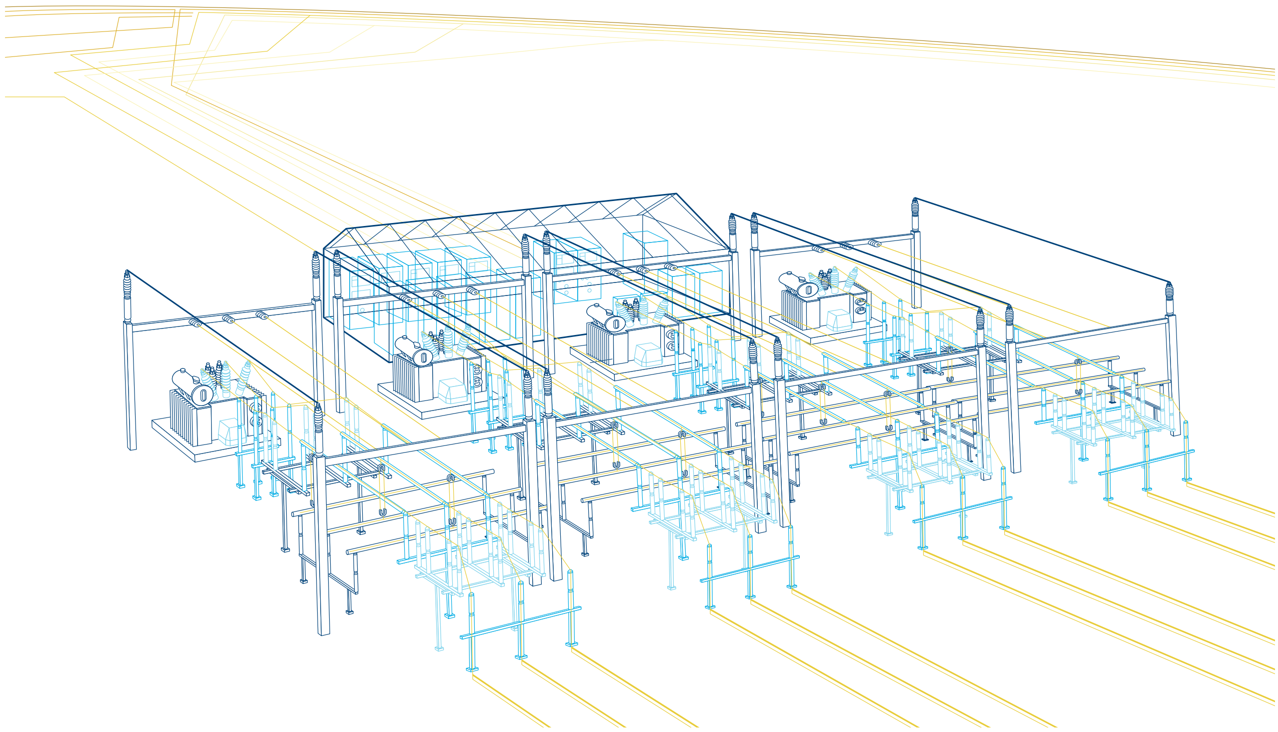
Distribution Automation Handbook

Section 8.6 MV Feeder Earth-fault Protection



Contents

8.6 MV Feeder Earth-fault Protection

This chapter contains a description of the earth-fault protection of MV feeders. A feeder may consist of: (1) an overhead line with bare conductors, (2) an overhead line with covered conductors, (3) an aerial cable, (4) an underground cable or (5) a combination of such line and cable sections. The feeder is a part of a distribution system that may be: (1) effectively earthed or (2) non-effectively earthed.

Phase overcurrent relays and residual overcurrent relays are often used to provide main earth-fault protection of MV feeders. The relays may have independent time or dependent time characteristics and may or may not be combined with a directional element. Neutral displacement voltage and neutral point current are the most common polarizing quantity for directional elements. Backup protection is often provided by a neutral displacement overvoltage relays.

8.6.1.1 Faults and Abnormal Conditions

Various forms of earth-faults are common on distribution systems. The most common fault is the *single phase-to-earth fault* but other types of earth fault also occur. They are:

- Phase-to-phase-to-earth faults
- Cross-country faults
- Back-fed earth faults

A long discussion on phase-to-phase-to-earth faults is not necessary. This fault may be detected by either the short-circuit protection or the earth-fault protection or by both.

The term *cross-country fault* is used to designate two single phase-to-earth faults that occur at two different locations on the system. A common cross-country fault starts as a single phase-to-earth fault anywhere on a distribution feeder. The voltage on the two healthy phases rises to a value close to the phase-to-phase voltage of the system. The increased voltage on the two healthy phases may cause damage to an already weakened lightning arrester on the same or on another feeder. The resulting fault current is usually higher than the fault current at a single phase-to-earth fault. The fault current at a cross-country fault is normally lower than the fault current associated with a short circuit with zero fault resistance at the fault location closest to the feeding substation.

