Power Cable Protection in Transmission System

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Power cable is widely used in Extra High Voltage (EHV), High Voltage (HV) transmission, Medium Voltage (MV) sub-transmission, and MV / Low Voltage (LV) distribution applications. Basically, the protection principles used for cable are similar with the ones for overhead transmission line. However, the inherent characteristics of cables make its fault behavior more complicate than that of transmission lines, therefore, the cable protection schemes have some particular and unique features. The report discusses the cable characteristics, differences between cable and transmission line, cable fault characteristics, and protection schemes.

1. Cable Characteristics

Power cable protection must consider the cable types, cable electrical characteristics, and sheath ground configurations.

Three cable types are normally used in power systems, namely, High-Pressure Fluid-Filled (HPFF) Pipe-Type, Self-Contained Fluid-Filled (SCFF) Type, and Solid Dielectric Type. The solid dielectric type cable with XLPE or EPR insulation has increasingly been applied due to the following advantages over other two types[1]: 1) lower capacitance, 2) higher load-carrying capability, 3) lower losses, 4) absence of insulating fluids, 5) lower maintenance costs. The following figure illustrates a typical XLPE MV single-conductor cable.

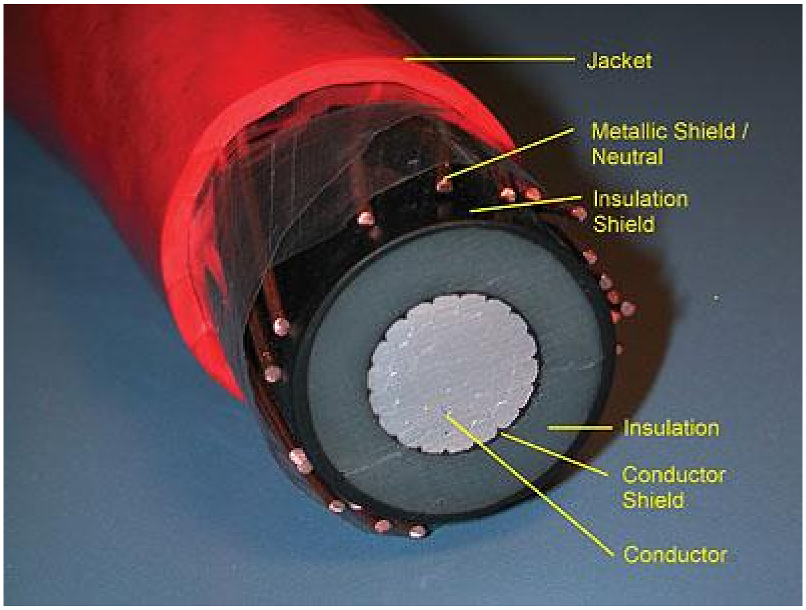


Figure 1. A Typical MV Single-Conductor Cable

Since the XLPE single-conductor cable is widely used, the characteristics of this type are emphatically discussed in this report.

The AC **resistance** of a single-conductor in a group of three cables is

$$R = R_C + \frac{R_S X_m^2}{R_S^2 + X_m^2} \tag{1}$$

$$X_m = 0.002893 \cdot f \cdot \log \frac{2 \cdot GMD}{r_o + r_i} \quad \Omega / phase / km \tag{2}$$

$$R_S = \frac{k}{(r_o + r_i)(r_o - r_i)} \tag{3}$$

$$GMD = \sqrt[3]{S_{ab} S_{bc} S_{ca}} \tag{4}$$

Where, R_C is conductor DC resistance, R_S is sheath AC resistance, Xm is mutual reactance between conductor and sheath, f is system frequency, GMD is geometric mean distance, S_{ab}/ S_{bc}/S_{ca} are distance between conductors, r_o is sheath outer radius, r_i is sheath inner radius, k is sheath material function.

We can know that the cable resistance 1) is greater than the conductor resistance indicated in Equ(1); 2) depends on conductor geometry indicated in Equ(2); 3) depends on sheath material and thickness indicated in Equ(3).

