DYNAMIC CHARACTERISTICS IN DISTANCE PROTECTION

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ABSTRACT

Many protection engineers use to consider the distance characteristics as static elements. This can lead to mistakes when evaluating their operation, both in real events and during laboratory tests.

The Mho characteristic in the new generation relays is normally polarized by a voltage which involves a healthy phase or which is memorized. This produces an expansion for forward faults and a contraction for reverse faults. The same happens for the directional unit included in the quadrilateral characteristic; as a consequence of the polarization voltage it is shifted backwards for forward faults and upwards for reverse faults. On the other hand, the reactance line of the quadrilateral characteristic is normally designed to compensate the load flow for resistive faults. This makes it tilt depending on the load flow direction and magnitude.

This paper describes the algorithms most commonly used for the distance characteristics in order to explain the variation they experience. On the hand, it proposes tests to force these variations which allows the evaluation of the dynamic behavior. Tests which does not create any variation in the characteristics are also described so that the static response can be checked.

1 INTRODUCTION

The distance protection is the main function used in transmission and subtransmission networks. It is even starting to be used at the distribution level due to the great increase of distributed generation. The algorithms of the distance characteristics have been improved along the days in order to increase their security and dependability during complex disturbances as zero-voltage faults, faults with voltage inversions, resistive faults with high load flow, etc. The new algorithms have made the distance characteristics quite complicated and difficult to be represented in the impedance diagram (R-X diagram), the main tool for analyzing the distance relay operation. Due to the lack of knowledge simplified algorithms are considered; this can lead to mistakes when evaluating the relay behavior.

This paper reviews, first of all, basic concepts of a distance function: fault loops and its relation to the sequence networks, the impedance measured, the voltage and the impedance diagram. It then reviews the most common algorithms used both for Mho and quadrilateral characteristics, explaining how the characteristics are represented in the impedance diagram. The paper also describes different type of tests to check both the static and dynamic characteristics. Finally it includes some real cases which analysis required the representation of the dynamic characteristics in the impedance plane.

2 POSITIVE, NEGATIVE AND ZERO SEQUENCE IMPEDANCES OF A LINE

Before talking about the impedance measured by a distance relay let´s review the concepts of positive sequence, negative sequence and zero sequence impedance of a line.

Figure 1 shows an overhead three-phase line based on Carson´s representation [1]. The line consists of three aerial conductors and one fictitious underground conductor which represents the earth return.

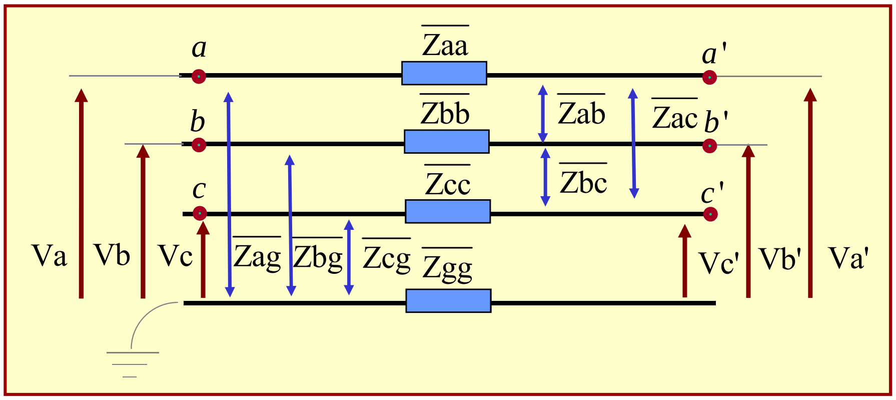

Figure 1. Overhead line based on Carson´s representation

The impedances shown are:
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$\overline{Zaa}$ self impedance in phase A
$\overline{Zbb}$ self impedance in phase B
$\overline{Zcc}$ self impedance in phase C
$\overline{Zgg}$ self impedance of the ground conductor
$\overline{Zab}$ mutual impedance between phases A and B
$\overline{Zbc}$ mutual impedance between phases B and C
$\overline{Zac}$ mutual impedance between phases A and C
$\overline{Zag}$ mutual impedance between phase A and ground
$\overline{Zbg}$ mutual impedance between phase B and ground
$\overline{Zcg}$ mutual impedance between phase C and ground

The relation between the voltages at both ends of the line and the currents is given by the following matrix:

$$\begin{pmatrix} Va - Va' \\ Vb - Vb' \\ Vc - Vc' \\ Vg - Vg' \end{pmatrix} = \begin{pmatrix} \overline{Zaa} & \overline{Zab} & \overline{Zac} & \overline{Zag} \\ \overline{Zab} & \overline{Zbb} & \overline{Zbc} & \overline{Zbg} \\ \overline{Zac} & \overline{Zbc} & \overline{Zcc} & \overline{Zcg} \\ \overline{Zag} & \overline{Zbg} & \overline{Zcg} & \overline{Zgg} \end{pmatrix} \cdot \begin{pmatrix} Ia \\ Ib \\ Ic \\ Id \end{pmatrix}$$

If we consider the voltage only in one end of the line, short-circuiting the other end, we get [1]:

$$\begin{pmatrix} Va \\ Vb \\ Vc \end{pmatrix} = \begin{pmatrix} Zaa & Zab & Zac \\ Zab & Zbb & Zbc \\ Zac & Zbc & Zcc \end{pmatrix} \cdot \begin{pmatrix} Ia \\ Ib \\ Ic \end{pmatrix}$$

Where:

$$Zaa = \overline{Zaa} - 2 \cdot \overline{Zag} + \overline{Zgg}$$
$$Zbb = \overline{Zbb} - 2 \cdot \overline{Zbg} + \overline{Zgg}$$
$$Zcc = \overline{Zcc} - 2 \cdot \overline{Zcg} + \overline{Zgg}$$

$$Zab = \overline{Zab} - \overline{Zad} - \overline{Zbg} + \overline{Zgg}$$
$$Zbc = \overline{Zbc} - \overline{Zbd} - \overline{Zcg} + \overline{Zgg}$$
$$Zac = \overline{Zac} - \overline{Zag} - \overline{Zcg} + \overline{Zgg}$$

Let´s call $\overline{Zgg} = \overline{Zret}$

If the line is transposed:

$$\overline{Zaa} = \overline{Zbb} = \overline{Zcc} = \overline{Zs}$$
$$\overline{Zab} = \overline{Zbc} = \overline{Zac} = \overline{Zm}$$
$$\overline{Zag} = \overline{Zbg} = \overline{Zag} = \overline{Zm}'$$
$$Zaa = Zbb = Zcc = Zs$$
$$Zab = Zbc = Zca = Zm$$

The phase impedance matrix will be:

$$Z_{ABC} = \begin{pmatrix} Zaa & Zab & Zac \\ Zab & Zbb & Zbc \\ Zac & Zbc & Zcc \end{pmatrix} = \begin{pmatrix} Zs & Zm & Zm \\ Zm & Zs & Zm \\ Zm & Zm & Zs \end{pmatrix}$$

We can get the sequence impedance matrix Z_{012} by applying the transformation between the phase quantities and the sequence quantities:

$$\begin{pmatrix} V_0 \\ V_1 \\ V_2 \end{pmatrix} = \frac{1}{3} \cdot \begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix} \cdot \begin{pmatrix} Va \\ Vb \\ Vc \end{pmatrix} \text{ and } \begin{pmatrix} I_0 \\ I_1 \\ I_2 \end{pmatrix} = \frac{1}{3} \cdot \begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix} \cdot \begin{pmatrix} Ia \\ Ib \\ Ic \end{pmatrix}$$

If we call $A = \frac{1}{3} \cdot \begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix}$, $Z_{012} = A \cdot Z_{ABC} \cdot A^{-1} = \begin{pmatrix} Zs + 2 \cdot Zm & 0 & 0 \\ 0 & Zs - Zm & 0 \\ 0 & 0 & Zs - Zm \end{pmatrix}$

We can conclude that:

$$Z0 = Zs + 2 \cdot Zm$$
$$Z1 = Zs - Zm$$
$$Z2 = Zs - Zm$$

Anyway, let´s obtain the sequence impedances by applying currents at one end of the line and measuring the voltage drop.

2.1 POSITIVE SEQUENCE IMPEDANCE

The positive sequence impedance of a line is the impedance offered to a positive sequence system of currents.

Let´s connect a source of positive sequence currents to ends a, b and c of the line shown in Figure 1. Because the sum of the three currents is null there will not be any current flowing through the ground conductor.

The voltage at point “a” will be:

$$Va1 = Ia1 \cdot \overline{Zs} + Ib1 \cdot \overline{Zm} + Ic1 \cdot \overline{Zm}$$

As $Ia1 + Ib1 + Ic1 = 0$

$$Va1 = Ia1 \cdot (\overline{Zs} - \overline{Zm})$$

As $Zs - Zm = \overline{Zs} - 2 \cdot \overline{Zm}' + \overline{Zret} - \overline{Zs} + \overline{Zm}' + \overline{Zm}' - \overline{Zret} = \overline{Zs} - \overline{Zm}$

$$Z1 = Zs - Zm$$

2.2 NEGATIVE SEQUENCE IMPEDANCE

The negative sequence impedance of a line is the impedance offered to a negative sequence system of currents.

We can also connect a source of negative sequence currents to ends a, b and c of the line shown in Figure 1. Negative sequence currents also sum cero so they will not either flow through the ground.

The voltage at point "a" will be:

$$Va2 = Ia2 \cdot \overline{Zs} + Ib2 \cdot \overline{Zm} + Ic2 \cdot \overline{Zm}$$

As $Ia2 + Ib2 + Ic2 = 0$, we get the same result as for Z1: $Z2 = Zs - Zm$

2.3 ZERO SEQUENCE IMPEDANCE

The zero sequence impedance of a line is the impedance offered to a zero sequence system of currents.

In order to measure the zero sequence impedance we can connect a source of zero sequence currents to ends a, b and c of the line represented in Figure 1. The zero sequence currents do not sum zero so they will flow through the ground conductor.

The voltage at point "a" will be:

$$Va0 = Ia0 \cdot \overline{Zs} + Ib0 \cdot \overline{Zm} + Ic0 \cdot \overline{Zm} - 3 \cdot Ia0 \cdot \overline{Zm}' + 3 \cdot Ia0 \cdot \overline{Zret} - 3 \cdot Ia0 \cdot \overline{Zm}'$$

$$Va0 = Ia0 \cdot (\overline{Zs} + 2 \cdot \overline{Zm} - 6 \cdot \overline{Zm}' + 3 \cdot \overline{Zret})$$

$$Zs + 2 \cdot Zm = \overline{Zs} - 2 \cdot \overline{Zm}' + \overline{Zret} + 2 \cdot \overline{Zm} - 2 \cdot \overline{Zm}' + 2 \cdot \overline{Zret}$$

$$Zs + 2 \cdot Zm = \overline{Zs} + 2 \cdot \overline{Zm} - 6 \cdot \overline{Zm}' + 3 \cdot \overline{Zret}$$

$$Z0 = Zs + 2 \cdot Zm$$

3 FAULT LOOPS

A distance relay calculates the impedance from its location to the fault point. In order to calculate this impedance it is necessary to check the voltage drops in the fault loop. This is difficult if we consider the line represented in Figure 1 because of the coupling between phases and with the ground. Therefore simplified fault loops are obtained from the sequence networks for each fault type.

Let´s start deducing the simplified fault loops for bolted faults, without fault resistance.

3.1 PHASE-PHASE FAULT

Let´s consider a BC fault. The sequence networks for this fault are represented in Figure 2.

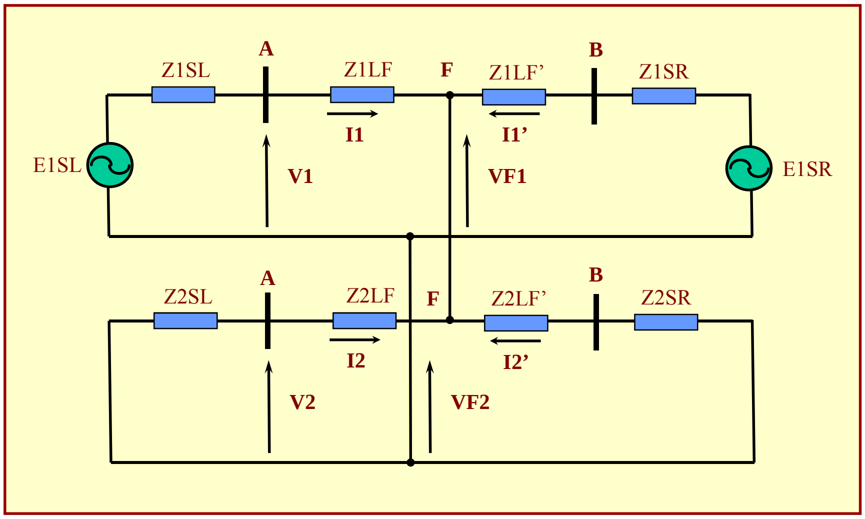

Figure 2. Sequence networks for a BC fault

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The following conditions are fullfilled:

$$VF1 = VF2$$

$$V1 - Z1LF \cdot I1 = V2 - Z2LF \cdot I2$$

Taking into account that $Z1LF = Z2LF$

$$(V1 - V2) = Z1LF \cdot (I1 - I2)$$

Applying the transformation matrix between sequence and phase quantities:

$$\begin{pmatrix} V_0 \\ V_1 \\ V_2 \end{pmatrix} = \frac{1}{3} \cdot \begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix} \cdot \begin{pmatrix} Va \\ Vb \\ Vc \end{pmatrix} \text{ and } \begin{pmatrix} I_0 \\ I_1 \\ I_2 \end{pmatrix} = \frac{1}{3} \cdot \begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix} \cdot \begin{pmatrix} Ia \\ Ib \\ Ic \end{pmatrix}$$

$$\frac{1}{3} \cdot (a - a^2) \cdot (Vb - Vc) = Z1LF \cdot \frac{1}{3} \cdot (a - a^2) \cdot (Ib - Ic)$$

$$(Vb - Vc) = Z1LF \cdot (Ib - Ic) \, (1)$$

3.2 PHASE-PHASE-GROUND FAULT

The sequence networks for a BCG fault are shown in Figure 3. As it can be seen the positive and negative sequence networks are connected the same way as in a BC fault so the same relation deduced before is fulfilled:

$$(Vb - Vc) = Z1LF \cdot (Ib - Ic)$$

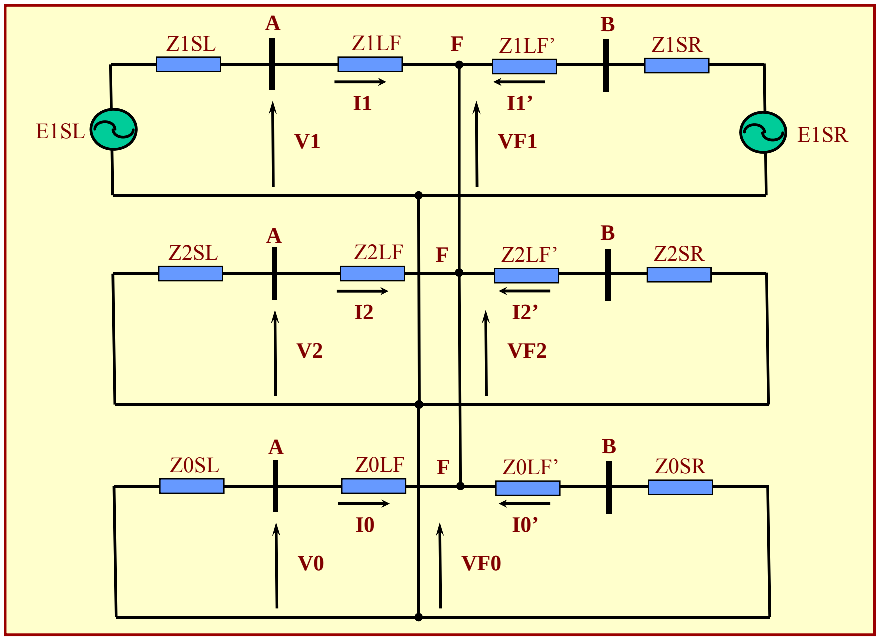


Figure 3. Sequence networks for a BCG fault

Based on the sequence networks we can get the relation between the source phase voltages and the phase voltages at the relay location:

In the circuit of Figure 2:

$$V1 = E1 - I1 \cdot Z1SL$$

$$V2 = -I2 \cdot Z2SL$$

If we consider $Z1SL = Z2SL$ (the positive and negative sequence impedances for lines and transformers are equal. For generators they can also be considered as equal [1])

$$V1 - V2 = E1 - (I1 - I2) \cdot Z1SL$$

Applying the transformation from sequence to phase quantities:

$$\frac{1}{3} \cdot (a - a^2) \cdot (Vb - Vc) = Ea - \frac{1}{3}(Ib - Ic) \cdot Z1SL$$

$$(Vb - Vc) + (Ib - Ic) \cdot Z1SL = -\frac{3 \cdot Ea}{(a - a^2)} = Eb - Ec \text{ (2)}$$

Based on equations (1) and (2) we can build the following faulted loop:

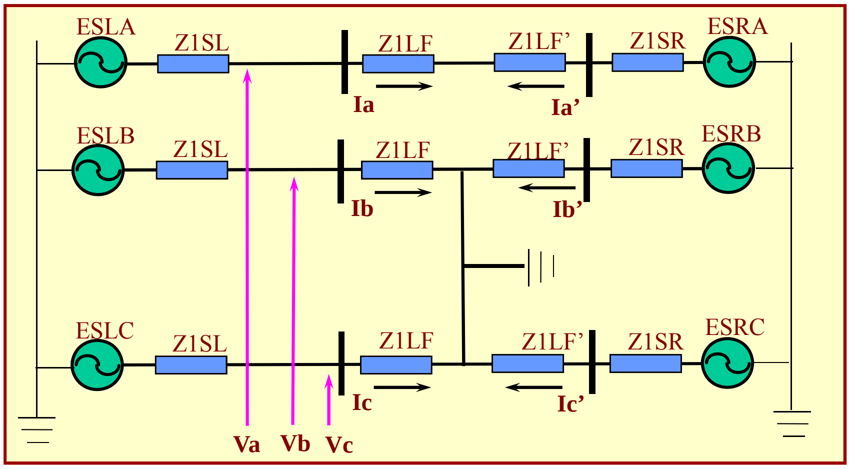


Figure 4. Faulted loop for a BC(G) fault

3.3 THREE PHASE FAULT

The sequence networks for an ABC fault are shown in Figure 5.

