Chapter 3
IMPEDANCE PROTECTION RELAY ALGORITHMS

3.1   Introduction

With the basics on types of faults, radial versus complex networks and line impedance calculations covered, the next logical approach is to analyse some of the protection relays that are being used to protect the overhead lines in the Eskom transmission system. This chapter is intended to provide information on specific numerical relay algorithms and steady state characteristics. The sections to follow will only focus on the forward reach elements and more specifically on the zone 1 and zone 2 reaches, since the maloperation which occurred in the system pertaining to the 7SA513 and the REL531 relays invariably affected these reaches. Both relays are quite extensively used to protect the 275 kV and 400 kV network.

3.2   Relay A (Siemens 7SA513)

This numerical relay has been in use in the Eskom transmission network since 1994 on 275 kV and 400 kV circuits. Eskom had originally requested the manufacturer to provide setting criteria that would ensure tripping outputs in the 10 ms domain are obtained, for all faults on any of the transmission overhead lines for which the relay would be used. This clearly presented the manufacturer with a challenge, since many variations such as length of lines, parallel circuits, series capacitors, different source impedances, fault resistances, harmonic oscillations etc. had to be considered.   Several system fault incidents occurred for which the relay maloperated, some of which were already referred to in Chapter 1, initially remained unexplained.

It was only after extensive in depth study of manufacturer and other related documentation, as well as the measurement of the overhead line impedances, that specific issues with the original setting criteria provided by Siemens was discovered. This chapter focuses on some of the actual measurement techniques and algorithms

of this relay. The fault types that were discussed in Chapter 1 as well as the theoretical fault analysis techniques of Chapter 2 dictates the relay algorithms and measurement techniques that will be discussed in this chapter. For this purpose the protection relays earth fault detection, impedance fault detection, directional determination, etc. will be discussed in the sub-sections that follow. This information together with that obtained in the following chapters will show what changes in the relay settings had to be made and why.
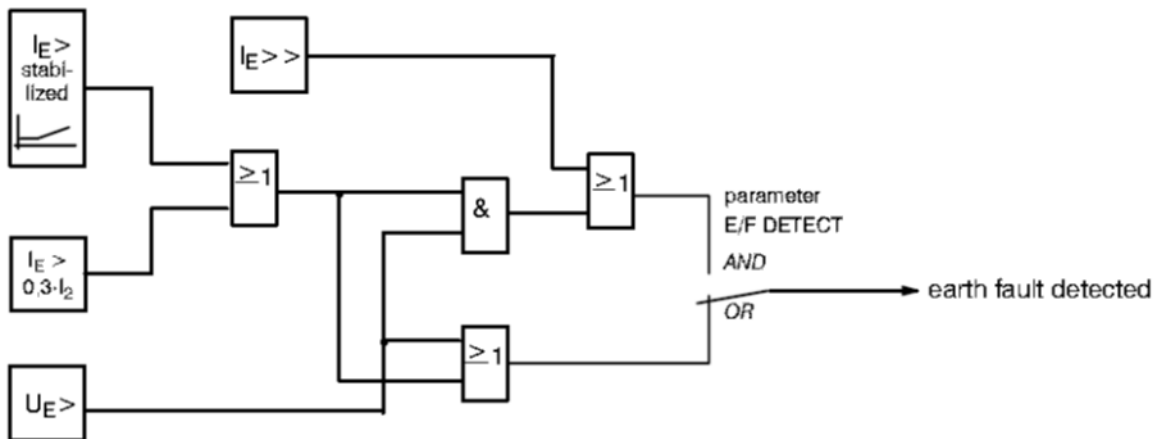
3.2.1 Earth fault detection

To enable a protection relay to detect phase-to-earth faults, an earth fault detection function must be active. The 7SA513 relay is equipped with a measurement technique that involves a comparison of negative phase sequence and zero phase sequence currents and displacement voltage. An earth fault for a specific phase is only validated once the line loop impedance and fault detection criteria have been met. The earth current detector monitors the fundamental (50 Hz) wave of the vector sum of all the phase currents derived from numerical filters. The value obtained is then compared with the set threshold value $I_E>$ [16].

The relay is stabilized against incorrect pick-up caused by asymmetric operating currents or distorted secondary currents due to current transformer saturation with earth-free short circuits. The actual pick-up value is automatically increased as the phase currents increase. Strong stabilization can therefore occur on long heavily loaded lines (see Figure 3.1 and Figure 3.2). This is overcome by comparison of the earth fault current with the negative phase sequence current. An earth fault is detected when zero sequence current in excess of 0.3 times the negative phase sequence current is measured, irrespective of stabilization.
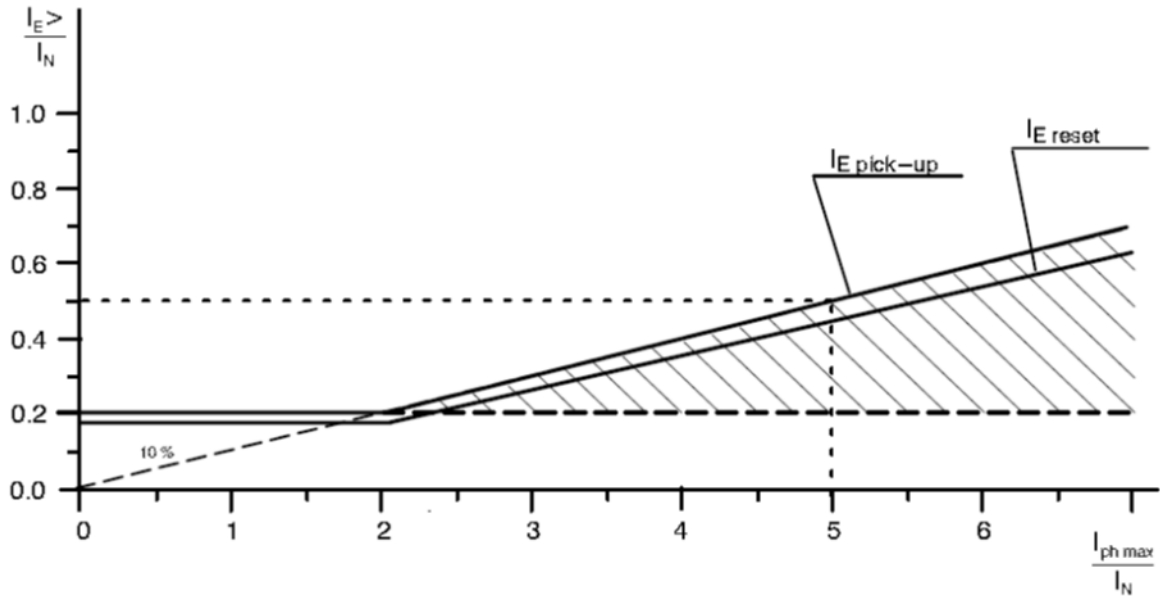
Figure 3.1: Pick-up/reset characteristic for earth current detector [16]

Figure 3.2 also shows that the residual voltage and current criteria can be combined through a logical AND or an OR function before an earth fault is detected [16]. Utilising the AND-function allows for increased security against maloperation during single-phase open conditions when zero-sequence currents could exceed the required 30% of negative phase sequence current (I_2).

Figure 3.2: Earth fault processing [16]

3.2.2 Impedance fault detection

The protection relays used on transmission systems also uses an impedance fault detection technique. Impedance fault detection is a loop dedicated fault detection technique. For phase-to-phase loop detection the phase currents as well as the difference current, decisive for the loop, must exceed a settable minimum value I_{ph}. For phase-to-earth measurement the assigned phase current must exceed a settable minimum I_e value and the earth fault processing must have detected an earth fault as described above. Pick-up results for the measurement loop in which the impedance vector lies within the fault detection polygon [16].

The resistance and reactance values of fault impedance are calculated separately in cyclic time intervals and are then compared with the set values for all six line loops for which the current conditions have been satisfied. The A, B and C-phase-to-earth as well as A-B, B-C and A-C-phase loops are all individually measured. The impedance fault detection polygon is portrayed in Figure 3.3. Forward reactive reach (X+A) and reverse reactive reach (X-A) can be set independently as can the two resistive settings for phase (RA1, RA2) and earth fault (RA1E) (see Figure 3.3). Load compensation, which is mostly only required on long lines, is made possible by setting the resistive reach settings RA1 and RA2 together with the load phase angle, thereby creating a load encroachment blinder such that operation under heavy load conditions will not occur.

If fault detection occurs in more than one loop, a loop verification process becomes effective. Loop verification operates in two steps

- A line simulation is calculated from the loop impedances and its part impedances (line or earth alone). If a plausible simulation can be found, then the corresponding loop is marked as "unconditionally valid". If the impedances of more than one loop are found within the fault detection polygon, the smallest is equally marked as valid [16].
- The relay regards as valid all those loops whose impedances are not greater than 150% of the smallest impedance. Loops with higher impedances are eliminated with the exception of those already marked as "unconditionally valid", which

remain valid even if they are greater than 150% of the smallest realized loop impedance [16].

Siemens claims that this method eliminates the loops with apparent fault impedances, whilst ensuring that unsymmetrical multi-phase faults are correctly evaluated by the relay [16]. The apparent fault impedances being referred to are often seen on the healthy phases during single-phase close-up faults. The healthy phase impedance is also pulled in towards the relay measuring position during the close-up fault. This phenomenon has been illustrated in the introduction section of chapter 1 (see Figure 1.1 to Figure 1.4).
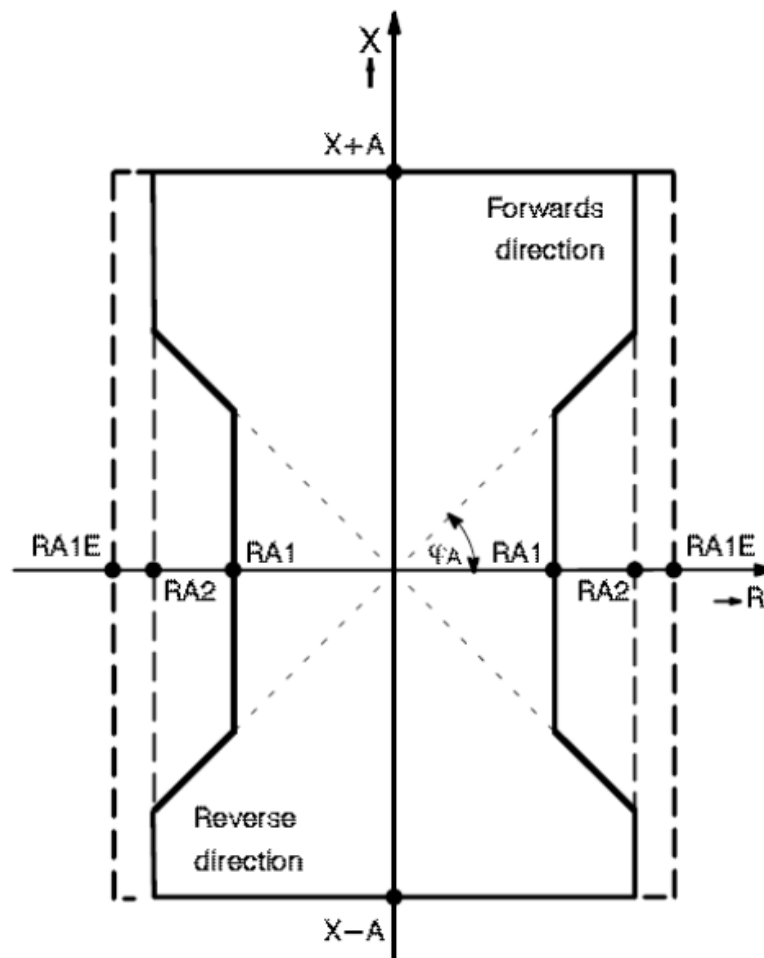

Figure 3.3: Impedance fault detection characteristics [16]

For a L_1 to L_2 phase-to-phase fault loop the relay uses the following equation to evaluate the fault impedance [16]

$$Z_L = \frac{V_{L1-E} - V_{L2-E}}{I_{L1} - I_{L2}}$$

(3.1)

For a L_3 earth fault detection loop the equation is given as

$$Z_L = \frac{V_{L3-E}}{I_{L3} - \dfrac{Z_E}{Z_L} \cdot I_E}$$

(3.2)

where;

V = Complex measured voltage

I = Complex measured current

Z = Complex line impedance

Note that, due to the convention used by the manufacturer, Eq. (3.2) differs from the generic equation with the assumption that I_E = -I_{L3}. Fault impedance calculation in the relay is done through methods of integration and an adaptive algorithm. The phase-to-phase loop values are then calculated using the instantaneous values for voltage (v) and the difference of the phase currents (i) at an instant (t). For a L_1 to L_2 phase-to-phase and L_3 phase-to-earth fault the following equations has been defined [16]

$$v_{L1-E} - u_{L2-E} = L \cdot \left(\frac{di_{L1}}{dt} - \frac{di_{L2}}{dt} \right) + R \cdot \left(i_{L1} - i_{L2)} \right)$$

(3.3)

$$v_{L3-E} = L \cdot \left(\frac{di_{L3}}{dt} - \frac{X_E}{X_L} \cdot \frac{di_E}{dt} \right) + R \cdot \left(i_{L3} - \frac{R_E}{R_L} i_{L2} \right)$$

(3.4)

with

$$\frac{R_E}{R_L} = \frac{1}{3} \cdot \left(\frac{R_0}{R_1} - 1 \right)$$

(3.5)

and

$$\frac{X_E}{X_L} = \frac{1}{3} \cdot \left(\frac{X_0}{X_1} - 1 \right)$$

(3.6)

where

V_{L1-E} = *Phase-to-earth voltage for phase L_1*

V_{L2-E} = *Phase-to-earth voltage for phase L_2*

V_{L3-E} = *Phase-to-earth voltage for phase L_3*

i_{L1} = *Phase current for phase L_1*

i_{L2} = *Phase current for phase L_2*

i_{L3} = *Phase current for phase L_3*

di_{L1}/dt = *Change in current for a change in time for phase L_1*

di_{L2}/dt = *Change in current for a change in time for phase L_2*

di_{L3}/dt = *Change in current for a change in time for phase L_3*

di_E/dt = *Change in earth current for a change in time*

X_E/X_L = *Inductance ratio*

R_E/R_L = *Resistance ratio*

X_0 = *Zero sequence inductance of the overhead line*

X_1 = *Positive sequence inductance of the overhead line*

R_0 = *Zero sequence resistance of the overhead line*

R_1 = *Positive sequence resistance of the overhead line*

The relay has the capability to use an additional current input from a parallel line in order to compensate for the mutual coupling effect during faults, but this option is not implemented in Eskom Transmission and for that reason will not be discussed.