The **reactance** of a single-conductor in a group of three cables is

$$X = X_C - \frac{X_m^3}{R_S^2 + X_m^2} \tag{5}$$

$$X_C = 0.002893 \cdot f \cdot \log \frac{GMD}{GMR} \quad \Omega / phase / km \tag{6}$$

Where, X_C is single conductor reactance, GMR is geometric mean radius of conductors.

We can know that 1) the cable reactance is smaller than the conductor reactance indicated in Equ(5); 2) the conductor reactance has a smaller value when the conductors are closer to each other, indicated in Equ(6).

The **zero-sequence impedance** depends on the bonding and grounding methods of the cable sheath. Three possible return paths are shown in Figure 2, which can be used to calculate the zero-sequence impedance.

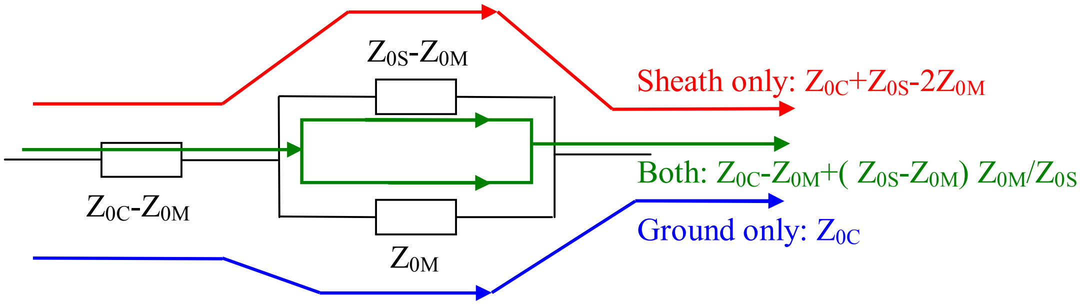


Figure 2. Zero-sequence Return Paths

We can know that 1) the zero-sequence impedance depends on the bonding and grounding methods of the cable sheath; 2) the zero-sequence impedance may vary from a small angle (red path in the figure, sheath return only) to zero-sequence impedance angle of conductor (blue path, ground return only).

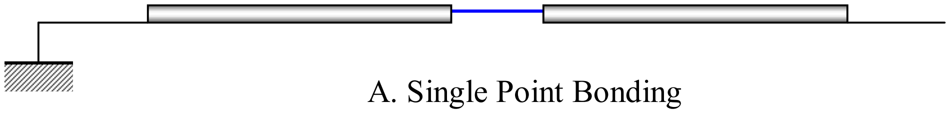
The **shunt capacitance** between the conductor and sheath, or the capacitance to ground if sheath grounded, is

$$C = \frac{0.024127 \cdot e_R}{\log \frac{r_{do}}{r_{di}}} \tag{7}$$

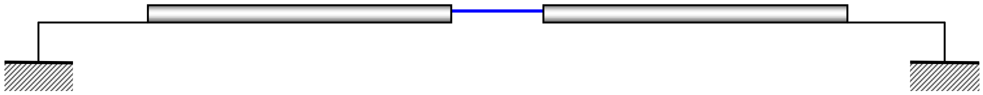
Where, ε_R is relative permittivity of the insulation material, r_{do} is outside radius of the insulation, r_{di} is radius of the conductor.

We can know that 1) the shunt capacitance depends on single-conductor geometry; 2) the shunt capacitance has no relation to the geometric distance among conductors; 3) the positive, negative, and zero sequence capacitances are the same for a single conductor with a metallic sheath.

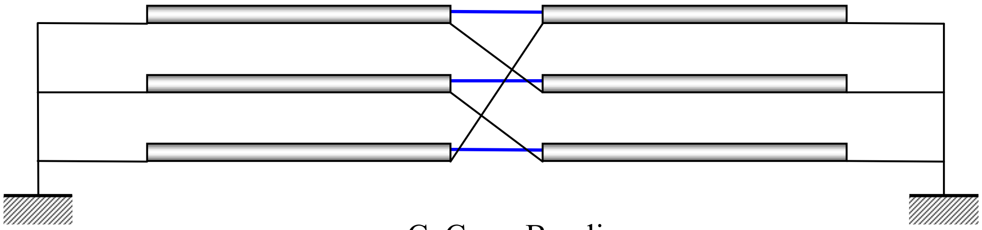
The cable sheath must be grounded to limit the voltage induced by the magnetic field radiated from a current-carrying conductor. There are three bonging and grounding methods for cable sheath, namely, single point bonding, solid bonding, and cross bonding, shown in Figure 3.



