Back to Table of Contents

Applying Distance Protection to Cable Circuits

B. Kasztenny -GE Multilin, Markham, Canada

I. Voloh - GE Multilin, Markham, Canada

J.G. Hubertus -PSE&G, New Jersey, US

Presented at the
31st Annual
WESTERN PROTECTIVE RELAY CONFERENCE
Spokane, Washington
October 19-21

1. Introduction

Protection of AC cable circuits creates some unique problems that are normally not encountered when protecting overhead transmission lines [1].

Zero-sequence impedance varying with the fault current, low impedance of the protected circuit, lower angles of sequence impedances, varying and different than usual Z0/Z1 ratios, significant non-homogeneity of circuits that include overhead lines and cables are the main issues of concern.

This paper reviews type of cables and main electrical characteristics of cables and protection techniques for AC cables. This paper will focus specifically on applications of distance protection.

The reactance distance characteristic is covered in detail – an optimum reactance line is derived and its practical implementations using negative- or zero-sequence currents for polarization are discussed. The issue of network homogeneity is addressed, and a concept of correction for non-homogeneity is presented and illustrated with examples.

Simulation examples are included to illustrate the need for detailed fault studies in order to properly apply and verify distance protection applications and settings for cables.

2. Types and Major Characteristics of Cables

2.1. Types of Cables

Construction of a cable impacts greatly its basic electrical characteristics and therefore is relevant from the protective relaying point of view. Three major cable types dominate the Extra High Voltage (EHV) and High Voltage (HV) transmission and sub-transmission applications.

Pipe-type cables (Figure 1a) designed either as High-Pressure Fluid-Filled (HPFF) or Gas-Filled (HPGF) utilize the isolation medium (oil or gas) under high pressure (200 psi range). The high-pressure cables are relatively expensive and thus are applied at higher voltages – closer to the 500kV end of the spectrum, although the gas-filled cables tend to be manufactured for lower voltages. Because of the cost of the pressurizing and/or cooling equipment, the pipe cables are three-phase cables with three conductors enclosed in a steel pipe. This affects greatly their zero-sequence impedance.

Solid dielectric cables of a single-conductor design (Figure 1b) are commonly applied at the sub-transmission and distribution levels, although the cables are manufactured for EHV applications as well. Various dielectric materials can be used for isolation such as cross-linked polyethylene (XLPE) and Ethylene Propylene Rubber (EPR).

Self-Contained Fluid-Filled (SCFF) cables are also of a single- conductor design and use non-pressurized fluids for isolation. Hollow-core copper conductor (Figure 1c) allows natural distribution of the isolating fluid. Thermal expansion of the fluid is accommodated by reservoirs distributed along the cable path. This type of a cable is manufactured for voltages up to 500kV.

Short circuits on overhead lines do not cause any considerable damage. The repair is relatively easy and not expensive. Protective relays for overhead lines protect more the remainder of the system than the faulty line. This is not the case for cables. Repair of a cable can be very costly and may take much longer time. Also, the extent of the damage may go beyond conductors and isolation. The fault clearing time becomes critical as the short-circuit energy may build up the pressure inside the cable and lead to extensive damage of the cable and its auxiliary pressurizing / cooling equipment. Cost, compact design, application of dielectric materials for isolation, presence of gases or fluids and their associated equipment, environmental concerns (spilled fluids) create analogies to protection of transformers and machines.

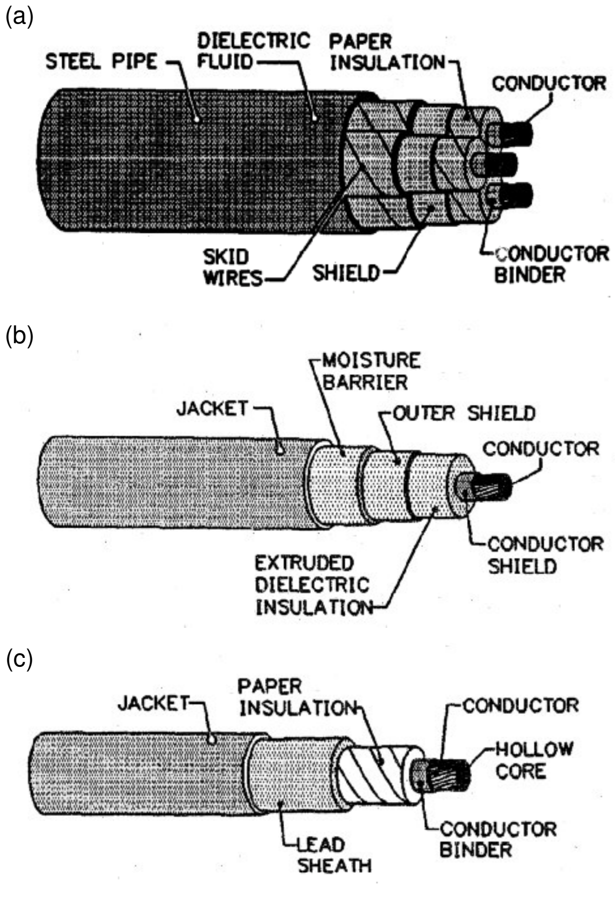


Figure 1. Basic types of cables

2.2. Basic Electrical Characteristics

Spacing between the conductors being of the order of magnitude shorter in cables than in overhead lines causes reactances of cables to be much lower compared to overhead lines.

Low reactance of cables creates several problems both operationally and from the point of view of protective relaying.

Low impedances make the cable circuits tightly connected resulting in high short circuit currents. Load flow control is more difficult because of the increased sensitivity of the parallel cable paths to various control actions. Even simple load sharing on plain parallel cable circuits may be a problem as small differences between the impedances may result in grossly uneven loading. This issue may get amplified by repairs (if any) that tend to result in relatively significant changes of the resistance of the repaired cable.

The X/R ratio is much lower as compared to overhead lines. This creates extra issues for protective relays from both the point of view of operating principles (reactance characteristic, for example) and setting ranges (maximum torque angle for various directional functions, reach impedance, etc.).

Capacitances in cables are much higher compared to overhead lines. The spacing between conductors and/or sheath is smaller while the dielectric constants are higher. This results in large charging currents. The charging currents take thermal effects on the cable (an extra current that needs to be fed through the conductors), impact performance of protective relays, and create extra transients during faults and switching events.

Shunt reactors may be installed at the ends of a cable or – for long cables – at few locations along the cable paths in order to reduce the capacitive effect. This does not reduce the charging current itself and its thermal effect, but does make a difference for the external network by reducing overvoltages and canceling the capacitive character of the shunt parameters of a cable.

2.3. Short-Circuits and Zero-Sequence Impedance

Short circuit studies for cables are complex. Several factors contribute to this [1-3]:

1. For single-phase cables the sheath currents impact both the resistance and reactance of the cable.

2. Circulating currents may be induced due to close proximity of conductors. This may increase the effective resistance of the cable

3. The skin effect must not be neglected in cables and may affect the resistance.

4. The zero-sequence impedance depends of the return path. The latter in turn depends on the way the sheath is grounded, presence of parallel circuits and resistivity of the ground. Variety of grounding techniques is used and should be considered in the analysis. In addition, the ground parameters and location of parallel circuits may vary along the cable path.

For pipe-type cables or cables placed in magnetic ducts, extra factors apply:

5. Proximity of the magnetic enclosure impacts the reactances. Being conductive but generating losses, the enclosure impacts the resistances as well.

6. The zero-sequence impedance depends on permeability of the steel enclosure. The latter depends on the zero-sequence current. As a result the zero-sequence impedance becomes current-dependent to a large degree (Figure 2 presents sample dependencies).