3.2.3   Directional determination

Directional determination is used by impedance protection relays to distinguish between faults that occur in front of and behind the relaying position. Without this functionality, impedance protection relays would not be able to correctly determine fault direction and could trip indiscriminatively. Directional determination is done similar to the impedance measurement except that sound phase and stored reference voltages are used. The voltage reference used is always at right angles to the short circuited voltages [16] (see Figure 3.4).
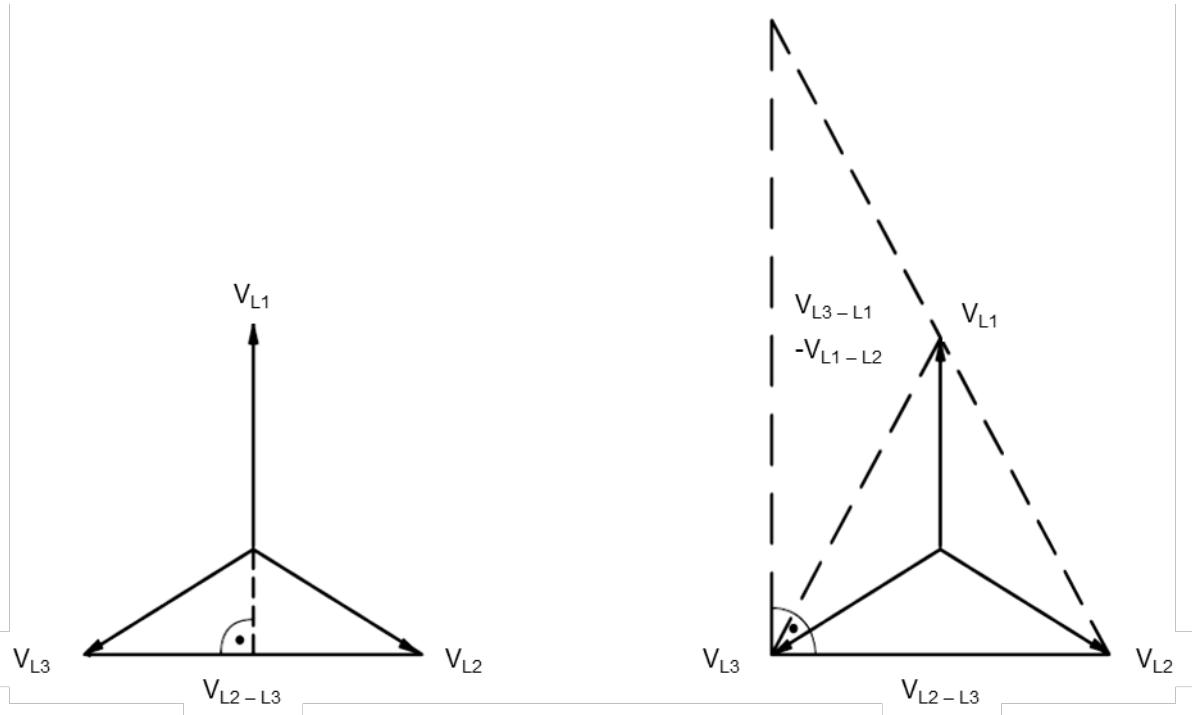
Figure 3.4: Voltage references for directional determination [16]

Figure 3.5 depicts the theoretical directional line on an R-X diagram. Network source impedance and load current immediately prior to fault inception influences the actual position of the directional line [6], [16].
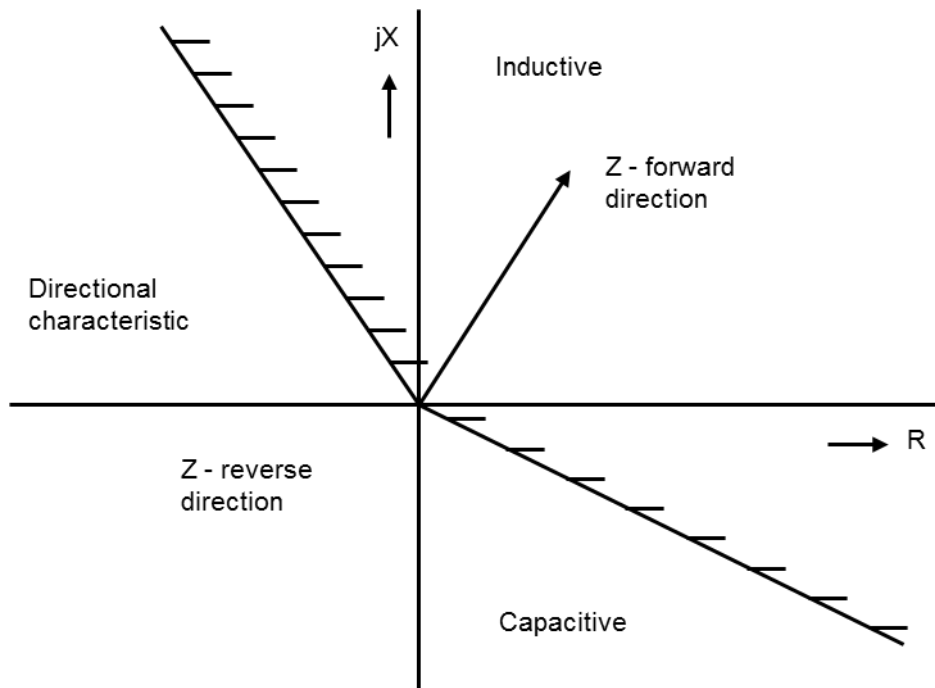
Figure 3.5: 7SA513 Directional characteristic [16]

The movement of the directional characteristic is best explained with the use of a simple network diagram (see Figure 3.6) [16].
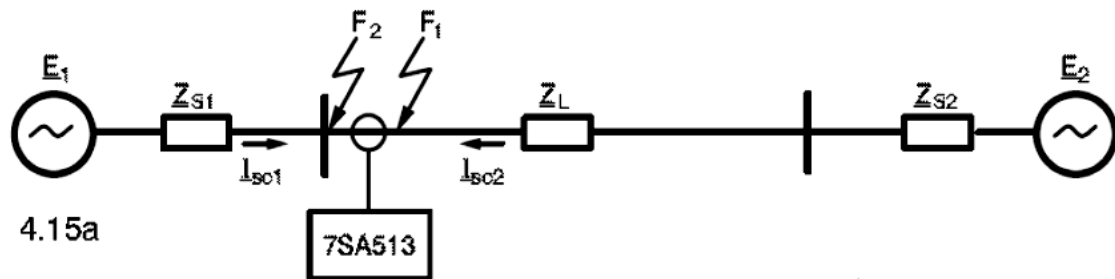

**Figure 3.6: Simple network diagram [16]**

For faults at (F_1) and beyond, as seen from the position of the current transformer to which the relay is connected and assuming no-load current, the directional line shown in Figure 3.7(a) will pull back to seemingly include the source impedance (Z_{s1}) located behind the relay position. The opposite is true for faults occurring behind the relay at position (F_2) and further back towards source (E_1). For these so-called reverse faults the directional line shown in Figure 3.7(b) will move forward by approximately the line impedance plus the remote end source impedance ($Z_L + Z_{S2}$) [6], [16].

Adding load to the equation complicates matters somewhat in the sense that now a drop in voltage occurs across the source impedance at the local end and across the source and line impedance as seen by the relay for faults behind the relay. The voltage drop is a function of the load current and results in a magnitude and phase angle change from the source voltage at the generators. This angular change (δ), as a result of the load current, causes a further angular deviation of the directional characteristic [6], [16] (see Figure 3.7).

The impact of the angular deviation shown in Figure 3.8 for a reverse fault on the directional characteristic is rather harsh in comparison to a forward fault. This is due to the bigger deviation in the remote end source voltage angle (β) and that of the unfaulted phase voltages at the relay location. The rotation in the unfaulted phase voltages causes a corresponding opposite rotation in the directional characteristic.
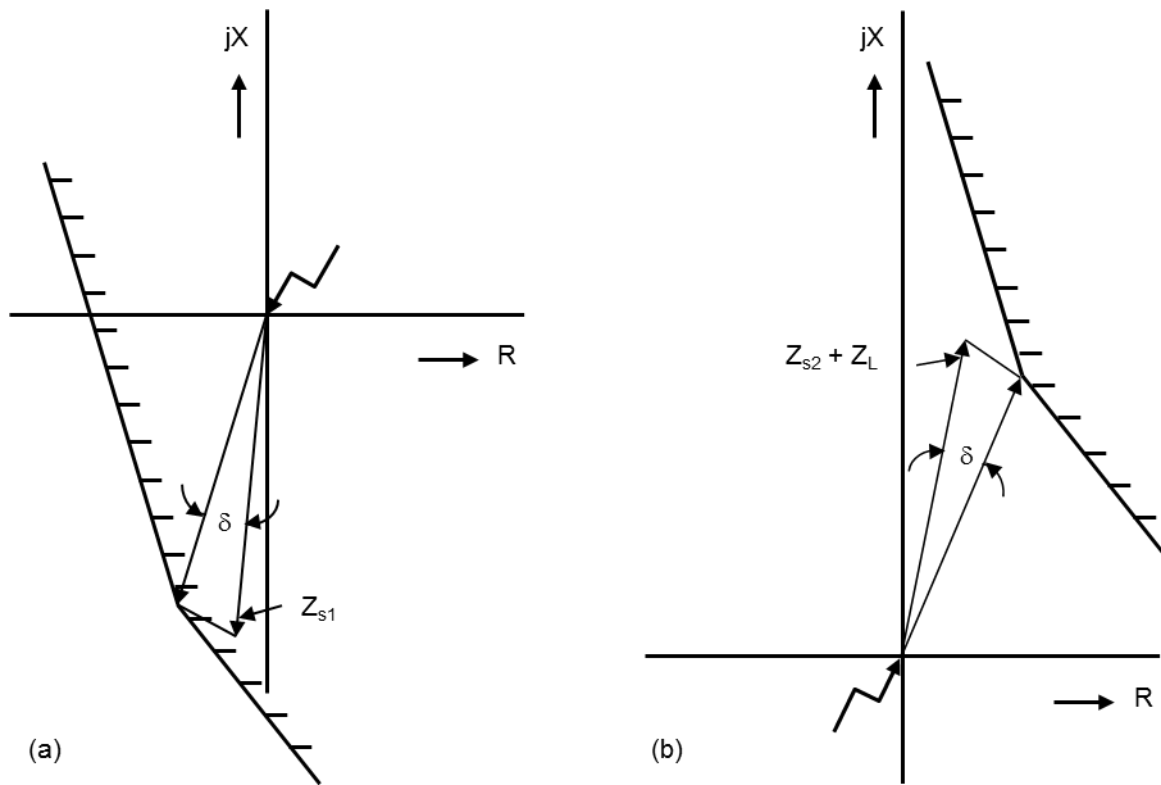
**Figure 3.7: Impact of source impedance and load on directionality of a distance relay [16]**
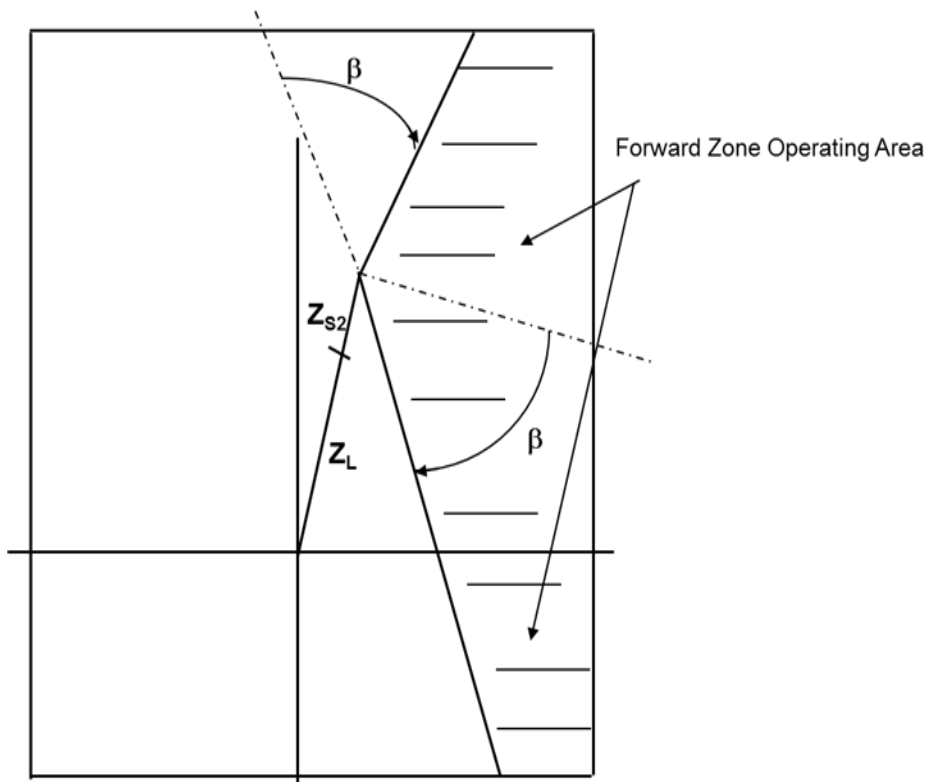
Figure 3.8: Reverse fault impact on forward characteristic [6]