A. Single Point Bonding



B. Solid Bonding



C. Cross Bonding

Figure 3. Bonding and Grounding Methods

The different bonding method has the different current-carrying capability, where single point can carry more and solid does less. The different bonding method also leads to large difference of zero-sequence impedance.

2. Differences with Transmission Line

The electrical differences between the underground cable and transmission line can be concluded as follows.

1) The cable impedance is less than line impedance.
2) The X/R ratio of cable is much lower than that of line.
3) The series inductance of cable is 30~50% lower than that of line.
4) The cable zero-sequence impedance is not constant and depends on many factors.
5) The cable zero-sequence impedance angle is less than line zero-sequence impedance angle.
6) The shunt capacitance of cable is 30~40 times higher than that of line.
7) The magnetic coupling exists among phase currents in cables.
8) High steady-state charging current.
9) High transient charging and discharging currents caused by the process of energization and deenergization when faults occur.

3. Fault Characteristics

Most faults in overhead transmission lines are temporary. But in cables, most faults are permanent. Before the permanent fault is fully developed in cables, there normally exists a pre-fault stage, namely, incipient fault, with quite long duration. Besides cable itself, the splice between cable sections is subject to developing to the permanent fault from the incipient fault.

Incipient faults in power cables are usually originated from gradual localized deterioration of insulations. There have two type damages. One is electrical tree, which is caused by periodic partial discharges in dry environment. The other type is water tree, which is caused by moisture ingress into the cable. Both types are starting from a few defect points, propagating through the insulation under electrical stress, and branching in the form of a tree. Most incipient faults involve intermittent arcing, induce relatively lower fault currents, and last short duration ranging from ¼ to 5 cycles. So the regular relays usually can not detect or operate on this kind of faults.