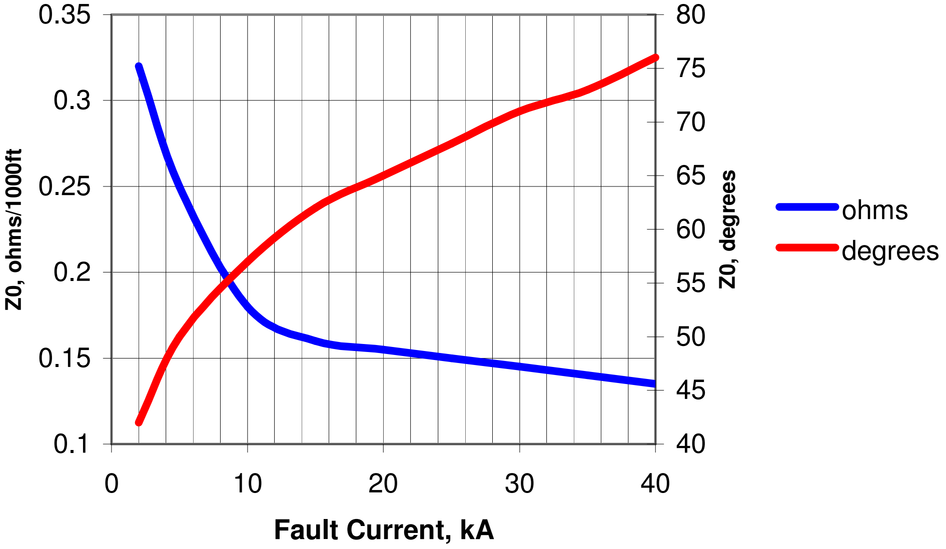


Figure 2. Sample zero-sequence impedance of a pipe-type cable

Dependability of the zero-sequence current on the current magnitude makes the traditional linear short-circuit analysis impossible. Either non-linear short circuit packages capable of handling cables should be used, or traditional software must be applied in an iterative way in order to find good approximations of the currents and voltages during internal and external faults.

Electrically floating sheaths are not permitted, as they are subjected to induced voltages that would otherwise accelerate corrosion and could lead to other failures. Grounding the sheaths is required and is done in a number of ways [4] greatly affecting sequence impedances of the cable. Longer cables must be sectionalized (sheaths electrically isolated) and each section is grounded separately. Single- or multiple-point grounding can be applied to a cable or its sections. A single-point sheath ground will not permit the zero-sequence return path for external faults, but would permit it for internal faults. This calls for different short circuit calculation approaches for internal versus external faults. A special cross-bonding cable design can be used to make the zero-sequence impedance more uniform along the cable paths [4].

In general, sequence impedances of cables depend on many complex conditions. Cable manufacturer data or cable commissioning measurements should be used to improve accuracy of short circuit studies and fine tune protection schemes.

2.4 Homogeneity of Cable Circuits

Parameters of cable sections are difficult to estimate and could be current-dependent. In addition, cable sections could be combined into parallel circuits, or in series with other devices: series reactors and Phase Angle Regulating (PAR) transformers in particular.

The former are applied as current-limiting devices and to facilitate better power flow control. The latter are installed for power flow control and often included into the cable zone of protection. Both series reactors and PAR transformer could be bypassed under certain conditions. This creates extra variability for protection systems.

Figure 3 presents three examples of complex circuits involving cables. Each section of these circuits will have drastically different X/R and Z0/Z1 ratios. This may create some unexpected effects such as a fault being more distant from the geometrical point of view appearing closer from the electrical point of view. It is a good practice to include all points between different sections in short circuit and protection selectivity studies.

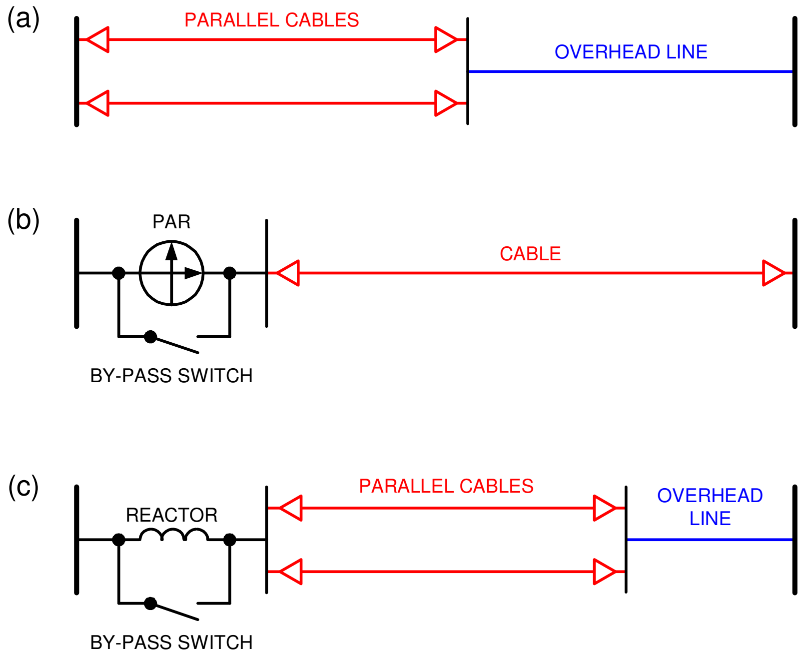


Figure 3. Examples of highly non-homogenous circuits with cables

3. Protection Issues and Options for Cables

3.1. Protection Issues

Larger capacitive charging currents impact the apparent impedance seen by phase distance elements and may result in an overreaching effect. Charging currents should also be considered when setting differential relays and switch-onto-a-fault logic.

Current-dependent zero-sequence impedance of pipe-type cables makes it difficult to apply ground distance elements with high accuracy. This becomes even more difficult if the protected circuit is composed of several sections connected in series as illustrated in Figure 3. Iterative short-circuit studies are often needed to calculate “optimum” zero sequence compensation settings.

Total impedance of cables is relatively short. Consideration must be given to the range of reach settings of impedance relays, associated resolution of settings at the low end of the range, and steady state accuracy of the relay at such low settings.

The Z0/Z1 ratio is not only current-dependent but the “optimum” value adopted for a given application may be significantly different as compared to average values for overhead line applications. Consideration must be given to the range, resolution and accuracy of the zero-sequence compensating factor settings.

As a result of variability of the zero-sequence impedance, it is relatively difficult to ensure good performance/coverage of an underreaching directly tripping ground zone 1. This is particularly true if high resistive faults due to contamination of outdoor cable potheads are considered.

The associated difficulties in protecting cables yield two groups of solutions.

First group relies on principles that do not depend on cable parameters or phenomena. This includes unit protection with current differential, phase comparison, and directional comparison applications. The latter should use ground directional overcurrent elements rather than ground distance functions.

Second approach applies distance relays and attempts to overcome the existing difficulties with cable impedances. Application of distance functions is always of interest because the unit protection relays require backup functions for the case of lost communications. Due to flat distribution of fault currents, the overcurrent backup is not effective and distance functions are a viable alternative. Modern relays provide for integrated distance backup functions that should be utilized and set when applying current differential, phase comparison or directional comparison protection schemes.

3.2. Current Differential Protection

Current differential principle does not depend on cable characteristic and is therefore the most reliable and sensitive protection option for cables. Cable charging currents and currents of shunt reactors shall be considered when applying the relay. Modern digital current differential relays provide for charging current compensation [5]. This feature calculates the cable charging current from the voltage signals, and subtracts it from the measured differential currents. This improves sensitivity to a great extent.

Digital current differential relays use direct fiber, or multiplexed channels via fiber (C37.94) or electrical interfaces (G.703, RS 422, etc.).

3.3. Phase Comparison Protection

The phase comparison principle does not depend on cable parameters either, and therefore is dependable and relatively easy to apply. Sensitivity of phase comparison protection is normally lower compared to the current differential protection. But this is not of a great concern in cable applications as the short circuit currents are typically very high.

The phase comparison principle is affected by the charging current to the extent proportional to the ratio between the magnitudes of charging and fault currents. In application for short cables under strong feed conditions, the charging current is not a problem. For long cables operating under weak feed condition, the charging current may create problems.

Cables are not considered a good medium for power line carrier applications due to variation of characteristics with frequency, losses due to standing wave reflections at the junction point and relatively high attenuation. Special care must be taken when using power line carrier applications on a cable circuit. Therefore, it is recommended to use dedicated wires, fiber or microwave channels for the phase comparison applications.

3.4. Directional Comparison Protection

Blocking or unblocking schemes are typically used. It is a good practice to minimize application of protection elements that are dependent on cable characteristics. In particular:

Ground directional overcurrent elements – such as neutral or negative-sequence – could be used instead of ground distance functions to detect ground faults.

Negative-sequence directional overcurrent function could be used instead of phase distance functions to cover all unbalanced phase faults.

Phase directional overcurrent could be used to supplement/substitute phase distance elements to cover three-phase symmetrical faults.