The term back-fed earth fault is used to designate a special combination of a series fault (broken conductor) and a single phase-to-earth fault. This single phase-to-earth fault is fed from the MV/LV distribution transformers downstream of the fault. The upstream end of the broken conduction is not in contact with earth. This means that the source impedance for the single phase-to-earth fault involves the load impedance transformed from the low-voltage side to the high-voltage side of the downstream distribution transformers.

8.6.1.2 Fault Statistics

The failure rate of overhead lines with bare conductors normally increases when the system voltage decreases. The reason is that many faults are caused by lightning overvoltages and that the percentage of overvoltages high enough to cause a flashover between conductor and earth decreases with increasing system voltage and insulation level. Such fault statistics are presented in Section 8.5. Figure 8.6.1 shows a breakdown of cable faults in the Mosenergo underground cable system.

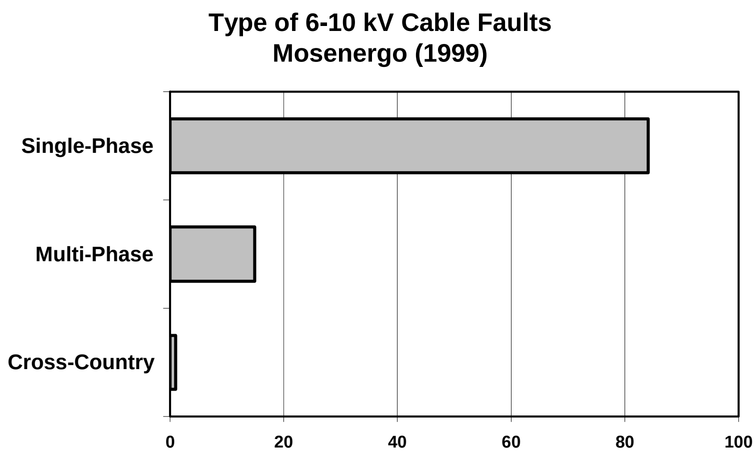


Figure 8.6.1: Type of cable faults in Mosenergo network

8.6.1.3 Fault Resistance

Short circuits are usually associated with high fault currents while earth faults may have considerable fault resistance. Figure 8.6.2 and Figure 8.6.3 show the cumulative distribution function for fault resistance in Petersen coil-earthed systems and systems with isolated neutral.

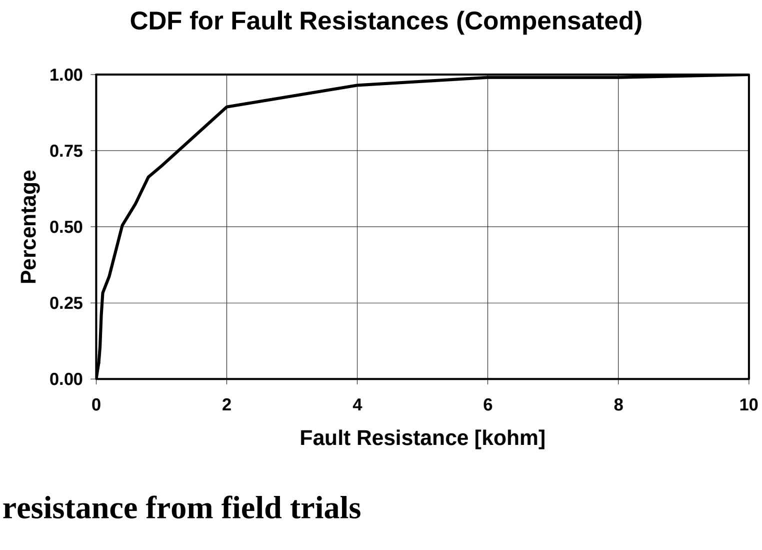


Figure 8.6.2: Fault resistance from field trials

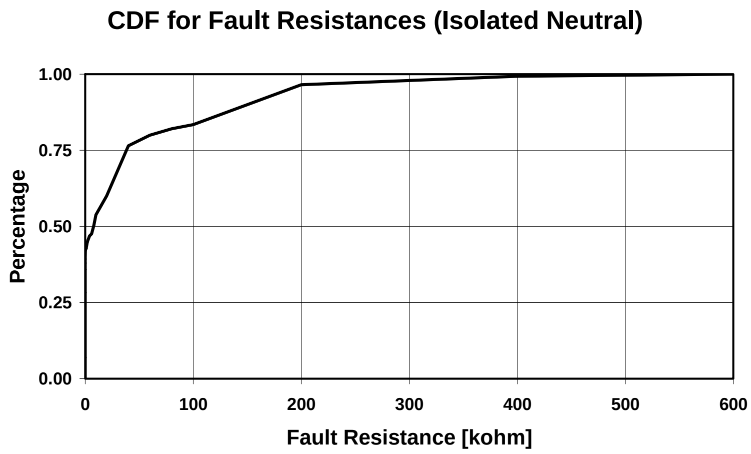


Figure 8.6.3: Fault resistance from field trials

Li and Redfern, reference [8.6.2], have published data on fault resistance to be expected when a 12 kV conductor falls on various types of soil as shown in Figure 8.6.4.

