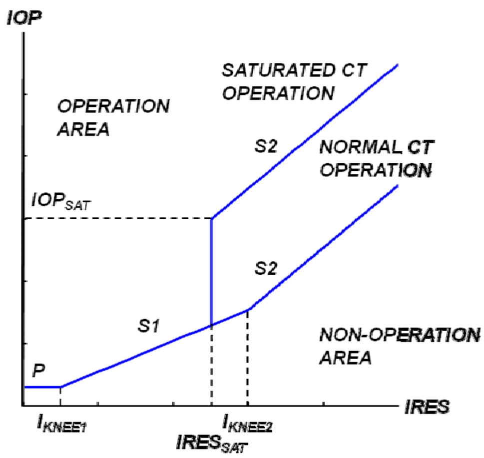


Figure 8.8.32: Example operating characteristic

Based on Figure 8.8.32 the operation criterion becomes as follows:

1. $IRES \le I_{KNEE1}$:
   - $IOP > P$
2. $I_{KNEE1} < IRES < I_{KNEE2}$:
   - $IOP > P + S1 \times (IRES - I_{KNEE1})$
3. $IRES \ge I_{KNEE2}$:
   - $IOP > P + S1 \times (I_{KNEE2} - I_{KNEE1}) + S2 \times (IRES - I_{KNEE2})$

If CT saturation is detected it is additionally required:

4. $IRES \ge IRES_{SAT}$:
   - $IOP > IOP_{SAT} + S2 \times (IRES - IRES_{SAT})$

In addition, differential computations can optionally be conducted based on negative-sequence current and zero-sequence current to increase the sensitivity and fault resistance coverage.

The shape of the operating characteristic is designed so that the operation is dependable and fast in inside faults and stable and secure in outside faults. To illustrate these operating requirements, the following simulation has been performed, taking into account the transient behavior of the CTs. In this simulation, the I_{RES},I_{OP}-trajectory has been plotted in relation to the selected operating characteristic of the IED after the fault inception, Figure 8.8.33. In case of an outside fault, the I_{RES},I_{OP}-trajectory stays well in the non-operation area of the characteristic, and the protection remains stable despite the apparent differential current caused by measuring errors and non-simultaneous CT saturation, which results from different CT types installed and their dimensioning. In case of an inside fault, the I_{RES},I_{OP}-trajectory shoots in the operation area of the characteristic, causing immediate operation despite the partial CT saturation.

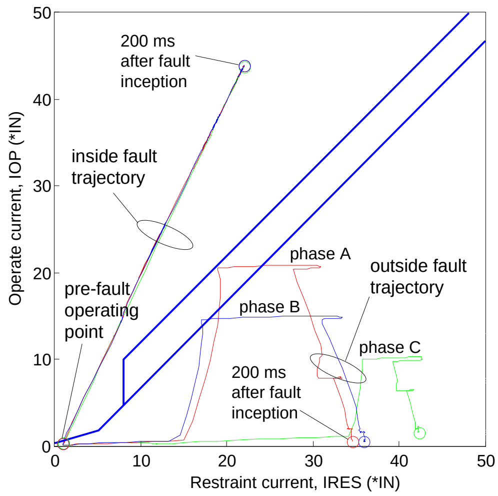


Figure 8.8.33: I_{RES},I_{OP}-trajectory in an inside and outside three-phase fault

8.8.3.3.6 Combined sequence scheme

In the combined sequence scheme, in order to reduce the communication capacity requirements while maintaining adequate operation speed and reliability of operation, only one single signal instead of all three-phase currents are interchanged between the ends of the line . This signal is a proper combination of line positive-sequence, negative-sequence, and zero-sequence currents. The dominance of each sequence current in this signal is determined by its corresponding weighting factor. The weighting factors are selected in a way that all kinds of faults are represented as equally as possible by the signal.