3.5. Distance Protection

Distance protection depends on the sequence impedances of the protected circuit. Dependence of the zero-sequence impedance on the fault current, system non-homogeneity, and large charging currents create problems for traditional distance functions. This is less of a problem for overreaching zones but is of a critical importance for underreaching zone(s) designed for instantaneous direct tripping.

Lower impedance angles of cable circuits create challenges for quadrilateral distance functions. Both over- and under reaching effects could occur depending on the system parameters and the pre-fault load. Section 4 derives an optimum reactance comparator and presents available relay design alternatives. Section 5 discusses applications of reactance characteristics to non-homogenous systems.

The issue of varying zero-sequence impedance in cable circuits must be addressed by simulation and short-circuit studies. Section 6 discusses this aspect of cable protection.

Distance relay algorithms with greater flexibility offer better chances for optimization of the application. In particular:

- Wide range of relevant settings is an advantage. Maximum torque angle settable down to 30 degrees, Z0/Z1 ratio settable from 0.0 to 10.0, Z0/Z1 angle settable from –90 to +90 degrees are good examples.

- Individual (decoupled) settings for the maximum torque angles for phase, ground and any embedded directional comparators.

- All distance settings (Z0/Z1, maximum torque angles, comparator limit angles, non-homogeneity correction angles, source of reactance polarization, blinder settings, etc.) provided on a per zone basis.

- All distance settings under setting group control allowing adaptive changes of all, even minor, settings depending on system operating conditions. For example, it is determined that the optimum distance settings are different if a Phase Angle Regulator is put in service. If the PAR is to be switched in (or out), a contact from the shorting breaker will communicate automatically to the relay to change setting groups based on this condtion.

4. Review of Distance Reactance Characteristics

4.1. Basic Equations

Cables and sub-transmission overhead lines are typically short while the angle of their positive-sequence impedances is much lower than 90 degrees. Because of this, it is important to understand the reactance characteristics of the quadrilateral distance function particularly if the intended resistive coverage is large compared with the relatively short reach.

The same fundamental difficulty exists in overhead transmission line applications. For example, if an overhead line is connected to cable circuits at the remote bus, this will lead to a non-homogeneous condition, which may adversely impact the performance of the quadrilateral distance functions. However, the issues are not as noticeable because the angle of the positive-sequence impedance (maximum torque angle of the relay) is much closer to 90 degrees.

Figure 4 presents an equivalent diagram for a single-line-to-ground fault in a two-ended system. This model is valid if the arc resistance is constant and the line itself is homogenous. If these two assumptions are not met the accuracy of the model becomes limited. Nonetheless this model allows for the derivation of an optimum reactance characteristic and explains the over- and under-reaching phenomena for a given relay design.

Voltages at the relay location (R) can be expressed as functions of relay currents (R) and residual voltages at the fault point (F):

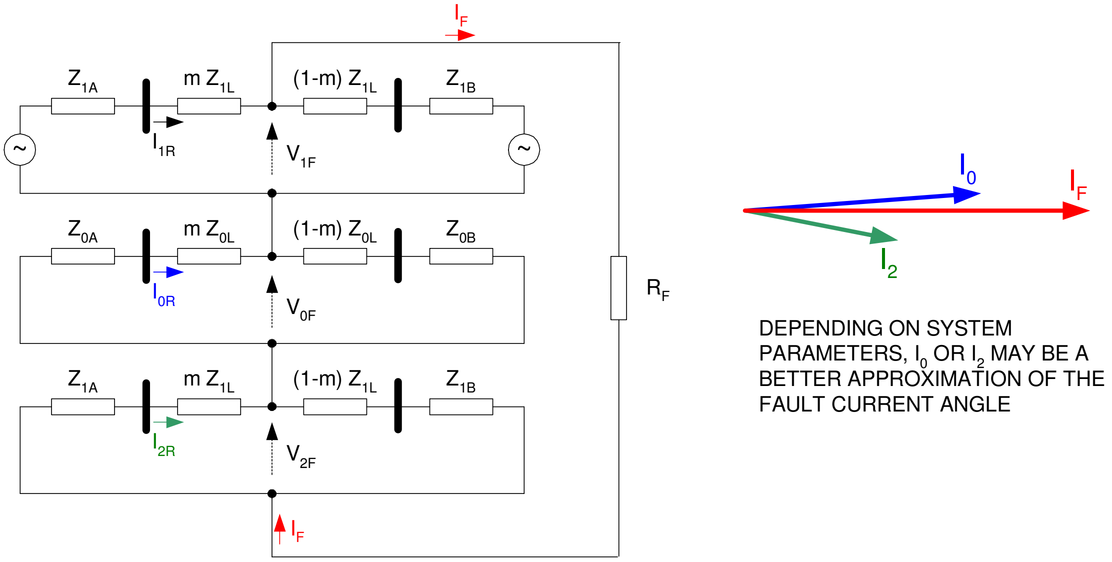
$$V_{1R} - I_{1R} \cdot m \cdot Z_{1L} - V_{1F} = 0 \tag{1a}$$
$$V_{2R} - I_{2R} \cdot m \cdot Z_{1L} - V_{2F} = 0 \tag{1b}$$
$$V_{0R} - I_{0R} \cdot m \cdot Z_{0L} - V_{0F} = 0 \tag{1c}$$

Adding the three equations yields:

$$V_{1R} + V_{2R} + V_{0R} - I_{1R} \cdot m \cdot Z_{1L} - I_{2R} \cdot m \cdot Z_{1L} - I_{0R} \cdot m \cdot Z_{0L} - V_{1F} - V_{2F} - V_{0F} = 0 \tag{2}$$

Assuming an AG fault and recognizing that:

$$V_{1R} + V_{2R} + V_{0R} = V_A \tag{3a}$$
$$V_{1F} + V_{2F} + V_{0F} = I_F \cdot R_F \tag{3b}$$



DEPENDING ON SYSTEM PARAMETERS, I_0 OR I_2 MAY BE A BETTER APPROXIMATION OF THE FAULT CURRENT ANGLE

Figure 4. Network equivalent diagram for single-line-to-ground faults

one may re-write equation (2) as follows:

$$V_A - m \cdot Z_{1L} \cdot \left(I_{1R} + I_{2R} + \frac{Z_{0L}}{Z_{1L}} \cdot I_{0R} \right) - I_F \cdot R_F = 0 \tag{4}$$

One may add and subtract the zero-sequence current at the relay without changing the meaning of equation (4):

$$V_A - m \cdot Z_{1L} \cdot \left(I_{1R} + I_{2R} + I_{0R} - I_{0R} + \frac{Z_{0L}}{Z_{1L}} \cdot I_{0R} \right) - I_F \cdot R_F = 0 \tag{5}$$

Recognizing that:

$$I_{1R} + I_{2R} + I_{0R} = I_A \tag{6}$$

one may re-write equation (5) as follows:

$$V_A - m \cdot Z_{1L} \cdot \left(I_A + I_{0R} \cdot \left(\frac{Z_{0L}}{Z_{1L}} - 1 \right) \right) - I_F \cdot R_F = 0 \tag{7}$$

Equation (7) leads to the well-known concept of zero-sequence compensation and the zero-sequence compensating factor. Introducing the compensated current:

$$I_{AG} = I_A + I_0 \cdot \left(\frac{Z_{0L}}{Z_{1L}} - 1 \right) \tag{8}$$

one gets the equation being a foundation of ground distance protection:

$$V_A - m \cdot Z_{1L} \cdot I_{AG} - I_F \cdot R_F = 0 \tag{9}$$

or

$$m \cdot Z_{1L} \cdot I_{AG} - V_A = -I_F \cdot R_F \tag{10}$$

When the $m \cdot Z_{1L}$ term is substituted by the intended reach of the relay, Z_{REACH}, equation (10) becomes a balance equation for an ideal distance relay:

$$I_{AG} \cdot Z_{REACH} - V_A = -I_F \cdot R_F \tag{11}$$

Equation (11) includes the “I*Z-V” term calculated by any distance that complies with the principle of distance protection. Using the notation of an angle comparator, equation (11) could be re-written into a line of a constant reach:

$$ang\left(I_{AG} \cdot Z_{REACH} - V_A\right) = ang\left(j \cdot I_F\right) \tag{12}$$