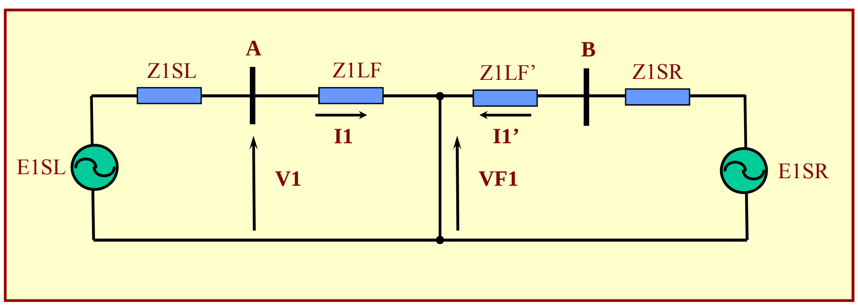


Figure 5. Sequence networks for a three-phase fault

$$V1 = Va = Z1LF \cdot I1 = Z1LF \cdot Ia$$

$$I2 = I0 = 0;\ V2 = V0 = 0$$

$$Vb = a^2 \cdot V1;\ Vc = a \cdot V1;\ Ib = a^2 \cdot I1;\ Ic = a \cdot I1$$

The following expressions are obtained:

$$(Va - Vb) = Z1LF \cdot (Ia - Ib)$$
$$(Vb - Vc) = Z1LF \cdot (Ib - Ic)$$
$$(Vc - Va) = Z1LF \cdot (Ic - Ia)$$

In a three-phase fault we will have three phase-phase fault loops.

3.4 PHASE-GROUND FAULT

The sequence networks for an AG fault are shown in Figure 6.

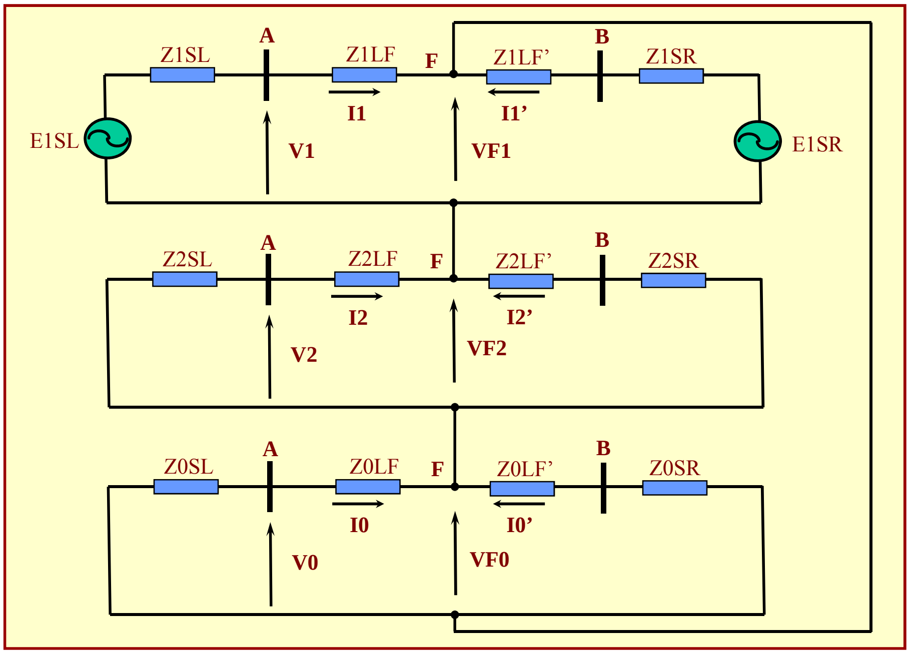


Figure 6. Sequence networks for an AG fault

$$VaF = VF0 + VF1 + VF2 = 0$$

$$VF1 = V1 - Z1LF \cdot I1$$
$$VF2 = V2 - Z2LF \cdot I2$$
$$VF3 = V2 - Z2LF \cdot I2$$

Taking into account that $Z1LF = Z2LF$

$$(V0 + V1 + V2) = (I1 + I2) \cdot Z1LF + I0 \cdot Z0LF$$

If we add and subtract $I0 \cdot Z1LF$ we get:

$$Va = Ia \cdot Z1LF + 3 \cdot I0 \cdot \frac{(Z0LF - Z1LF)}{3}$$

$ZN = \frac{(Z0LF - Z1LF)}{3}$ is called return impedance

The latter equation is normally expressed as:

$$Va = [Ia + I0 \cdot (\frac{Z0LF}{Z1LF} - 1)] \cdot Z1LF$$
$$\frac{Z0LF}{Z1LF} = \frac{Z0L}{Z1L}$$

Depending on the manufacturer, different expressions are used:

$Va = [Ia + I0 \cdot (K0 - 1)] \cdot Z1LF$ where $K0 = \frac{Z0L}{Z1L}$

$Va = (Ia + I0 \cdot K0') \cdot Z1LF$ where $K0' = \frac{Z0L - Z1L}{Z1L}$

$$Va = (Ia + 3 \cdot I0 \cdot K0'') \cdot Z1LF \text{ where } K0'' = \frac{Z0L - Z1L}{3 \cdot Z1L}$$

$$Ieq = Ia + I0 \cdot (K0 - 1) = Ia + I0 \cdot K0' = Ia + 3 \cdot I0 \cdot K0''$$

The relation between the phase source voltage and the voltage at the relay location can be easily obtained:

$$V1 = E1 - Z1SL \cdot I1$$
$$V2 = E2 - Z2SL \cdot I2$$
$$V0 = E0 - Z0SL \cdot I0$$

If we consider $Z1SL = Z2SL$ then:

$$Va = Ea - Z1SL \cdot (I1 + I2) - Z0SL \cdot I0$$

If we add and subtract $I0 \cdot Z1SL$ we get:

$$Va = Ea - Z1SL \cdot Ia - 3 \cdot I0 \cdot \frac{Z0SL - Z1SL}{3}$$

$$ZNSL = \frac{(Z0SL - Z1SL)}{3}$$ will be the source return impedance

If we consider the value for the positive and zero sequence impedances we got in point 2 we can get:

$$ZN = \frac{Z0LF - Z1LF}{3} = \frac{Zs + 2 \cdot Zm - Zs + Zm}{3} = Zm = \overline{Zm} - 2 \cdot \overline{Zm}' + \overline{Zret}$$

The positive sequence impedance includes the self impedance of the air conductors and the mutual coupling between phases. The return impedance includes the self impedance of the ground conductor, the coupling between phases and the coupling between phases and ground.

Based on the equations obtained we can draw the following circuit:

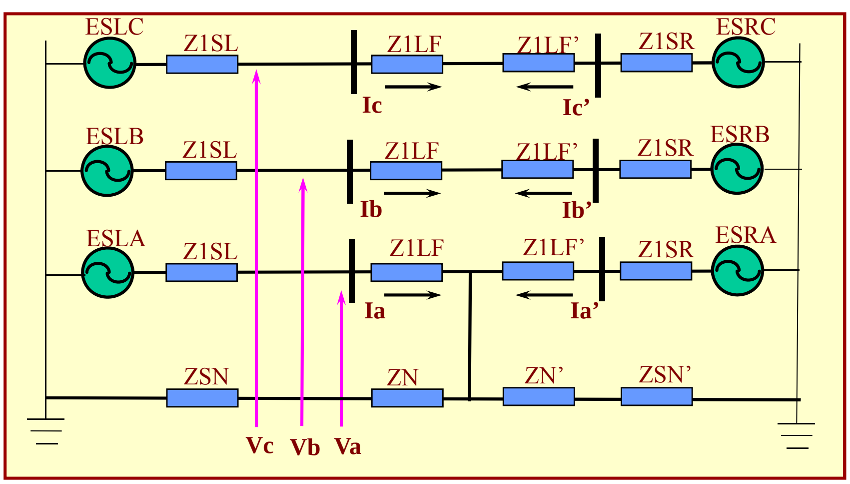


Figure 7. Fault Loop for an AG fault

3.5 IMPEDANCE MEASURED

In all the fault loops in Figure 4 and Figure 7 the represented impedance from the relay location to the fault point is the positive sequence one. This impedance is chosen because the positive sequence network is present in all the faults. Therefore, the distance relays will measure the positive sequence impedance with the following voltages and currents:

For phase-phase faults:

$$Z1LF = \frac{Va - Vb}{Ia - Ib} \text{ for an AB fault}$$

$$Z1LF = \frac{Vb - Vc}{Ib - Ic} \text{ for a BC fault}$$

$$Z1LF = \frac{Vc - Va}{Ic - Ia} \text{ for CA fault}$$

For three-phase faults: $Z1LF = \frac{Va - Vb}{Ia - Ib} = \frac{Vb - Vc}{Ib - Ic} = \frac{Vc - Va}{Ic - Ia}$

For single phase-ground faults:

$$Z1LF = \frac{Va}{Ieqa} \text{ for an AG fault, where } Ieqa = Ia + I0 \cdot (K0 - 1)$$

$$Z1LF = \frac{Vb}{Ieqb} \text{ for an BG fault, where } Ieqb = Ib + I0 \cdot (K0 - 1)$$

$$Z1LF = \frac{Vc}{Ieqc} \text{ for an BG fault, where } Ieqc = Ic + I0 \cdot (K0 - 1)$$

3.6 MODIFIED CIRCUITS WITH FAULT RESISTANCE

If we add the fault resistance we can obtain the following circuits for phase-phase (with or without ground) and single phase-ground faults:

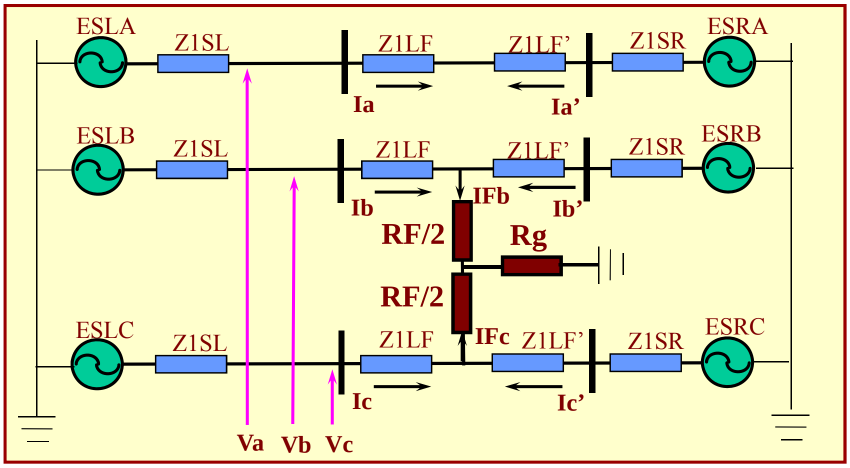


Figure 8. Fault loop for a BC(G) fault with fault resistance

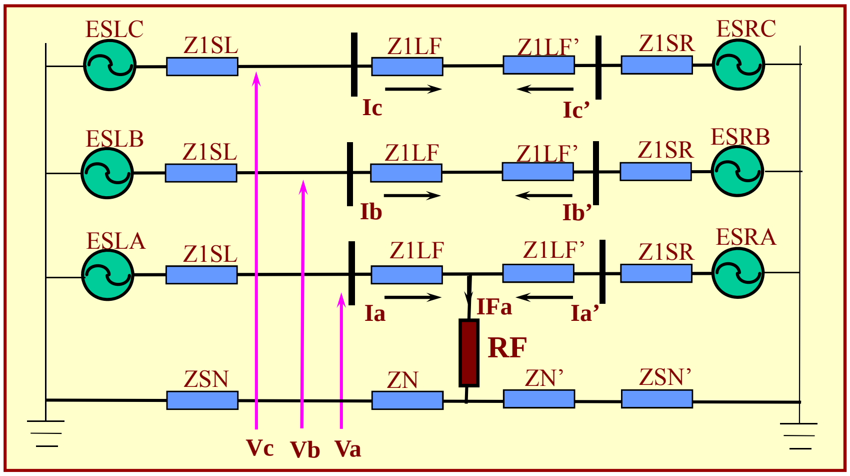


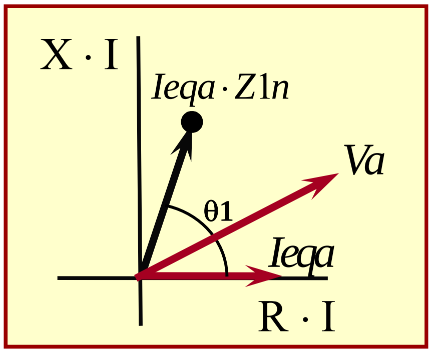
Figure 9. Fault loop for an AG fault with fault resistance

4 THE VOLTAGE AND THE IMPEDANCE DIAGRAMS

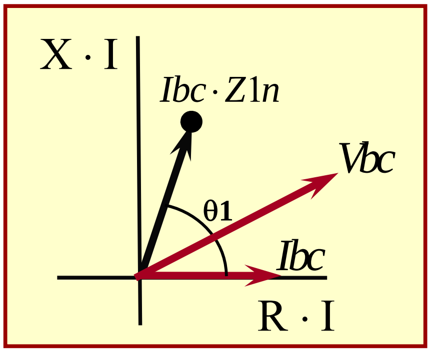
In order to analyze the operation of a distance relay the impedance measured has to be represented together with the distance characteristic in the impedance plane (polar or rectangular plane). As we will see later, to do this representation, it is much more easy to start from a voltage diagram ($R \cdot I - X \cdot I$ diagram) and choose a certain current as the reference. If we then divide all the voltages and currents by the reference current we will get the representation in the impedance diagram ($R - X$ diagram).

For a single-phase to ground fault the reference current will be the equivalent current and for the rest of the faults the reference current will be the phase-phase current.

Figures 10.a and 10.b show the voltage diagrams for an AG and a BC fault. Z1n represents the impedance reach of the zone n. Figures 11.a and 11.b show the corresponding impedance diagrams.

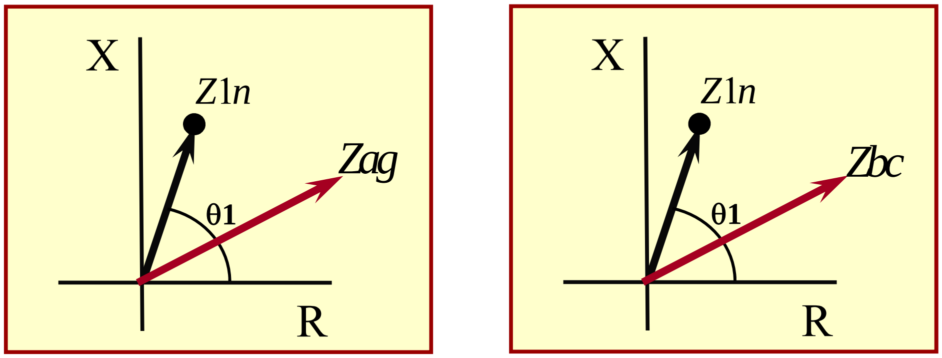


a. AG fault



b. BC fault

Figure 10. Voltage diagrams



a. AG fault

b. BC fault

Figure 11. Impedance diagrams

5 DISTANCE CHARACTERISTICS

Once the impedance has been represented in the R-X diagram it is necessary to check if it is inside or outside the distance characteristic.

Distance characteristics can be basically classified in two types: Mho and quadrilateral. Let´s review each of them. We will just focus on two types of faults: AG and BC. The phasors used for the rest of the faults can be easily obtained. For three-phase faults the distance zones will normally operate with the three phase-phase units: AB, BC and CA.

The phase selector, the unit is charge of determining the type of fault, is considered the core of the distance protection as a false phase selection will make the distance unit consider a fault loop different than the real one. This will make a wrong positive sequence impedance calculation. Anyway, no description about the phase selector used is given is this paper as it is considered out of the scope of it.

5.1 MHO CHARACTERISTIC

Even in numerical relays the Mho characteristic is implemented by a phase comparator which compares the angle between two phasors, an operating and a polarizing phasor.

The operating condition is: $-90^{o} \leq ang(Vop) - ang(Vpol) \leq 90^{o}$ (3)

The **operating phasor** follows this formula: $Vop = I \cdot Zn - V$

where

Zn is the positive sequence impedance of zone n
For a single-phase to ground fault (let´s consider an AG fault) $I = Ieqa$ and $V = Va$
For a phase-phase fault (let´s consider a BC fault) $I = Ibc$ and $V = Vbc$

The **polarizing phasor** ($Vpol$) depends on the type of Mho characteristic:

For single-phase to ground faults (let´s suppose an AG fault):

$Vpol = Va$: self-polarized

$Vpol = j\dfrac{Vbc}{\sqrt{3}}$: cross-polarized (with or without memory)

$Vpol = Va1$: positive-sequence polarized (with or without memory)

For phase-phase faults (let´s consider a BC fault):

$Vpol = Vbc$: self-polarized

$Vpol = -j\sqrt{3}Va(M)$: cross-polarized (with or without memory)

$Vpol = Vbc1(M)$: positive-sequence polarized (with or without memory)

The operating condition for a Mho characteristic (3) is based on the second Thales' Theoreme which states that if A, B and C are points on a circle where the line AC is a diameter of the circle, then the angle ABC is a right angle.