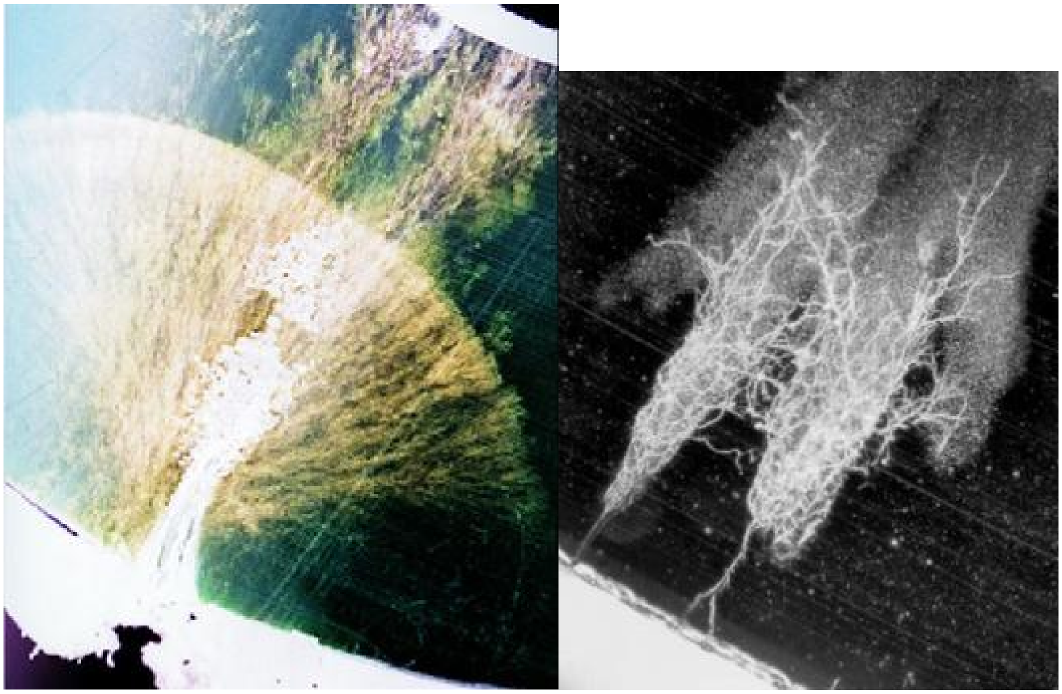


Figure 4. Water Trees and Electrical Trees in Cable Insulation

The incipient fault will cause an insulation breakdown sooner or later because the damage in insulations is irreparable and irreversible. Therefore, a permanent fault occurs. Explosion may occur, although rarely, in some situations. Since fault is permanent, auto-reclosing is not allowed for cable protection.

The faults in cables are affected by the following factors.

a) The sheath currents affect both resistance and reactance of cables.
b) The resistance may be affected by circulating currents generated by the close distance among conductors.
c) The skin effect may affect the resistance of cables.
d) The zero-sequence impedance depends on the fault current return paths, which depends on cable characteristics, sheath bonding and grounding methods, network topology, and fault conditions.

4. Protection Schemes

Two fault types are involved in cables. We only discuss the protection schemes for permanent faults in transmission system.

The cost of cable installation and restoration is 10~15 times higher than that of overhead transmission line. And the time to locate the faulty point and to repair the faulty cable is 3~5 times longer than the time required for overhead transmission line. So the communication-aid high-speed protection scheme is preferred for the protection of cables. In general, the principles used for protecting underground cables are similar to the ones used in overhead transmission lines. However, the different characteristics of underground cables challenge the design and application of the protective relays.

There are three basic pilot cable protection relay schemes, current differential, phase comparison, and directional comparison. In directional comparison scheme, the negative-sequence directional comparison, zero-sequence-based, and distance protection scheme are proposed respectively in Ref. [4][5][6].

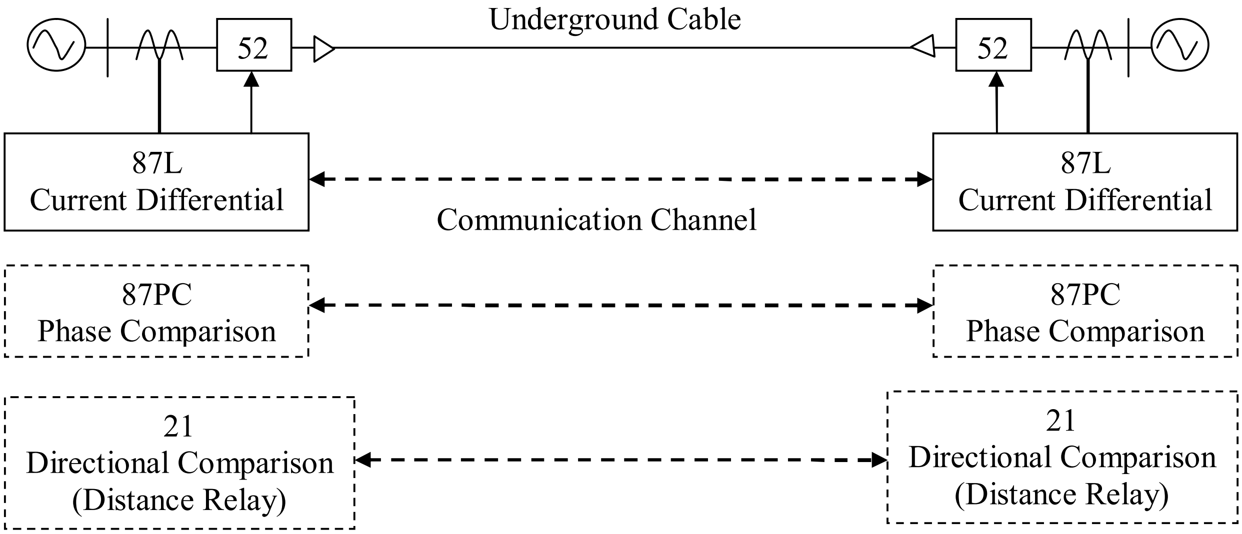


Figure 5. Three Protection Schemes for Cable Protection

4.1 Current Differential

Generally, the current differential relay is used to provide the protection for cables in power systems because it is less affected by the cable characteristics. When the communication channel is out-of-service, the directional overcurrent or distance relays are considered as backup protection.