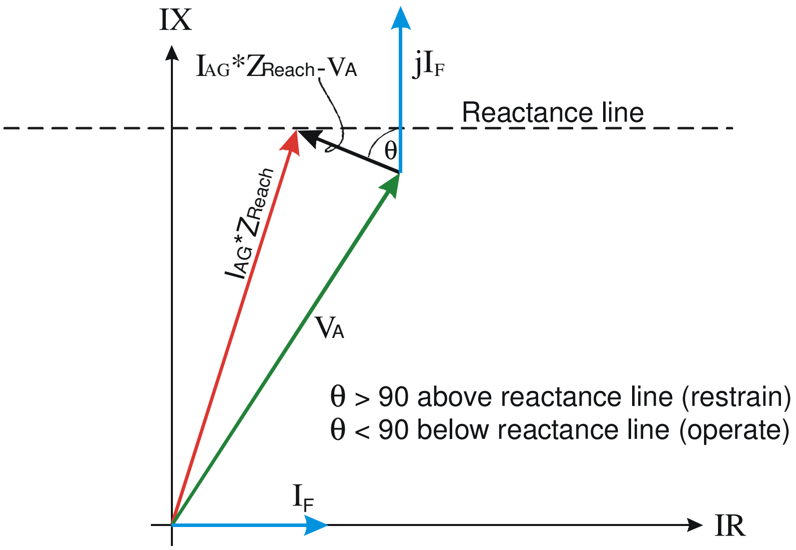


Figure 5. Ground Distance Reactance comparator

Equation (12) is a balance equation for an ideal reactance relay – the equation is satisfied for faults through any fault resistance located at the intended reach point. In steady state this equation is perfectly accurate and can distinguish the in-zone and out-zone faults with high accuracy limited only by accuracy of the measured voltages and currents, accuracy of the model of Figure 4, and accuracy of the line impedance.

The equation cannot be applied directly – of course – because it involves a remote signal (I_F) that is not available to the distance relay. It is worth noticing that only the angle of the fault current is required to make the equation work with perfect accuracy. Equation (12) becomes a design equation of a reactance line of a distance relay when all the involved signals are local signals at the relay point. There are several methods to approximate the unknown angle of fault current at the fault location with the local signals. This turns the ideal equation (12) into a variety of relay design equations as listed below.

4.2. Static Line Perpendicular to the Maximum Torque Angle Line

$$ang\left(I_{AG} \cdot Z_{REACH} - V_A\right) = ang\left(I_{AG} \cdot Z_{REACH}\right) \qquad (13)$$

The reactance line obtained by applying equation (13) is affected by the load component in currents at the relay location and the non-homogeneity of the system. The effect of non-homogeneity is complex in this case as each of the three components of the symmetrical currents at the relay may be shifted by various angle as compared with the fault current at the fault point.

The effect of under- and over-reaching can be easily analyzed for the static reactance lines. From equation (10) the apparent impedance seen by the relay is:

$$Z_{APP} = \frac{V_A}{I_{AG}} = m \cdot Z_{1L} + R_F \cdot \frac{I_F}{I_{AG}} \qquad (14)$$

The $m \cdot Z_{1L}$ term is a measure of the distance, and the $R_F \cdot \frac{I_F}{I_{AG}}$ is an error term, or the added "fault impedance" as explained in Figure 6.

The physical fault resistance R_F is amplified in the apparent impedance equation if the local current is lower than the total fault current at the fault point ($\left|\frac{I_F}{I_{AG}}\right| > 1$). Under a strong remote terminal and weak sourced local terminal, the physical fault resistance may be amplified considerably.

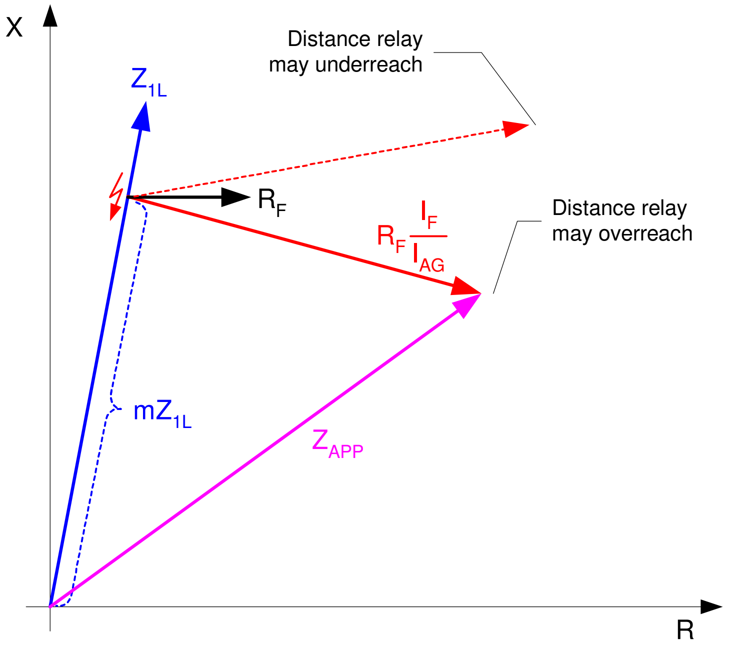


Figure 6. Impact of the added "fault impedance" on effective relay reach

Also, the added impedance may be tilted clockwise or counterclockwise depending on the angular relation between the two currents. If the compensated local current leads the fault current at the fault point, the physical resistance is rotated clockwise resulting in potential overreach of the relay. If the compensated local current lags the fault current at the fault point, the physical resistance is tilted counterclockwise resulting in potential underreach of the relay.

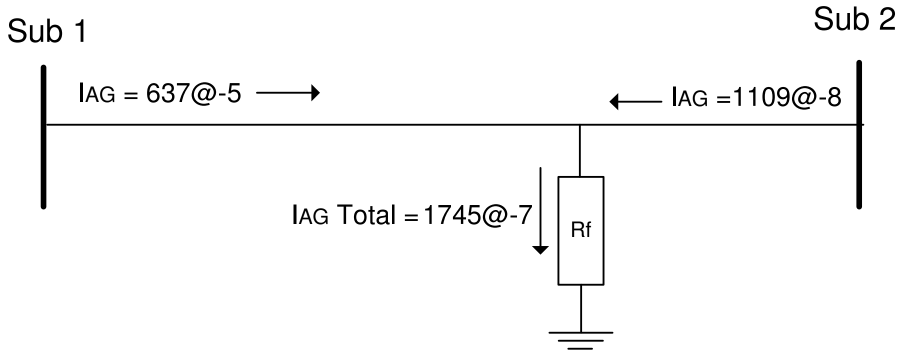


Figure 7. Example of fault current distribution on the non-homogeneous system

The figure above gives an example of the case where due to system non-homogeneity the relay at Sub 1 will potentially overreach, while the relay at Sub 2 will underreach.

Overlaying graphically the static reactance (13) with all possible apparent impedances (14) will allow the engineer to visually examine the specific likelihood of under- and/or over-reaching. It also allows fine-tuning the reach and blinder settings for a given application.

4.3. Static Line of a Constant Reactance

$$ang\left(I_{AG} \cdot Z_{REACH} - V_A\right) = ang\left(j \cdot I_{AG}\right) \qquad (15)$$

The reactance line obtained by applying equation (15) is similar to the line perpendicular to the maximum torque angle. The only difference is that solution (15) provides better coverage on applications with the maximum torque angles much lower than 90 degrees as explained in Figure 6.

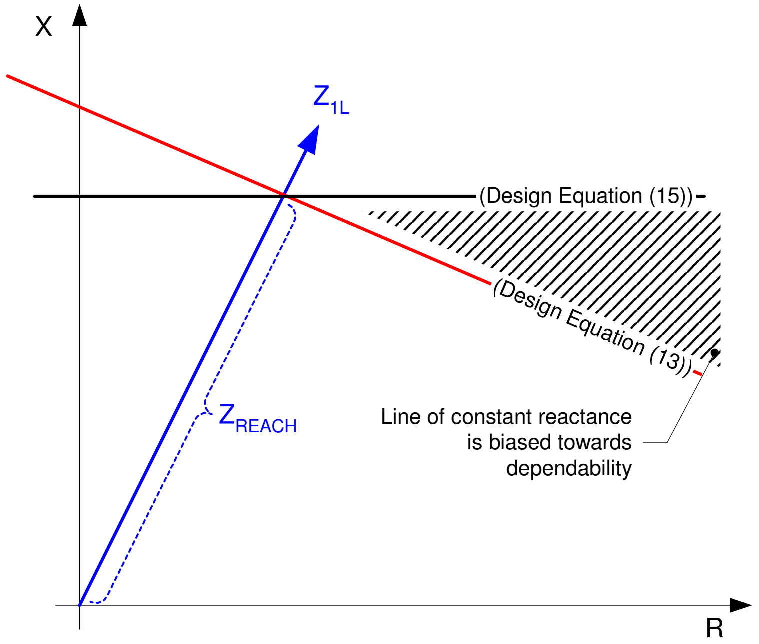


Figure 8. Line of constant reactance vs. a line perpendicular to the maximum torque angle

4.4. Dynamic Line Polarized from the Zero-Sequence Current

$$ang\left(I_{AG}\cdot Z_{REACH}-V_A\right)=ang\left(j\cdot I_{0R}\right) \tag{16}$$

Design solution (16) uses the angle of the zero-sequence current at the relay location to represent the angle of the fault current at the fault location. This approximation is more accurate compared to solution (13) and (15) because it is not affected by the load current. The actual accuracy depends on equivalent parameters of the zero-sequence network as explained below.