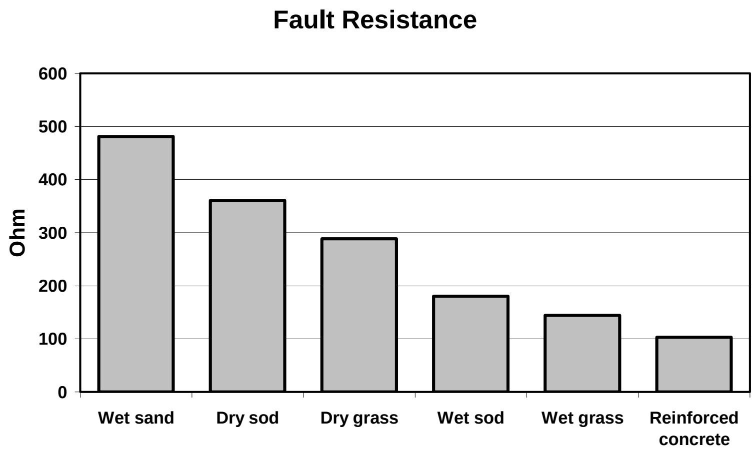


Figure 8.6.4: Fault resistance for various soil conditions

An even higher fault resistance is to be expected when a growing tree falls onto a feeder. Sydkraft (now E.ON Elnät Sverige AB) in Sweden has carried out field experiments to measure resistance of growing trees [8.6.6] . The aim was to measure the fault resistance and the rate of change of the fault resistance to assess the performance of MV earth-fault protection based on transient components of the fault current. Figure 8.6.5 shows the fault resistance of five different trees as a function of time. Figure 8.6.5 also shows the resistance measured at staged tests carried out by BBC (now ABB) to test the performance of a protective relay designed to detect high-resistance faults on EHV transmission lines [8.6.7].

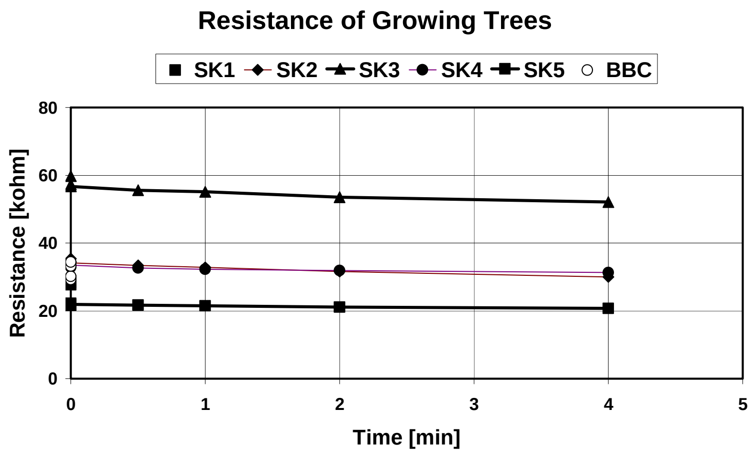


Figure 8.6.5: Fault resistance of growing trees

A growing tree that falls onto an electric power circuit with bare conductors will cause a fault resistance that ranges from 20 to 50 kΩ. The fault resistance seems to be more dependent on the type of tree than on the voltage. The rate of change of the fault resistance seems to be very low.

Stewart [8.6.5] has also published data on fault resistance and rate of change of fault resistance, as shown in Figure 8.6.6.

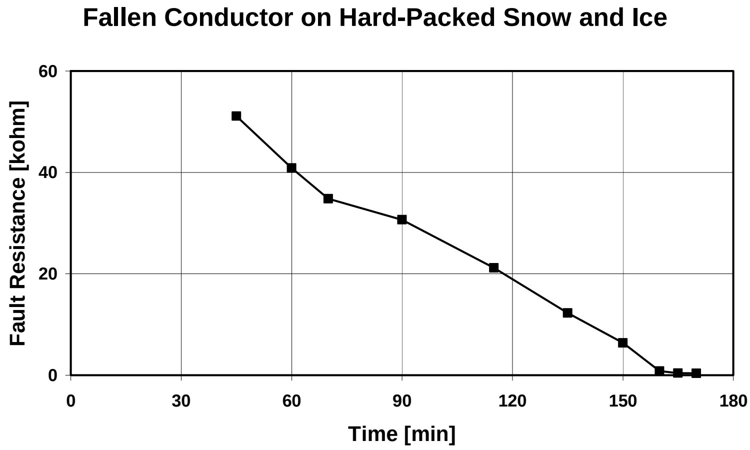


Figure 8.6.6: Fault resistance of a fallen conductor

The fault resistance may, hence, range from 20 to 60 kΩ and the rate of change of the fault resistance may be as low as a few percent per minute.