3.2.4   Impact of series compensation

The impact of series compensation or possible incorrect application thereof already became apparent in Chapter 1, when this type of protection relay had overreached for a busbar fault. Series compensation in protection relays are usually integrated with the directional determination function, and is required where overhead lines are reactively being compensated in order to achieve greater transfer of load current. Without series compensation in protection relays it is possible, dependent on various factors such as amount of compensation, position of compensation and position of fault, that overreaching of the instantaneous zone 1 could occur resulting in wrong tripping. Even with series compensation being active in a protection relay, it is possible that with incorrectly applied settings or variations in network conditions, that overreaching could occur. Series capacitors are mostly used on long lines in order to improve the power transfer capability across the line. The addition of a series capacitor in a transmission line effectively reduces the line impedance. Series capacitors are protected against high overvoltages through the use of spark-gap devices or metal oxide varistors (MOVS) or both. A by-pass breaker closes when the spark-gap flashes, taking the series capacitor out-of-service. Short circuit currents, which cause the spark-gap to flash, will also initiate closing of the by-pass breaker. The spark-gap will normally flash during the first half cycle for close-up faults with the result that distance protection will operate as normal [6].

It is however important to reduce the reach of the underreaching zone such as to ensure that should the capacitor bank not bypass, the zone would not overreach the line and trip incorrectly for an out-of-zone fault. This concept is best illustrated with the use of Figure 3.9(a) and Figure 3.9(b). A fault at F1 would result in an effective reduction in impedance as measured by the relay and could even present itself as a fault behind the relay dependant on the installed position of the capacitor bank on the line.
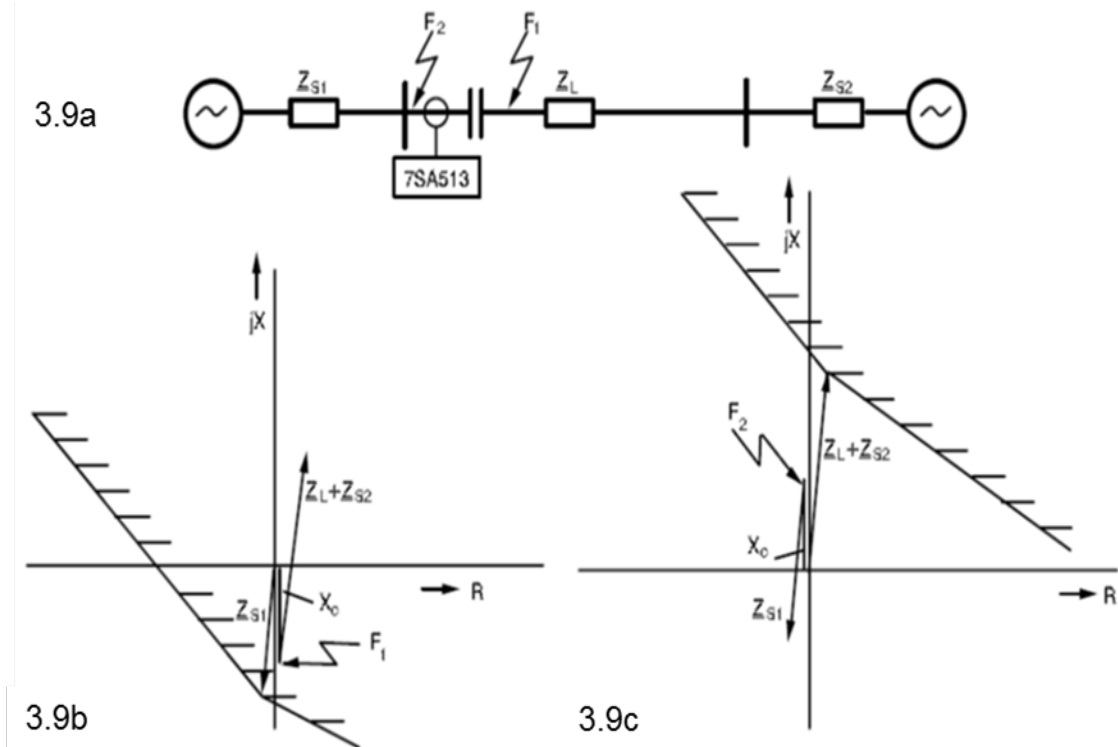
Figure 3.9: Influence of series compensation [16]

Should the underreaching zone therefore be set to the normal reach of 80% of line impedance, the relay would overreach the line by the difference between the percentage compensation and the 20% safety margin normally used. For this reason the underreaching zone is reduced with a factor calculated by the difference between the line inductance and the series capacitive reactance multiplied by a grading factor (K_{gf1}) as illustrated by   .

$$X_1 = K_{gf1} \cdot \left(X_1 - X_C\right)$$

(3.7)

where

X_1 = Overhead line inductive reactance

X_c = Series capacitor capacitive reactance

The grading factor normally used for series compensated lines on the Eskom transmission system is 0.75 pu.

Fault conditions for which the spark-gap does not flash presents an even more complex situation. Interaction between the capacitance of the series capacitor and the inductance of the line results in the development of oscillating harmonic

frequencies. The same situation holds true for series capacitor banks with MOVS fitted. A spiral shaped impedance curve results from the harmonic oscillation with the result that an impedance relay will measure short periods of under- and overreach [6].

The amount of non-linearity in the oscillations during a fault on a series compensated line is dependent on the level of MOV action. MOV action results in the measurement of a typical fault impedance spiral, an example of which can be seen in Figure 3.10. The amount of MOV action is directly related to the fault current through the series capacitor bank and therefore the voltage that develops across the bank. Conduction of the series capacitor MOV occurs primarily at a pre-defined voltage above the capacitor bank rated voltage, resulting in significant resistance and therefore damping being added to the network near the voltage peaks of every half-cycle. This action causes a non-linear impedance relationship, which can be summarized with the use of the picture and equivalent impedance calculations shown in Figure 3.11 [6]. The non-linear variation of the MOV resistance during a conductive cycle results in a similar variation in the equivalent network reactance (X_{ce}).

Distance protection relay filtering cannot totally filter out other frequency components due to the requirement that it should be able to operate at frequencies deviating from 50 Hz by plus or minus 5%. It is therefore required to reduce the reach of the underreaching zone by a further safety factor to safeguard against possible transient overreach.

The equation for calculating the transient factor is given as

$$K_{trans} = \frac{1}{1 + \dfrac{V_{mov}}{\sqrt{2} \cdot E}}$$

(3.8)

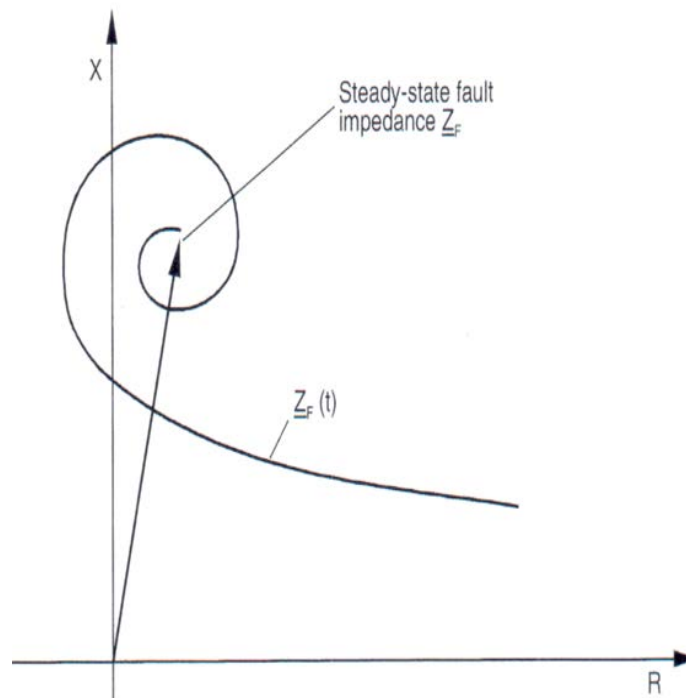*where*
V_{mov} = voltage across the MOV
E = Source voltage
K_{trans} = transient factor

The final equation for series compensated lines for this type of protection relay can then be given as [6]

$$X_1 = K_{trans} \cdot K_{gf1} \cdot (X_L - X_C)$$

(3.9)

In the 7SA513 relay the sub-synchronous oscillation is damped with the factor F_{sub}/F_{net} (F_{sub} = sub-synchronous frequency and F_{net} = network frequency) [6].

Figure 3.10: Fault impedance spiralling effect [6]

The equivalent series capacitor impedance applicable to the measured fault current can be calculated, with the use of the graph shown in Figure 3.11, Eq. (3.10) and Eq. (3.11) [6].

$$X_{CE} = X_{CE} \, p.u. \cdot |X_C|$$

(3.10)

$$R_E = R_E \, p.u. \cdot |X_C|$$

(3.11)