The fault current at the fault location is in phase with its zero-sequence component (Refer to Figure 4). The latter flows through the equivalent zero-sequence network being a parallel connection of the circuits on both sides of the fault point:

$$I_{0F}=\frac{V_{0F}}{Z_0}\text{, where } Z_0=\frac{\left(Z_{0A}+m\cdot Z_{0L}\right)\cdot\left(Z_{0B}+(1-m)\cdot Z_{0L}\right)}{Z_{0A}+Z_{0L}+Z_{0B}} \tag{17a}$$

The same voltage drives the zero-sequence current at the relay point, but only the portion of current, I_{0R} flowing through the local section of the zero sequence network is measured:

$$I_{0R}=\frac{V_{0F}}{Z_{0A}+m\cdot Z_{0L}} \tag{17b}$$

The angle between the fault current at the fault point (equation (17a)) and the zero-sequence current at the relay (equation (17b)) is:

$$\Theta_0 = ang\left(\frac{I_{0R}}{I_{0F}}\right) = ang\left(\frac{Z_{0B} + (1-m)\cdot Z_{0L}}{Z_{0A} + Z_{0L} + Z_{0B}}\right) \tag{17c}$$

Equation (17c) specifies an angular error introduced when using the zero-sequence current at the relay to polarize the reactance line (16).

The following is worth noticing:

a) The angular error is a function of fault location, *m*. The issue of under- and over-reaching applies to faults around the reach point. Therefore, it is enough to consider the value of *m* that corresponds to the intended reach point of a given zone.

b) With the value of *m* fixed at the intended per unit reach, the angle remains a function of the line and system equivalent impedances.

c) It could be proven that as long as the impedance angles of the two sections of the zero-sequence circuit are equal, the error (17c) is zero. This very condition:

$$ang(Z_{0A} + m\cdot Z_{0L}) = ang(Z_{0B} + (1-m)\cdot Z_{0L}) \tag{17d}$$

defines "homogeneous" systems in terms of the zero-sequence. In such homogeneous systems, the zero-sequence current at the relay is a perfect representation of the angle of the fault current, thus the reactance line (16) polarized from the zero-sequence current at the relay becomes a line of a perfect reach as illustrated in Figures 9a and 9b.

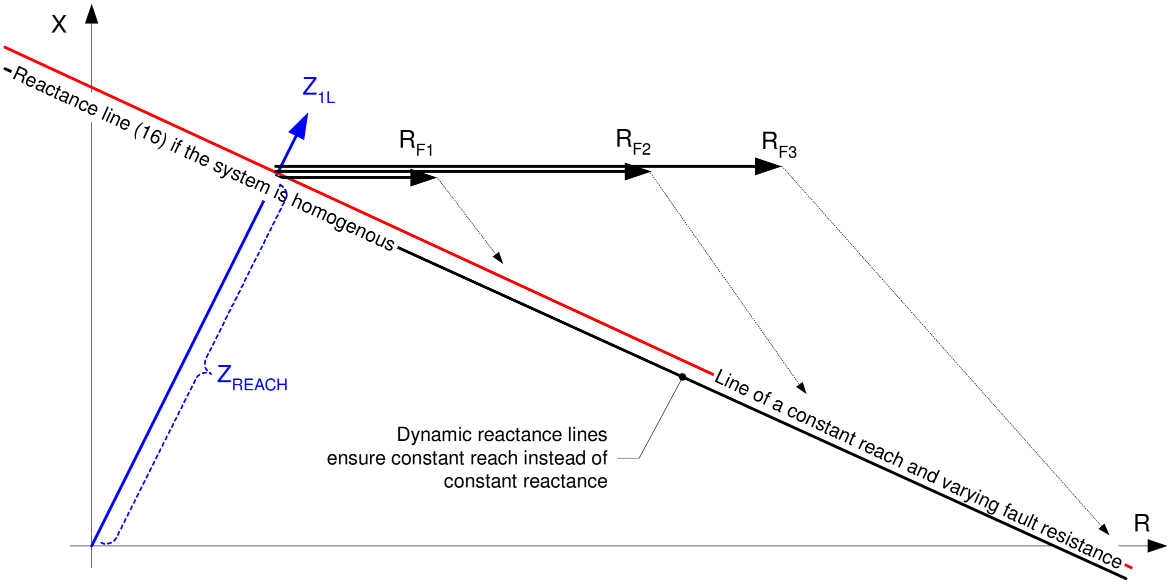


Figure 9a. Dynamic reactance lines provide optimum coverage (security aspect)

The tilt of the reactance line is a function of the $ang\left(\frac{I_{0R}}{I_{AG}}\right)$, which is dictated by the zero-sequence and positive-sequence impedances of the particular system. Reactance line per design equation (16) is dynamically shifted by the angular difference between relay zero-sequence current and phase current to provide optimum coverage.

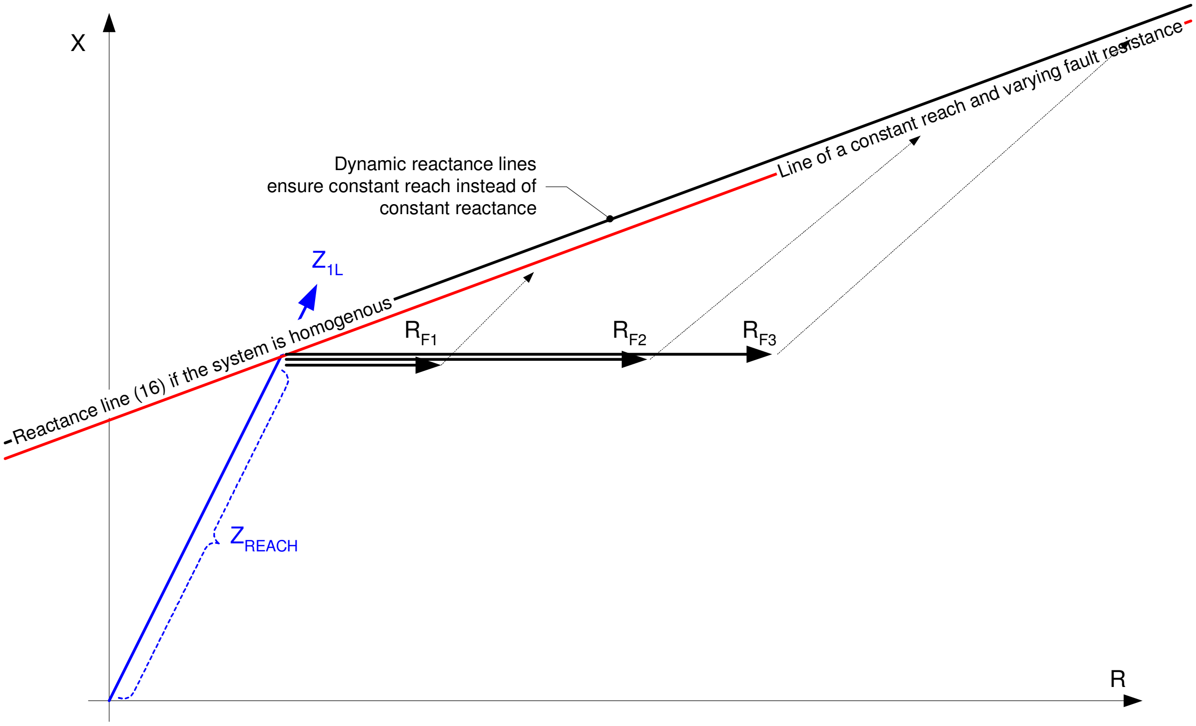


Figure 9b. Dynamic reactance lines provide optimum coverage (dependability aspect).