The combined sequence current used in the scheme is a weighted sum of phase A symmetrical component currents. Here, I_T represents the combined current and C_1, C_2 and C_0 represent the weighting coefficients for the positive-, negative- and zero-sequence components, then $\underline{I}_T$ can be described as

$$\underline{I}_T = C_1\underline{I}_1 + C_2\underline{I}_2 + C_0\underline{I}_0 \quad \textbf{(8.8.35)}$$

where

$\underline{I}_1$	is phase A positive-sequence current phasor
$\underline{I}_2$	is phase A negative-sequence current phasor

$\underline{I}_0$ is phase A zero-sequence current phasor

For a certain combination of the weighting factors, the relationship between $\underline{I}_T$ and fault currents is determined by the fault types. Because $\underline{I}_T$ is always based on phase A sequence currents regardless of the faulted phase or phases, $\underline{I}_T$s are different even for the same fault type when different phase or phases are involved in the fault. For example, AE-faults result in different $\underline{I}_T$ as BE- or CE-faults, and BC-faults result in different $\underline{I}_T$ as CA- or AB-faults. However, BE- and CE- faults create the same $\underline{I}_T$, and so does CA- and AB-faults. The relationship between $\underline{I}_T$ and the actual fault current also depends on the ratios between the positive-, negative- and zero-sequence impedances of the system.

Similar calculation of the operate and restraint quantities and the operating characteristic presented above can also be used in context with the combined sequence scheme.

8.8.3.3.6.1 Combined sequence currents and fault currents

The best way to see the effect of the coefficients on the sensitivity of the protection is to calculate the ratio of $\underline{I}_T$ and the corresponding fault current phasor flowing in the fault point for different fault types. In the derivation of the equations below, it has been assumed that the system negative-sequence impedance equals to the positive-sequence impedance, and that the system zero-sequence impedance equals to three times the positive-sequence impedance.

For three-phase fault, Equation (8.8.36) applies.

ABC-fault:

$$\left|\frac{\underline{I}_T}{\underline{I}_{PhABC}}\right| = |C_1| \qquad \textbf{(8.8.36)}$$

For two-phase faults, equations (8.8.37), (8.8.38) and (8.8.39).

BC-fault:

$$\left|\frac{\underline{I}_T}{\underline{I}_{PhBC}}\right| = \left|\frac{C_1 - C_2}{\sqrt{3}}\right| \qquad \textbf{(8.8.37)}$$

AB-fault:

$$\left|\frac{\underline{I}_T}{\underline{I}_{PhAB}}\right| = \left|\frac{C_1 + C_2(0.5 - j\frac{\sqrt{3}}{2})}{\sqrt{3}}\right| \qquad \textbf{(8.8.38)}$$

CA-fault:

$$\left|\frac{\underline{I}_T}{\underline{I}_{PhCA}}\right| = \left|\frac{C_1 + C_2(0.5 + j\frac{\sqrt{3}}{2})}{\sqrt{3}}\right| \qquad \textbf{(8.8.39)}$$

For single-phase-to-earth faults, equations (8.8.40), (8.8.41) and (8.8.42).

AE-fault:

$$\left|\frac{\underline{I}_T}{\underline{I}_{PhA}}\right| = \left|\frac{C_1 + C_2 + C_0}{3}\right| \qquad \textbf{(8.8.40)}$$

BE-fault:

$$\left|\frac{\underline{I}_T}{\underline{I}_{PhB}}\right| = \left|\frac{C_1 + C_2(-0.5 + j\frac{\sqrt{3}}{2}) + C_0(-0.5 - j\frac{\sqrt{3}}{2})}{3}\right| \qquad \textbf{(8.8.41)}$$

CE-fault:

$$\left|\frac{\underline{I}_T}{\underline{I}_{PhC}}\right| = \left|\frac{C_1 + C_2(-0.5 - j\frac{\sqrt{3}}{2}) + C_0(-0.5 + j\frac{\sqrt{3}}{2})}{3}\right| \qquad \textbf{(8.8.42)}$$