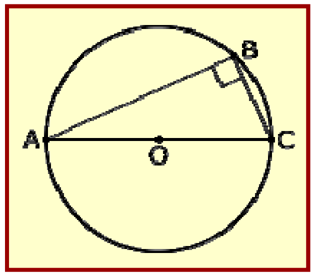
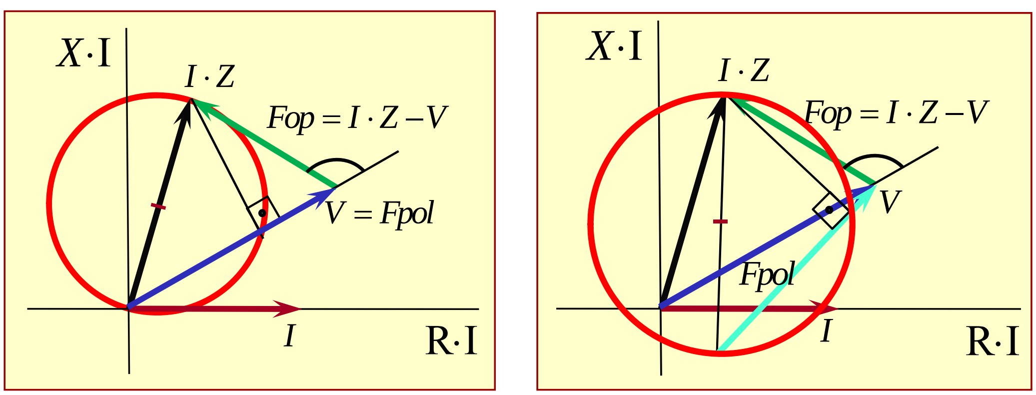


Figure 12. Thales' Theoreme

If we have a point in the voltage diagram (V, end of voltage vector) and we want to see its relative position to the Mho characteristic we just have to draw the operating and polarizing phasors from that point. These two phasors will be the arcs that have to be 90º phase-shifted so that the point V is in the border of the circle. If the polarizing phasor is equal to V the circle will pass through the origin (Figure 13.a). If the polarizing phasor is different from V the circle will not pass thorough the origin (Figure 13.b)



a. Vpol=V

b. Vpol≠V

Figure 13. Generic Mho characteristics

5.1.1 Self-polarized Mho characteristic

5.1.1.1 <u>Single phase to ground faults</u>

The operating and polarizing phasors for an AG fault will be:

$Vop = Ia \cdot Z1n - Va$

$Vpol = Va$

Figure 14 shows the Mho characteristic for an AG fault. It is a circle centered in the middle of the vector $Vpol + Vop$ and with a radio equal to $\frac{|Vpol + Vop|}{2}$. For the self-polarized Mho $Vpol + Vop = Ieqa \cdot Z1n$

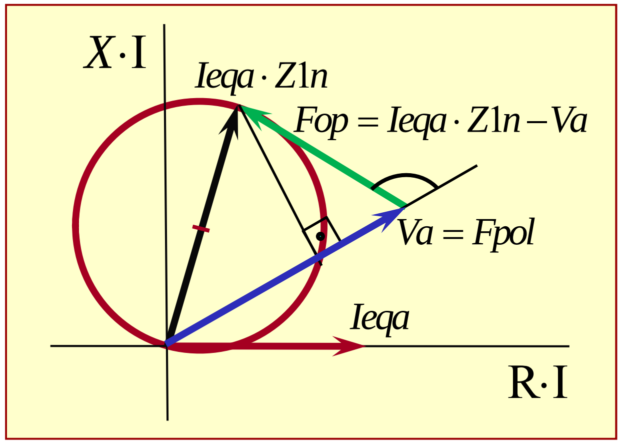


Figure 14. Self polarized AG Mho characteristic

5.1.1.2 <u>Phase-phase faults</u>

The operating and polarizing phasors for a BC fault will be:

$Vop = Ibc \cdot Z1n - Vbc$
$Vpol = Vbc$

The Mho characteristic is shown in Figure 15. In this case $Vpol + Vop = Ibc \cdot Z1n$

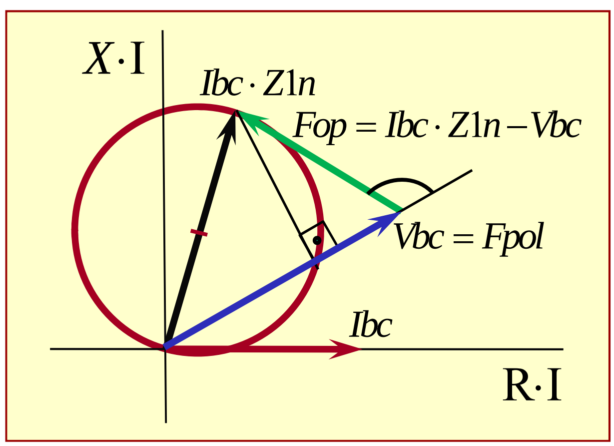


Figure 15. Self-polarized BC Mho characteristic

The self-polarized Mho characteristic is a static characteristic. It has a low resistive coverage and it is not reliable for zero-voltage faults.

5.1.2 Cross-polarized Mho characteristic

5.1.2.1 <u>Single phase to ground faults</u>

The operating and polarizing phasors for an AG fault will be:

$Vop = Ia \cdot Z1n - Va$

$Vpol = j\frac{Vbc}{\sqrt{3}}$

The Mho characteristic is shown in Figure 16. As it was mentioned before, the Mho characteristic will be a circle centered in the middle of the vector $Vpol + Vop$ and with a radius equal to $\frac{|Vpol + Vop|}{2}$. As it can be seen the Mho has expanded with regard to the self-polarized characteristic. The expansion will depend on the difference between Va and Vpol. Let´s calculate this value:

If we consider the fault loop of Figure 7 we can get the following expressions:

$Va = Ea - Iaeq \cdot Z1SL$ (4) (we have considered that K0 for the line and the source are equal)

$Vbc = Ebc - Ibc \cdot Z1SL \rightarrow j\frac{Vbc}{\sqrt{3}} = Ea - j\frac{Ibc}{\sqrt{3}} \cdot Z1SL$ (5)

$Vpol - Va = (Iaeq - \frac{jIbc}{\sqrt{3}}) \cdot Z1SL$

If there is no load flow and the distribution factors between the zero sequence and positive sequence networks are equal [2] Ib=Ic=0. If we convert the voltage diagram into an impedance diagram, the expansion of the Mho characteristic will be equal to the positive sequence local source impedance.

In general the expansion of the Mho characteristic occurs because Vpol has a higher magnitude than Va and, on the other hand, Vpol is normally leading Va. If we take into account the equations (4) and (5) we can see that the voltage drop due to $j\frac{Ibc}{\sqrt{3}}$ will be lower than the voltage drop due to $Ieqa$, which explains the former statement.

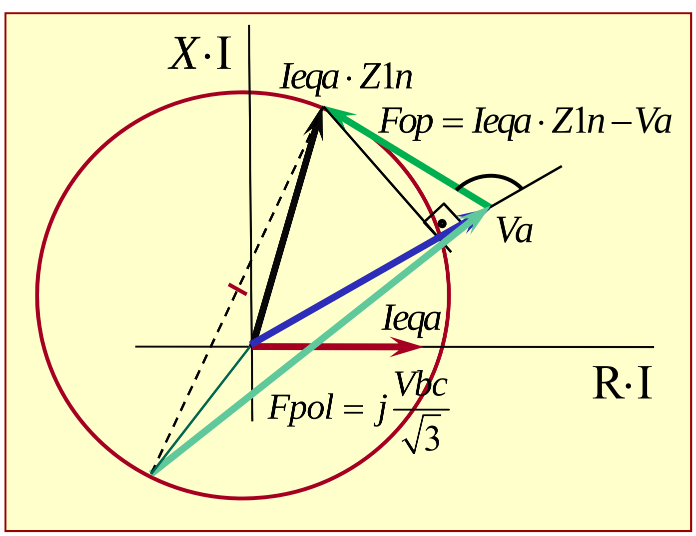


Figure 16. Cross-polarized AG Mho characteristic

5.1.2.2 Phase-Phase Faults

The operating and polarizing phasors for a BC fault will be:

$$Vop = Ibc \cdot Z1n - Vbc$$
$$Vpol = -j\sqrt{3}Va$$

The Mho characteristic is shown in Figure 17. Let´s see the expansion of the characteristic with regard to the self-polarized one:

If we consider the fault loop of Figure 4 we can get the following expressions:

$$Vbc = Ebc - Ibc \cdot Z1SL$$

$$-j\sqrt{3}Va = -j\sqrt{3} \cdot (Ea - Ia \cdot Z1SL) \rightarrow -j\sqrt{3}Va = Ebc + j\sqrt{3}Ia \cdot Z1SL \quad (6)$$

$$Vpol - Vbc = (Ibc - j\sqrt{3}Ia) \cdot Z1SL$$

If there is no load flow Ia=0. Converting the voltage diagram into an impedance diagram, the expansion of the Mho characteristic will be equal to the positive sequence local source impedance.

As for the case of single-phase to ground faults Vpol will be higher in magnitude and lead Vbc.

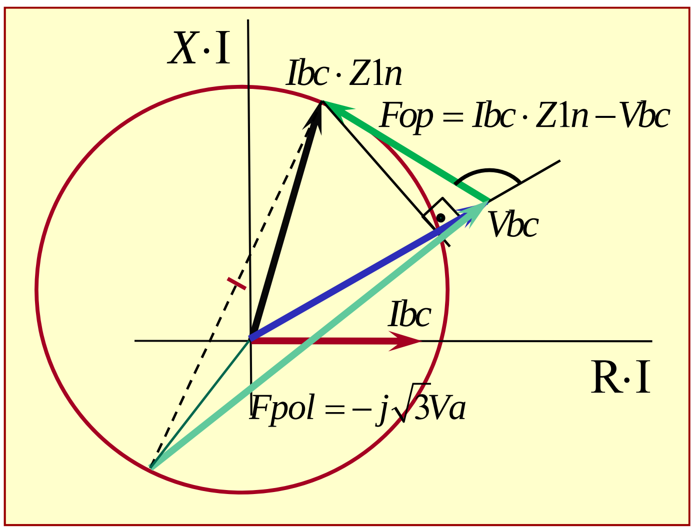


Figure 17. Cross-polarized BC Mho characteristic

The cross-polarized characteristic is reliable for zero-voltage single-phase and phase-phase faults. On the other hand it has better resistive coverage than the self-polarized Mho. However it is not reliable for zero-voltage three-phase faults.

5.1.3 Positive-sequence polarized Mho characteristic

5.1.3.1 Single phase to ground faults

The operating and polarizing phasors for an AG fault will be:

$$Vop = Ia \cdot Z1n - Va$$
$$Vpol = Va1$$

The Mho characteristic is shown in Figure 18. Let´s calculate the expansion with regard to the self-polarized characteristic.

If we consider the sequence networks and the fault loop for an AG fault (Figure 6 and Figure 7, respectively) we can get the following expressions:

$Va1 = Ea1 - Ia1 \cdot Z1SL$
$Va = Ea - Iaeq \cdot Z1SL$ (we have considered that K0 for the line and the source are equal)

$Vpol - Va1 = (Iaeq - Ia1) \cdot Z1SL$

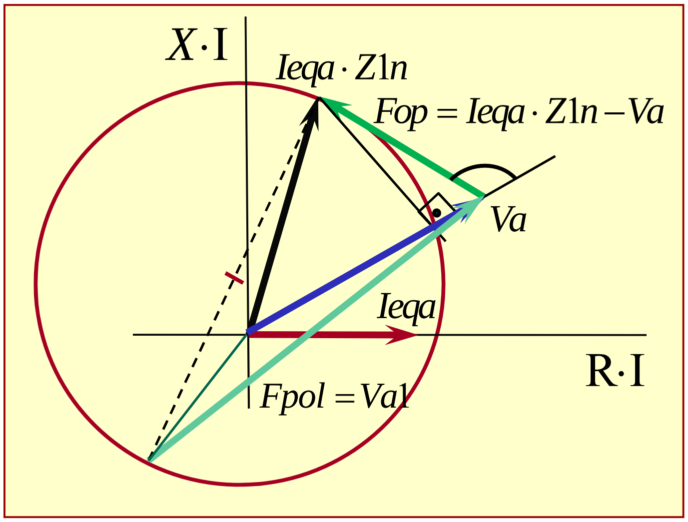


Figure 18. Positive-sequence polarized AG Mho characteristic

5.1.3.2 Phase-phase faults

The operating and polarizing phasors for a BC fault will be:

$Vop = Ibc \cdot Z1n - Vbc$
$Vpol = Vbc1$

The Mho characteristic is shown in Figure 19. Let´s calculate the expansion with regard to the self-polarized characteristic.

If we consider the sequence networks and the fault loop for a BC fault (Figure 2 and Figure 4, respectively) we can get the following expressions:

$Va1 = Ea1 - Ia1 \cdot Z1SL$ so: $Vb1 = Eb1 - Ib1 \cdot Z1SL$ and $Vc1 = Ec1 - Ic1 \cdot Z1SL$. Therefore:

$Vbc1 = Ebc1 - Ibc1 \cdot Z1SL$
$Vbc = Ebc - Ibc \cdot Z1SL$

$Vpol - Vbc1 = (Ibc - Ibc1) \cdot Z1SL$

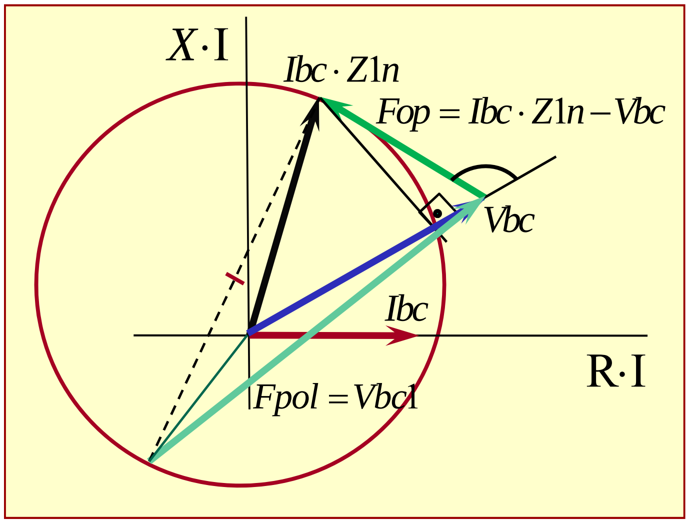


Figure 19. Positive-sequence polarized BC Mho characteristic

The positive-sequence polarized Mho characteristic has the same limitations as the cross-polarized one with regard to zero-voltage three-phase faults so it has to be complemented with memory voltage. The memory voltage, on the other hand, solves the problems with voltage inversions in series compensated lines.

5.1.4 Positive-sequence memory polarized Mho characteristic

5.1.4.1 Single-phase to ground faults

The operating and polarizing phasors for an AG fault will be:

$$Vop = Ia \cdot Z1n - Va$$
$$Vpol = Va1M$$

The expansion will be:

$Va1M = Ea1 - Ia1p \cdot Z1SL$, where Ia1p is the prefault positive sequence current

$Va = Ea - Iaeq \cdot Z1SL$ (we have considered that K0 for the line and the source are equal)

$$Vpol - Va = (Iaeq - Ia1p) \cdot Z1SL$$

If there is no load flow the expansion of the Mho characteristic will be equal to the local positive sequence source impedance.

5.1.4.2 Phase-phase faults

The operating and polarizing phasors for a BC fault will be:

$$Vop = Ibc \cdot Z1n - Vbc$$
$$Vpol = Vbc1M$$

The expansion will be:

$Vbc1M = Ebc1 - Ibc1p \cdot Z1SL$, where Ibc1p is the prefault phase-phase positive sequence current

$Vbc = Ebc - Ibc \cdot Z1SL$

$$Vpol - Vbc = (Ibc - Ibc1p) \cdot Z1SL$$

If there is no load flow the expansion of the Mho characteristic will be equal to the local positive sequence source impedance

5.1.5 Reverse faults

The Mho cross-polarized or positive-sequence polarized characteristics expand for forward faults. However, for reverse faults, they shrink. Let´s see this case for a positive-sequence memory polarized characteristic.

5.1.5.1 <u>Single-phase to ground faults</u>

The positive sequence network and the fault loop for an AG reverse fault can be seen in Figure 20 and Figure 21, respectively.

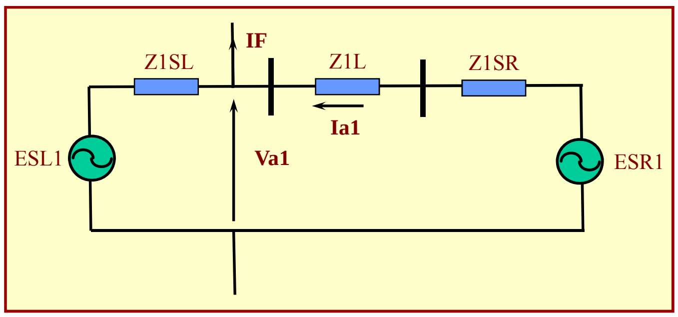


Figure 20. Positive sequence network for a reverse fault

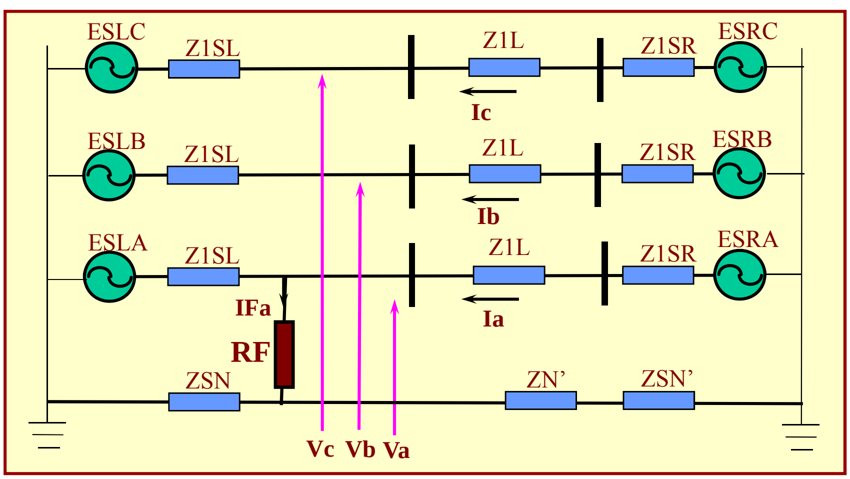


Figure 21. Fault loop for a reverse AG fault

Figure 22 shows the Mho characteristic. The shift experienced is defined by the vector Vpol-Va1. If we consider the circuits in Figure 20 and Figure 21, taking into account the CT polarization we get the following expressions:

$$Va1M = Ea1R + Ia1p \cdot (Z1SR + Z1L)$$
$$Va = EaR + Iaeq \cdot (Z1SR + Z1L)$$

$$Vpol - Va = (Ia1p - Iaeq) \cdot (Z1SR + Z1L)$$

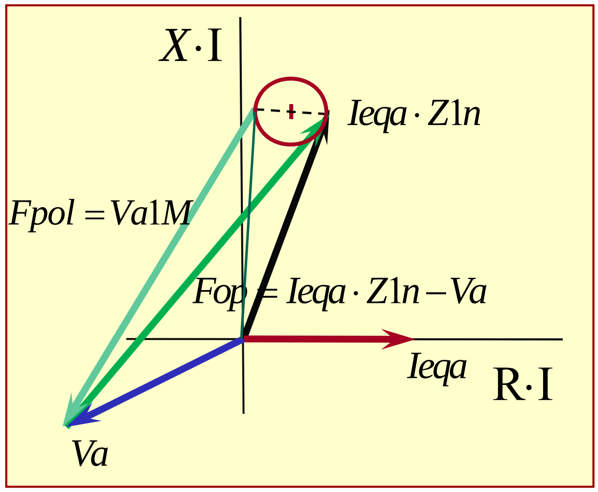


Figure 22. Positive sequence memory polarized AG Mho characteristic for a reverse fault

5.1.5.2 Phase-phase faults

The Mho characteristic is shown in Figure 23. By considering the positive sequence network and the fault loop for a reverse BC fault we get:

$$Vpol - Vbc = (Ibc1p - Ibc) \cdot (Z1SR + Z1L)$$

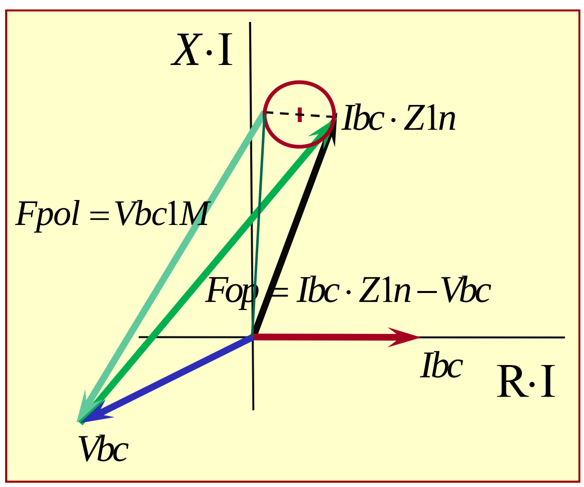


Figure 23. Positive sequence memory polarized BC Mho characteristic for a reverse fault

5.1.6 Mho in the impedance plane

The representation in the impedance plane of the Mho characteristic is achieved by just dividing all the voltages by the reference current (Ieqa for AG faults and Ibc for BC faults). Figure 24 and Figure 25 show the Mho characteristics of Figure 18 and Figure 19, respectively, in the impedance plane.