It is convenient to illustrate the optimum reactance line as a straight line. In reality, however, the line of a constant reach and varying fault resistance is a curve as illustrated in Figure 10 for a sample line and surrounding system.

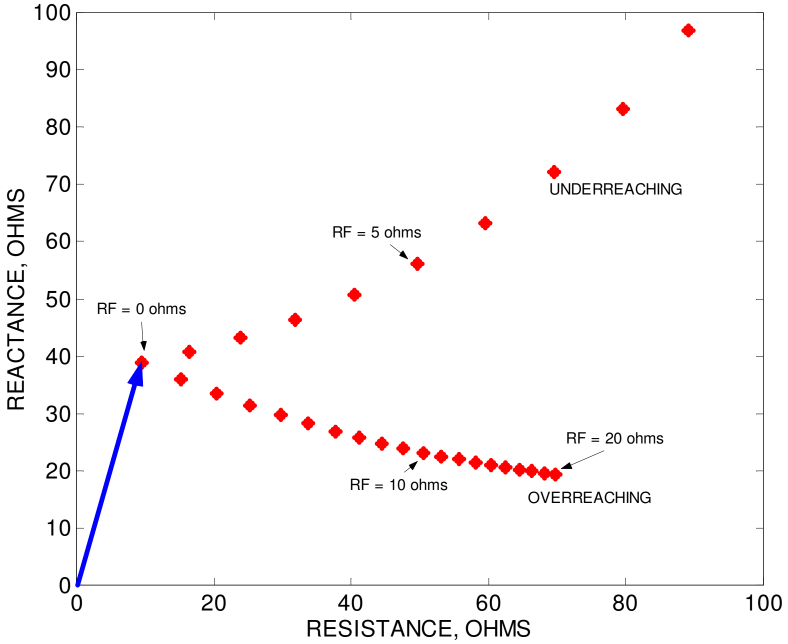


Figure 10. Actual lines of constant reach and varying fault resistance

Given dependability of the angle (17c) on system conditions, the worst-case study can be conducted and the worst-case overreaching angle can be calculated (positive angles indicate that the relay current is leading the total fault current. In this case, the relay, based on equation (16) may overreach; the negative values indicate that the relay may potentially underreach.

It is beneficial to allow compensating for the non-homogeneity angle (17c) when applying the reactance relay defined by equation (16). An improved version of the reactance comparator shifts the polarizing current to compensate for the error:

$$ang\left(I_{AG} \cdot Z_{REACH} - V_A\right) = ang\left(j \cdot I_{0R}\right) - \Theta_0 \qquad (18)$$

where Θ_0 is a user setting calculated using equation (17c) and indicating angular difference between the local terminal zero sequence current angle and the total fault zero sequence current angle.

Version (18) of the distance reactance line is attractive if the compensating angle is constant under variety of system conditions, or when the system conditions are static. The former may happen in weak systems with strong zero-sequence infeed from grounded wye-connected windings of transformers. Under such conditions the transformer zero-sequence impedances dominate equation (17c) and system topology beyond the transformers influences the non-homogeneity angle only to a very small degree.

4.5. Dynamic Line Polarized from the Negative-Sequence Current

$$ang\left(I_{AG} \cdot Z_{REACH} - V_A\right) = ang\left(j \cdot I_{2R}\right) \tag{19}$$

Similar to the zero-sequence polarization, the angle of the negative-sequence current at the relay location may be used to represent the angle of the fault current at the fault location, yielding the reactance line of equation (19). This approximation is accurate if the negative-sequence network is homogenous.

The latter holds true if the following non-homogeneity angle is close to zero:

$$\Theta_2 = ang\left(\frac{I_{2R}}{I_{2F}}\right) = ang\left(\frac{Z_{1B} + (1-m) \cdot Z_{1L}}{Z_{1A} + Z_{1L} + Z_{1B}}\right) \tag{20}$$

Again, a provision can be made to compensate for the non-homogeneity yielding the following relay design:

$$ang\left(I_{AG} \cdot Z_{REACH} - V_A\right) = ang\left(j \cdot I_{2R}\right) - \Theta_2 \tag{21}$$

5. Optimum Reactance Characteristic

5.1. General Considerations

As shown in the previous section both the load current and non-homogeneity of the network affect the static reactance characteristics. They may severely over- and under-reach particularly on short circuits with low impedance angles and large resistive coverage of the quadrilateral characteristic.

Dynamic reactance lines polarized from the zero-sequence or negative–sequence currents perform better because they are not affected by the load current, and can compensate for the non-homogeneity to a great degree. There is no single “best” polarizing signal for the reactance line: under some system conditions the negative-sequence current is a better polarizing source, under other conditions – the zero-sequence current may be a better polarizing signal.

Some relays [6] use the negative- and zero-sequence polarizing signals simultaneously. Moreover, the third polarizing source –the fault component of the positive-sequence current – is used. The reactance comparator consists of three conditions (zero-, negative- and positive-sequence polarization). This results in a design that is biased toward security and would prevent overreach at the expense of limited coverage under other conditions.

Another solution is to provide the user with a choice of the polarizing current (zero- or negative-sequence) and allow extra compensation for non-homogeneity [7]. The setting selection process includes three steps:

1. Given the expected range of system configurations, investigate the non-homogeneity angles for the zero- and negative-sequence networks (equations (17c) and (20)).

2. Select the polarizing signal with lower and more consistent non-homogeneity angle.

3. Apply appropriate non-homogeneity correction angle.

The following two examples illustrate the process.

Example 1:

A static system is to be considered with relays installed at terminals A and B and the intended reach for the underreaching directly tripping quadrilateral ground distance Z1 of 80%. The system parameters are:

$$Z_{1A} = 15\Omega \angle 87^o \quad Z_{0A} = 10\Omega \angle 67^o$$
$$Z_{1L} = 20\Omega \angle 65^o \quad Z_{0L} = 55\Omega \angle 61^o$$
$$Z_{1B} = 6\Omega \angle 85^o \quad Z_{0B} = 12\Omega \angle 75^o$$

For the terminal-A relay the angles are:

$$\Theta_2 = 1.04^o \qquad \Theta_0 = 4.35^o$$

and the negative-sequence current is a better polarizing signal. The value of 1.04 degree should be used for the compensating angle, if such setting is available.

For the terminal-B relay the angles are:

$$\Theta_2 = 6.44^o \qquad \Theta_0 = -0.09^o$$

and the zero-sequence current is a better polarizing signal. The value of –0.09 degree should be used for the compensating angle, if such setting is available. For this terminal, usage of zero-sequence provides less angular difference between polarizing current and fault current.

This example shows that even for a static system, one terminal of the line could be polarized for optimum performance of the reactance line differently compared with the other terminal. Because no coordination is required between the first zones, mixing different polarizing modes is allowed (in other circumstances such as directional comparison scheme, mixing different modes of operation or polarization may lead to coordination problems).

Example 2

A considerably dynamic system is to be considered with relays installed at terminals A and B and the intended reach for the underreaching directly tripping quadrilateral ground distance Z1 of 85%. The system parameters are:

$$Z_{1A} = 5-25\Omega\ \angle 75-87^o \quad Z_{0A} = 5-12\Omega\ \angle 65-67^o$$

$$Z_{1L} = 25\Omega\ \angle 75^o \quad Z_{0L} = 78\Omega\ \angle 60^o$$

$$Z_{1B} = 6-15\Omega\ \angle 75-85^o \quad Z_{0B} = 12-18\Omega\ \angle 60-75^o$$

Assuming all combinations of angles and magnitudes can occur, one may scan the specified ranges and calculate the two non-homogeneity angles for each combination of system parameters.

Analysis for terminal-A results in the zero-sequence non-homogeneity angle varying between –6.21 deg and 2.44 deg while the negative-sequence angle varies between –5.35 deg and 5.71 deg (Figures 11a and 11b). Positive values of the angle result in a potentially overreaching condition. Because 2.44 < 5.71, zero-sequence polarization should be selected, and 2.44 deg shall be entered as the correction angle. This will ensure maximum security. Also the zero-sequence angle is more consistent – the relay would statistically underreach in smaller percentage of cases if set to use zero-sequence polarization.