A somewhat different set of equations is provided by [17]

$$R_C = X_N \left(0.0745 + 0.49e^{-0.243 K_{bc}.I_{Lu}} - 35.0e^{-5.0 K_{bc}.I_{Lu}} - 0.6e^{-1.4 K_{bc}.I_{Lu}} \right) \quad (3.12)$$

$$X_C = X_N \left(0.101 - 0.005749 K_{bc} I_{Lu} + 2.088e^{-0.8566 K_{bc}.I_{Lu}} \right) \quad (3.13)$$

$$K_{bc} = \frac{I_B}{k_P I_N} \quad (3.14)$$

$$I_{TH} = k_P I_N \quad (3.15)$$

$$I_{Lu} = \frac{I_L}{I_B} \quad (3.16)$$

where

X_{CE}, X_C = Equivalent series capacitor reactance

X_{CE} p.u. = per unit series capacitor reactance

R_E, R_C = Equivalent series capacitor resistance

R_E p.u. = per unit series capacitor resistance

X_N = Rated value of the capacitive reactance, A rms

I_B = Capacitor bank base current

I_N = Rated capacitor bank current, A rms

I_L = Line current, A rms

I_{Lu} = Normalised line current

I_{TH} = Capacitor threshold rating, A rms

K_{bc}, K_p = constants

It is important that careful consideration be given prior to implementation of final protection relay settings for commissioning purposes when used on series compensated lines. Further considerations such as voltage reversal and the impact for relays on adjacent feeders, not covered in the relay manual, but must also be taken into account. This impact will be covered under section 3.3.6.2.
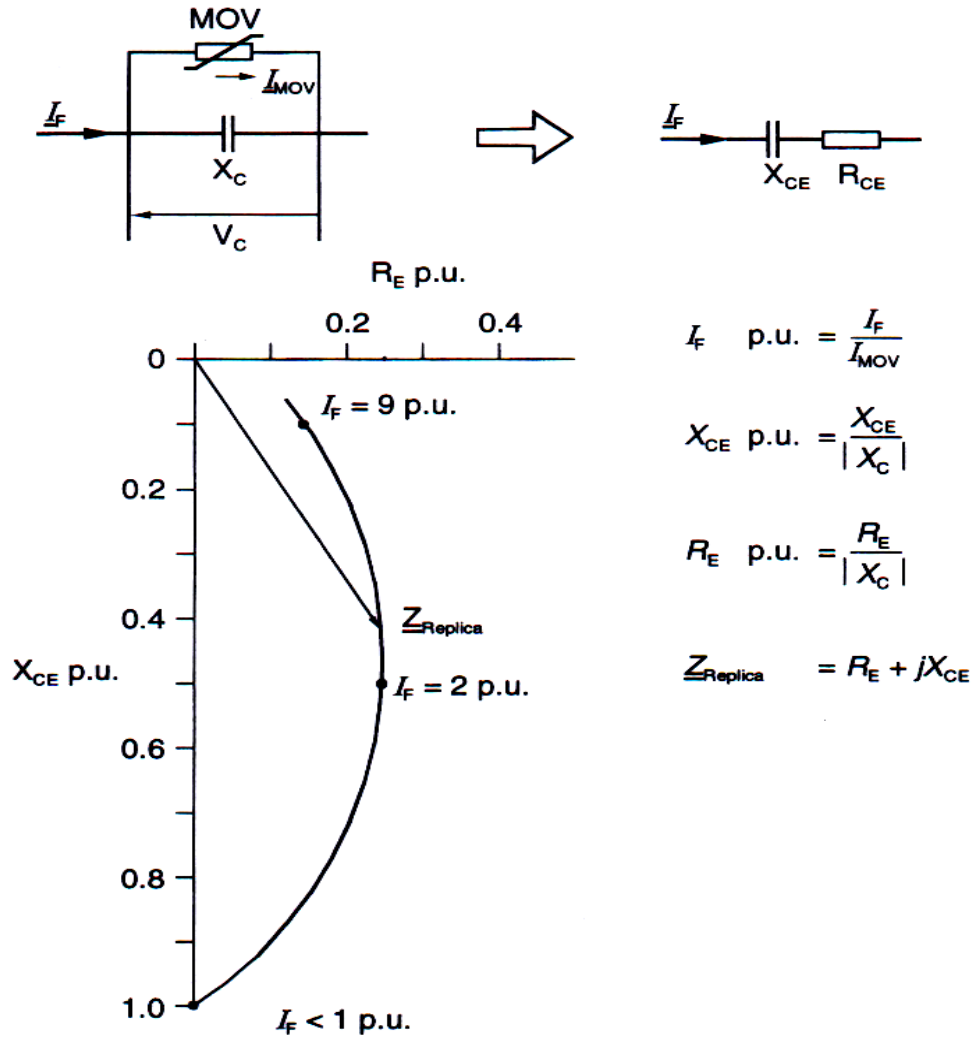
Figure 3.11: Equivalent series impedance [6]

The diagram shows the following equations:

$$I_F \text{ p.u.} = \frac{I_F}{I_{MOV}}$$

$$X_{CE} \text{ p.u.} = \frac{X_{CE}}{|X_c|}$$

$$R_E \text{ p.u.} = \frac{R_E}{|X_c|}$$

$$\underline{Z}_{Replica} = R_E + jX_{CE}$$

3.2.5   Relay tripping characteristics

The relay's tripping characteristics are essentially the different zones of protection. The relay's tripping characteristics are non-directional elements, which are directionalised with the use of the directional determination element as discussed in section 3.2.3. It is important to note that tripping of any of the relay's protection zones can only occur when set to fall within the fault detector coverage for the reactive (X) as well as resistive (R) reach (see Figure 3.12). The phase-to-earth loops in the 7SA513 relay are normally always active, but may be conditioned to only release with residual current and/or voltage. Eq. (3.17), Eq. (3.18), Eq. (3.20) and Eq. (3.21) are used to calculate the phase-to-phase fault loops [6].

$$R_{L2-L3} = \frac{V_{L2-L3}\left[I_{L2}\cos(\phi_{VL2-VL3} - \phi_{IL2}) - I_{L3}\cos(\phi_{VL2-VL3} - \phi_{IL3})\right]}{I_{L2}^2 - 2I_{L2}I_{L3}\cos(\phi_{IL2} - \phi_{IL3}) + I_{L3}^2} \tag{3.17}$$

$$X_{L2-L3} = \frac{V_{L2-L3}\left[I_{L2}\sin(\phi_{VL2-VL3} - \phi_{IL2}) - I_{L3}\sin(\phi_{VL2-VL3} - \phi_{IL3})\right]}{I_{L2}^2 - 2I_{L2}I_{L3}\cos(\phi_{IL2} - \phi_{IL3}) + I_{L3}^2} \tag{3.18}$$

Suffixes 1, 2 and 3 refer to the different phases of the high voltage circuit. The fault condition being evaluated is significantly simplified when being fed from a single ended in-feed (see Figure 2.3), which also simplifies Eq. (3.17) and Eq. (3.18) to that shown in Eq. (3.20) and Eq. (3.21). The relevant condition, which leads to simplification of the equations, is shown in Eq. (3.19) [6].

$$I_{L3} = -I_{L2} = I_L \tag{3.19}$$

$$R_{L2-L3} = \frac{V_{LL}\cos(\phi_{VLL} - \phi_{IL})}{2I_L} \tag{3.20}$$

$$X_{L2-L3} = \frac{V_{LL}\sin(\phi_{VLL} - \phi_{IL})}{2I_L} \tag{3.21}$$

where

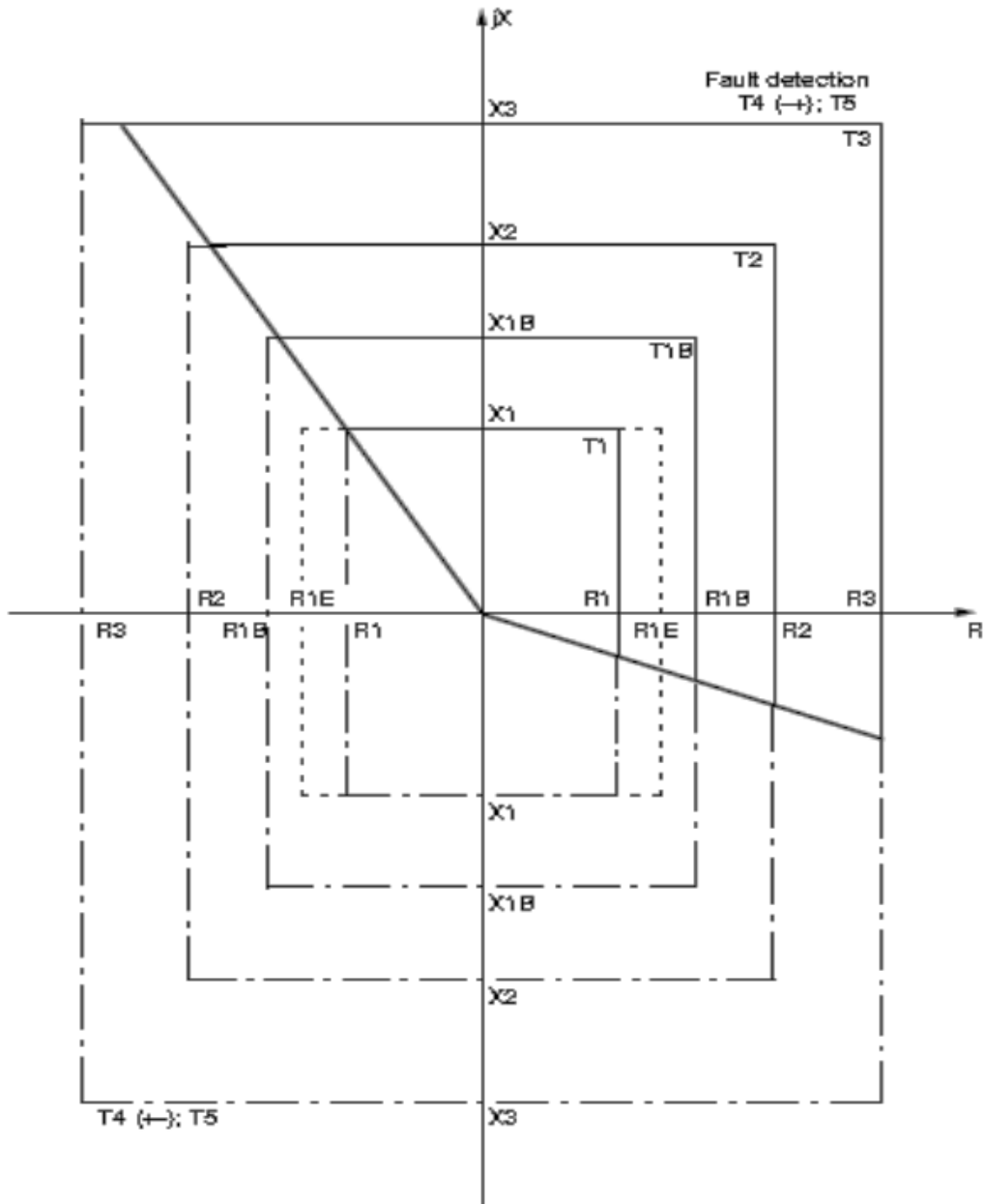*$V_{LL} = V_{L2-L3}$, Short circuit line voltage (rms)*

I_L = Short circuit phase current (rms)

ϕ_{VLL} = Phase angle of the short circuit line voltage

ϕ_{IL} = Phase angle of the short circuit phase current

R_{L2-L3} = Phase-to-phase fault loop resistance measurement

X_{L2-L3} = Phase-to-phase fault loop reactance measurement

Figure 3.12: 7SA513 Tripping characteristic [16]

For all loops involving earth faults (single, two or three-phase-to-earth) Eq. (3.22) and Eq. (3.23) should be used. For single-phase-to-earth faults where the phase angle of the phase current and the earth return is displaced by approximately 180°, simplified Eq. (3.24) and Eq. (3.25) can be used [6].

$$R_{Ph-E} = \frac{V_{Ph-E}}{I_L} \cdot \frac{\cos(\phi_V - \phi_L) - \dfrac{I_E}{I_L} \cdot \dfrac{X_E}{X_L} \cdot \cos(\phi_V - \phi_E)}{1 - \left(\dfrac{X_E}{X_L} + \dfrac{R_E}{R_L}\right) \cdot \dfrac{I_E}{I_L} \cdot \cos(\phi_E - \phi_L) + \dfrac{R_E}{R_L} \cdot \dfrac{X_E}{X_L} \cdot \left(\dfrac{I_E}{I_L}\right)^2}$$

(3.22)

$$X_{Ph-E} = \frac{V_{Ph-E}}{I_L} \cdot \frac{\sin(\phi_V - \phi_L) - \dfrac{I_E}{I_L} \dfrac{R_E}{R_L} \cdot \sin(\phi_V - \phi_E)}{1 - \left(\dfrac{X_E}{X_L} + \dfrac{R_E}{R_L}\right) \cdot \dfrac{I_E}{I_L} \cdot \cos(\phi_E - \phi_L) + \dfrac{R_E}{R_L} \cdot \dfrac{X_E}{X_L} \cdot \left(\dfrac{I_E}{I_L}\right)^2}$$

(3.23)

$$R_{Ph-E} = \frac{V_{Ph-E} \cos(\phi_V - \phi_L)}{I_L + \dfrac{R_E}{R_L} \cdot I_E}$$

(3.24)

$$X_{Ph-E} = \frac{V_{Ph-E} \sin(\phi_V - \phi_L)}{I_L + \dfrac{X_E}{X_L} \cdot I_E}$$

(3.25)

where

V_{Ph-E} = Short circuit phase voltage (rms)

I_L = Short circuit phase current (rms)

I_E = Short circuit earth current (rms)

ϕ_V = Phase angle of the short circuit voltage

ϕ_L = Phase angle of the short circuit phase current

ϕ_E = Phase angle of the short circuit earth current (return current)

R_E/R_L and X_E/X_L are the residual compensation factors set in the relay

R_{Ph-E} = Phase-to-earth resistance fault loop measurement

X_{Ph-E} = Phase-to-earth reactance fault loop measurement

3.2.6   Impact of fault resistance

Impedance protection relays are influenced by fault resistance dependant on remote-end in-feed. On a radial circuit the impact on the measured impedance (distance to fault) for a phase-to-phase and a phase-to-earth fault is best explained remembering how the relevant faulted circuits discussed in Chapter 2 looks like. For the phase-to-phase fault with fault resistance refer to Figure 2.3 and for the single-phase-to-earth fault with fault resistance refer to Figure 2.1. By assuming that $Z_a = Z_b = R_L + jX_L$ in Figure 2.3, Eq. (3.26) can be written for the short circuit line voltage at the relay location [6].