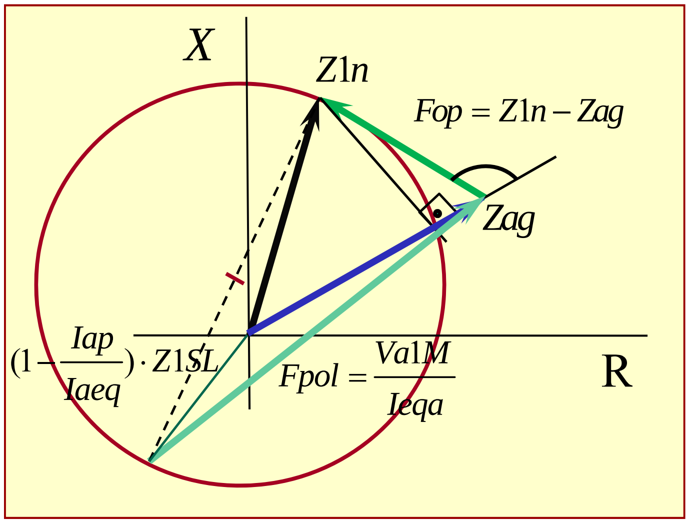


Figure 24. Positive-sequence polarized AG Mho characteristic in the impedance plane

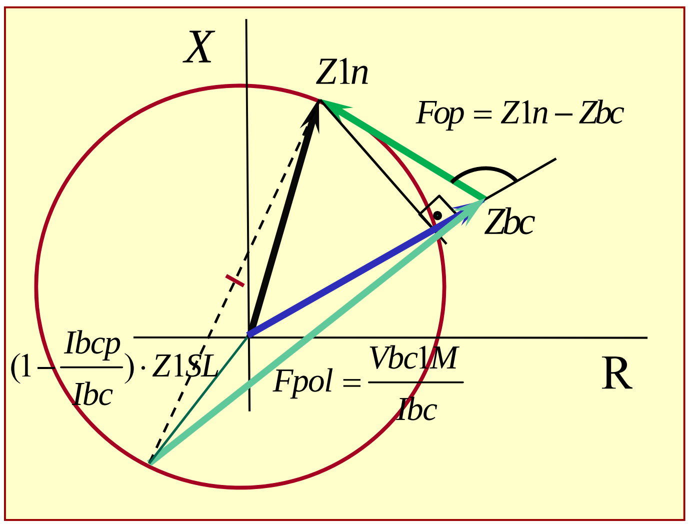


Figure 25. Positive-sequence polarized BC Mho characteristic in the impedance plane

5.2 QUADRILATERAL CHARACTERISTIC

The Mho characteristic offers less resistive coverage than the quadrilateral characteristic. Although a positive-sequence memory polarized Mho characteristic expands for a forward fault increasing the resistive coverage the value offered is not enough for applications in short-lines.

The quadrilateral characteristic is composed by three units (see Figure 26):

- Reactance line
- Directional line
- Resistive limiters

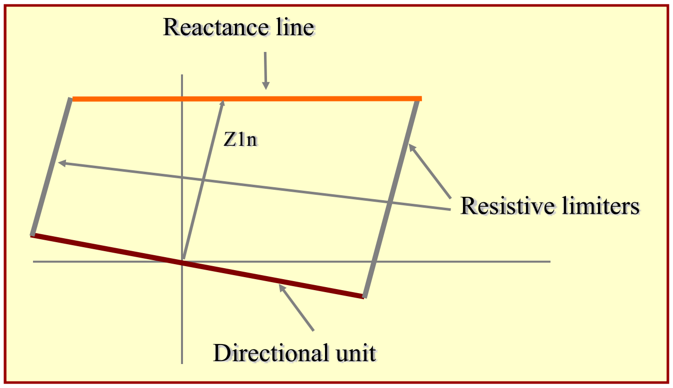


Figure 26. Quadrilateral characteristic

5.2.1 Reactance line

The reactance line is normally implemented with a phase comparator, in a similar way as the Mho characteristic.

The operating voltage is the same as for the Mho characteristic:

$Fop = Ia \cdot Z1n - Va$ for an AG fault

$Fop = Ibc \cdot Z1n - Vbc$ for a BC fault

The polarizing voltage depends on the algorithm:

For an AG fault:

$Fpol = Ia$ phase polarization
$Fpol = I2$ negative sequence polarization
$Fpol = I0$ zero sequence polarization
$Fpol = Ia - Iap$ pure fault phase polarization (Iap is the prefault phase current)

For a BC fault:

$Fpol = Ibc$ phase-phase polarization
$Fpol = Ibc - Ibcp$ pure fault phase-phase polarization (Ibcp is the prefault phase-phase current)

The operating condition is the following: $0^\circ \leq ang(Fop) - ang(Fpol) \leq 180^\circ$

Let´s start with the basic reactance line, the phase-polarized one and see its limitations, which has led to the improved polarizations.

5.2.1.1 <u>Phase polarization</u>

The reactance line is shown in Figure 27. It can be seen that when the angle between the operating and the polarizing phasors is lower than 180º the fault point is below the reactance line.

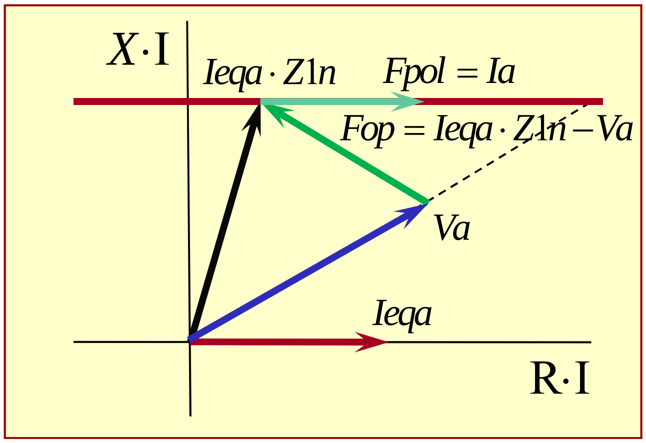


Figure 27. Phase polarized AG reactance line

The polarization phasor, Ia, has been drawn parallel to the equivalent current, $Ieqa = Ia + I0 \cdot (K0 - 1)$, $K0 = \frac{ZL0}{ZL1}$. The angle between Ia and Iaeq depends on the load flow, on the system homogeneity and on the K0 angle. It is normally different from zero.

If there is no load flow and the system is homogeneous Ia and I0 will be parallel, as we will see later. In this case if the K0 angle is zero Ia will be in phase with Iaeq. For an overhead line the K0 angle is normally close to zero; this is not the case for cables.

Load flow effect on phase-polarized reactance line

The phase polarized reactance line can have overreaching and underreaching effects for resistive faults due to the load flow.

Let´s consider the circuit of Figure 9. Due to the load flow, current Ia and Ia' will not be in phase. The angle between the currents can be obtained if we use the superposition principle. The circuit in Figure 9 can be decomposed in two circuits: prefault (subscript "p") and pure fault (subscript "pf"). The fault quantities will be equal to the sum of the corresponding prefault and pure fault quantities.

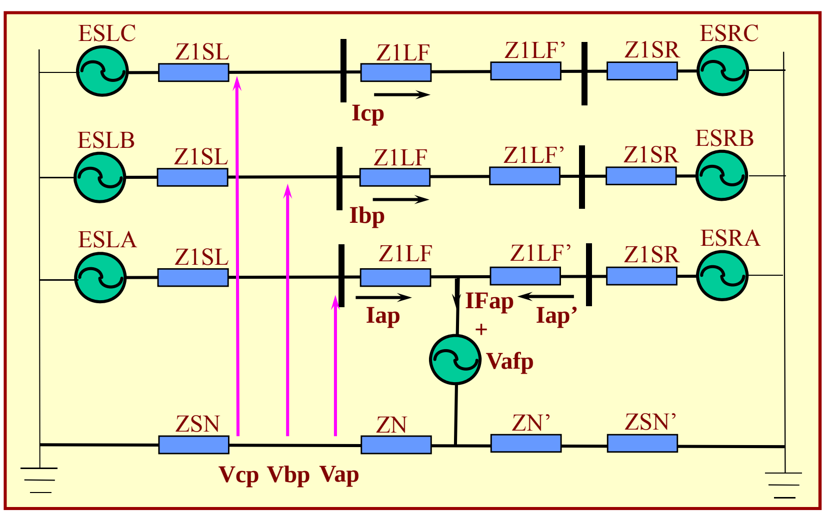


Figure 28. Prefault circuit for an AG fault

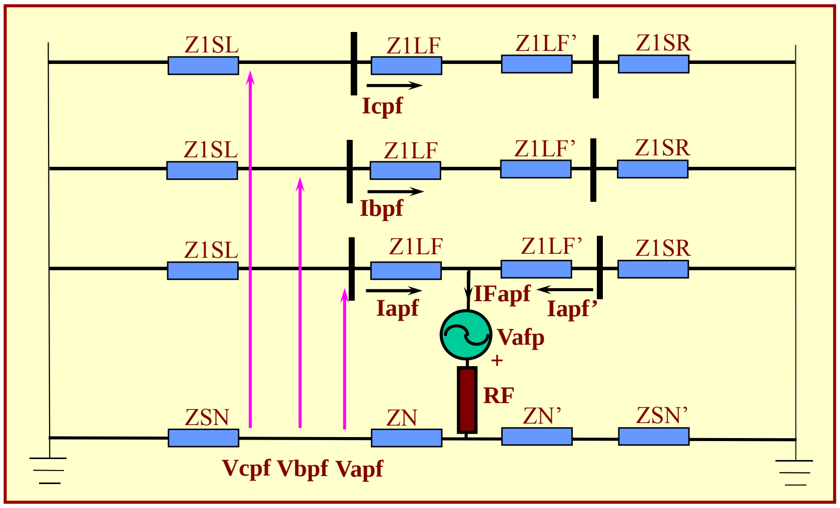


Figure 29. Pure fault circuit for an AG fault

During prefault conditions we assume that IN=0 so IN=Iapf

Defining

$$Z1X = Z1SL + Z1LF$$

$$Z1Y = Z1SR + Z1LF'$$

$$ZNX = ZN + ZNS$$

$$ZNY = ZN' + ZNS'$$

$$Z1T = Z1SL + Z1L + Z1SR$$

Assuming that INp=0, we can calculate Ia=Iap+Iapf and Ia'=Iap'+Iapf'

$$\text{Iap} = \frac{\text{ESLA-ESRA}}{\text{ZT}};\ \text{Iap} = \text{-Iap}' \text{ (we neglect the line capacitances);}$$

$$\text{Vafp} = \text{ESLA} - \text{Iap} \cdot Z1X$$

$$\text{Iapf} = \frac{\text{Vafp}}{\text{Z1X+RF}\cdot(1+\frac{\text{Z1X+ZNX}}{\text{Z1Y+ZNY}})};\ \text{Iapf}' = \frac{\text{Vafp}}{\text{Z1Y+RF}\cdot(1+\frac{\text{Z1Y+ZNY}}{\text{Z1X+ZNX}})}$$

The phasor diagram is shown in Figure 30. It is assumed that the system is homogeneous so Z1X and Z1Y have the same angle.

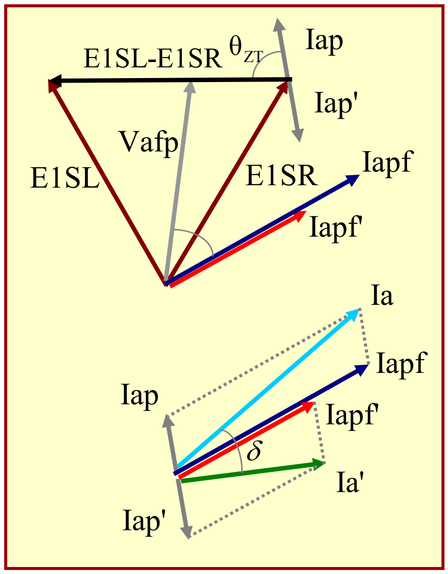
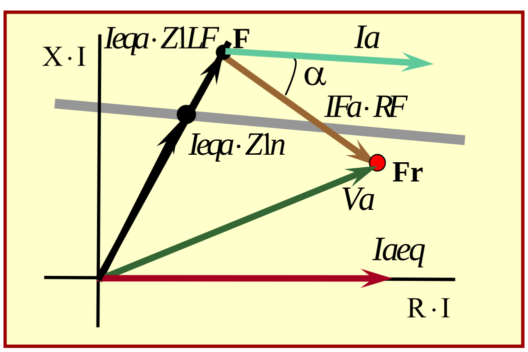


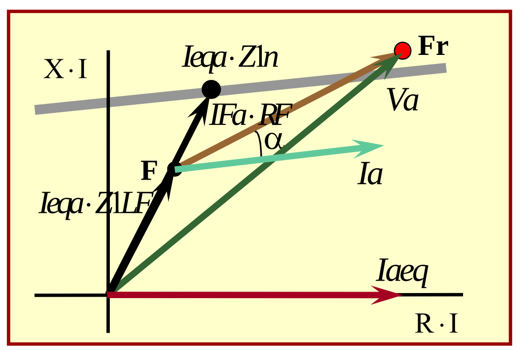
Figure 30. Phasor diagram for Figure 9, Figure 28 and Figure 29

We can see that due to a forward load flow Ia leads Ia', so Ia will lead IFa=Ia+Ia'. If the load flow is reverse E1SR will lead E1SL, so Iap, in Figure 30, will be shifted 180º. In this case Ia' will lead Ia, so Ia will lag IFa.

Going back to Figure 9, we can represent the phase polarized reactance line together with the measured voltage for forward and reverse load flows (Figure 31.a and Figure 31.b, respectively). As it can be seen there is an overreaching effect for forward load and an underreaching effect for reverse load. Note that the reactance line is parallel to the phase current (Ia), not to the equivalent current (Iaeq).



a. Forward load flow



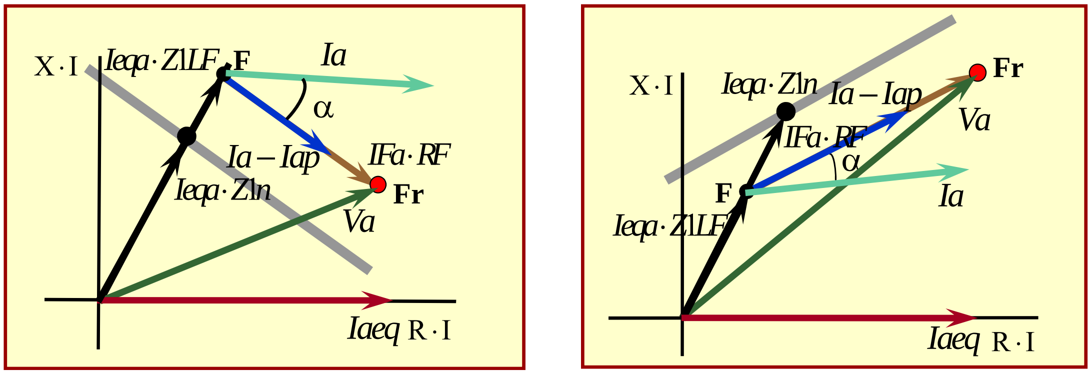
b. Reverse load flow

Figure 31. Phase polarized AG reactance line for a resistive fault with load flow

In order to avoid the latter effects, improved polarizations are used.

5.2.1.2 Pure fault phase polarization

It uses Iapf=Ia-Iap as the polarizing phasor. In the circuit of Figure 29, assuming that Z1X+ZNX and Z1Y+ZNY have the same angle (homogeneous system), Iapf will be in phase with Iapf', so Iapf will be in phase with IFa (IFap=0). The reactance line for forward and reverse load flows is shown in Figure 32.a and Figure 32.b. As it can be seen the overreaching and underreaching effects are removed.



a. Forward load flow b. Reverse load flow

Figure 32. Pure fault phase polarized AG reactance line

5.2.1.3 <u>Negative sequence polarization</u>

Negative sequence polarization has the same effect as the pure fault phase polarization. On the other hand it can be used during a close onto fault, condition where the pure fault phase polarization cannot be applied as there is no prefault current.

If we check the negative sequence network in Figure 6 we can see that I2F=I2+I2’=IFa. If the angle between Z2SL+Z2LF and Z2LF´+Z2SR is zero (homogeneous negative sequence network) I2 and I2’ will be in phase so I2 will be in phase with IFa.

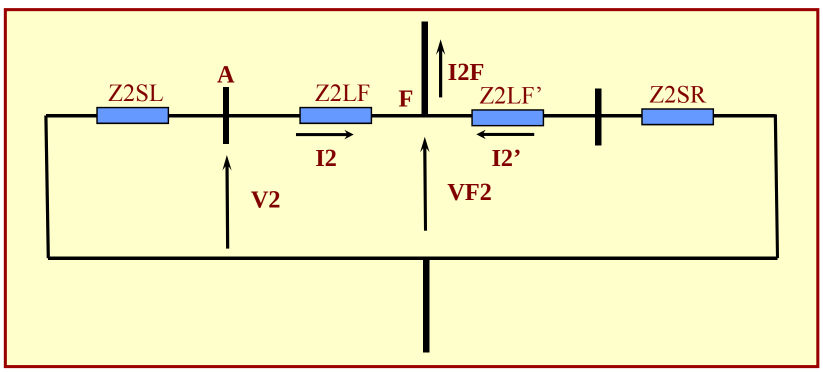


Figure 33. Negative sequence network

5.2.1.4 <u>Zero sequence polarization</u>

Zero sequence polarization is similar to negative sequence polarization. The same deduction done for the negative sequence current can be done for the zero sequence current by taking the zero sequence network of figure 6.

5.2.1.5 <u>Influence of the system non-homogeneity</u>

We have seen before that the pure fault phase current, the negative and the zero sequence currents were parallel to the current flowing through the fault resistance. However this was deduced by taking into account that the system is homogeneous, that is: the angle of Z1X+ZNX is equal to the angle of Z1Y+ZNY (see Figure 29); or the angle of Z2X (Z2SL+Z2LF) is equal to the angle of Z2Y (Z2SR+Z2LF’); or the angle of Z0X (Z0SL+Z0LF) is equal to the angle of Z0Y (Z0SR+Z0LF’). If this condition is not fulfilled, there will be a phase-shift between the polarizing current and the current flowing through the fault resistance.

Normally the negative sequence network is more homogeneous than the zero-sequence network so negative sequence polarization is preferred than zero-sequence polarization and pure fault phase polarization (this involves both the positive sequence network, similar to the negative sequence one, and the zero sequence network, due to the return impedances).

In order to compensate the system non-homogeneity the reactance line normally includes a settable angle that allows tilting it downwards or upwards. The tilt can be performed during a settable time once a fault detector has activated [3].

5.2.1.6 Phase-phase polarization

The reactance line is shown in Figure 34. In this case the reactance line is parallel to the abscissa axis.