Similar analysis for the terminal-B relay yields the zero-sequence angle varying between –5.44 deg and 1.88 deg and the negative-sequence angle varying between –3.33 deg and 6.39 deg. Zero-sequence polarization should be selected (1.88 < 6.39).

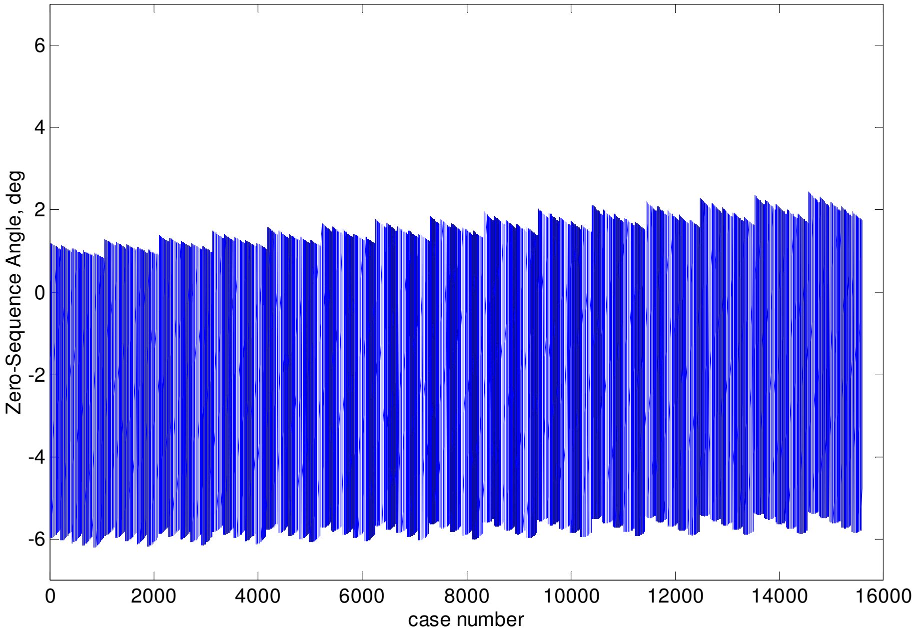


Figure 11a. Analysis of the zero-sequence non-homogeneity for Example 2

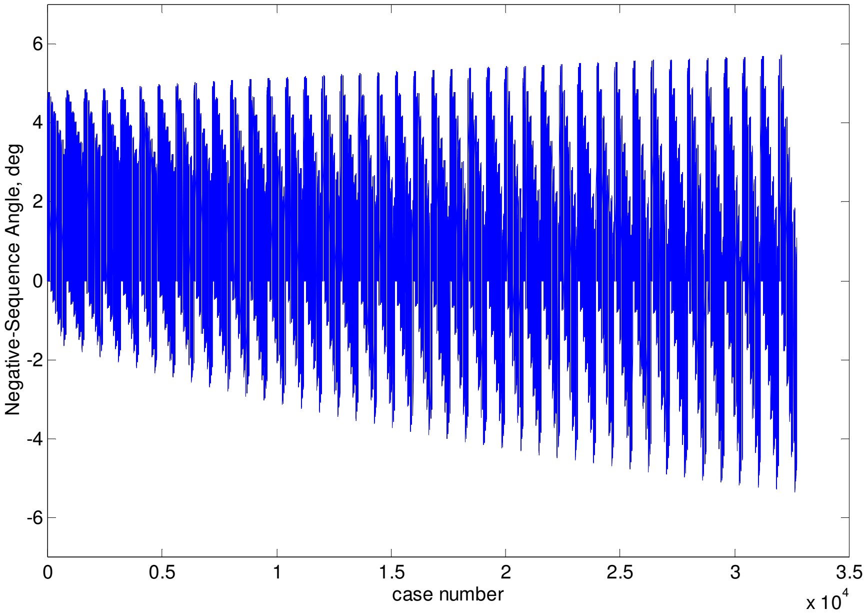


Figure 11b. Analysis of the negative-sequence non-homogeneity for Example 2

5.2. Special Considerations for Cables

The above analysis must be performed in an iterative way for cable applications.

Variance of the zero-sequence impedance with the fault current. For a given system configuration, the zero-sequence impedance of the cable shall be assumed, and a fault current shall be calculated. Knowing the fault current, a correction shall be applied for the zero-sequence impedance as per cable manufacturer data, and the process shall be repeated until good accuracy is achieved.

Typically, distance relays support constant zero-sequence compensation. This must be factored into the application. For each fault level and different cable impedance, the relay will apply the same compensation. Alternatively – through setting groups or different zones of protection – more than one zero-sequence compensating factors could be applied resulting in adaptive schemes. For example, one zone could be enabled for direct underreaching tripping, utilizing a compensation factor that will ensure security. For a permissive overreaching scheme, the tripping zone should utilize a compensation factor that will never result in an underreaching condition. Different zones may be configured to use different zero-sequence factors, and will be set with different reach for better security and dependability. Overcurrent supervision may also be used to effectively block a zone with the inappropriate (for a given fault current level) zero-sequence compensation. This would indicate a weaker than expected source, and could result in unexpected relay response

Non-homogeneity of the protected circuit. As illustrated in Figure 3 the protected circuit may be highly non-homogenous: series reactors, PAR transformers, overhead lines can be connected with cable sections – including parallel cables. The significant non-homogeneity may yield unexpected effects. For example, the relay may reach to a fault located at the end of the zone, but may fail to reach to a fault located closer. It is a good practice to consider several fault locations for the analysis and setting development to ensure security and dependability. All transition points between overhead and cable sections, series reactors and PAR transformers should be included into the analysis.

For sections with parallel cables, several internal fault locations along the cable pathway should be considered.

For circuits with series reactors and PAR transformers, the by-pass switches should be assumed opened and closed in the considered variants. Multiple setting groups and digital communications between line terminals are excellent tools to deal with changing configurations.

6. Utilization of Short-Circuit and Transient Analysis Programs

Short circuit and transient analysis programs offer great aid in setting distance relays for cable applications. Variety of system conditions and fault locations can be studies to fine tune relay settings.

Figure 12 shows a Real Time Digital Simulator (RTDS) model of a sample 26.4kV network grounded via resistor. The network consists of both cable and overhead sections.

Figure 13 presents signals and the R-X plot of the apparent impedance measured by the D1 relay for an AG fault at the far end busbar. The static reactance line would result in overreaching. The dynamic reactance line adjusts accordingly in order to ensure security for this particular fault.

Figure 14 presents an example of an evolving external-to-internal fault. An external AG fault at location F1 evolves into an internal BG fault at location F2. The local relay trips fast from distance Z1. The remote relay shown in Figure 12 sees the fault in its time-delayed Z2 and trips as in stepped distance mode.

7. Conclusions

Cable circuits can be effectively protected with unit protection: current differential, phase comparison or directional comparison schemes.

Distance applications – both main and back up protection – create some unique problems. In order to ensure good performance of distance protection schemes short-circuit studies both steady state and transient are recommended.

Direct underreaching tripping from distance zones is a particularly difficult problem. The reactance comparator of a quadrilateral function must be implemented appropriately to ensure good coverage in low-line-angle situations and non-homogenous networks. Proper selection of the zero-sequence compensation settings is important but not straightforward as the cable zero-sequence impedance may vary with the current.

Results of setting optimization studies may call for a relay that provides great deal of flexibility and wide ranges of settings.