$$V_{LL} = 2(R_L I_L + jX_L I_L) + R_F I_L$$
(3.26)

The measured impedance (distance to fault) can then be presented as

$$Z_{L2-L3} = \frac{2(R_L I_L + jX_L I_L) + R_F I_L)}{2I_L}$$
(3.27)

which when simplified gives

$$Z_{L2-L3} = R_L + \frac{R_F}{2} + jX_L$$
(3.28)

It has been shown by [6] that for a single-phase-to-earth fault with fault resistance the measured impedance (distance to fault) can be represented by Eq. (3.29) and Eq. (3.30).

$$R_{Ph-E} = \frac{R_L\left(I_L + \frac{R_E}{R_L}\cdot I_E\right) + R_F I_L}{I_L + \left(\frac{R_E}{R_L}\right)_{SET}\cdot I_E}$$
(3.29)

$$X_{Ph-E} = \frac{X_L \left(I_L + \dfrac{X_E}{X_L} \cdot I_E \right)}{I_L + \left(\dfrac{X_E}{X_L} \right)_{SET} \cdot I_E}$$

(3.30)

From Eq. (3.29) and Eq. (3.30), it was shown by [6] that by setting the relay X_E/X_L and R_E/R_L settings to represent the line values accurately, the reactive and resistive measurements for a resistive fault reduce to

$$R_{Ph-E} = R_L + \frac{R_F}{1 + \left(\dfrac{R_E}{R_L} \right)_{SET}}$$

(3.31)

$$X_{Ph-E} = X_L$$

(3.32)

where

(R$_E$/R$_L$)$_{SET}$, (X$_E$/X$_L$)$_{SET}$ = the actual settings applied to the relay

For a dual supply system as shown in Figure 3.13 the fault impedance measurement becomes more complicated with factors unknown to the relay. Current from the remote end supply now causes an additional voltage drop across the fault resistance with a resultant increase in measured resistance by a factor (K_F) of

$$K_F = 1 + \frac{I_B}{I_A}$$

(3.33)

For the purpose of this document we will refer to this factor as the impedance enhancement factor (K_F). Moving the fault along the line towards substation B results in an increase in impedance between the relay at substation A and the fault and a decrease in impedance as measured by a relay at substation B. The result is that the current (I_B) from substation B increases and that from A (I_A) decreases, thereby increasing the impedance enhancement factor.
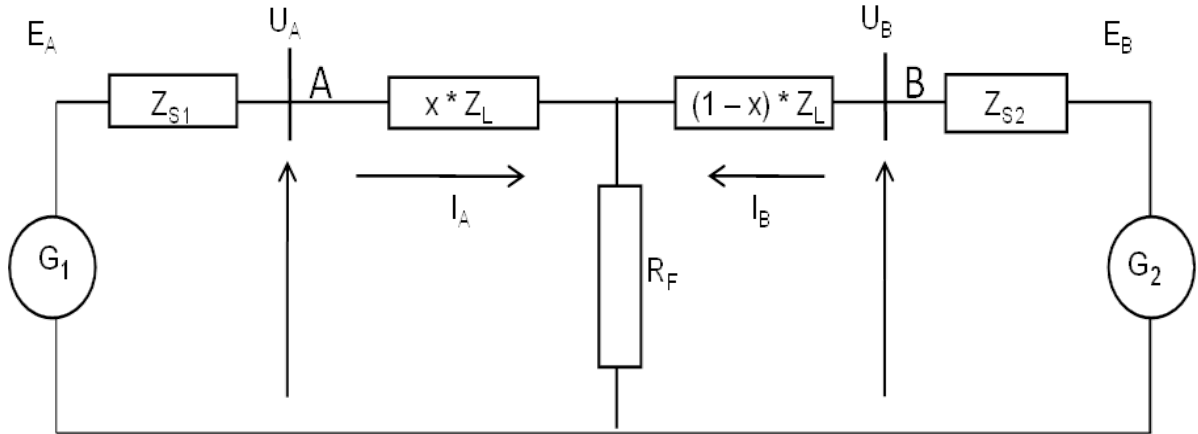
Figure 3.13: Double ended in-feed supply circuit

For a distance protection relay at substation A the resultant impedance is [6]

$$Z_A = xZ_L + \frac{I_B}{I_A} \cdot R_F$$

(3.34)

where

Z_A = *Impedance measured by relay at point A*

Z_L = *Line impedance between point A and B*

R_F = *Fault resistance*

I_A = *Current measured by relay A at point A*

I_B = *Current measured by relay B at point B*

x = *factor in per unit of line length*

The additional voltage drop causes an increase in the measured fault impedance, with a resultant underreaching effect at the relaying point. This phenomenon is graphically represented in Figure 3.14. The 7SA513 relays load adaptive fault detection characteristic (see section 3.2.7) provides a solution to this apparent increase in fault resistance measured by the relay. Superimposed relay tripping and fault detection characteristic illustrate this capability in Figure 3.15 [6]. The relay can therefore theoretically detect higher resistive faults further away from the relaying point based on the characteristic graphically illustrated in Figure 3.15.
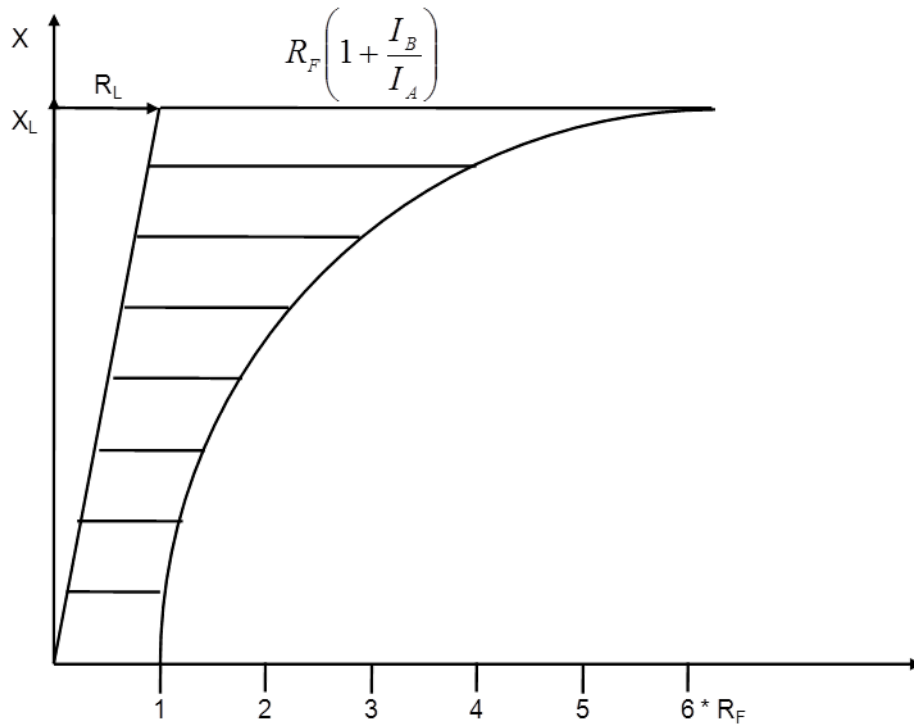
Figure 3.14: Apparent fault resistance dependent on fault location [6]
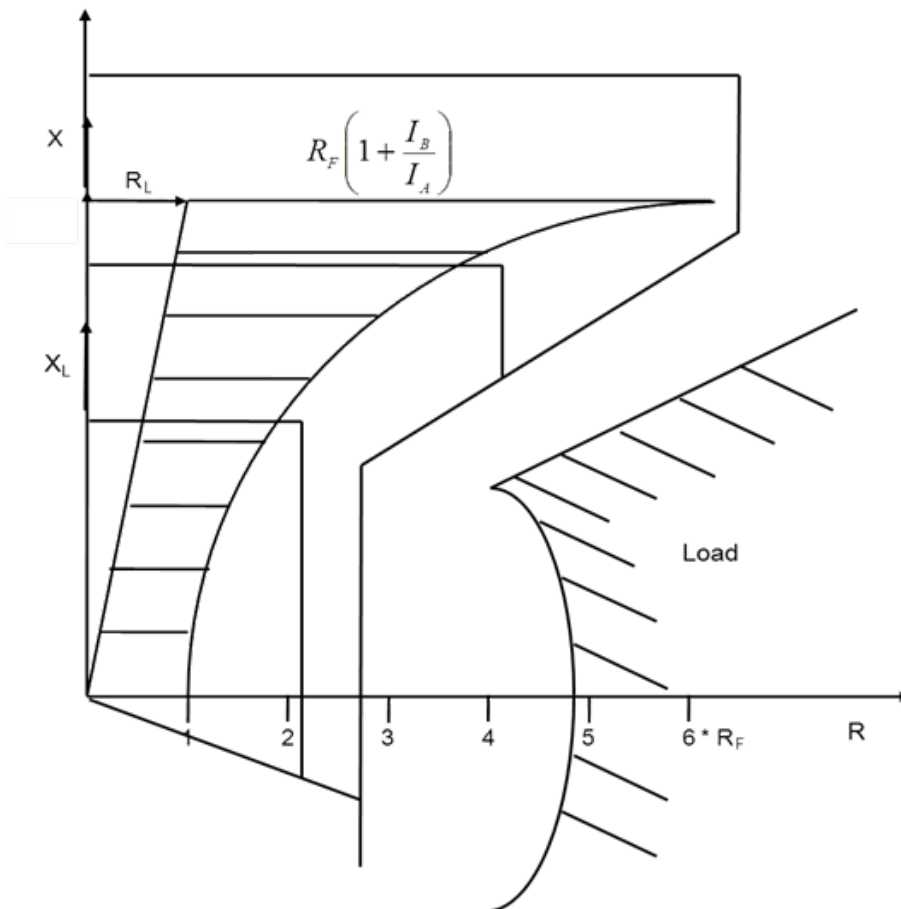

Figure 3.15: 7SA513 Tripping characteristics with fault resistance [6]

3.2.7   Influence of load

As is the case with fault resistance, load and therefore load impedance has a similar influence on impedance relay measurement. A transmission line carrying load is characterized with an angular difference between the sending end and the receiving end voltages. This angular difference (transmission angle) is necessary in order to transfer real power across the line. Unfortunately, this angular difference is also responsible for an initial angular difference between currents I_A and I_B originating from the sending and receiving ends, should a fault occur on the line [6].

The latter part of Eq. (3.34) refers to the ratio of currents I_B and I_A through the resistive fault. It is this current ratio multiplied with the resistance of the fault that causes the distance protection relay at the sending end to overreach, whilst that at the receiving end tends to underreach with respect to reactive impedance measured. This phenomenon is illustrated in Figure 3.16.   The I_B/I_A * R_F vector shows a downward slope as determined from the power sending end, whilst the inverse happens at the receiving end. This phenomenon becomes worse with long lines with large power transfer [6].
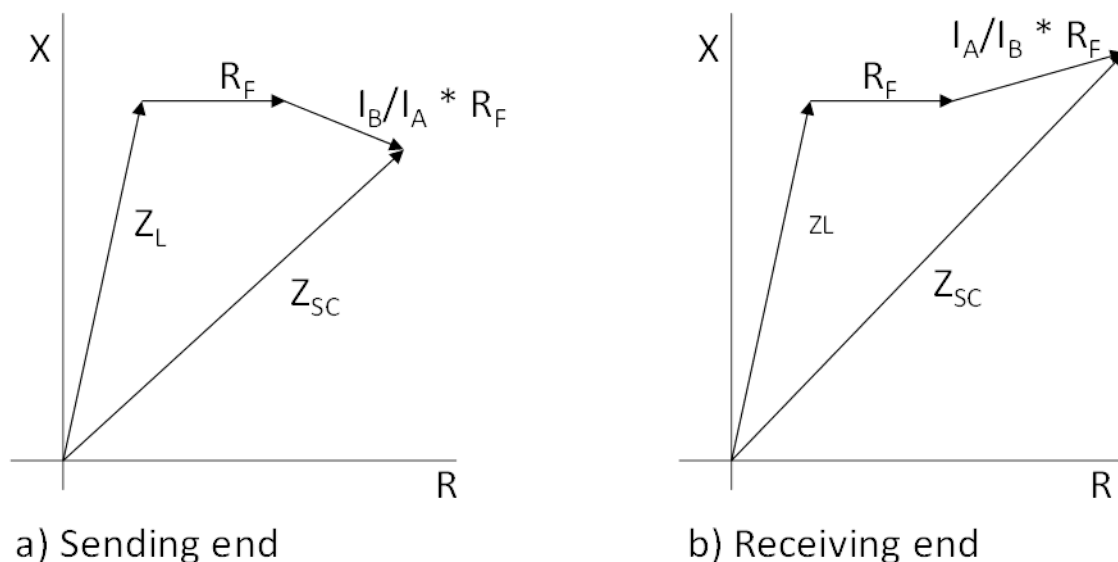
Figure 3.16: Influence of load transfer on distance relay measurement [6]

A graphical illustration has been provided by [6], shown in Figure 3.17, giving an insight into the possible overreach and underreach that a normal distance relay would experience on a 440 km, 400 kV line with a load transfer angle of around 35°.