8.8.3.3.6.2 Selection of weighting coefficients, no contribution from zero-sequence current, C_0=0

In cases where the scheme is applied only for short circuit protection like in high-impedance earthed networks, it is sufficient to use only positive- and negative-sequence currents. With no zero-sequence current contribution, the magnitudes of $\left|\underline{I}_T / \underline{I}_{FAULT}\right|$ -ratios are calculated in Figure 8.8.34 and Figure 8.8.35 by using equations (8.8.37) to (8.8.42). In these calculations, a value of -1 has been given for the coefficient C_1.

For short circuit faults, it can be found that BC-faults have bigger sensitivity than AB- and CA-faults. If C_2 is higher than 2, the resulting combined sequence currents for phase-to-phase faults are higher than the corresponding fault currents. For three-phase faults, the sensitivity is constant as no negative-sequence current exists.

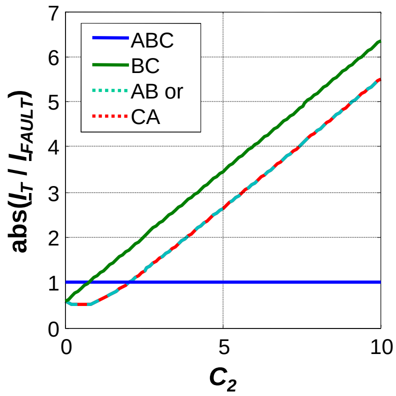


Figure 8.8.34: $|\underline{I}_T/\underline{I}_{FAULT}|$-ratios for two- and three-phase faults as a function of C_2

For phase-to-earth faults, it can be seen that BE- and CE-faults have a bigger sensitivity than AE-faults. If C_2 is higher than 4, the resulting combined sequence currents for single-phase-to-earth faults are higher than the corresponding fault currents.

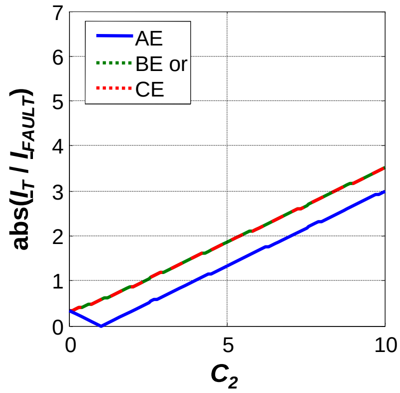


Figure 8.8.35: $|\underline{I}_T/\underline{I}_{FAULT}|$-ratios for single-phase-to-earth faults as a function of C_2

Table 8.8.7 summarizes the conclusions of Figure 8.8.34 and Figure 8.8.35.

Table 8.8.7: Combined sequence current phasor $\underline{I}_T$ in multiples of fault current

Fault type	**abs($\underline{I}_T/\underline{I}_{FAULT}$)**	**abs($\underline{I}_T/\underline{I}_{FAULT}$)**	**abs($\underline{I}_T/\underline{I}_{FAULT}$)**
	C_1=-1, C_2=2, C_0=0	C_1=-1, C_2=4, C_0=0	C_1=-1,C_2=7, C_0=0
ABC	1	1	1
AE	0.3	1	2
BE	0.9	1.5	2.5
CE	0.9	1.5	2.5
AB	1	2.1	3.8
BC	1.7	2.9	4.6
CA	1	2.1	3.8

8.8.3.3.6.3 Selection of weighting coefficients, contribution from zero-sequence current, $C_0 \neq 0$

Increasing of C_2 can increase the earth-fault sensitivity and reduce the sensitivity difference between three-phase faults and earth faults in cases where the earth-fault current is lower than the three-phase fault current. For example, when C_2 equals to 7 and the earth-fault current is 50% of the three-phase fault current, the sensitivities become almost equal.