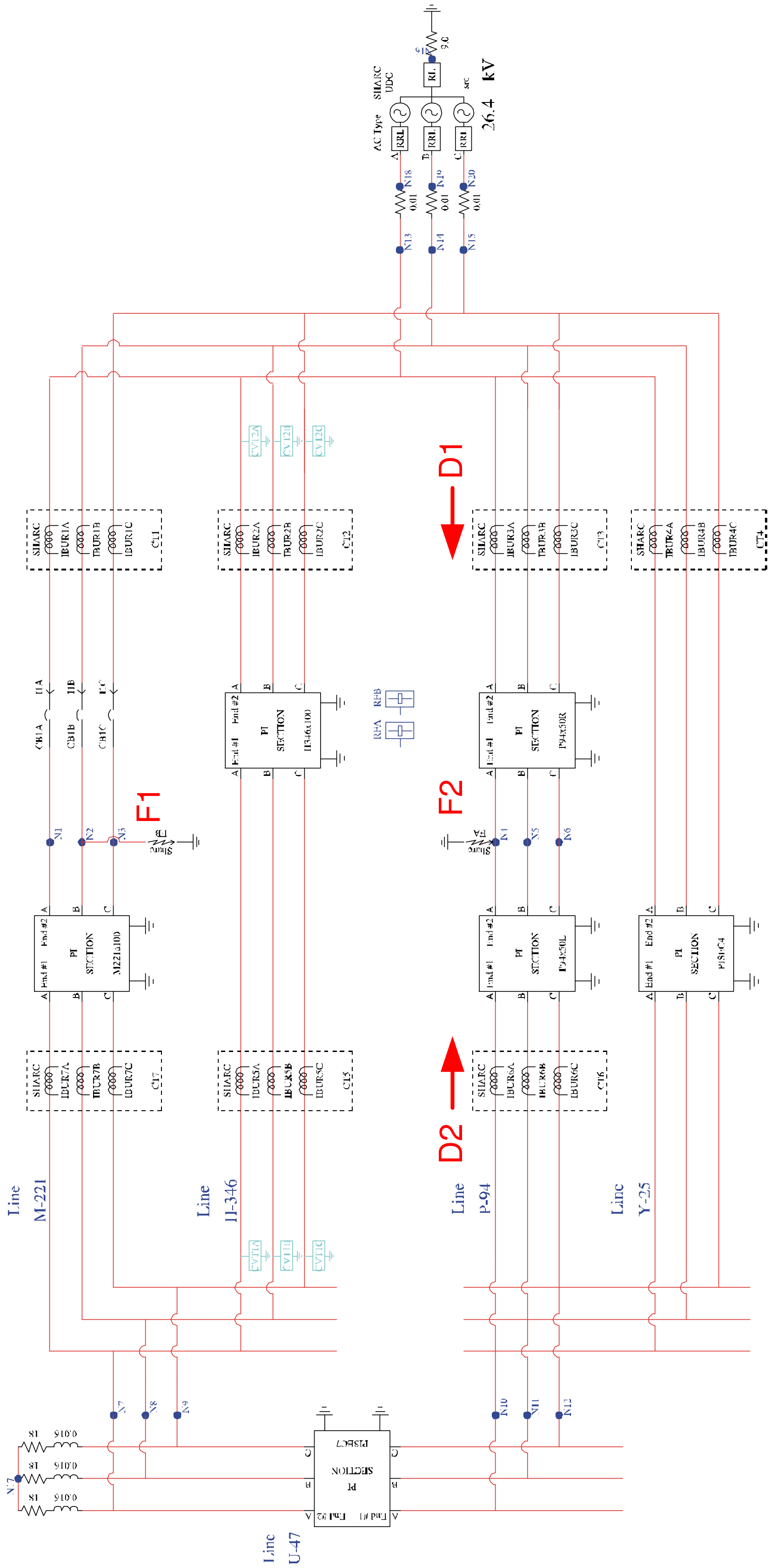


Figure 12. RTDS model of a sample 26.4kV network

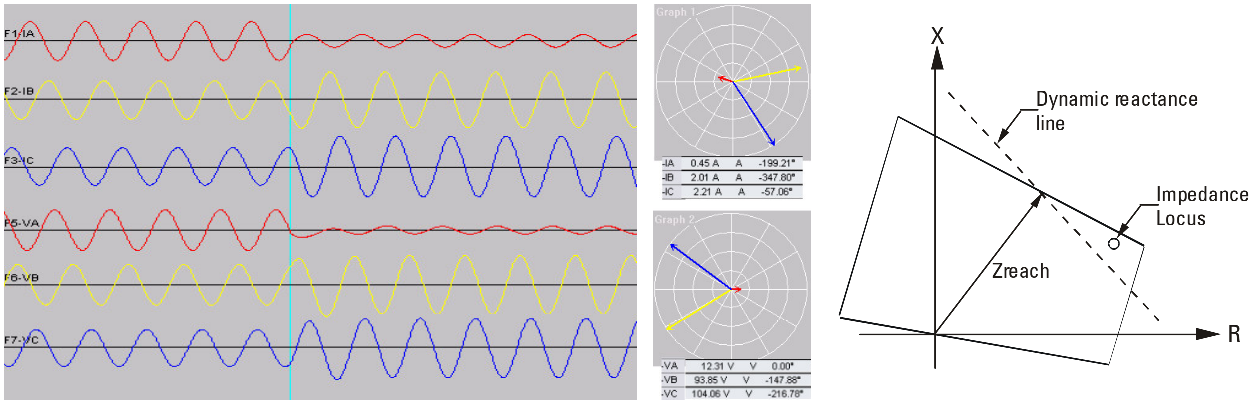


Figure 13. Currents, voltages and R-X plots for an external AG fault

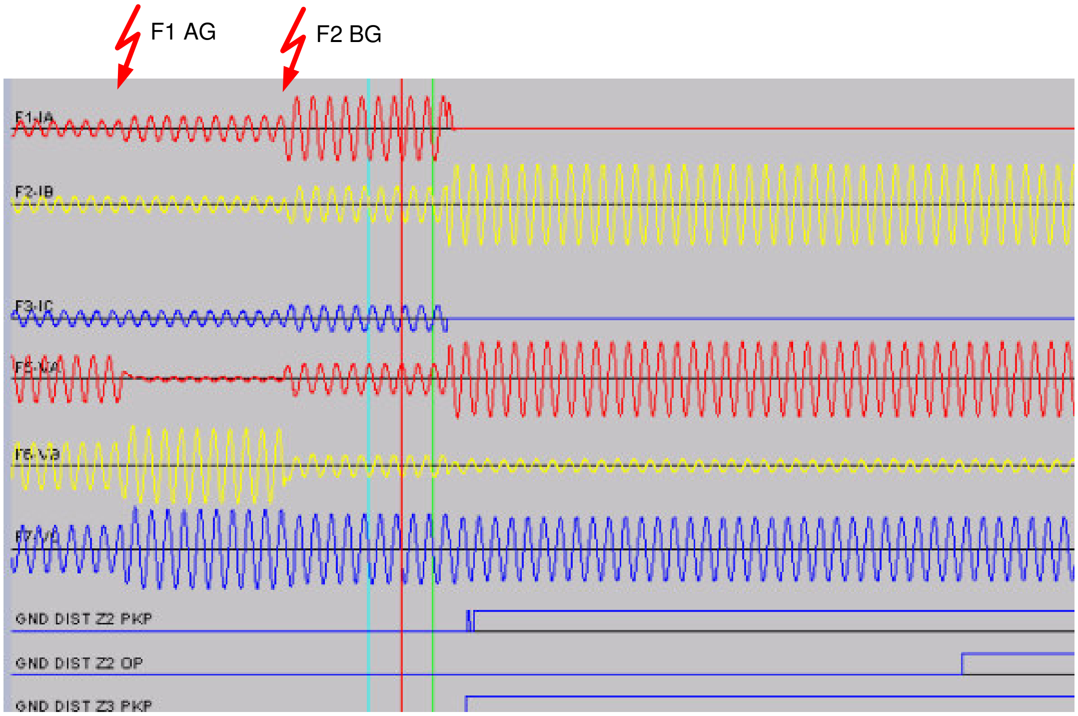


Figure 14. Response of a remote distance relay to an evolving external-to-internal fault

8. References

[1] J. Zipp (Chairman), "Protective Relaying Considerations for Transmission Lines with High Voltage AC Cables", PSRC WG D12 paper published in *IEEE Transactions on Power Delivery*, Vol.12, No.1, January 1997, pp.83-96.

[2] J.G.Neher, "The Phase Sequence Impedance of Pipe-type Cables", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS 83, August 1964, pp.795-804.

[3] E.R.Thomas, R.H.Kershaw, “Impedance of Pipe Type Cable”, *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS 84, No.10, October 1965, pp.953-965.

[4] IEEE Guide for the Application of Sheath-Bonding Methods for Single-Conductor Cables and the Calculation of Induced Voltages and Current in Cable Sheaths, ANSI/IEEE Standard 575.

[5] L90 Line Differential Relay – Instruction Manual, GE Publication, P/N 1601-0081.

[6] ALPS – Advanced Line Protection System – Instruction Manual, GE Publication, P/N GEK-105555G.

[7] D60 Line Distance Relay – Instruction Manual, GE Publication, P/N 1601-0089.

Back to Table of Contents