(a)

(b)

(c)

with load compensation

without load compensation
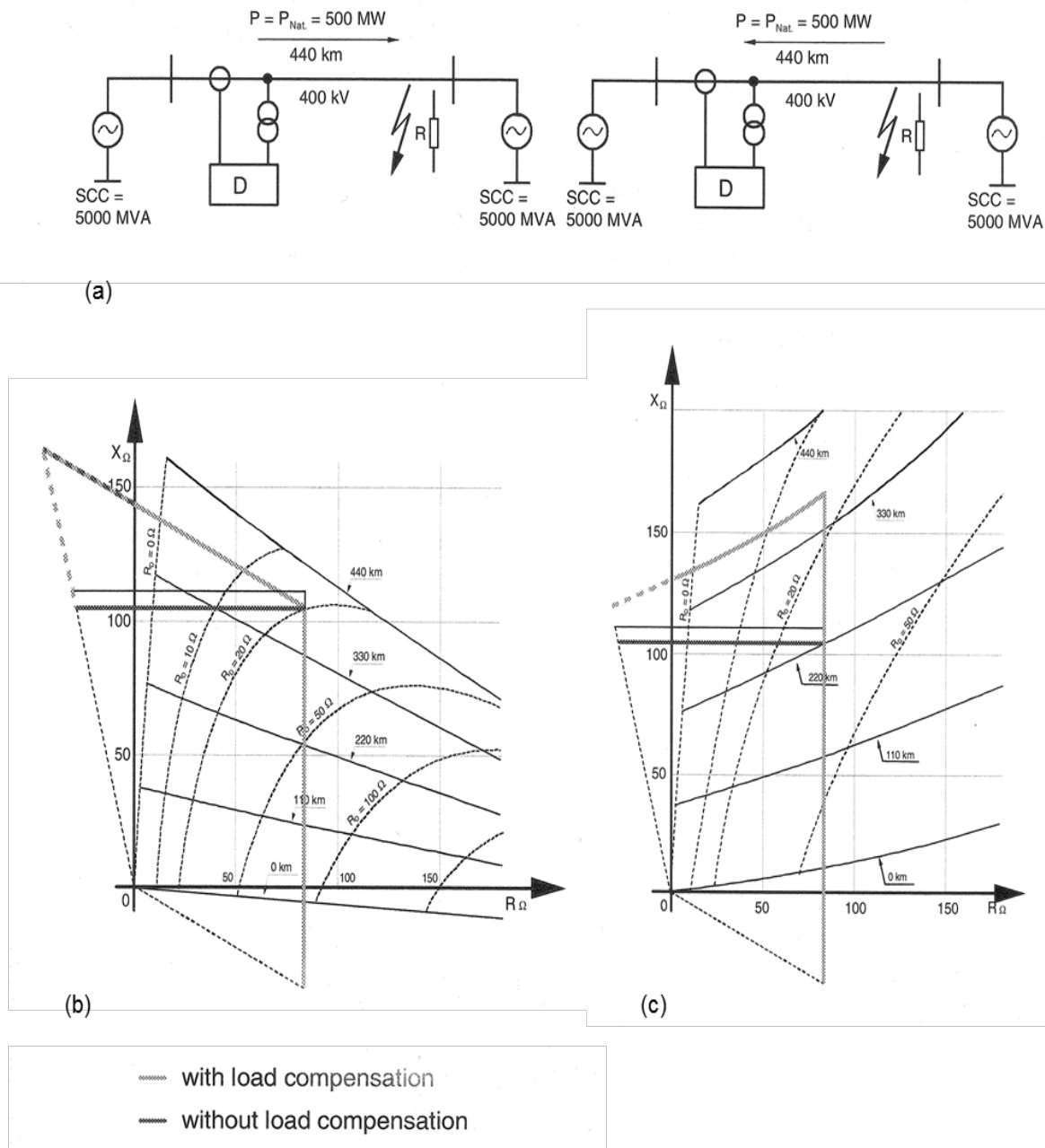
Figure 3.17: Approximate reaches with and without load compensation [6]

From Figure 3.17 approximate distance relay reaches can be obtained for the load transfer sending and receiving ends. Considering normal distance relay reach applications for zone 1 or zone 2 reactive reaches of 80% and 120% respectively,

the approximate reaches for both ends at defined resistive reaches can be obtained. This numerical relay manufacturer has defined a load compensation algorithm that aims to correct the measuring error due to load. The algorithm is based on the assumption that both relay ends have approximately the same X/R ratio and that the earth return currents have nearly the same phase angle as the total fault current at the point of fault. This type of network is referred to as a homogeneous system.

The relay then makes an automated angular correction based on the angle difference between the phase current and the earth return current. It is therefore reasonable to assume that the relay would not be able to compensate correctly should the earth return currents at both ends not have the same phase angle as the total fault current at the point of fault. For the purpose of this study only the impact of the export or import of load current on the relay characteristic has been investigated and is discussed in Chapter 4.

3.2.8   Summary

Sections 3.2.1 to 3.2.7 discussed various relay measurement elements of relay A. The following points are highlighted for careful consideration;

- Earth fault detection sensitivity can be decreased, by combining the residual voltage and current criteria, to allow for increased security against maloperation during single-phase open conditions. This is especially required during single pole open conditions when zero-sequence currents could exceed the required 30% of negative phase sequence current.

- Fault detection for phase-to-phase and phase-to-earth loops are supervised by two independent current supervision settings. Pick-up of the relay for any of the measuring loops is furher supervised by the relay's fault detection polygon. The relay manufacturer claims that this method eliminates the apparent fault impedance loops, which is prominent during single-phase close-up faults. This phenomenon has been illustrated in Chapter 1 (see Figure 1.1 to Figure 1.4). Faults have therefore occurred on the Eskom transmission system for which this method of faulted loop determination had seemingly failed.

- The amount of protection reach compensation that is required where series capacitors are installed could be underestimated due to the harmonic resonant frequencies that exists during fault conditions. Distance protection relay filtering cannot totally filter out the harmonic resonant frequency signals due to the requirement that it should be able to operate at frequencies deviating from 50 Hz by plus or minus 5%. It is therefore required to reduce the reach of the underreaching zone by a further safety factor to safeguard against possible transient overreach.

- The relay's load adaptive fault detection characteristic, which theoretically allows the relay to detect higher resistive faults further away from the relaying point, is a feature to be explored.

- The relay has a load compensation algorithm that aims to correct the measuring error due to load. The algorithm is however based on the assumption that both relay ends have approximately the same X/R ratio and that the earth return currents have nearly the same phase angle as the total fault current at the point of fault. This near homogeneous situation is often not the case in the Eskom network. It is therefore reasonable to assume that the relay would not be able to compensate correctly under non-homogeneous system conditions.

The next section covers similar theory related to relay B, with the aim of gaining a detailed understanding of what the relay's capability and limitations are.

3.3   Relay B (ABB REL531)

This relay was introduced into the Eskom transmission system in early 2003. Problems were experienced with phase-to-earth type faults with high fault resistance, since excessively long fault duration times were recorded. Investigation into the cause of these long duration trip times required an in depth study of the manufacturer's documentation, covering relay logic and algorithms. In a quest to find answers for the relay maloperations, this chapter will focus on the relay theory with the aim of providing a thorough understanding of its functionality, logics and algorithms. Secondary non-intrusive three-phase voltage and current injection testing will be discussed in chapter 6 in an attempt to determine how the relay responds in relationship to theory. The relay uses independent digital signal processors with millisecond accuracy for each measurement element to calculate the apparent impedance. A differential equation capable of evaluating the complete line replica impedance is used prior to fault loop impedance calculation [20]. It should be noted that for this relay the manufacturer is focused towards impedance fault loop evaluation and representation.   Single-phase-to-earth   and   phase-to-phase measurement elements for this relay will be evaluated in accordance with the main focus for this dissertation as discussed in Chapter 1. Relay B has separate zone and phase selection elements for each impedance zone of protection. The zone measuring elements are supervised by the phase selection elements, and as such operation of a zone element cannot occur without pick-up of the relevant phase selection element. Sections 3.3.1 to 3.3.4 will cover the respective zone and phase selection elements for the phase-to-earth and phase-to-phase selection elements.

3.3.1   Single-phase-to-earth - zone measuring element

The single-phase-to-earth zone measuring elements are used by the relay to determine the respective zone for operation during a single-phase-to-earth fault condition.   Single-phase-to-earth loop characteristic as defined by the relay manufacturer is shown in Figure 3.18 on an R-X plane. The relay measures loop phase-to-earth fault impedance and compares the calculated resistive value R_m and reactance X_m with the respective setting values of resistance and reactance. Eq. (3.35) to Eq. (3.38) are provided for relay reach determination by the

manufacturer. Three independent, one for each phase, phase-to-ground measuring elements are available [20]. Positive and negative zone reach limitations have been defined by the manufacturer and are shown as R_m and X_m respectively for resistive and reactive limits.

$$R_m \geq \left[R1PE + \frac{1}{3}(R0PE - R1PE) \right] \cdot p - RFPE$$

(3.35)

$$R_m \leq \left[R1PE + \frac{1}{3}(R0PE - R1PE) \right] \cdot p + RFPE$$

(3.36)

$$X_m \geq -X1PE - \frac{1}{3}(X0PE - X1PE)$$

(3.37)

$$X_m \leq X1PE + \frac{1}{3}(X0PE - X1PE)$$

(3.38)

where

X_m = Measured fault loop reactance

R_m = Measured fault loop resistance

R1PE = Set positive sequence resistance for phase-to-earth element

R0PE = Set zero sequence resistance for phase-to-earth element

RFPE = Set Fault resistance coverage for phase-to-earth element

X1PE = Set positive sequence reactance for phase-to-earth element

X0PE = Set zero sequence reactance for phase-to-earth element

p = per unit value of distance to fault on overhead line
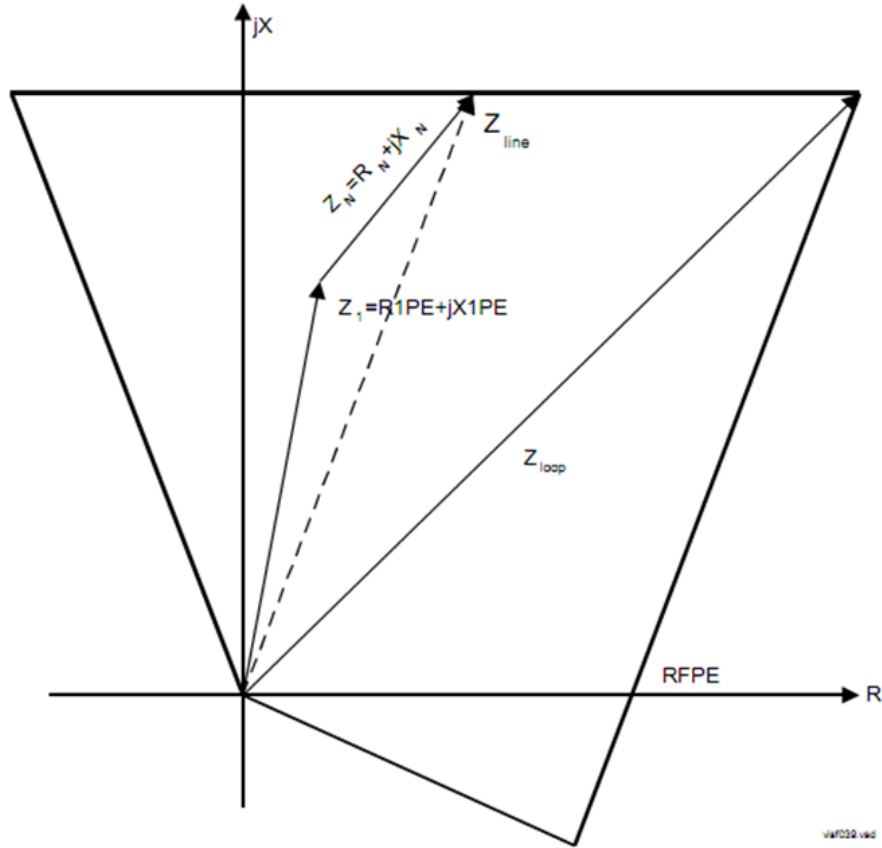
Figure 3.18: Characteristic for the phase-to-earth measuring loop [20]