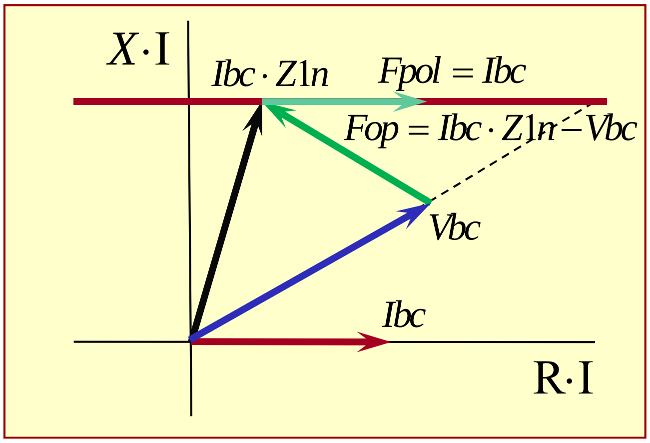


Figure 34. Phase polarized BC reactance line

The same overreaching effects explained for single-phase to ground faults also occur for phase-phase faults. This can be easily deduced by decomposing the circuit of Figure 8 into prefault and pure fault circuits.

5.2.1.7 Pure phase-phase polarization

The pure phase-phase current will be parallel to the phase-phase current that flows through the fault resistance so it avoids the overreaching and underreaching effects caused by the load flow.

Load flow effect on positive sequence memory polarized Mho characteristic

The positive sequence memory polarized Mho characteristic automatically compensates the load flow by rotating in the same direction as the voltage drop in the fault resistance. Figure 35 and Figure 36 show a Mho characteristic for a resistive fault without and with reverse load flow, respectively. The Mho characteristic without load flow is shown in dashed line in Figure 36. As it can be seen, the reverse load flow turns the Mho characteristic anticlockwise (the same direction as the voltage drop in the fault resistance). This is because of the phase-shift in the polarization phasor. Without load flow the positive sequence memory voltage is equal to the local source voltage. For a reverse load flow the first voltage will lead the second one. If the load is forward the positive sequence memory voltage will lag the local source voltage so the Mho characteristic will turn clockwise.

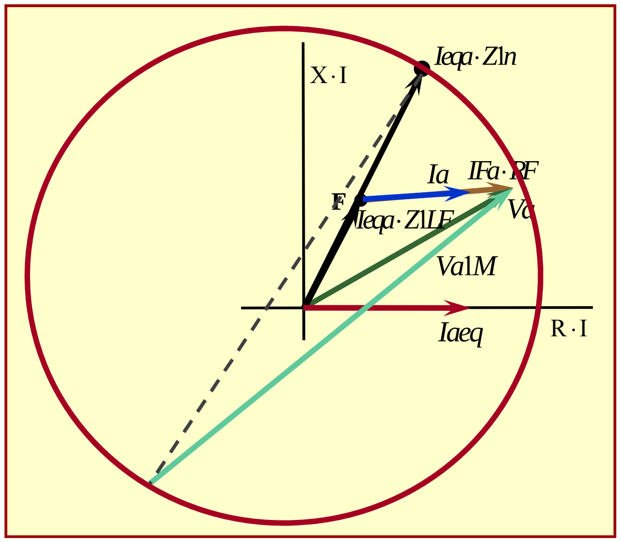


Figure 35. Positive sequence memory polarized AG Mho characteristic for a resistive fault without load flow

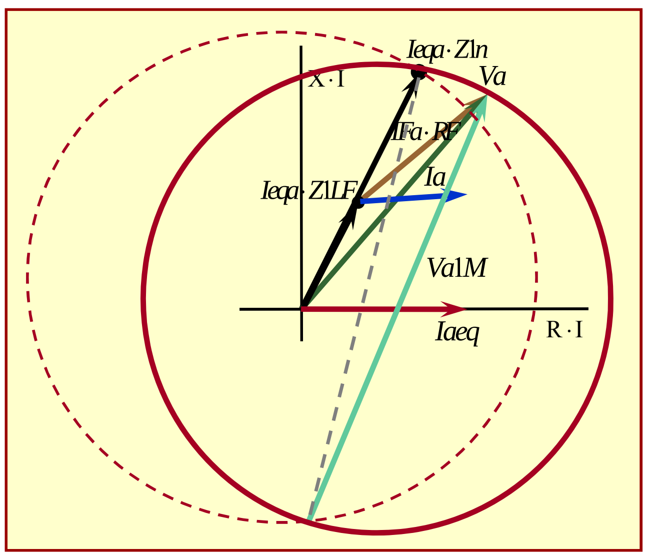


Figure 36. Positive sequence memory polarized AG Mho characteristic for a resistive fault with reverse load flow

5.2.2 Directional line

The directional line is also implemented with a phase comparator. The operating and polarizing phasors vary from one relay to another. We will see the basic self-polarized directional unit and the most common directional units implemented in the new generation relays: positive sequence memory polarized and negative sequence polarized.

5.2.2.1 Self polarized directional unit

Single-phase to ground faults

Let´s consider an AG fault. The polarizing and operating phasors are the following:

$$Fop = Ia$$

$Fpol = Va$

The forward direction will be activated if $-(90^{o} + \alpha) \leq ang(Fop) - ang(Fpol) \leq (90^{o} - \alpha)$, where α is the characteristic angle of the directional unit.

A directional unit is normally represented by taking the polarizing phasor (voltage) as the reference and by varying the operating phasor (current); see Figure 37. In the voltage plane, R*I – X*I, the reference is the current and the quantity that is varied is the voltage. The directional unit of Figure 37 can be converted into the directional line of Figure 38.

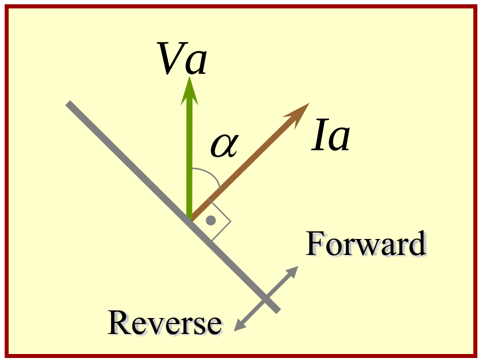


Figure 37. Representation of a directional line with the voltage as the reference

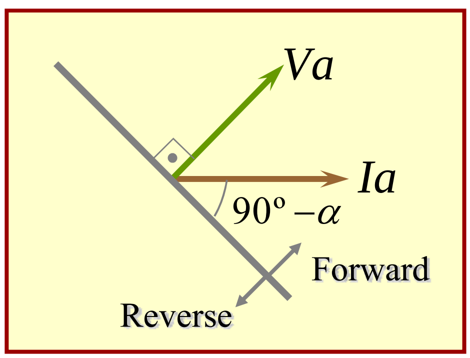


Figure 38 Representation of a directional line with the current as the reference

The self-polarized AG directional line in the R*I-X*I diagram is shown in Figure 39. Note that the angle 90º-α is referred to current Ia instead of current Iaeq.

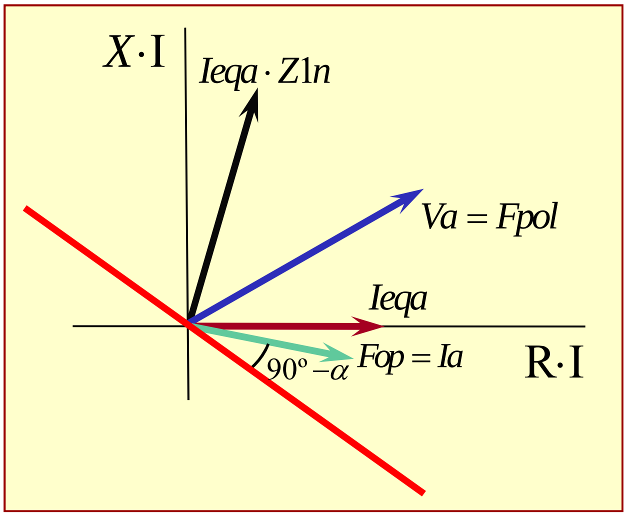


Figure 39- Self polarized AG directional line

Phase-phase faults

Let´s consider a BC fault. The polarizing and operating phasors are the following:

$$Fop = Ibc$$
$$Fpol = Vbc$$

The directional line in the R*I-X*I diagram is shown in Figure 40.

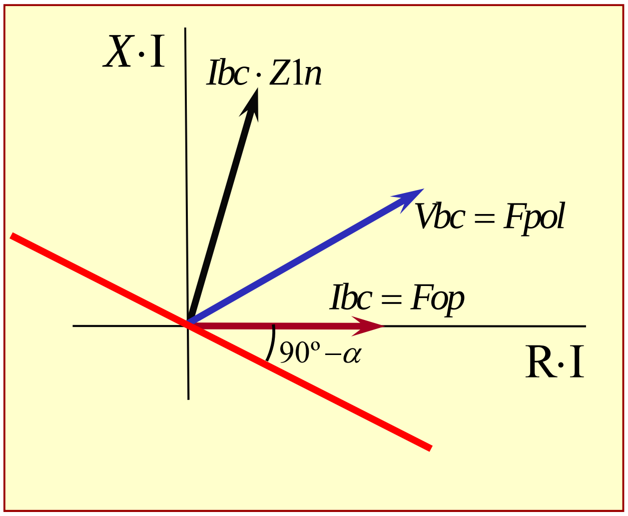


Figure 40- Self polarized BC directional line

The self-polarized directional unit cannot operate for zero-voltage faults. On the other hand it misoperates during voltage inversions in series compensated lines. Therefore, other improved directional units are used.

5.2.2.2 Positive sequence memory directional unit

Single-phase to ground faults

For an AG fault the polarizing phasor is Va1M.

The operating phasor can be Ia1 or Ia. Let´s consider Ia.

How can we represent this directional unit in the voltage plane (R*I-X*I)?:

The directional line has to be below the voltage Va when the fault is forward and above Va when the fault is reverse. As the unit does not use Va but uses Va1M we must use some trick. The directional line will be represented by a line parallel to the self-polarized directional unit but displaced by the vector Va1M-Va, which value has already been obtained for the Mho characteristic.

$Va1M - Va = (Iaeq - Ia1p) \cdot Z1SL$ for a forward fault
$Va1M - Va = (Ia1p - Iaeq) \cdot (Z1L + Z1SR)$ for a reverse fault

The directional line for forward and reverse faults is shown in Figure 41 and Figure 42.

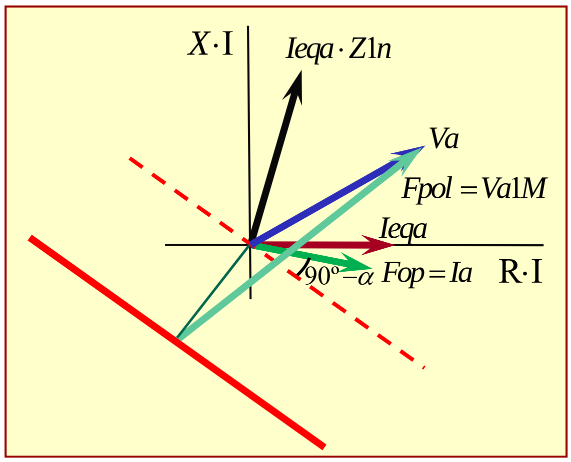


Figure 41. Positive sequence memory polarized AG directional unit for a forward fault

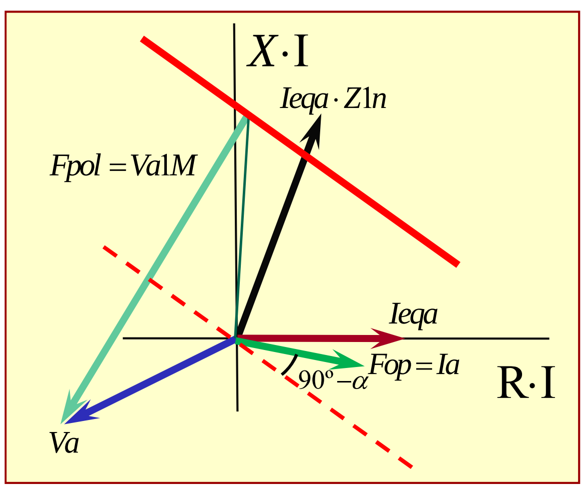


Figure 42. Positive sequence memory polarized AG directional unit for a reverse fault

Let´s check how the directional line works for a voltage inversion in a series compensated line. Figure 43 represents a forward AG fault just after the capacitor (for a configuration with a VT on the bus side of the capacitor bank). The directional line is shown in Figure 45.

Figure 44 represents a bus AG fault for a configuration with a VT on the line side of the capacitor. The directional line is shown in Figure 46.

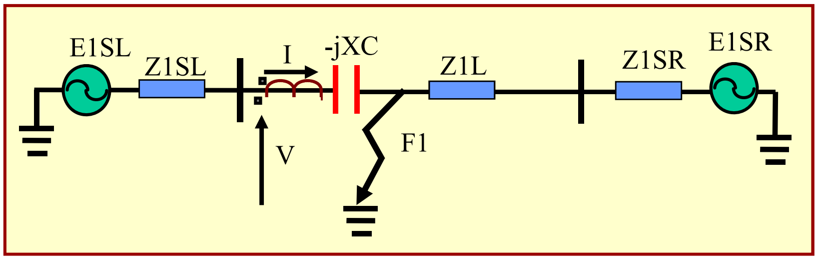


Figure 43. Forward fault on a series-compensated line (VT on the bus side of the capacitor bank)

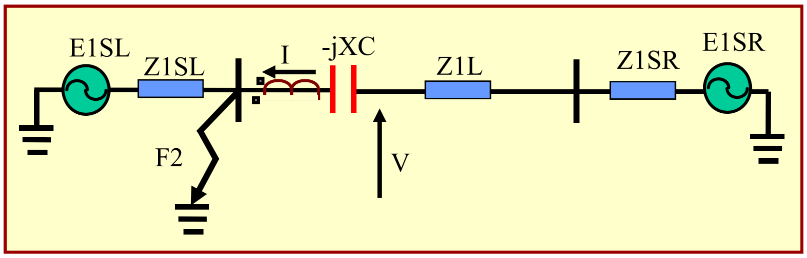


Figure 44. Reverse fault on a series-compensated line (VT on the line side of the capacitor bank)

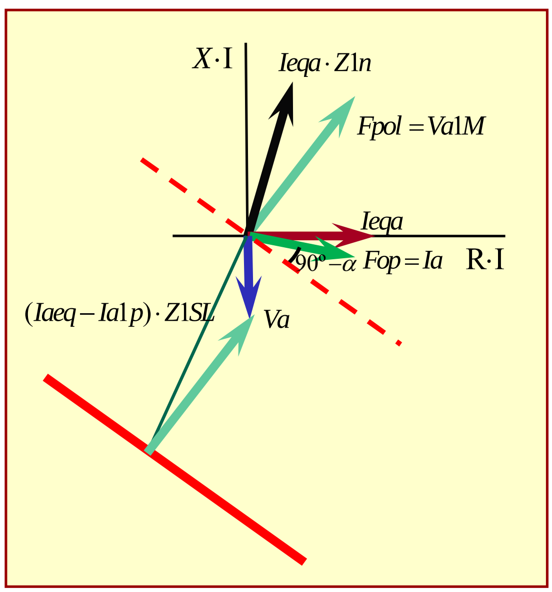


Figure 45. Positive sequence memory polarized AG directional unit for a forward fault on a series compensated line (VT on the bus side of the capacitor bank)

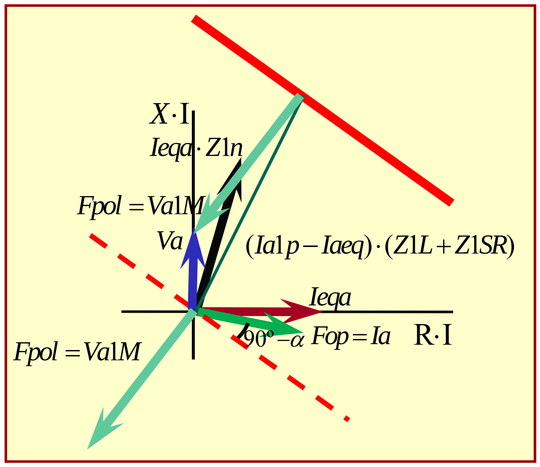


Figure 46. Positive sequence memory polarized AG directional unit for a reverse fault on a series compensated line (VT on the line side of the capacitor bank)

Phase-phase faults

For a BC fault, the polarizing phasor can be Vbc1 or Va1, depending on the algorithm; the operating phasor may be Ibc or Ia1, respectively. Let´s consider Vbc1 and Ibc.

Figure 47 and Figure 48 show the directional unit for forward and reverse faults, respectively. The shift of the directional unit in each case has already been calculated for the Mho characteristic:

$Vbc1M - Vbc = (Ibc - Ibc1p)\cdot Z1SL$ for forward faults

$Vbc1M - Vbc = (Ibc1p - Ibc)\cdot (Z1SR + Z1L)$ for reverse faults

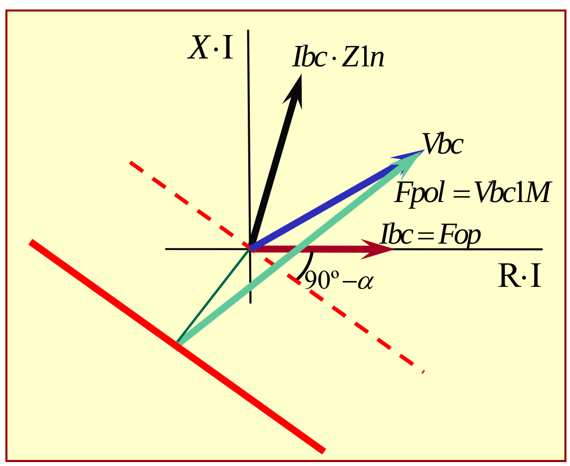


Figure 47. Positive sequence memory polarized BC directional unit for a forward fault

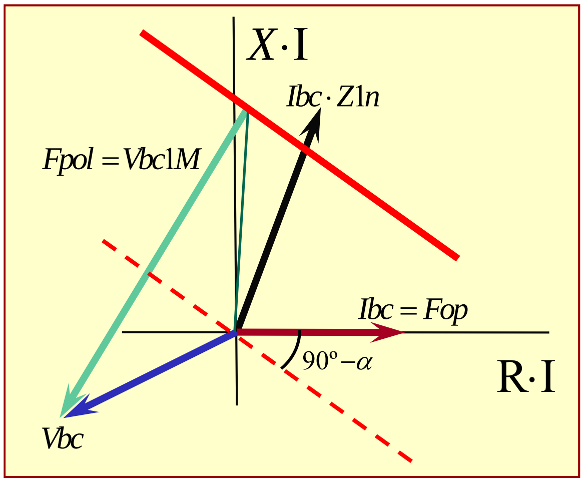


Figure 48. Positive sequence memory polarized BC directional unit for a reverse fault

5.2.2.3 Negative sequence directional unit

The negative sequence directional unit works for both single-phase and phase-phase faults (for three-phase faults it cannot be used) with the following operating and polarizing phasors:

Fop=Ia2
Fpol=-Va2

As the voltage compared against the distance characteristic is Va and the directional unit uses –Va2 the same trick used for the positive sequence directional unit has to be used: define a reference directional line that passes through the origin with an angle equal to 90º-α (α is the directional unit characteristic angle) with regard to Ia2; draw the real directional unit displaced by the vector $(-Va2 - Va)$.