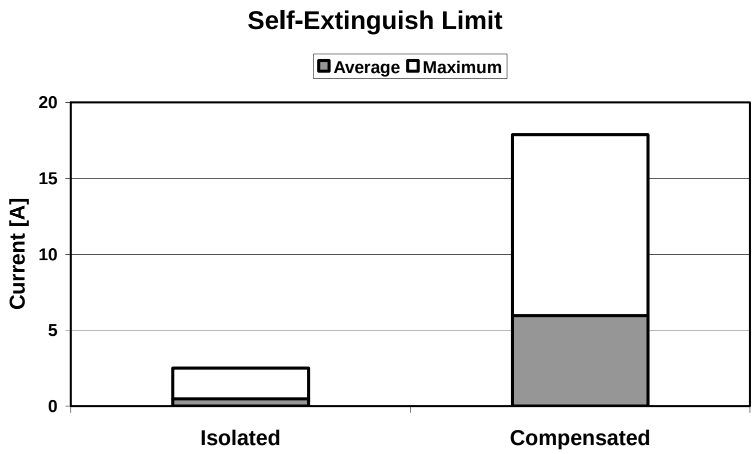


Figure 8.6.7: Self-extinguish limit from field tests

8.6.1.4 Effectively Earthed Systems

The earth-fault current in effectively earthed networks are of the same order of magnitude as the short-circuit current in the network. Expected load currents under peak load conditions set a lower limit to the setting of the phase overcurrent relays. This limits the sensitivity of the earth-fault protection. More sensitive protection against earth faults can be obtained by using a relay which responds only to the residual current I_r defined below.

$$I_r = 3I_0 = I_a + I_b + I_c \qquad \textbf{(8.6.1)}$$

Here I_a, I_b, and I_c are the phase currents and it is possible to form the residual current as shown in Figure 8.6.8.

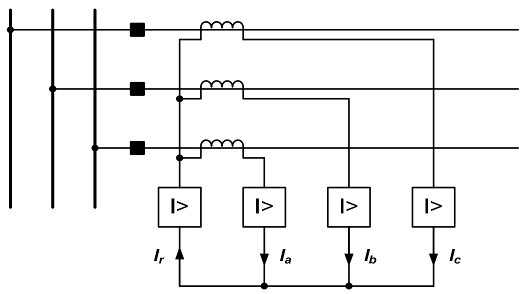


Figure 8.6.8: Three-phase short-circuit and earth-fault protection

The feeder protection consists of three-phase overcurrent relays and one residual overcurrent relay fed from the same core of the phase current transformers. The energizing current ($3I_0$) is close to zero under normal operating conditions. The residual overcurrent relay is unaffected by phase-to-phase faults and by symmetrical short-circuit currents. The setting of the residual relay may be lower than 10% of the rated current of the current transformers. The residual overcurrent relay must not operate at false residual overcurrent caused by current transformer errors or unequal loading in the three secondary circuits in the set of three current transformers. The residual overcurrent relay must not operate for primary residual currents, which may be caused by series unbalances caused on non-transposed power lines or by induction from parallel circuits. Some utilities use residual overcurrent relays to detect series faults and other abnormalities that may cause non-desirable zero-sequence currents.

8.6.1.5 Non-effectively Earthed Systems

Figure 8.6.9 shows a classical feeder protection in non-effectively earthed systems. The feeder protection consists of two-phase overcurrent relays and one residual overcurrent relay energized from three-phase current transformers. The designation "classical" is used to indicate that the feeder protection was introduced when only electromechanical and analog electronic relays were available. It was then desirable to reduce the number of relays as much as possible and at least one of the phase overcurrent relays responded to all types of short circuits.

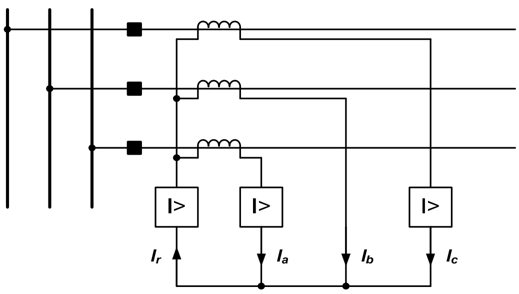


Figure 8.6.9: Two-phase short-circuit and earth-fault protection

The earth-fault currents in non-effectively earthed system are small and may range from less than one ampere to some tens of amperes. It may then be desirable to use a high transformation ratio for phase currents and a lower transformation ratio for the residual current. It is a common practice in many MV distribution systems to use a window-type current transformer to measure the residual current.

8.6.1.6 Measurement of Earth-fault Currents

Section 8.6.1.3 demonstrates that the fault resistance may be very high and it is often desirable to detect a higher fault resistance than the short-circuit protection can detect. Two approaches can be used to achieve the residual current: (1) the residual current is formed by adding the secondary current from the phase current transformers and (2) the use of a window-type (core balance) transformer as shown in Figure 8.6.10 and Figure 8.6.11.