The disadvantage in increasing C_2 further is that the sensitivity difference between earth faults and phase-to-phase faults becomes even larger. In order to increase the sensitivity of earth faults and in the same time to keep the sensitivity of phase faults unaffected, a non-zero C_0 should be used. With the zero-sequence current contribution included, the magnitudes of $\left|\underline{I}_T / \underline{I}_{FAULT}\right|$-ratios are calculated in Figure 8.8.36 by using Equation (8.8.40), (8.8.41), and (8.8.42). In these calculations the coefficient C_1 equals to -1 and C_2 equals to 4. By adjusting C_0, the magnitude of earth fault current can vary between 30-75% of the three-phase fault current, and it is still possible to keep the sensitivity of earth faults the same in relation to the sensitivity of three-phase faults.

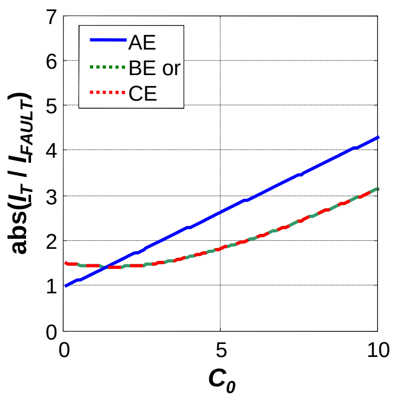


Figure 8.8.36: $|\underline{I}_T/\underline{I}_{FAULT}|$-ratios for single-phase-to-earth faults as a function of C_0

8.8.3.4 Example of using IEDs with line differential protection in a meshed MV-network

Figure 8.8.37 shows a distribution network where differential protection is applied as the main protection for feeders and transformers. Due to absolutely selective operation of the differential protection, a backup protection based on overcurrent or underimpedance is additionally required. This functionality is not shown in Figure 8.8.37.