Figure 49 and Figure 50 show the directional unit for a forward and a reverse fault, respectively.

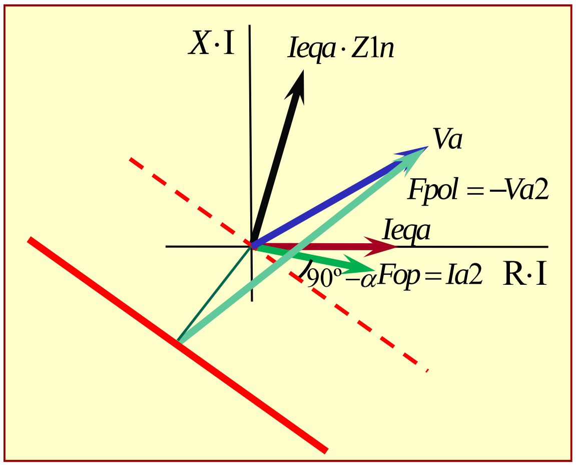


Figure 49. Negative sequence polarized directional unit for a forward AG fault

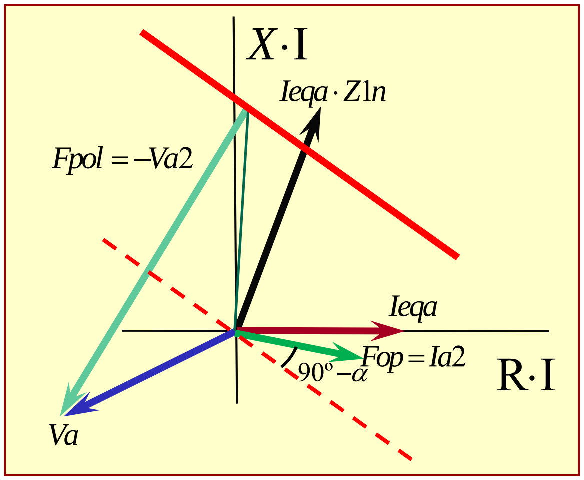


Figure 50. Negative sequence polarized directional unit for a reverse AG fault

5.2.2.4 Compensated negative sequence directional unit

Some relays include a compensated negative sequence directional unit which compensates the polarizing phasor by adding a virtual inductive impedance to the source.

The polarizing phasor is $-V2 + I2 \cdot ZSL2v$ where ZSL2v represents a virtual additional negative sequence impedance in the source. ZSL2v is set only in magnitude as its angle is the same as the existing negative sequence source impedance.

The aim of this additional impedance is:

- Increase the negative sequence voltage magnitude in cases of low source impedance (strong negative sequence networks)
- Invert the negative sequence voltage when this voltage has experienced a voltage reversal. This can occur when there are series capacitors that make the negative sequence source impedance capacitive.

With the aim of not inverting the negative sequence voltage for a reverse fault (in this case the fault will be seen as forward) ZSL2v has to be set lower than ZL2+ZSR2, where ZL2 and ZSR2 are the negative sequence line and remote source impedances [3].

In order to represent this directional unit in the impedance plane we just need to replace voltage –V2 by the voltage $-V2 + I2 \cdot ZSL2v$. Figure 51 and Figure 52 show the compensated directional unit for forward and reverse faults. As it can be seen the directional line has a higher displacement for a forward fault (with regard to the non-compensated unit, see Figure 49) and a lower shift for a reverse fault (with regard to the non-compensated unit, see Figure 50).

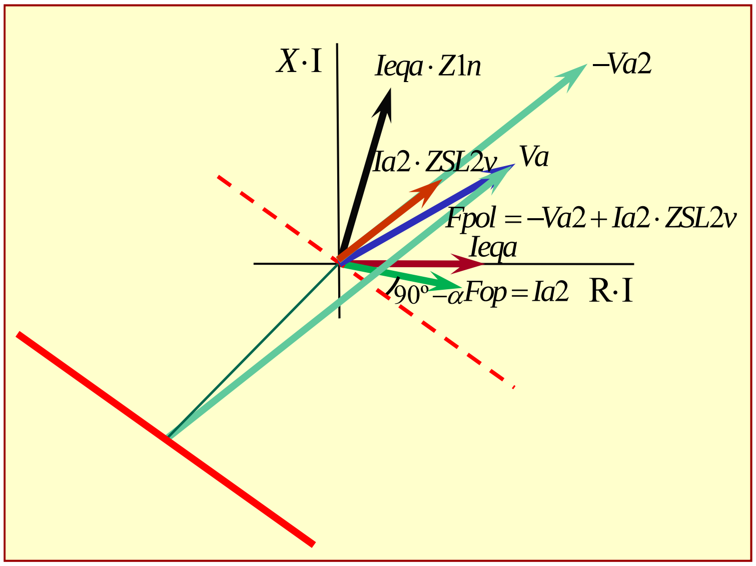


Figure 51. Compensated negative sequence polarized directional unit for a forward AG fault

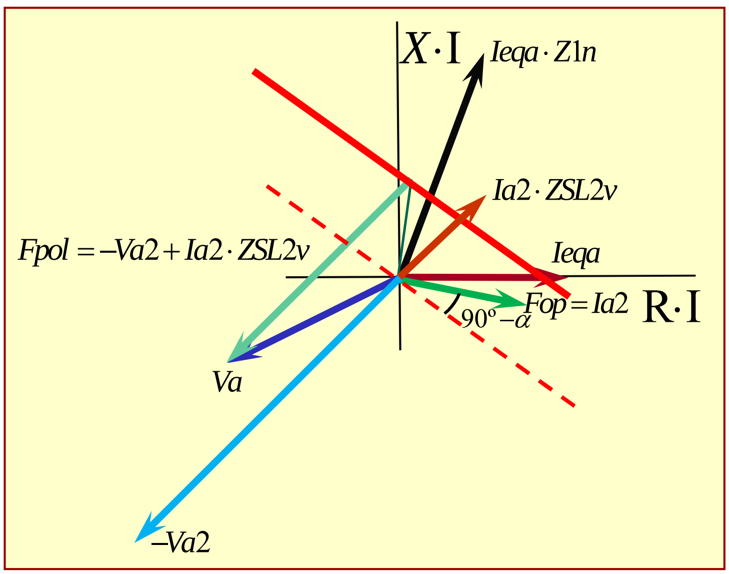


Figure 52. Compensated negative sequence polarized directional unit for a reverse AG fault

5.2.3 Resistive limiters

The resitive limiters are also, normally, implemented with a phase comparator:

5.2.3.1 Single-phase to ground faults

The operating and polarizing phasors can be based on the phase or on the equivalent current, depending on the manufacturer. In the first case the resistive reach will be set in ohms/loop and in the other case it will be set in ohms/phase.

Resistive reach in ohms / loop

The operating and polarizing phasors for an AG fault will be:

$Fop = Ia \cdot RG - Va$
$Fpol = Ia$

The operating condition is: $-(180^{o} - \theta_{loop}) \leq ang(Fop) - ang(Fpol) \leq \theta_{loop}$ where $\theta_{loop} = \theta 1 + [ang(Iaeq) - ang(Ia)]$, $\theta 1$ is the angle of the positive sequence line impedance. Figure 53 shows the resistive limiter for an AG fault.

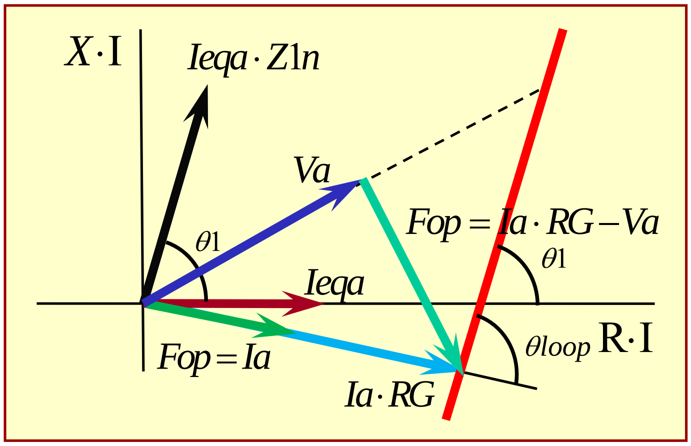


Figure 53. AG Resistive limiter for forward faults set in ohms / loop

Resistive reach in ohms / phase

The operating and polarizing phasors for an AG fault will be:

$Fop = Ieqa \cdot RG - Va$
$Fpol = Ieqa$

The operating condition is: $-(180^{o} - \theta 1) \leq ang(Fop) - ang(Fpol) \leq \theta 1$ where

Figure 54 shows the resistive limiter for an AG fault.

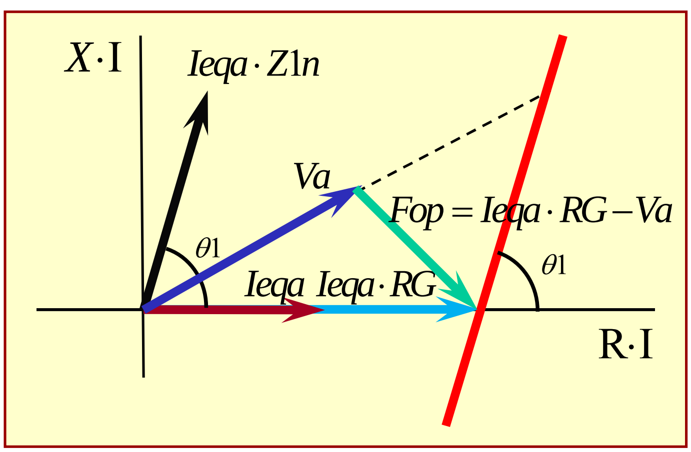


Figure 54. AG Resistive limiter for forward faults set in ohms / phase

Comparison between the two methods

Let´s consider the AG fault loop of Figure 7 without the remote source. In this case the voltage drop in the fault resistance will be Ia*RF.

The first method, which uses Ia*RG, will determine the correct voltage drop (as a vector) so RG would be set based on the real resistance value we want to cover. In this case the fault resistance is treated as a loop resistance (impedance in the fault loop, independent from Z1LF and ZN) and not as a positive sequence resistance.

The second method, which uses Ieqa*RG, will calculate a voltage drop in the fault resistance higher (Iaeq>Ia) than the real one. In this case RG has to be set lower than the real value that is to be covered. The fault resistance is treated the same way as the line impedance, as a positive sequence resistance, because a voltage drop in the return impedance is added.

When the line is a two-source one the voltage drop in the fault resistance will not be equal to Ia*RF neither to Ieqa*RF but equal to (Ia+Ia`)*RF.

It is important to know the method used in order to represent correctly the resistive limiter.

5.2.3.2 Phase-phase faults

The operating and polarizing phasors for a BC fault will be:

$$Fop = Ibc \cdot RP - Va \text{ or } Fop = Ibc \cdot \frac{RP}{2} - Va$$

$$Fpol = Ibc$$

The term RP/2 is used instead of RP because the voltage drop in the fault resistance will be RF/2*IFbc (see Figure 8). When RP/2 is used, the fault resistance is supposed to be set in ohms / loop. If there is no infeed from the remote end, the real resistance value to be covered will be set. When RP is used the fault resistance is set in ohms / phase.

Figure 55 shows a BC resistive limiter for a forward fault set in ohms / phase.

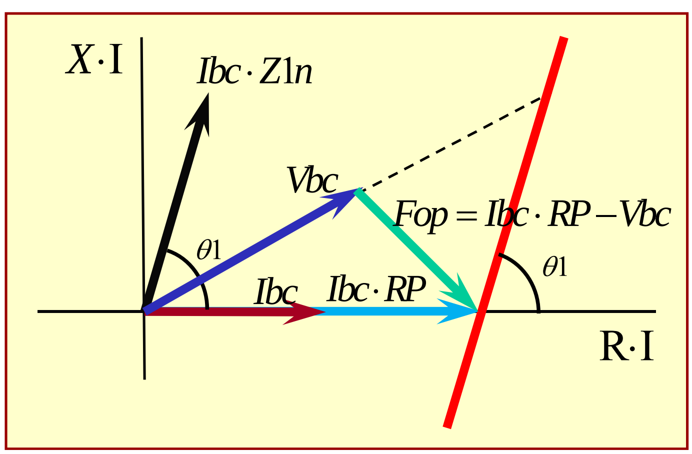


Figure 55. BC Resistive limiter for forward faults set in ohms / phase

5.2.4 Quadrilateral characteristic in the impedance plane

In order to change from the voltage plane to the impedance plane we just need to divide all the phasors by the reference current: Ieqa for AG faults and Ibc for BC faults.

Figure 56 shows an AG quadrilateral characteristic which is composed of a negative sequence polarized reactance line, a positive sequence memory polarized directional unit and a resistive limiter based on ohms / loop.

Figure 57 shows a BC quadrilateral characteristic formed by a pure fault phase-phase polarized reactance line, a positive sequence memory polarized directional unit and a resistive limiter based on ohms / phase.

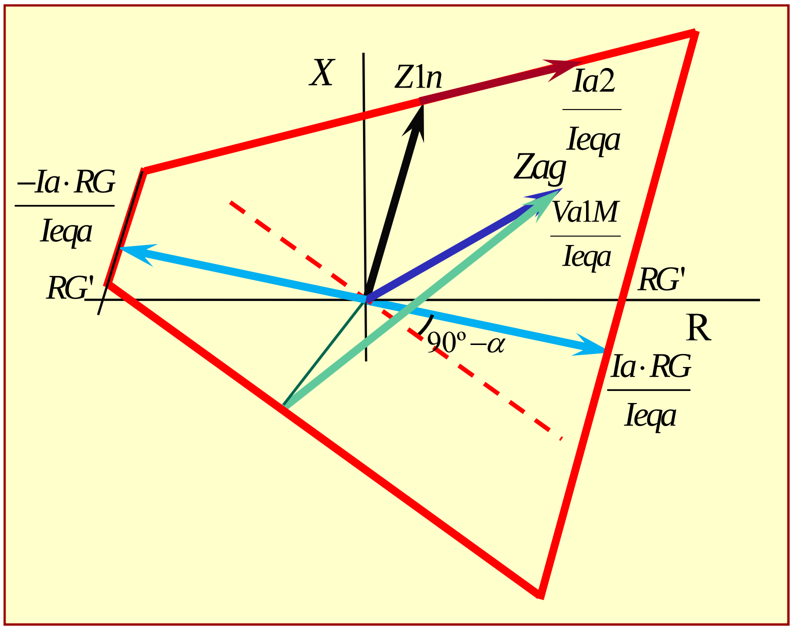


Figure 56. AG quadrilateral characteristic with negative sequence polarized reactance line, positive sequence memory polarized directional line and resistive limiter set in ohms / loop

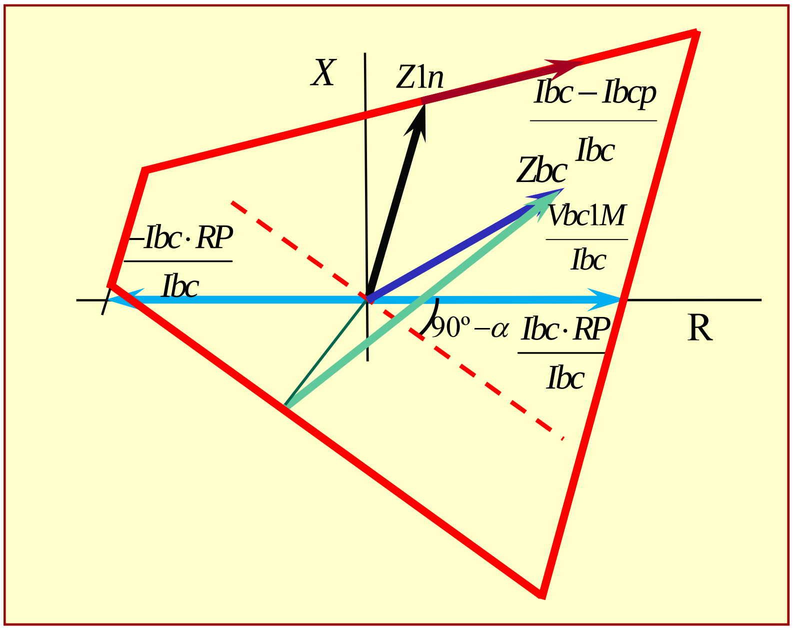


Figure 57. BC Quadrilateral characteristic with pure fault phase-phase polarized reactance line, positive sequence memory polarized directional line and resistive limiter set in ohms / phase

6 TESTING DISTANCE CHARACTERISTICS

6.1 TESTING WITH STATIC CHARACTERISTICS

The dynamic characteristics explained in the latter section have to be considered in order to analyze the behavior of the distance relay for faults taken from real events or generated with a simulation tool. As it was mentioned before the best way to evaluate the operation of the relay is to draw the characteristic in a voltage plane (R*I-X*I). Once this has been done we can easily change to the impedance plane. However, there are some tests which just require a quick check of the characteristic. For example, during commissioning tests it is normally checked that the characteristic works with the downloaded settings. In order to simplify the testing, the operation of the static characteristic is checked avoiding any dynamic behavior. The characteristic is normally tested at different impedance angles. A tolerance band is defined and internal and external faults at the limits of the tolerance band are normally injected checking the tripping times. The following points describe procedures that make the testing unaffected by the dynamic condition of the distance characteristic.

6.1.1 Mho Characteristic

If the polarization phasor is in phase with the voltage phasor used to calculate the positive sequence fault impedance (Vphase for single-phase to ground faults and Vphase-phase for phase-phase faults) the angle between the polarizing and operating phasors of both the self-polarized Mho and a more advanced polarized characteristic will be the same. That means that both characteristics will operate for the same impedance value. Therefore, during the testing, we will not see any difference between both characteristics so the advanced polarized one will behave as a static characteristic.

Figure 58 shows a self-polarized Mho characteristic and a more advanced polarized Mho characteristic for an AG fault in which Va is in phase with Fpol. As it can be seen Va is in the border of both characteristics.