Using the relay characteristic as depicted by Figure 3.18 and using the zero sequence compensation factor KN = 1/3((Z0 − Z1)/Z1), the following equation derivation is possible

$$Z_N = \frac{1}{3}(Z_0 - Z_1) \tag{3.39}$$

$$Z_0 = R_0 + jX_0 \tag{3.40}$$

$$Z_{Loop} = Z_1 + Z_N + R_F \tag{3.41}$$

$$Z_{Loop} = Z_1 + \frac{1}{3}(Z_0 - Z_1) + R_F \tag{3.42}$$

$$R_{Loop} = R_1 + \frac{1}{3}(R_0 - R_1) + R_F \tag{3.43}$$

$$X_{Loop} = X_1 + \frac{1}{3}(X_0 - X_1) + X_F$$

(3.44)

Also, from Eq. (3.42) it follows that

$$Z_{Loop} = Z_1 + \frac{1}{3}Z_0 - \frac{1}{3}Z_1 + R_F$$

(3.45)

$$Z_{Loop} = \frac{2}{3}Z_1 + \frac{1}{3}Z_0 + R_F$$

(3.46)

$$Z_{Loop} = \frac{1}{3}(2Z_1 + Z_0) + R_F$$

(3.47)

where

X_0 = Zero sequence reactance of overhead line

X_1 = Positive sequence reactance of overhead line

Z_0 = Zero sequence impedance of overhead line

Z_1 = Positive sequence impedance of overhead line

Z_N = Earth-return impedance

R_F = Fault resistance

Eq. (3.47) derived above is the same as Eq. (2.25) derived in Chapter 2, which serves to qualify the algorithm used by the manufacturer for phase-to-earth faults. Replacing the variables R_1, R_0, X_1 and X_0 in Eq. (3.43) and Eq. (3.44) respectively with the actual setting parameters R1PE; R0PE; X1PE and X0PE provides the same equation as that used by the relay manufacturer for the evaluation of the measured impedances.

It is important to note that the value of X_F in Eq. (3.44) is equal to zero (0) for purely resistive faults. The apparent impedance measured for phase-to-earth faults is given by [20].

$$\overline{Z}_{ap} = \frac{\overline{V}_{L1}}{\overline{I}_{L1} + \overline{K}_N \cdot \overline{I}_N} \tag{3.48}$$

where

Z_{ap} = Apparent impedance

V_{L1} = Faulted phase voltage

I_{L1} = Faulted phase current

I_N = Earth return current

$K_N = 1/3(Z_0/Z_1 - Z_1)$

3.3.2   Single-phase-to-earth phase selection element

As already mentioned in the introduction of this chapter, the single-phase-to-earth phase selection elements are used to supervise the single-phase-to-earth zone measuring elements. The relay uses a completely independent phase selection function, commonly referred to as PHS, resulting in improved phase selectivity required for phase selective tripping to ensure stability in transmission networks with long and heavily loaded lines (see Figure 3.19). The phase-selection measurement elements use the same basic algorithm as for the distance-measurement functions, with the exception being the combination of measured quantities for different fault types. The phase selection element ignores the residual current for single-phase-to-earth fault loops. Phase-to-earth fault impedance loop equations for phases L_1, L_2 and L_3 are respectively given by Eq. (3.49), Eq. (3.50) and Eq. (3.51) [20].

$$\overline{Z}_{L1-N} = \frac{\overline{V}_{L1}}{\overline{I}_{L1}} \tag{3.49}$$

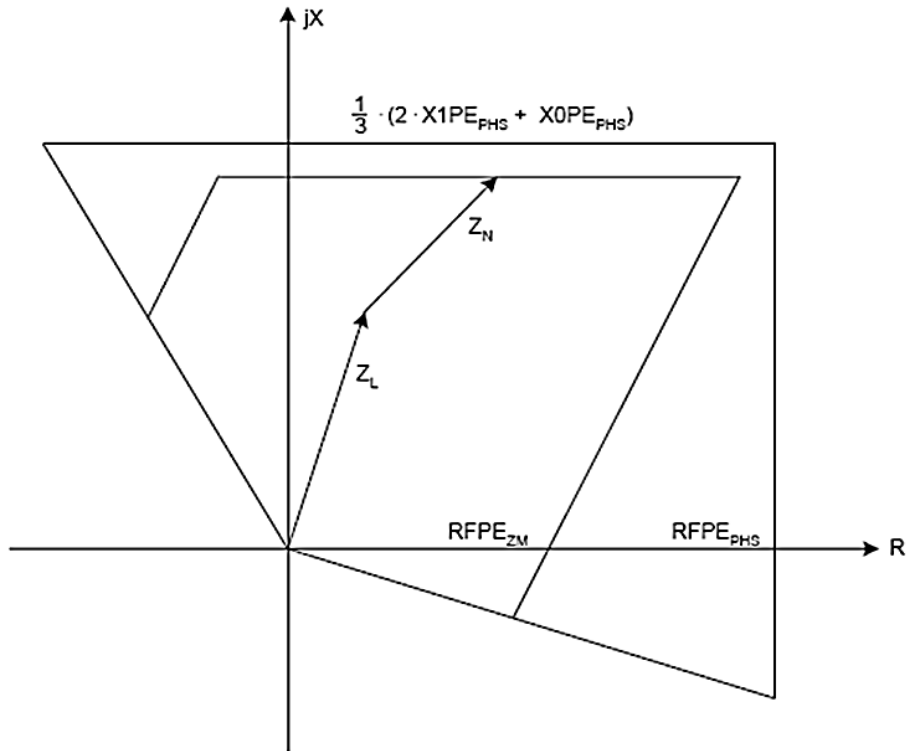$$\overline{Z}_{L2-N} = \frac{\overline{V}_{L2}}{\overline{I}_{L2}} \tag{3.50}$$

$$\overline{Z}_{L3-N} = \frac{\overline{V}_{L3}}{\overline{I}_{L3}} \tag{3.51}$$

Resistive and reactive limitations that must be met before operation in each of the faulted loops (n = 1, 2 or 3) can occur are defined by Eq. (3.52) and Eq. (3.53) [20].

$$-RFPE \le \mathrm{Re}(\overline{Z_{Ln-N}}) \le RFPE \tag{3.52}$$

$$-\left(\frac{1}{3}\right) \cdot \left(2 \cdot X1PE - X0PE\right) \le \mathrm{Im}\left(\overline{Z_{Ln-N}}\right) \le \frac{1}{3} \cdot \left(2 \cdot X1PE + X0PE\right) \tag{3.53}$$

Figure 3.19: Phase-to-earth loop operational characteristics for zone and phase elements [20]

The criteria for setting of the phase selection elements is governed by the requirement to obtain correct and reliable phase selection for all faults on the overhead line to be protected. Protection schemes used on the EHV (extremely high voltage) transmission system normally cater for single-phase reclosing for single-phase-to-earth faults and as such it is therefore important to provide correct phase selection for the first overreaching zone providing 100% line coverage. A 10% to 15% additional safety margin is advised [20]. Figure 3.19 illustrates the operating characteristics of the phase selection as well as the zone measurement elements in the loop domain. It is important to note that this relationship is represented in the loop domain. The significance of this will be highlighted in the laboratory test results discussed in Chapter 6.

It must be noted that the phase selector earth loop characteristic resistive reach crosses the R-axis at 90°. Should careful consideration not be given to this fact, overreaching of the zone elements resistive reach could occur towards maximum reactive reach resulting in incorrect tripping or no tripping at all for faults in this region. $RFPE_{ZM}$ and $RFPE_{PHS}$ in Figure 3.19 represent the set resistive reaches for the zone ($_{ZM}$) and phase selection ($_{PHS}$) measurement elements respectively. The phase-to-earth fault phase selector setting conditions shown in Eq. (3.54), Eq. (3.55) and Eq. (3.56) are relevant for relay operation [20].

$$RFPE_{PHS} > \frac{1}{3} \cdot \left(2 \cdot R1PE_{ZM} + R0PE_{ZM} \right) + RFPE_{ZM}$$

(3.54)

$$X1PE_{PHS} > X1PE_{ZM}$$

(3.55)

$$X0PE_{PHS} > X0PE_{ZM}$$

(3.56)

These conditions are also true for the reverse and non-directional measuring elements. The resistive fault blinder for the zone measurement form and angle with the R-axis of φ_{Loop} [20]

$$\varphi_{Loop} = \arctan\left(\frac{2 \cdot X_1 + X_0}{2 \cdot R_1 + R_0} \right)$$

(3.57)

3.3.3 Phase-to-phase zone measuring element

Phase-to-phase zone measuring elements in this relay are there to determine phase-to-phase fault loops which enter any one of the specific zones that has been set. Impedance measurement for phase-to-phase faults are performed on a per phase basis through comparison of the measured resistance (R_m) and reactance (X_m) with the relative set reach values. It is important to note that the fault resistance (R_F) reach settings are set in ohm per loop, whilst that for the reactive (X_L) reaches shown in Figure 3.20 is set in ohm per phase.

The following resistive (R_m) and reactive (X_m) reach limiting equations must be satisfied for relay operation

$$R_m \geq R1PP \cdot p - \frac{1}{2} \cdot RFPP$$

(3.58)

$$R_m \leq R1PP \cdot p + \frac{1}{2} \cdot RFPP$$

(3.59)

$$X_m \geq -X1PP$$

(3.60)

$$X_m \leq X1PP$$

(3.61)

where

R1PP = Set positive sequence resistance for phase-to-phase element

RFPP = Set Fault resistance coverage for phase-to- phase element

X1PP = Set positive sequence reactance for phase-to- phase element

The factor p in Eq. (3.58) and Eq. (3.59) represents the relative fault position within the reactive reach of the zone, with -1< p <1. For faults on radial lines, the equations for R_m provide two lines parallel to the line angle. These lines cross the R-axis at points D and B respectively as shown in Figure 3.20.

$$D = -\frac{1}{2} \cdot RFPP + j0$$

(3.62)

$$B = \frac{1}{2} \cdot RFPP + j0$$

(3.63)

The resistive limits form an angle (α) with the R-axis, which is given by **Error! Reference source not found.**.

$$\alpha = a \tan\left(\frac{X1PP}{R1PP}\right)$$

(3.64)

The reactive operating limits are illustrated in Figure 3.20 as A = X1PP and C = -X1PP respectively. The relationship of the zone measurements are compared with that of the phase selector measurements and are shown in the loop domain (see Figure 3.21).
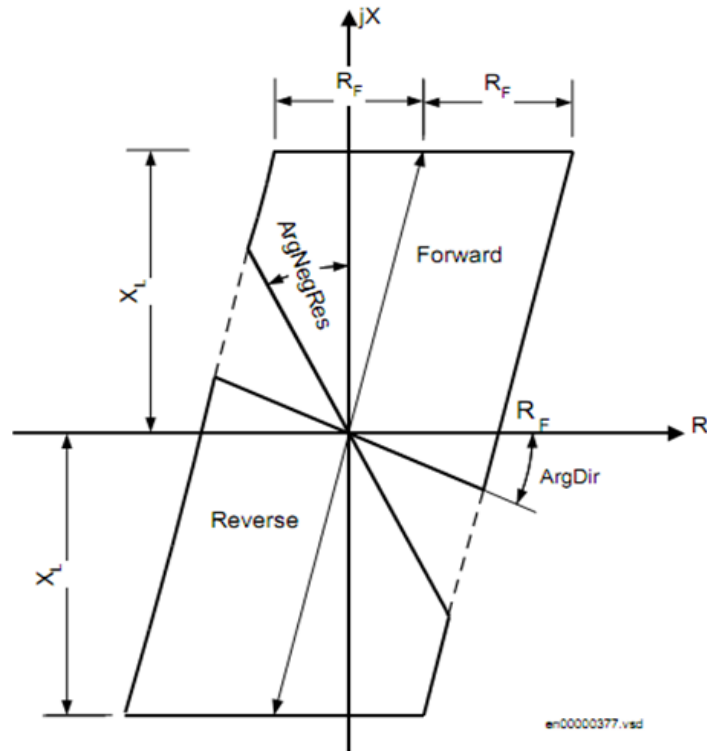
Figure 3.20: Operating characteristic of phase-to-phase zone elements [20]

The relay determines the loop impedance in accordance with Eq. (3.65) [20].

$$\overline{V} = R \cdot \overline{i} + \frac{X}{\omega_0} \cdot \frac{\overline{\Delta i}}{\Delta t} \tag{3.65}$$

where

$\overline{V}$ = sampled values of phase voltage

$\overline{i}$ = sampled values of phase current

ΔI = changes in phase current between samples

R = Loop resistance

Δt = change in time

X = Loop reactance

ω_0 = fundamental system frequency

The reactive (X_m) and resistive (R_m) values are then determined from the real (Re) and imaginary (Im) components of the measured voltage (V) and current (I) as well as the change (Δ) in the real and imaginary components of the measured current. Eq. (3.66) and Eq. (3.67) represent the reactive and resistive portions of the measured impedance [20].