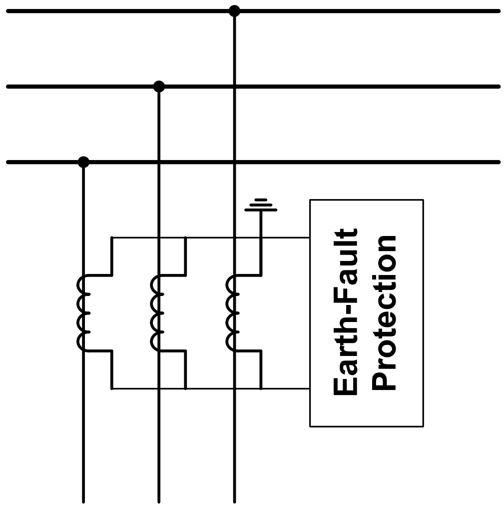


Figure 8.6.10: Summation circuit to form the residual current

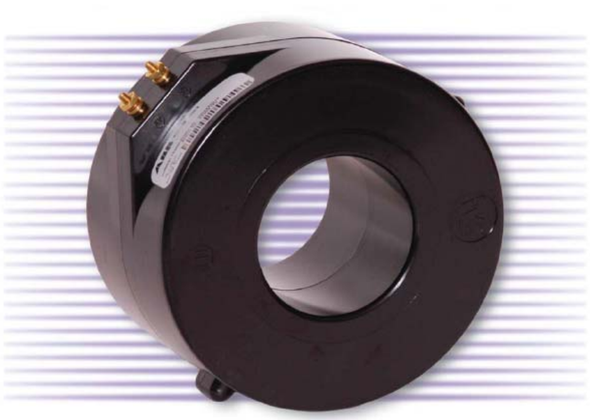


Figure 8.6.11: Window-type (core balance) transformer

Figure 8.6.12 shows a classical type of feeder protection in non-effectively earthed MV distribution systems. The feeder protections consists of two-phase overcurrent relays and one residual overcurrent relay energized from a window-type current transformer.

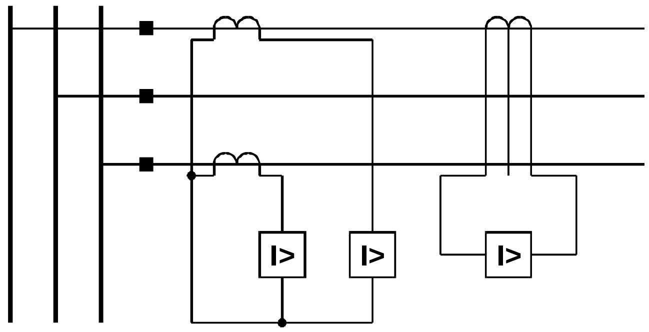


Figure 8.6.12: Two-phase short-circuit and earth-fault protection

8.6.1.7 Limitations of Non-directional Residual Relays

Non-directional residual overcurrent relays may provide adequate protection in systems with isolated neutral and many feeders of approximately the same length. The total capacitive earth-fault current in such systems is significantly higher than any of the capacitive earth-fault current from any of the feeders. This means that a non-directional residual overcurrent relay on the faulty feeder will measure a residual current which is larger than its own capacitive earth-fault current at a fault on another feeder. It will hence operate only for earth fault on the protected feeder and will not operate for earth faults on the other feeders as long as the setting of the residual overcurrent relay is higher than the capacitive earth-fault current of the protected feeder.

Non-directional residual overcurrent relays provide adequate protection of feeders in MV cable system if the largest capacitive earth-fault current is less than about 1/3 of the total capacitive earth-fault current.

8.6.1.7.1 Systems with Isolated Neutral

The sensitivity of a protection scheme using non-directional residual overcurrent relays may not be sufficient to detect high-resistance faults. The total fault current will drop below the capacitive earth-fault current of the feeder when the fault resistance assumes a sufficiently high value. This value may be lower than the value required by authorities or by the utility itself.

A directional element can increase the sensitivity of earth-fault protection in MV distribution systems with isolated neutral. Usually the neutral displacement voltage is used as the polarizing quantity in the directional element. The residual current leads the neutral displacement voltage by slightly less than 90 degrees in case of a single phase-to-earth fault on the protected feeder. The residual current lags the neutral displacement voltage by slightly less than 90 degrees in case of a single phase-to-earth fault on any other feeder. The accuracy of such a protection is not very high because the phase angle difference between residual current and neutral displacement voltage at a forward fault differs by almost 180 degrees from the phase angle difference at a reverse fault.

8.6.1.7.2 Petersen Coil-earthed Systems

Protection schemes using non-directional residual overcurrent relays are usually not suitable for Petersen coil-earthed systems. The reason is that the fault current at a single phase-to-earth fault is much smaller than the total capacitive earth-fault current. The fault current is sometimes also smaller than the capacitive earth-fault current of the protected feeder. The residual current will lag the neutral displacement voltage if the capacitive earth-fault current is smaller than the vector sum of the inductive current from the Petersen coil and the capacitive current from the other feeders. The residual current will, on the other hand, lead the neutral displacement voltage if the condition is not fulfilled. In addition, the residual current on the faulty feeder in a Petersen coil-earthed system is significantly smaller than the total capacitive earth-fault current. This means that the losses in the zero-sequence system will affect the phase-angle difference between the residual current and the neutral displacement voltage.