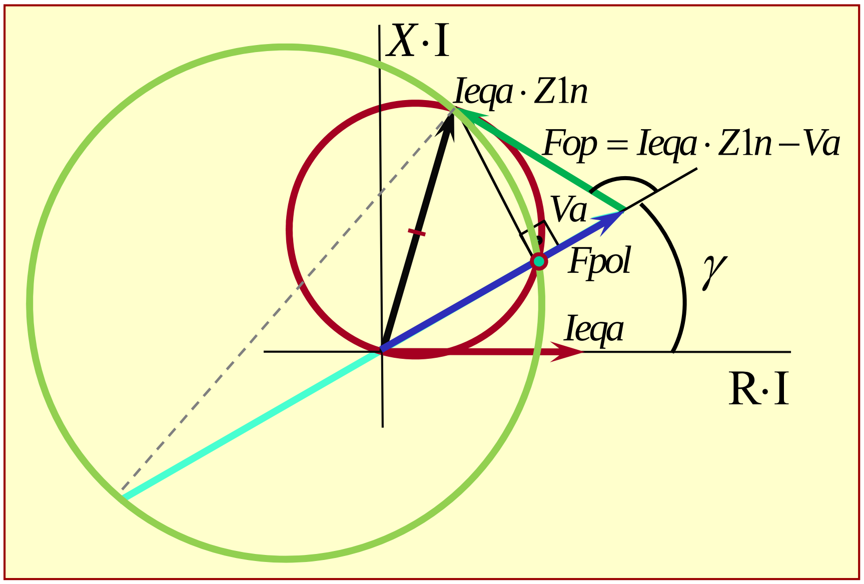


Figure 58. AG Self-polarized and other AG advanced polarized Mho characteristic with Va in phase with the polarization phasor

Let´s see the voltages and currents that should be injected to a distance relay in order to make Fpol in phase with V for a positive sequence memory polarized Mho characteristic.

6.1.1.1 Single phase to ground faults

With the aim that Va1M is in phase with Va, the angle of the faulted voltage is not changed from prefault to fault. In this case both Va1 and Va1M will be in phase with Va.

Let´s consider the following Mho characteristic:

$$Z1 = 3_{75^\circ}$$

$$K0 = \frac{ZL0}{ZL1} = 3_{0^\circ}$$

The prefault and fault values for a 30º impedance that makes the characteristic trip are shown in Figure 59. As it can be seen Va1M is in phase with Va1 and Va. The self polarized and positive sequence memory polarized Mho characteristics are shown in Figure 60. As it can be observed Va is in the limit of both characteristics (cutting point of both circles).

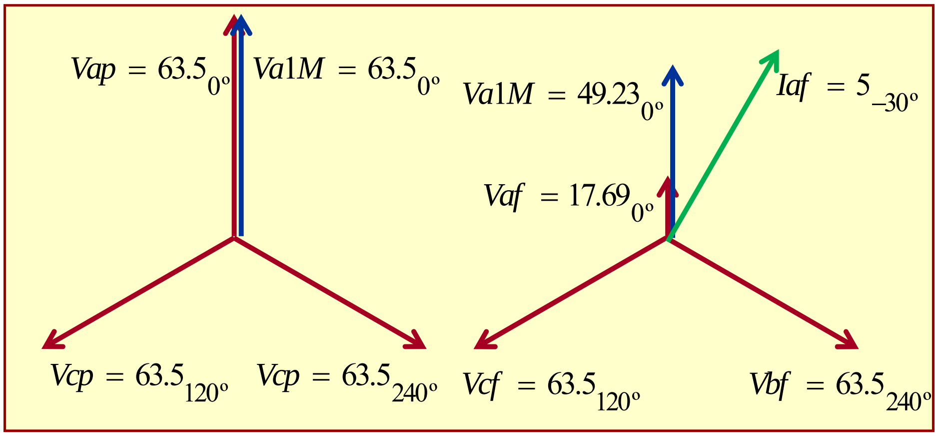


Figure 59. Prefault and fault voltages and currents for a 30º AG impedance

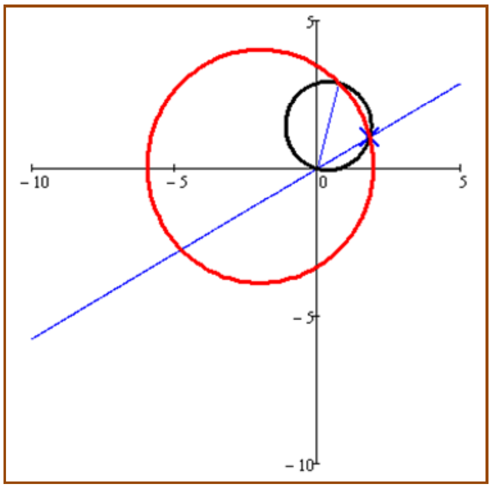


Figure 60. AG Self-polarized (black) and positive sequence memory polarized (red) Mho characteristics

6.1.1.2 Phase-phase faults

For phase-phase faults the sum of the faulted voltages will be forced to be 180º with regard to the healthy voltage. Let´s consider a BC fault. The prefault and fault values for a 30º impedance that makes the characteristic trip are shown in Figure 61. As it can be seen Vbc1M is in phase with Vbc1 and Vbc. The self polarized and positive sequence memory polarized Mho characteristics are shown in Figure 62. Again, it can be seen that Vbc is in the limit of both characteristics.

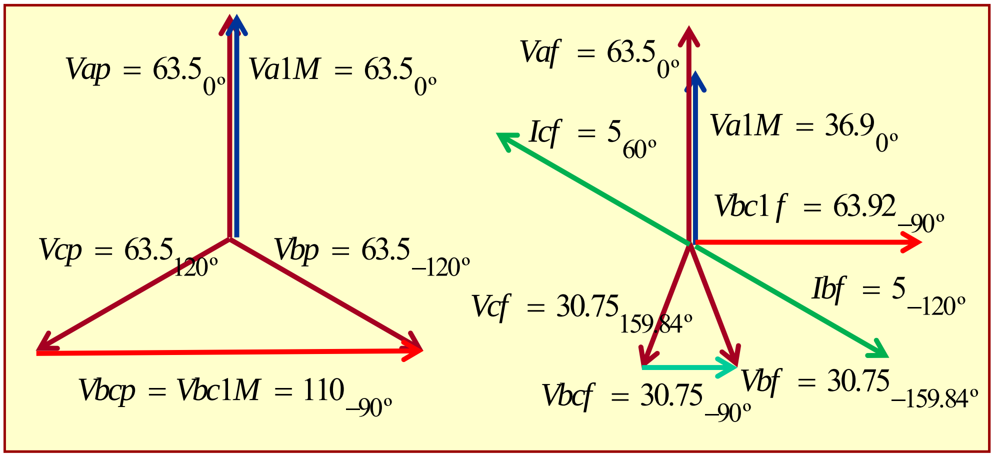


Figure 61. Prefault and fault voltages and currents for a 30º BC impedance

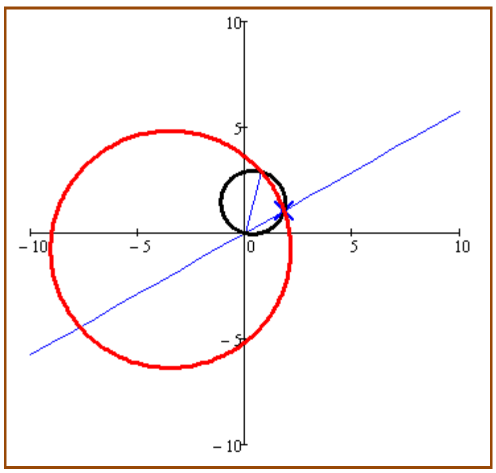


Figure 62. BC Self-polarized (black) and positive sequence memory polarized (red) Mho characteristics

6.1.2 Quadrilateral Characteristic

6.1.2.1 Reactance line

With the aim that a reactance line with load flow compensation does not tilt, the load current must be zero.

Single-phase to ground fault

Let´s consider an AG fault for a negative sequence polarized reactance line. As the currents in the healthy phases will be zero: Ia2=Ia/3. As the reference current will be Iaeq, the reactance line will have an angle with regard to the abscissas axis equal to ang(Ia) - ang(Iaeq).

Phase-phase fault

Let´s consider a BC pure fault phase-phase polarized reactance line. As there is no prefault current Ibc-Ibcp=Ibc. The reactance line will be parallel to the abscissas axis.

6.1.2.2 Directional line

The same strategy applied for the Mho characteristic is used with the directional line: the polarization phasor is in phase with the measured voltage. The result of the testing is that the directional unit will behave as a static line.

The system of voltages and currents described in 6.1.1 also make –V2, inverted negative sequence voltage, in phase with voltage Va (for an AG fault) and voltage Vbc (for a BC fault), making the negative sequence directional unit behave as the phase polarized directional unit.

6.1.2.3 Resistive limit

Single-phase to ground fault

In most of the programs that automatically test distance relays the reference current for the impedance diagram is the equivalent current. In order to build the characteristic in the impedance plane we need to know the resistive reach in the abscissas axis (RG' in Figure 56), so the ohms / phase.

During a simplified testing, as there is no current in the healthy phases:

$Ieqa = Ia + I0 \cdot (K0 - 1)$, $K0 = \frac{ZL0}{ZL1}$, can be simplified as $Ieqa = Ia \cdot [1 + \frac{1}{3} \cdot (K0 - 1)]$

RG' can be obtained from RG (value set in the relay) with the following formula:

$RG' = \frac{RG \cdot |k|}{\sin[\pi - ang(Z1n)]} \cdot \sin[ang(Z1n) - ang(k)]$ (5) , where $k = \frac{1}{1 + \frac{1}{3} \cdot (K0 - 1)}$

Phase-phase fault

As the reference current in most of the testing programs is $I_{phase\text{-}phase}$ no conversion has to be done for the phase-phase resistive reach.

6.2 TESTING WITH DYNAMIC CHARACTERISTICS

6.2.1 Mho characteristic

6.2.1.1 Single-phase to ground faults

Let´s consider the Mho characteristic of point 6.1.1.1. If we want to test its expansion we just have to introduce a phase-shift between Va prefault (Vap) and Va fault (Vaf). Figure 63 shows the static and dynamic characteristics if we apply a 20º phase shift for a 30º impedance. As we can see Va is on the limit of the static characteristic but is not on the limit of the dynamic one. The voltage Va magnitude for the static characteristic operation will be 17.67 V and for the dynamic one 24.11 V.

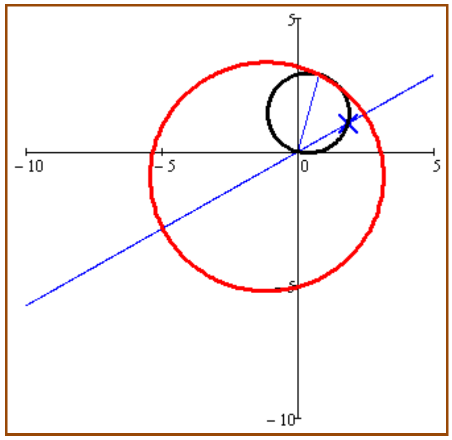


Figure 63. AG Self-polarized (black) and positive sequence memory polarized (red) Mho characteristics for a 30º impedance with a 20º phase-shift between Vap and Vaf

Table 1 shows values for prefault and fault voltages and currents for the operation of the AG static and AG dynamic Mho characteristics for different impedance angles. Table 2 shows similar values for a BC unit.

Impedance angle	Prefault values	Fault values for static Mho operation	Fault values for dynamic Mho operation
10º	Va=63.5 $_{0º}$ Vb=63.5 $_{-120º}$ Vc=63.5 $_{120º}$ Ia=Ib=Ic=0	Va=10.56 $_{-20º}$ Vb=63.5 $_{-120º}$ Vc=63.5 $_{120º}$ Ia=5 $_{-30º}$ Ib=Ic=0	Va=18.81 $_{-20º}$ Vb=63.5 $_{-120º}$ Vc=63.5 $_{120º}$ Ia=5 $_{-30º}$ Ib=Ic=0
30º	Va=63.5 $_{0º}$ Vb=63.5 $_{-120º}$ Vc=63.5 $_{120º}$ Ia=Ib=Ic=0	Va=17.67 $_{-20º}$ Vb=63.5 $_{-120º}$ Vc=63.5 $_{120º}$ Ia=5 $_{-50º}$ Ib=Ic=0	Va=24.11 $_{-20º}$ Vb=63.5 $_{-120º}$ Vc=63.5 $_{120º}$ Ia=5 $_{-50º}$ Ib=Ic=0
50º	Va=63.5 $_{0º}$ Vb=63.5 $_{-120º}$ Vc=63.5 $_{120º}$ Ia=Ib=Ic=0	Va=22.65 $_{-20º}$ Vb=63.5 $_{-120º}$ Vc=63.5 $_{120º}$ Ia=5 $_{-70º}$ Ib=Ic=0	Va=26.5 $_{-20º}$ Vb=63.5 $_{-120º}$ Vc=63.5 $_{120º}$ Ia=5 $_{-70º}$ Ib=Ic=0

Table 1. Voltage and current values for the operation of an AG self-polarized Mho characteristic (static one) and an AG positive-sequence memory polarized Mho characteristic (dynamic one)

Impedance angle	Prefault values	Fault values for static Mho operation	Fault values for dynamic Mho operation
10º	Va=63.5 $_{0°}$ Vb=63.5 $_{-120°}$ Vc=63.5 $_{120°}$ Ia=Ib=Ic=0	Va=63.5 $_{0°}$ Vb=29.56 $_{-187.61°}$ Vc=29.56 $_{147.61°}$ Ia=0 Ib=5 $_{-120°}$ Ic=5 $_{60°}$	Va=63.5 $_{0°}$ Vb=52.6 $_{-187.61°}$ Vc=52.6 $_{147.61°}$ Ia=0 Ib=5 $_{-120°}$ Ic=5 $_{60°}$
30º	Va=63.5 $_{0°}$ Vb=63.5 $_{-120°}$ Vc=63.5 $_{120°}$ Ia=Ib=Ic=0	Va=63.5 $_{0°}$ Vb=30.75 $_{-179.84°}$ Vc=30.75 $_{139.84°}$ Ia=0 Ib=5 $_{-140°}$ Ic=5 $_{40°}$	Va=23.53 $_{-20°}$ Vb=41.97 $_{-179.84°}$ Vc=41.97 $_{139.84°}$ Ia=0 Ib=5 $_{-140°}$ Ic=5 $_{40°}$
50º	Va=63.5 $_{0°}$ Vb=63.5 $_{-120°}$ Vc=63.5 $_{120°}$ Ia=Ib=Ic=0	Va=63.5 $_{0°}$ Vb=31.91 $_{-174.78°}$ Vc=31.91 $_{134.78°}$ Ia=0 Ib=5 $_{-160°}$ Ic=5 $_{20°}$	Va=63.5 $_{0°}$ Vb=37.3 $_{-174.78°}$ Vc=37.3 $_{134.78°}$ Ia=0 Ib=5 $_{-160°}$ Ic=5 $_{20°}$

Table 2. Voltage and current values for the operation of a BC self-polarized Mho characteristic (static one) and a BC positive-sequence memory polarized Mho characteristic (dynamic one)

These tests can only be done if:

- The memory voltage duration is enough: most of the relays limit the memory voltage duration to prevent erroneous operation during frequency excursions [4]. If the relay includes a setting for memory voltage time it should be fixed to its maximum value.

- The use of memory voltage is enabled: when the relay is not applied to a series compensated line the memory voltage is only used when the fault voltage is below a certain threshold. The setting indicating that the relay is going to be applied to a series compensated line can be a good choice to make the memory voltage be used independently of the voltage magnitude.

It has to be taken into account that when the memory voltage expires the positive-sequence polarized Mho characteristic is going to maintain expanded (not as much as with the memory voltage) because of the positive-sequence voltage effect.

6.2.2 Quadrilateral characteristic

Let´s consider the following ground characteristic:

$Z1 = 3_{75°}$

$K0 = \frac{ZL0}{ZL1} = 3_{-5°}$

$RG = 15$ ohms / loop

$\alpha = 75º$ (directional characteristic angle)

6.2.2.1 Reactance line

If we don´t inject any load flow, the operating values for a 30º impedance are the following:

Vap=63.5 $_{0^\circ}$; Vbp=63.5 $_{-120^\circ}$; Vcp=63.5 $_{120^\circ}$

Iap=Ibp=Icp=0

Vaf=19.54 $_{0^\circ}$; Vbp=63.5 $_{-120^\circ}$; Vcp=63.5 $_{120^\circ}$

Iaf=2 $_{-30^\circ}$; Ibf=Icf=0

The behavior of the reactance line can be seen in Figure 64.a

If we inject a reverse load flow, the operating values for a 30º impedance will be:

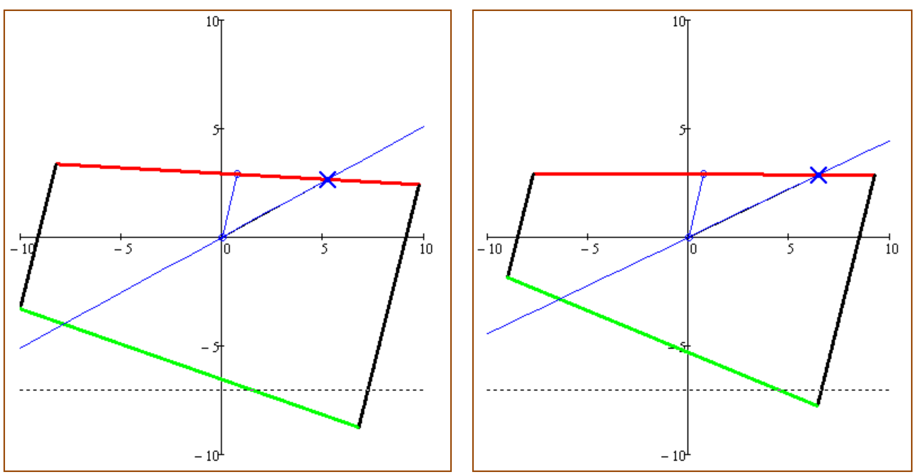
Vap=63.5 $_{0^\circ}$; Vbp=63.5 $_{-120^\circ}$; Vcp=63.5 $_{120^\circ}$

Iap=0.5 $_{-180^\circ}$; Ibp=0.5 $_{60^\circ}$; Icp=0.5 $_{-60^\circ}$

Vaf=25.6 $_{0^\circ}$; Vbp=63.5 $_{-120^\circ}$; Vcp=63.5 $_{120^\circ}$

Iaf=2 $_{-30^\circ}$; Ibp=0.5 $_{60^\circ}$; Icp=0.5 $_{-60^\circ}$

The behavior of the reactance line can be seen in Figure 64.b



a. Without load flow b. With reverse load flow

Figure 64. Reactance line for an AG fault

6.2.2.2 Directional line

If we inject a -18º impedance with a 20º phase shift between prefault and fault:

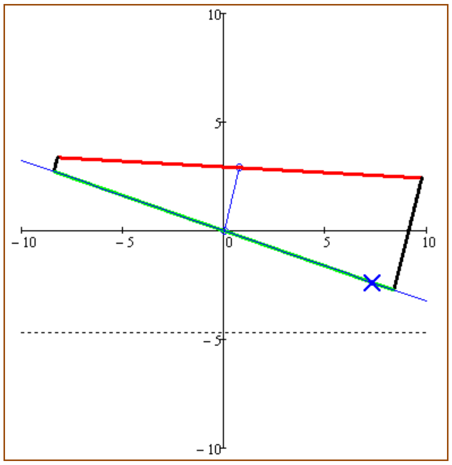
Vap=63.5 $_{0^\circ}$; Vbp=63.5 $_{-120^\circ}$; Vcp=63.5 $_{120^\circ}$

Iap=Ibp=Icp=0

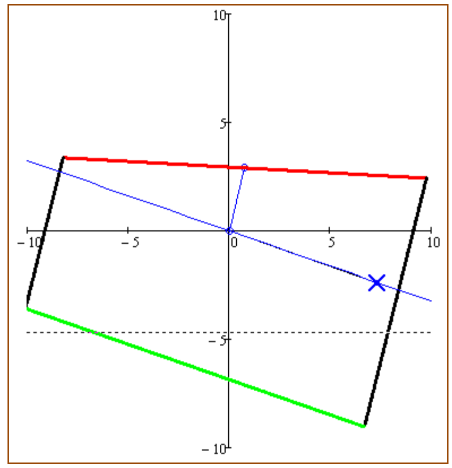
Vaf=25.6 $_{-20^\circ}$; Vbp=63.5 $_{-140^\circ}$; Vcp=63.5 $_{100^\circ}$

Iaf=2 $_{-30^\circ}$; Ibp=Icp=0

A self-polarized directional unit will see the fault in the limit of the directional unit (see Figure 65.a); a positive sequence memory polarized directional unit will see the fault as forward.



a. Self-polarized



b. Positive sequence memory polarized

Figure 65. **Directional unit for an AG fault**

7 REAL CASES EXPERIENCED

7.1 MHO CHARACTERISTIC TRIP FOR A BROKEN CONDUCTOR

Figure 66 shows a very simplified scheme of the network involved in the event. It is a radial network with just one source at station A.