The current differential relay compares the local currents with the remote currents to determine that the fault is inside the protection zone or not.

The **advantages** of the current differential protection scheme are:

1) Instantaneous protection.
2) Protection for entire cable length.
3) Immune to system swings.
4) Immune to current reversal.
5) Less affected by cable characteristics.
6) Only current required, segregated-current or composite-current.

The **disadvantages** are:

1) Not a backup protection.
2) Dependent on communication channel availability and bandwidth.
3) Affected by CT saturation in the presence of external fault.
4) Security logic required for restraining the CT saturation.
5) Settings affected by the steady-state charging currents.

4.2 Phase Comparison

The phase comparison relay compares the phase angle between local currents and remote currents. If the phase difference is greater than a preset threshold, the relay considers the system status as an internal fault.

The basic principle of the phase comparison scheme (blocking type, composite current) is shown in Figure 6. The logic diagram of the phase comparison relay is shown in Figure 7, where Time delay 1 unit is to compensate the transferring delay through the communication channel and Time delay 2 unit is to decide the threshold is exceeded or not.

The **advantages** of the current phase comparison protection scheme are:

1) Instantaneous protection.
2) Protection for entire cable length.
3) Immune to system swings.
4) Immune to current reversal.
5) Less affected by cable characteristics.
6) Only current phase information required, segregated-current or composite-current.
7) Less affected by CT saturation in the presence of external fault.
8) In the presence of internal fault with the failure of communication channel, both terminals trip correctly. (Blocking type)

The **disadvantages** are:

1) Not a backup protection.
2) Dependent on communication channel availability and bandwidth.

3) Settings affected by steady-state charging currents.
4) Lower sensitivity than the current differential relay.
5) Affected by charging currents, especially for long cables with one weak infeeder.
6) In the presence of external fault, the blocking unit must be more sensitive and faster than the tripping unit. (Blocking type)
7) In the presence of external fault with the failure of communication channel, far-fault terminal can not receive the blocking signal, so the CB at that side would misoperate. (Blocking type)