The conclusion is then that the phase-angle difference between the residual current and the neutral displacement voltage is not a reliable criterion for the determination of the detection to a single phase-to-earth fault. The residual current will, however, have a component that is in phase with the neutral displacement voltage. This component can be increased by the installation of a neutral point resistor in the feeding substation.

8.6.1.7.3 Parallel Feeders

In Figure 8.6.13, the parallel feeders are running from a source bus S to a load bus L. It is not possible to set non-directional residual overcurrent relays so that they provide a selective protection of the feeders. If a solid single phase-to-earth fault occurs close to the load bus L at F as shown in Figure 8.6.13, all residual overcurrent relays sense the same residual current and independent time residual overcurrent relays will operate if the residual current is higher than the pickup current. Dependent time residual overcurrent relays will also operate if the energizing current is higher than the pickup current but the operating time will differ slightly. Non-directional relays cannot provide a selective protection of parallel feeders.

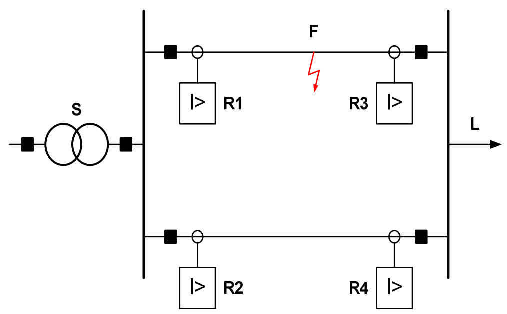


Figure 8.6.13: Residual overcurrent relays applied to parallel feeders

With this type of system configuration, it is necessary to use directional relays at the load bus L. It is also necessary to grade them with the non-directional relays at the sending end S to ensure selective protection of both feeders. The directional elements of relays R3 and R4 must look into the protected feeder. The pickup current of the directional relays R3 and R4 must be lower than the pickup current of the non-directional relays R1 and R2. The operating time of the directional relays R3 and R4 must be shorter than the operating time of the non-directional relays R1 and R2.

8.6.1.8 Directional Earth-fault Relays

Section 8.6.1.7 demonstrated the need for directional earth-fault elements. There is a need for one directional element that responds to the quadrature component of the residual current and another directional element that responds to the in-phase component of the residual current. Here it is assumed that the polarizing quantity is in phase with the neutral displacement voltage.

8.6.1.8.1 Directional Power Relays

A classical directional earth-fault relay responds to the average value of the product of the residual current, and the polarizing voltage and the directional power P_d is given by equation (8.6.2) below.

$$P_d = U_p I_r \cos \varphi \tag{8.6.2}$$

Here

U_p	is the polarizing voltage
I_r	is the residual current
φ	is the phase angle difference

It is also possible to detect the quadrature component of the residual current by suitable phase shifting of the energizing quantities.

$$Q_d = U_p I_r \sin \varphi \tag{8.6.3}$$

The symbol Q_d indicates the similarity to a reactive energy (kvar) meter.

The advantage of power relays is that they are based on technology that is widely used with proven reliability. The disadvantage with power relays is that the directional power decreases with the product of the residual current and the polarizing voltage. This means that the sensitivity of the directional earth-fault relay limits the possibility of the selective clearance of high-resistance single phase-to-earth faults. Another disadvantage is that harmonic components contribute to the directional power.

8.6.1.8.2 Directional Current Relays

Modern technology makes it possible to measure the in-phase quantity I_d and quadrature component I_q of the residual current as defined by:

$$I_d = \frac{U_p}{|U_p|} I_r \cos\varphi$$
$$I_q = \frac{U_p}{|U_p|} I_r \sin\varphi \qquad \textbf{(8.6.4)}$$

Such directional current relays must be designed carefully. One challenge is to determine the phase angle difference when the magnitude of the polarizing voltage is small. It may be necessary to allow the relay to operate only if the polarizing quantity exceeds a (settable) level. Another challenge is to avoid incorrect operation of the $I_r \cos\varphi$ relay when the phase angle difference is close to 90 degrees. This is the case on healthy feeders with large capacitive earth-fault current. It may be necessary to allow the relay to operate only if $|\varphi| \le \varphi_m$ where φ_m is a (settable) phase angle difference slightly less than 90 degrees. It may also be necessary to allow the relay to operate only if the magnitude of the residual current exceeds a (settable) value.

8.6.1.8.3 Typical Characteristics

Figure 8.6.14 shows the characteristic of a typical directional current relays.

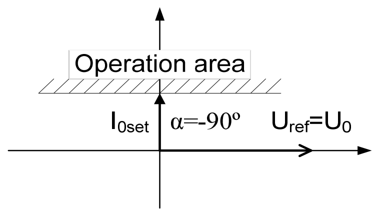


Figure 8.6.14: Characteristic of one type of directional relay

Figure 8.6.15 shows the characteristic of a modern (digital) directional current relay with a very flexible characteristic.