The phase A conductor of the line A-B broke and touched the line creating a high impedance fault that was cleared by the ground overcurrent unit of the relay A. The relay in B, protecting the line B-C, tripped erroneously.

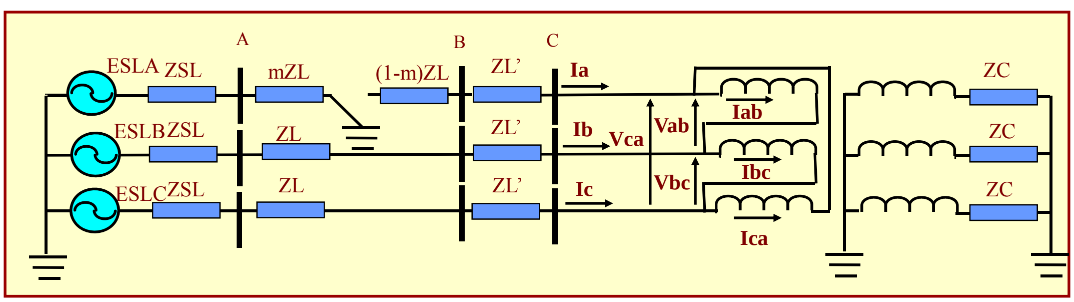


Figure 66. Simplified scheme of the network

Figure 67 shows the voltage and currents measured by the distance relay at the end B of the line B-C. The tripping instant is shown with a dashed line.

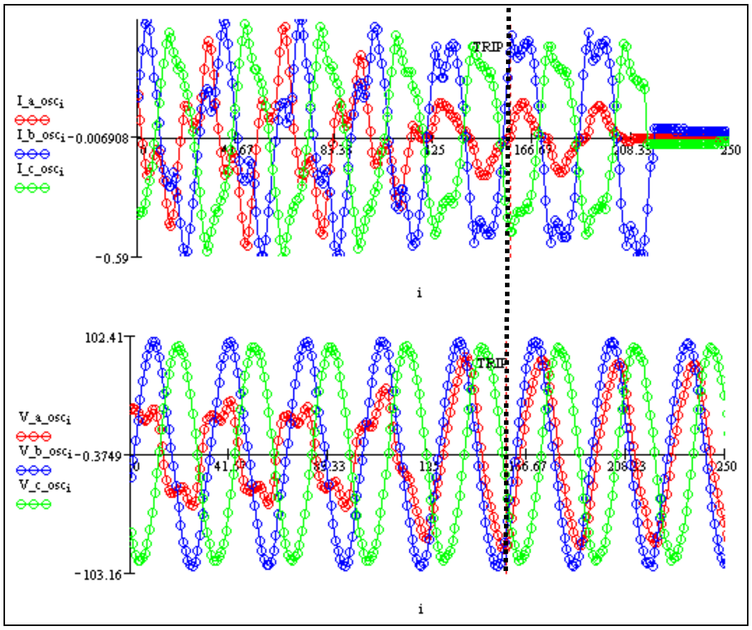


Figure 67. Voltages and currents measured by the distance relay at end B of the line BC

As it can be observed, at the tripping instant, the voltage in phase A is slightly leading voltage B, so it has experienced a phase-shift larger than 120º. The voltage system that appears is due to the presence of a delta-wye transformer connected to substation C. The breakage of the conductor in phase A isolates this phase, theoretically making zero the current in that phase. If Ia=0, the currents inside the delta Iab and Ica will be equal which will make Vab and Vca to be equal as well. As Vab+Vbc+Vca=0 then Vbc=-2Vab. Vb and Vc have the same relation as before the breakage of the conductor, 120º phase-shift, so Va will be 60º phase-shifted with regard to Vb and Vc and its magnitude will be Vb/2. The resulting voltage system is shown in Figure 68. During the event, the currents were very low and there was no significant negative sequence current so the phase selector (unit in charge of detecting the type of fault, based on the angle between the negative sequence and pure fault positive sequence currents [3]) considered the fault as three-phase, using the three phase-phase units: AB, BC and CA. As the minimum phase-phase current required for distance units to operate was set at the minimum value the phase-phase units had trip permission. The type of characteristic set for phase-phase faults was Mho, which used positive sequence polarization. The voltage system created a phase shift between Vab and Vab1 which caused a big expansion of the zone 1 AB characteristic (see Figure 69)

Note that the memory voltage was not used in this case because the AB voltage was above the setting.

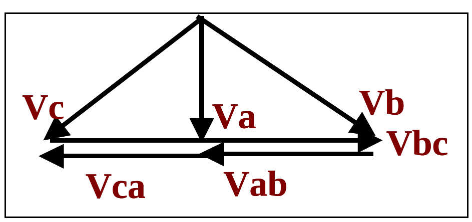


Figure 68. Voltage system

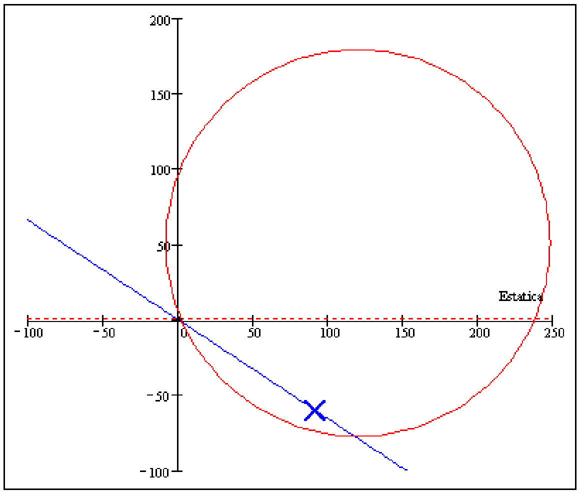


Figure 69. Positive sequence polarized AB Mho characteristic and AB impedance measured

The following solutions were given:

- Increase the minimum current for distance zones operation
- Use of a quadrilateral characteristic: the resistive limiters would have avoided the impedance to enter the characteristic.

7.2 MHO CHARACTERISTIC TRIP FOR A MANUAL CLOSE WITHOUT SYNCHROCHECK

A part of a distribution network was islanded. The reconnection was done manually from a 132 kV line without any synchrocheck supervision with a high phase-shift between the island and the network. The currents and voltages measured are shown in Figure 70.

The connection of both systems created a high phase-shift between prefault and “fault” voltages. The phase-phase characteristic was a positive-sequence memory polarized Mho characteristic. Due to the memory action there was a big expansion of the BC Mho characteristic that made it trip. The solution given was reducing the minimum voltage for the memory usage.

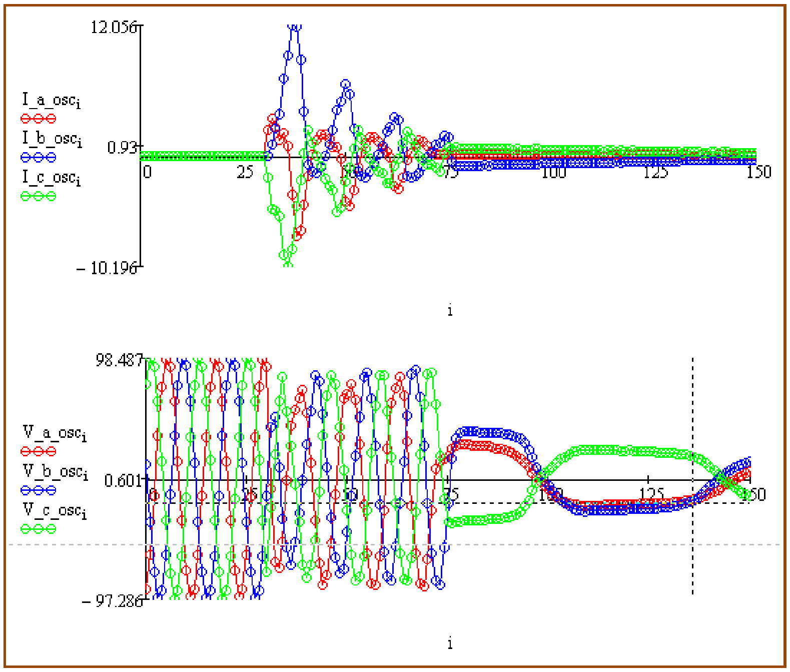


Figure 70. Voltages and currents measured

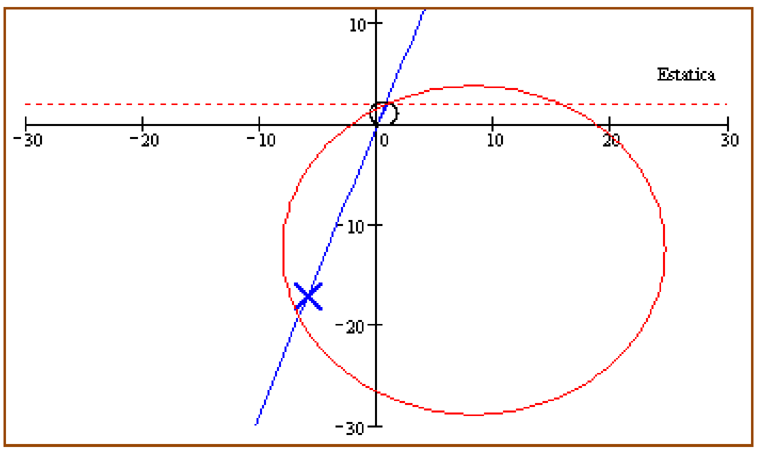


Figura 1. BC Zone 1 Mho characteristic

7.3 ERRONEOUS CONCEPT OF THE POSITIVE-SEQUENCE MEMORY DIRECTIONAL UNIT

A customer called telling that the quadrilateral characteristic was tripping for a reverse AG fault during a testing. The directional unit used was a positive sequence memory polarized one.

The zone 1 settings were:

$Z1=7.11_{79°}$
$Z0=3.25*7.11_{73°}$
RG=21 ohms / loop
α=75º (characteristic angle of the directional unit)

The voltages and currents injected were:

Prefault:

Vap=63.5_{0°
Vbp=63.5_{-120°
Vcp=63.5_{240°
Iap=Ibp=Icp=0

Fault:

Vaf=10_{0°
Vbf=63.5_{-120°
Vcf=63.5_{240°
Iaf=5_{-165°

The AG characteristic and impedance are shown in Figure 71. As it can be seen the impedance is inside the quadrilateral characteristic.

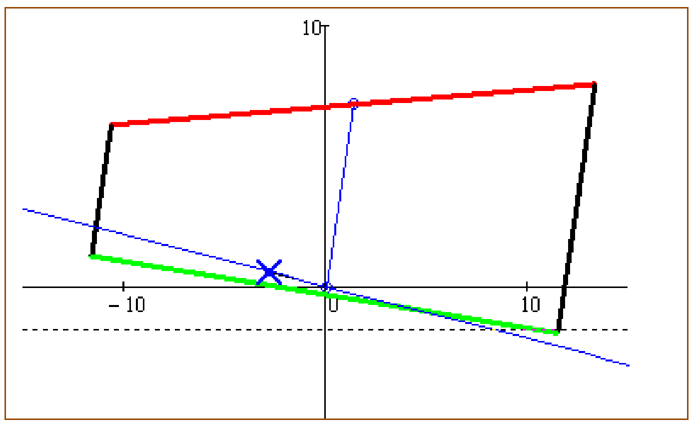


Figure 71. AG Quadrilateral characteristic with positive sequence memory voltage polarized directional line and AG impedance for the values injected

The customer was simulating a resistive bus fault with reverse load flow. In this case it is true that the impedance can fall in the second quadrant of the impedance plane. If we consider Figure 21 for a reverse load flow Ia will lead IFa. As the CT looks forward, IFa*RF=Va will follow in the second quadrant. What has been simulated erroneously is the angle of Vaf and Iaf:

When there is a resistive fault, the fault loop seen from the relay will be purely resistive. However, the fault loop seen from the remote source (ESR) will be a mix between resistive and inductive. The latter fault loop will be more inductive than the first fault loop, so the remote source voltage will lead the faulted voltage Va. The memory voltage will be the source voltage minus the voltage drop in the remote source impedance plus the line impedance due to the load flow: V1M=Iap*(Z1L+Z1SR), where Iap is the prefault current. The memory voltage will still be leading the fault voltage. In this case the directional line will shift upwards maintaining the reverse directionality.

Real fault voltages and currents could be:

Vaf=10_{-20°
Vbf=63.5_{-120°
Vcf=63.5_{240°
Iaf=5_{-185°

The quadrilateral characteristic related to these values is shown in Figure 72. Va1 will also lead Va so, if the memory voltage expires, the directional unit will still see the fault as reverse (see Figure 73)

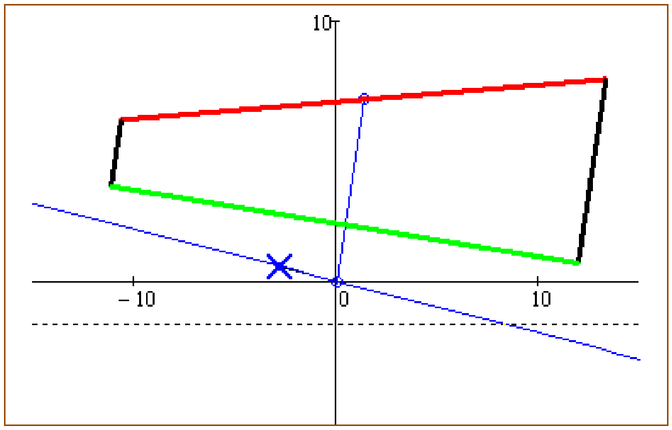


Figure 72. AG Quadrilateral characteristic with positive sequence memory voltage polarized directional line and AG impedance for the more real values

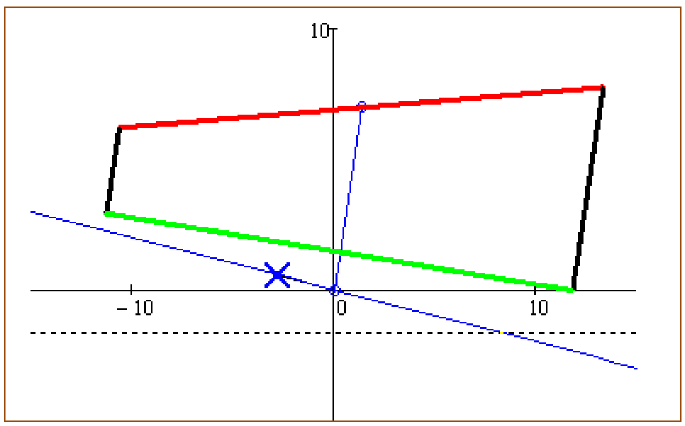


Figure 73. AG Quadrilateral characteristic with positive sequence voltage (no memory) polarized directional line and AG impedance for the more real values

8 CONCLUSIONS

The analysis of the fault loops with a line represented by its phase impedances is quite complex due to the mutual coupling between phases and with the ground. Simplified fault loops with no mutual coupling have been reviewed.

The representation of a distance characteristic has to be started in the voltage plane (R*I-X*I). The change from the voltage plane to the impedance plane is done by dividing all the voltages by the reference current: equivalent current for a single-phase to ground fault and phase-phase current for the rest of the faults.

The most common algorithms for Mho and quadrilateral characteristics have been review, focusing on the most advanced ones.

It has been deduced that the expansion and the contraction of the Mho characteristic for forward and reverse faults, respectively, does not only depend on the local source impedance and on the remote source plus line impedances, respectively. It also depends on the ratio of the fault current and the positive sequence fault current for the positive sequence polarized Mho; and on the ratio of the fault current and the load current if memory voltage is used. The same applies for the positive sequence memory polarized directional unit.

The negative sequence, zero sequence and pure fault phase reactance line compensates for the load flow but only if the system is homogeneous. The same happens for the phase-phase pure fault polarized reactance line.

It is important to know if the ground resistive reach is given in ohms / loops or ohms / phase in order to build the resistive limiters of the quadrilateral characteristic. If it is given in ohms / loop the voltage drop in the fault resistance will use phase current. If it is given in ohms / phase this voltage drop is based on the equivalent current.

Tests that maintain the static condition of the distance characteristic require:

- The polarization phasor to be in phase with measured voltage of the distance unit
- No load flow

Two real cases of a Mho characteristic false trip have been included. In both cases the trip was due to a phase-shift not related to a normal fault. Regarding the quadrilateral characteristic one erroneous testing concluded in a false operation of the directional unit. It was not considering the phase-shift that the fault voltage experience during resistive faults.

9 REFERENCES

[1] Analysis of Faulted Power Systems, Paul M. Anderson. IEEE Press Power Systems Engineering Series

[2] Symmetrical Components for Power System Engineering, J. Lewis Blackburn

[3] Instruction Manual. ZIV Distance Protection Model ZLV, Zamudio (Spain), Reference BZLV1111Av03

[4] R. Cimadevilla, R. Quintanilla, S. Ward “Adapting Protection to Frequency Changes”, WPRC, October 2005

10 BIOGRAPHY

Roberto Cimadevilla graduated in Electrical Engineering from the Superior Engineering College of Gijón, Spain in 2001. He later obtained a master´s degree in “Analysis, simulation and management of electrical power systems” from the University of País Vasco, Spain. He previously worked for Red Eléctrica de España (REE – Spanish TSO) as a Protection Relay Engineer. Roberto joined ZIV in 2003 as an Application Engineer, being responsible in this area for the development of a new distance relay, a new transformer differential relay, a phasor measurement unit and a line differential relay. Roberto is currently working as the Manager of the Application Engineering Department. He has written several technical papers, most of them presented at international conferences. Roberto has also participated in some CIGRE B5 working groups. He is currently a regular member of B5.48 working group.