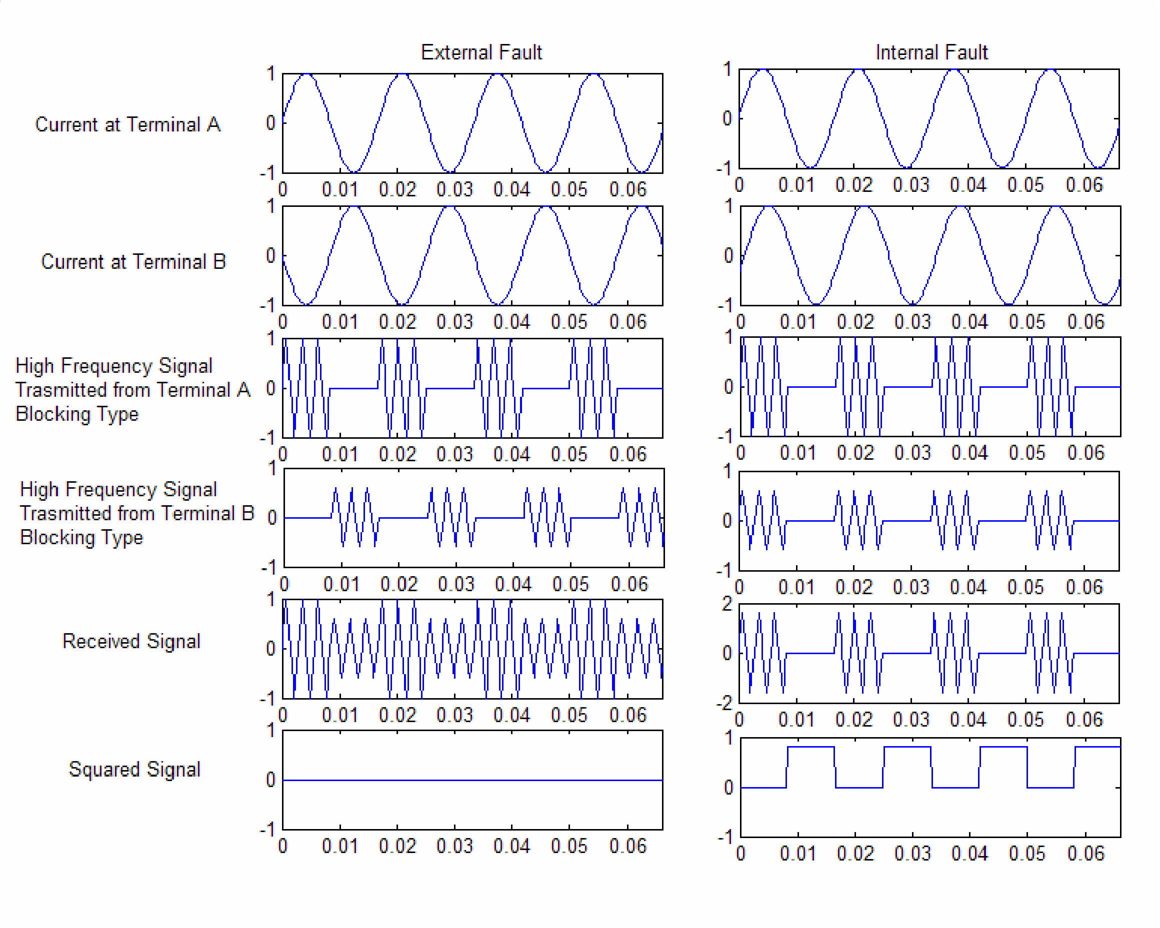


Figure 6. Principle of Phase Comparison Relay (Blocking Type)

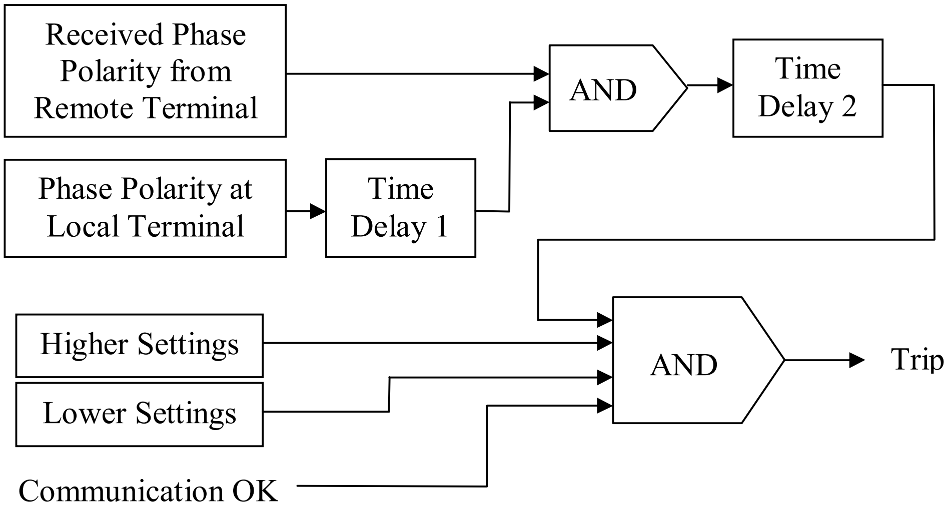


Figure 7. Logic Diagram of Phase Comparison Relay

4.3 Directional Comparison

The above two schemes transfer and compare measurements at two terminals directly to determine the fault location. The directional comparison scheme transfers the pre-calculated results and relative information, which are obtained and decided locally, and then determines the operation.