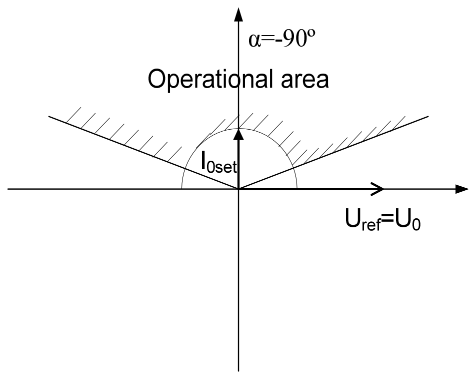


Figure 8.6.15: Characteristic of one type of directional relay

8.6.1.9 Measurement of Residual Voltages

Section 8.6.1.7 demonstrates that there is a need to measure the neutral displacement voltage. Three approaches can be used to measure the neutral displacement voltage: (1) the neutral displacement voltage is formed by adding the secondary voltage from the phase-to-earth voltage transformers in the feeder bay, (2) the neutral displacement voltage is formed by adding the secondary voltage from the phase-to-earth voltage transformers in (one of) the feeding transformer bay(s) and (3) the use of a single-phase voltage transformer connected to the neutral of (one of) the feeding power transformer(s) as shown in Figure 8.6.16, Figure 8.6.17 and Figure 8.6.18.

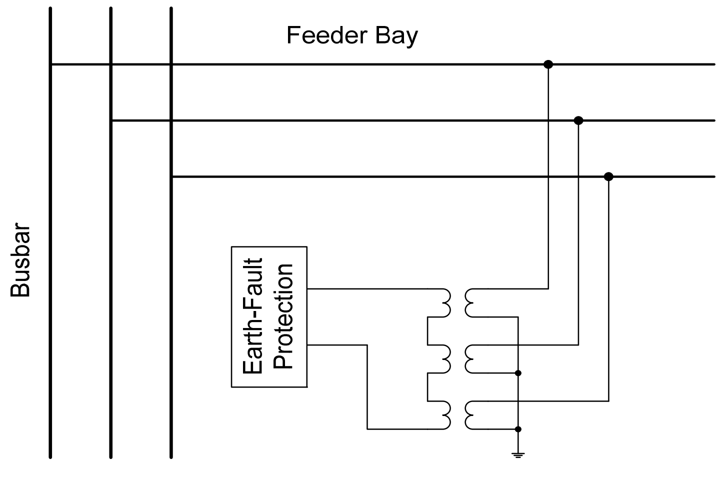


Figure 8.6.16: Use of voltage transformers in the feeder bay

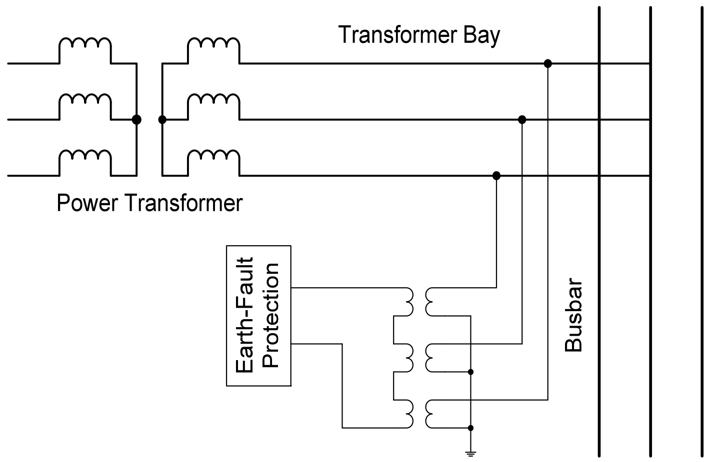


Figure 8.6.17: Use of voltage transformers in the transformer bay

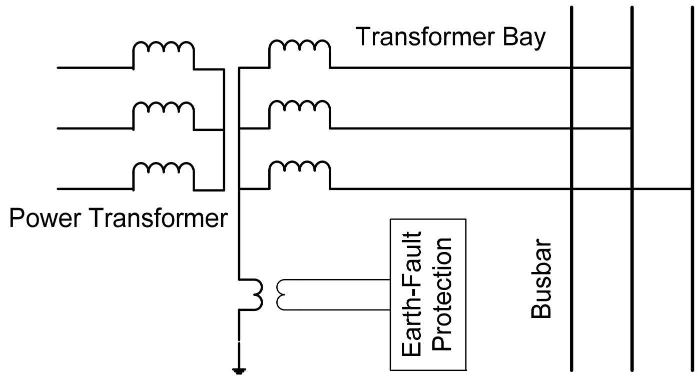


Figure 8.6.18: Use of one voltage transformer at the transformer neutral

8.6.1.10 Earth-fault Protection of Closed Rings

The distribution system shown in Figure 8.6.19 is the simplest configuration of an interconnected (meshed) distribution system. This fairly simple network configuration presents problems to the designer of the earth-fault protection. One challenge is that the in-phase component of the earth-fault current will be divided into two parts. One of these parts will be only a tiny fraction of the in-phase component of the earth-fault current and may be lower than the operate value of some of the directional residual overcurrent relays. Another challenge is that the electric power circuits may have different zero-sequence impedance. This means that one part of the earth-fault current may lead the other one. Each part will have a "false" in-phase component, which may cause incorrect operation of the directional residual current relay.