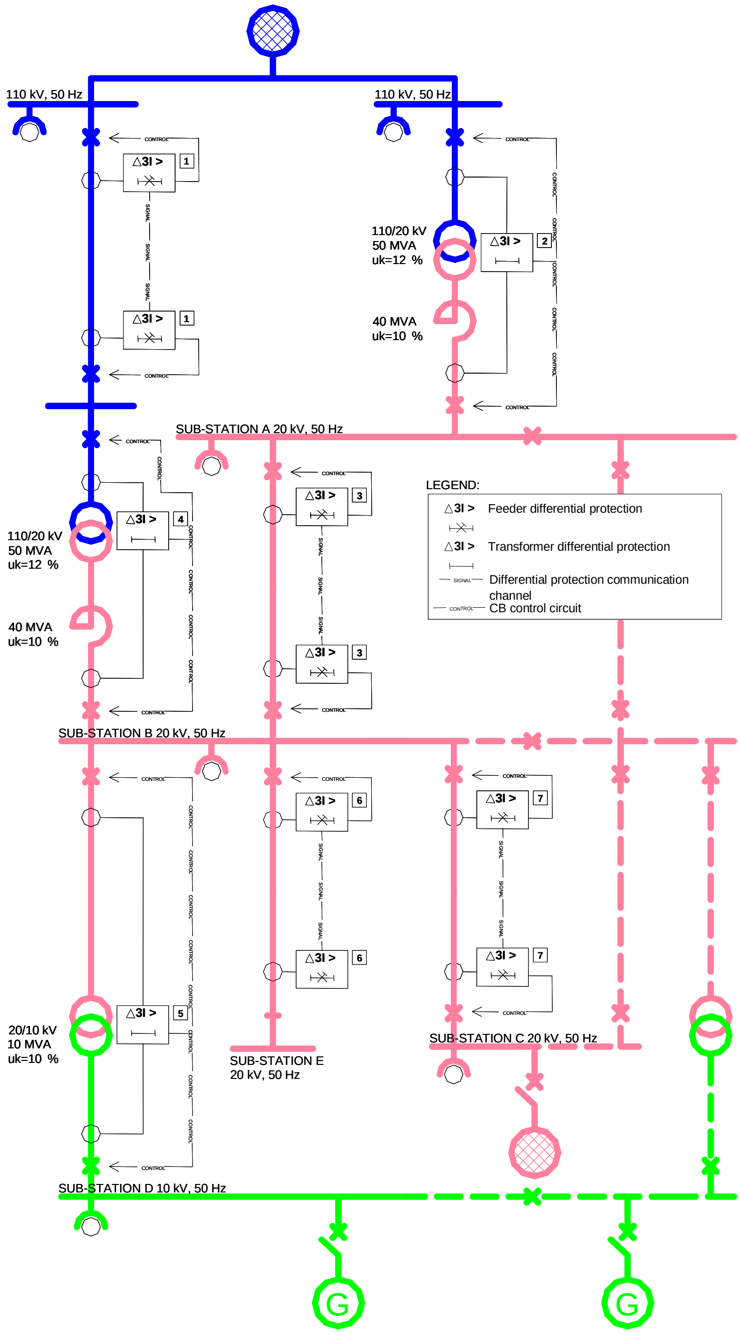


Figure 8.8.37: Example of using IEDs with differential protection in a meshed MV-network. Back-up protection functionality not shown.

Pros and Cons of Differential ProtectionIn conclusion, like distance protection, the differential protection is suitable for the main protection in ring and meshed systems with possible multiple supply points and changing network connections where a fast fault clearing is required.

Pros:

- Absolute selective operation, that is, operates only in faults inside the zone of protections

- Fast operation, operating time typically 1-2 cycles
- Generally the choice of setting values is easy and independent of network conditions
- Applicable also for short lines
- Depending on the algorithm design, power transformers can be included in the zone of protection
- To some extent, tapped loads can be included in the zone of protection
- Does not require knowledge of the line impedance characteristic
- Does not require voltage transformers
- Modern IEDs offer versatile communication alternatives to be used both in retrofit and in new installations as a standard feature

Cons

- Interconnecting channel, pilot wire or fiber optic cable, between line ends required
- Possible failure on a communication channel makes the system inoperable, that is, a local backup protection is always required
- Due to the absolutely selective operation, a local backup protection is always required
- Separate earth fault protection is often called for, because the sensitivity of the differential protection can be inadequate, especially in non-solidly earthed systems

References

[8.8.1] REF630, Feeder Protection Terminal, Technical Manual, ABB Oy Distribution Automation 2008.

[8.8.2] RED615, Line Differential Protection and Control, Technical Manual, ABB Oy Distribution Automation 2008.

[8.8.3] IEEE 802.1D MAC Bridges.

[8.8.4] Harte, L.: "Standards Development for Digital Subscriber Line Systems"

[8.8.5] SHDSL technology complementing other transport technologies, ISBN: 0-7803-7763-X

[8.8.6] Communication networks and systems for power utility automation - Part 90-1: Use of IEC 61850 for the communication between substations (draft)

[8.8.7] IEEE 802.3 Standard

[8.8.8] Global Positioning System: Theory and Practice, ISBN-10: 3211828397

[8.8.9] Wang L. & Hedding R.: "Line Current Differential Relaying", 54th Annual Georgia Tech Protective Relaying Conference, Atlanta, Georgia, 2000

[8.8.10] Altonen, J. & Wahlroos, A.: "Novel method for implementing the mho characteristic into distance relays", The IET 9th International Conference on Developments in Power System Protection (DPSP) , Glasgow 2008.

Document revision history

Document revision/date	History
A / 07 October 2010	First revision

Disclaimer and Copyrights

Trademarks

This page is intentionally left blank.

Contact information

ABB Oy, Distribution Automation
P.O.Box 699
Visiting address: Muottitie 2A
FI-65101 Vaasa, FINLAND
Phone: +358 10 22 11
Fax: +358 10 22 41094

www.abb.com/substationautomation