The directional comparison relay compares the phase-distance, ground-distance, directional zero-sequence, or negative-sequence information between local terminal and remote terminal. The techniques of the phase-distance and ground-distance are frequently used. The good understandings of cable characteristics and sheath bonding/grounding methods are required to design this scheme. Since the zero-sequence greatly depends on the cable characteristics, sheath bonding and grounding methods, this quantity is not recommended for cable protection.

Most faults in cables involve ground fault or sheath fault. The compensated impedance seen by the ground distance relay is given as,

$$\begin{aligned} Z_{seen} &= \frac{V_a}{I_a + 3I_0 k} \\ k &= \frac{Z_{0L} - Z_{1L}}{3Z_{1L}} \end{aligned} \tag{8}$$

Since the compensation loop parameter k is constant for transmission lines, the seen impedance is linearly proportional to the line length. But for cables, the relay would observe the different impedance for the different grounding method.

For **cables with single-point bonding**, we can find the following characteristics about the seen impedance in the presence of ground fault:

a) k is constant, but may have different values for relays at two terminals.
b) The seen impedances at two sides are not symmetric to the middle point of cable, depending on the location of the grounding point of cable circuit.

c) The seen impedances may be different for the conductor-ground fault and conductor-sheath fault.
d) The seen reactance at the ungrounded side is not zero when fault is closed to that side.
e) The seen reactance at the ungrounded side increases when the fault distance increases, while the seen resistance decreases.
f) The zero-sequence source impedance may affect the value of the seen impedance.

For **cables with solid bonding**, we can find the following characteristics about the seen impedance in the presence of ground fault:

a) *k* is not constant for internal faults, depending on the fault location.
b) Two ground fault current return paths.
c) The seen impedance is nonlinear along the cable.
d) The seen reactance increases nonlinearly and monotonically when the fault distance increases.
e) The seen resistance changes nonlinearly and quadratically when the fault distance increases. The maximum resistance appears at 50~70% of whole length rather than at the longest length of cable.

The **cross bonding** is more used for longer cables. We can find the following characteristics about the seen impedance in the presence of ground fault:

a) *k* is not constant for internal faults, depending on the fault location.
b) The ground fault current return path changes with fault location.
c) The seen impedance is nonlinear and discontinuous along the cable. The discontinuity occurs at the joint section.
f) The seen reactance increases nonlinearly, discontinuously, and monotonically when the fault distance increases.
d) The seen resistance changes nonlinearly, discontinuously, and quadratically when the fault distance increases. The maximum resistance appears at 50~70% of whole length rather than at the longest length of cable.

The main **characteristics** of the directional comparison protection scheme are:

1) Instantaneous or timed protection.
2) Protection for entire cable length.
3) Main and backup protection.
4) Normally, Permissive over-reaching transfer trip (POTT) with Frequency Shift Keying (FSK).
5) Communication channel unavailability does not lose directional protection functions for local and remote backup.
6) Voltages and currents required.
7) Settings affected by many factors.
8) Negative-sequence directional comparison relay can tolerate large fault resistance.

The **settings** of the distance relay can be concluded as follows.

a) The principles to set the distance relay for underground cables are similar with these applied for overhead transmission lines.

b) Zone 1 should not overreach faults at the remote terminal.
c) Zone 2 and Zone 3 should protect whole cable and coordinate with distance relays at adjacent circuits.
d) The zero-sequence compensation factor should be selected suitably for ground distance relays.
e) The large capacitive charging currents should be considered for phase distance relays, which may lead to overreach for Zone 1.
f) The network topology should be considered, such as parallel circuits.
g) The adjacent circuits, lines or cables, should be considered when coordinating.

4.4 Scheme Applied

It is really difficulty to design the protect scheme of cables by using distance relays because of the influential factors mentioned in section 4.3. Most applications are using the current differential scheme, which is more sensitive, reliable and easy to calculate the settings, however, the effect of charging currents and shunt-reactor, if applicable, must be compensated. The distance relay usually acts in the differential comparison blocking or unblocking function and as backup protection. The negative sequence directional element can also be integrated into the scheme.

5. References

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