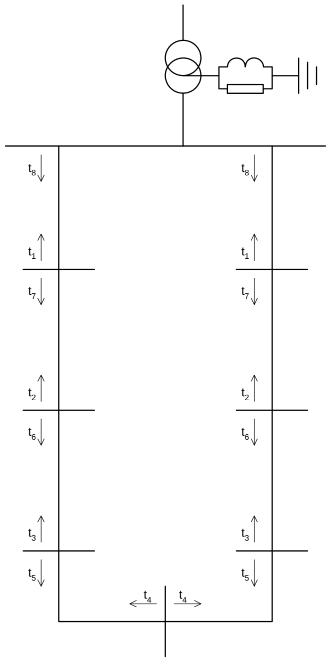


Figure 8.6.19: Distribution system consisting of one closed ring

One classical method for the protection of closed rings is to trip a circuit breaker to open the ring if the neutral displacement voltage exceeds a threshold value. An overvoltage relay energized by the neutral displacement voltage operates with a delay sufficiently long for self-extinction of temporary faults. The operating conditions for the directional residual overcurrent relays are now similar to the conditions in a radially operated network and they can be time-graded in a traditional manner. The disadvantage of this classical approach is that the electricity supply to some customers is interrupted in spite of the ring structure, which, in principle, should allow any feeder earth fault to be disconnected without service interruption.

8.6.1.11 Detection of High-resistive Faults

Non-effectively earthed systems are often protected by a combination of a directional overcurrent relay and an overvoltage relay energized from the neutral displacement voltage. Such a protection scheme can usually detect single phase-to-earth faults with a fault resistance up to a limit ranging from 3 to 5 kΩ. Growing trees may, as described in section 8.6.1.3, cause fault resistances in the range of 20 to 60 kΩ. It is often desirable to detect single phase-to-earth faults with a higher fault resistance that the classical earth-fault protection scheme can detect.

One straight-forward method to detect a high-resistance fault is described in reference [8.6.3]. The methods can be applied on high-impedance earthed systems, and the method requires that the Petersen coil is tuned so that the difference between the inductive current from the Petersen coil and the capacitive earth-fault current $|I_L - I_C|$ is smaller than the limits specified in Table 8.6.1. In addition, the method requires that there is a neutral point resistance with a rated current I_R as specified in Table 8.6.1.

Table 8.6.1: Dimensioning of the neutral point equipment

System voltage	$\lvert I_L - I_C \rvert$	I_R
kV	A	A
6.6	5	5
11	5	5
22	10	10
33	20	10
44	20	10
55	20	10

The recommended setting of the overvoltage relay energized by the neutral-point displacement voltage is about 3% of the voltage obtained at a single phase-to-earth fault with zero-fault resistance. The recommended operate time of the earth-fault detector is in the order of five *minutes*. This makes it possible to detect earth-faults with a fault resistance up to some 20 kΩ. The earth-fault detector is proposed to issue only an alarm and should not be allowed to trip the circuit breaker.

More advanced methods must be used to detect earth faults with a fault resistance larger than 10 kΩ. Reference [8.6.4] documents the development and prototype installation of an advanced method to detect high-resistive earth faults. The experience from the prototype installation indicates that it is possible to detect single phase-to-earth fault with a fault resistance of up to a couple of *hundred kiloohms*. This is close to the practical limit determined by the switching operations and other events that may occur in a distribution system free of earth faults.

8.6.1.12 Detection of Intermittent Earth Faults

Intermittent earth fault occurs occasionally in MV distribution systems, especially in systems dominated by power cables. It appears that distribution systems with low losses in the neutral point equipment and along the feeders are more prone to intermittent earth faults.

The sequence of events is as follows: (1) the insulation withstand levels decrease gradually to a level where a single phase-to-earth fault occurs, (2) the earth fault causes a transient residual current and a transient neutral-point displacement voltage, (3) the residual current transient decreases to zero within one or two milliseconds, (4) the neutral displacement voltage transient lasts much longer than the residual current transient, (5) the residual overcurrent relay operates but resets quickly, (6) the neutral-point displacement relay operates but resets slowly, (7) a new single phase-to-earth fault occurs when the zero-sequence voltage has returned to a value close to zero and the phase-to-earth voltage on the faulty feeder has increased to a value close to normal phase-to-neutral voltage and (8) the sequence of event repeats. There is a risk that the overvoltage relay sensing the neutral-point displacement voltage used as a backup earth-fault protection does not reset. The overvoltage relay will then operate and deenergizes all feeders.

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