$$X_m = \omega_0 \cdot \Delta t \cdot \frac{\text{Re}(\overline{V}) \cdot \text{Im}(\overline{I}) - \text{Im}(\overline{V}) \cdot \text{Re}(\overline{I})}{\Delta \text{Re}(\overline{I}) \cdot \text{Im}(\overline{I}) - \Delta \text{Im}(\overline{I}) \cdot \text{Re}(\overline{I})}$$ (3.66)

$$R_m = \frac{\text{Im}(\overline{V}) \cdot \Delta \text{Re}(\overline{I}) - \text{Re}(\overline{V}) \cdot \Delta \text{Im}(\overline{I})}{\Delta \text{Re}(\overline{I}) \cdot \text{Im}(\overline{I}) - \Delta \text{Im}(\overline{I}) \cdot \text{Re}(\overline{I})}$$ (3.67)

where

R_m = measured resistance

X_m = measured reactance

3.3.4 Phase-to-phase phase selection element

The phase-to-phase phase selection elements are utilised by this relay to supervise the phase-to-phase zone elements. Operation of the phase-to-phase zone elements can therefore not occur, unless the relevant phase selection element has picked up. The different fault loop equations for phase-to-phase fault reactive and resistive reaches are given by Eq. (3.68) and Eq. (3.69) [20]

$$X_{Lm-Ln} = \text{Im}\left(\frac{\overline{V}_{Lm} - \overline{V}_{Ln}}{-\overline{I}_{Ln}}\right)$$ (3.68)

$$R_{Lm-Ln} = \text{Re}\left(\frac{\overline{V}_{Lm} - \overline{V}_{Ln}}{-\overline{I}_{Ln}}\right)$$ (3.69)

where
X_{Lm-Ln} = measured reactance in relevant phase-phase measuring loop

R_{Lm-Ln} = measured resistance in relevant phase-to-phase measuring loop

m, n = 1, 2 and 3, m ≠ n

Operational conditions for phase-to-phase measuring loops are given by [20] for the reactive and resistive reaches respectively in Eq. (3.70) and Eq. (3.71).

$$-2 \cdot X1PP \leq X_{Lm-Ln} \leq 2 \cdot X1PP \tag{3.70}$$

$$-RFPP + p \cdot X1PP \cdot \tan(20°) \leq R_{Lm-Ln} \leq RFPP + p \cdot X1PP * \tan(20°) \tag{3.71}$$

Where $-1 \leq p \leq 1$ is the relative fault position within the reactive reach of X1PP. The reach setting parameters for the phase-to-phase measurement loops are X1PP and R1PP respectively. A further two conditions are imposed on the residual current requirements during faults involving earth [20].

$$\left|3 \cdot I_0\right| < 0.2 \cdot I_r \tag{3.72}$$

or

$$\left|3 \cdot I_0\right| < \frac{INBlockPP}{100} \cdot I_{ph \max} \tag{3.73}$$

where

I_r = rated current of the terminal

INBlockPP = setting for the residual current below which operation of the phase-to-phase fault loops is allowed

When both conditions are satisfied, both the phase-to-earth and phase-to-phase measurement elements will operate.

Eq. (3.74), Eq. (3.75), Eq. (3.76), Eq. (3.77) and Eq. (3.78), Eq. (3.79) and Eq. (3.80) below strive to highlight the difference from a theoretical point of view between the apparent impedance calculated for the zone measuring elements and that for the phase selector. These equations can be derived from basic principles with the use of positive, negative and zero-sequence networks theory.

Equations for apparent impedance (Z_{ap}), resistance and reactance for phase-to-phase faults is given by [20]

$$Z_{ap} = \frac{V_A - V_b}{I_A - I_B} \quad \Omega \text{ per phase} \tag{3.74}$$

Knowing that $I_A = -I_B$ for the A to B phase loop, it follows that

$$Z_{ap} = \frac{V_A - V_b}{-2I_B} \quad \Omega \text{ per phase} \tag{3.75}$$

$$X_{ap} = \text{Im}\left(\frac{V_A - V_b}{-2I_B}\right) \quad \Omega \text{ per phase} \tag{3.76}$$

$$R_{ap} = \text{Re}\left(\frac{V_A - V_b}{-2I_B}\right) \quad \Omega \text{ per phase} \tag{3.77}$$

The phase selector loop reach equations for impedance (Z_{PHS}), reactance (X_{PHS}) and resistance (R_{PHS}) as given by [20] is

$$Z_{PHS} = \frac{V_A - V_b}{-I_B} \quad \Omega \text{ per loop} \tag{3.78}$$

$$X_{PHS} = \text{Im}\left(\frac{V_A - V_b}{-I_B}\right) \quad \Omega \text{ per loop} \tag{3.79}$$

$$R_{PHS} = \text{Re}\left(\frac{V_A - V_b}{-I_B}\right) \quad \Omega \text{ per loop} \tag{3.80}$$

where
Z_{ap} = Apparent impedance measured for protective zone

R_{ap} = Apparent resistance measured for protective zone

X_{ap} = Apparent reactance measured for protective zone

Z_{PHS} = Phase Selector impedance measured

R_{PHS} = Phase Selector resistance measured

X_{PHS} = Phase Selector reactance measured

From the apparent and phase selector loop reach, given in Eq. (3.75) and Eq. (3.78), it can be concluded that $Z_{PHS} = 2 * Z_{ap}$. With the actual setting of the reactive reach of the phase selector in ohm per phase instead of ohm per loop, it follows that in order to make a proper comparison between the phase-to-phase zone measurement and the phase-to-phase phase selector measurement, both should be represented in the same domain. This is especially important since the angles that the zone and phase selector reaches make with the resistive-axis differ, which can result in unwanted overlapping of the characteristics.
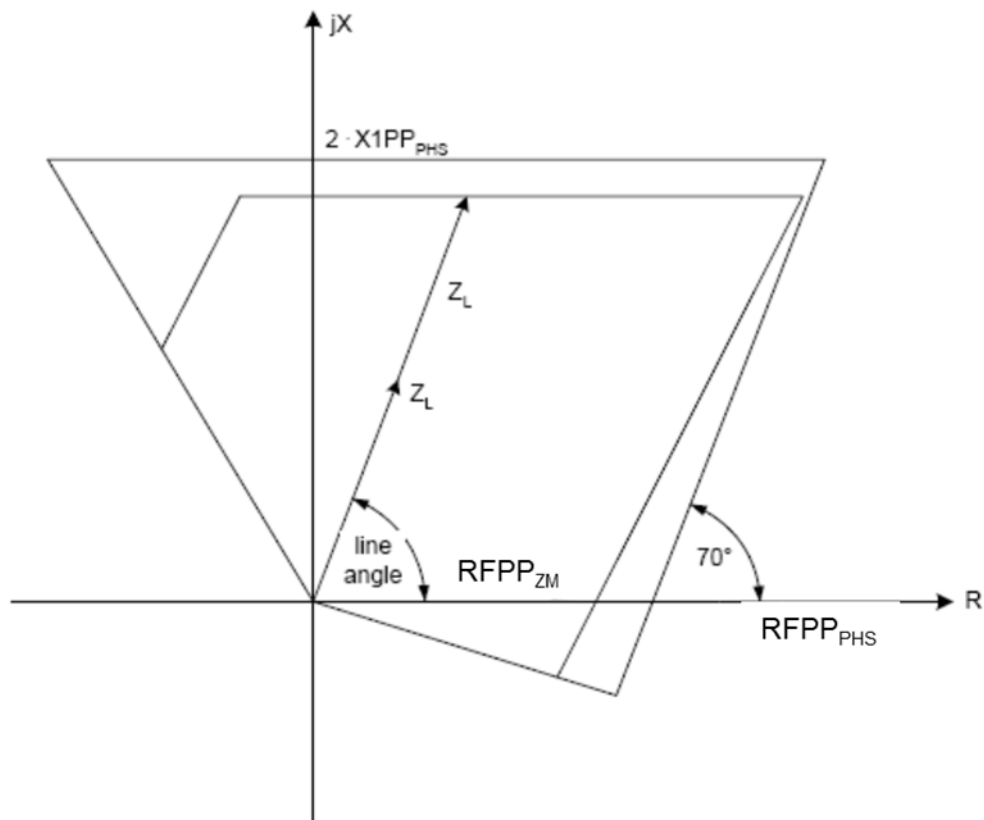
Figure 3.21: Phase selection with zone operating characteristic [20]

The required reactive reach of the phase selection element for phase-to-phase faults needs to satisfy the following condition [20]

$$X1PP_{PHS} > X1PP_{ZM}$$

(3.81)

The resistive reach setting is dependent on the line angle as dictated by the settings of the zone elements and is therefore [20]

$$\varphi_{Line} = a\tan\left(\frac{X1PP_{ZM}}{R1PP_{ZM}}\right)$$

(3.82)

The following conditions apply when the line angle is greater than 70° and less than 90° [20]

$$RFPP_{PHS} > RFPP_{ZM}$$

(3.83)

$$RFPP_{PHS} > 2\cdot R1PP + RFPP_{ZM} - 0.72\cdot X1PP_{ZM}$$

(3.84)

where

$X1PP_{PHS}$ = Reactive phase-to-phase setting for phase selector element

$R1PP_{PHS}$ = Resistive phase-to-phase setting for phase selector element

$RFPP_{PHS}$ = Fault resistance setting for phase selector element

For phase-to-phase-to-earth faults the criteria for earth fault detection as defined in Eq. (3.72) and Eq. (3.73) must be satisfied. Line parameters are entered for each independent zone of protection allowing the relay to accurately adjust the earth compensation factor and zone operating characteristics to fit the line characteristic angle.

3.3.5 Directional determination

This relay's independent operating protection zones can function in forward or reverse directional or non-directional mode. Five distance zones are available with only the first three having phase selective functionality and are therefore capable of doing single-phase tripping. Zone 5 is only used in a non-directional switch-onto-fault functionality, with zone 6 forming the outer zone of the out-of-step function. The directional elements use positive sequence memory voltage for directional polarization for each independent measuring loop. Correct directional determination for each measurement loop is therefore ensured, even during evolving faults within complex network configurations [20].

The directional lines, as illustrated in Figure 3.20, are settable within the second and fourth quadrant, but careful consideration is required before deviating from the manufacturers default settings of 15° and 25° (115°) for ArgDir and ArgNegRes respectively. Phase-to-phase-to-earth faults on very long heavily loaded lines could warrant such a deviation. For correct relay operation under a phase-to-phase-to-earth fault condition these angles must be selected to ensure that both phase-to-earth faulted loops measurements fall within the directional area defined by these angular lines. It must be noted that changing these angles also impacts the reverse reach directional line angles [20].

The angular limitation for phase L_1-N and L_1-L_2 are given by Eq. (3.85) and Eq. (3.86) [20].

$$-ArgDir < \arg \frac{0.8 \cdot V_{1L1} + 0.2 \cdot V_{1L1M}}{I_{L1}} < ArgNeg \operatorname{Re}s \tag{3.85}$$

$$-ArgDir < \arg \frac{0.8 \cdot V_{1L1L2} + 0.2 \cdot V_{1L1L2M}}{I_{L1L2}} < ArgNeg \operatorname{Re}s \tag{3.86}$$

where

V_{1L1} = Positive sequence voltage for phase L1

V_{1L1M} = Positive sequence memory voltage for phase L1

I_{L1} = Positive sequence current for phase L1

I_{L1L2} = Positive sequence current for phase L1 to L2

ArgDir = lower angular boundary for forward characteristic

ArgNegRes = upper angular boundary for forward characteristic

3.3.6   Impact of series compensation

3.3.6.1   Directional control

Protection relays require directional control functionality to facilitate tripping for faults in either the forward or reverse direction. The installation of series capacitors on overhead lines necessitates the use of directional elements. Without the directional functionality impedance protection relays could measure faults on the line being protected in reverse and cause the relay to block instead of tripping. Tripping is mostly only allowed in the forward direction, whilst the reverse elements will perform

a block function. This relay has a dedicated directional control function for series compensated lines, which has been designed to cope with voltage reversal during system faults. Directionality is ensured through the use of a continuously synchronized memory and healthy phase polarized voltage. Series capacitors installed on long lines to improve the load transfer capability has two negative side effects which impacts on distance relay impedance measurement. In the first instance the series capacitance has a steady state impact on the line inductance and secondly causes harmonic oscillations which interfere with inductive measurements [20

Series capacitors can cause voltage reversal during faults that causes conventional distance protection to not correctly determine directionality and therefore can trip incorrectly. This relay makes use of a memorized positive sequence polarizing voltage controlled by a criteria based on impedance measurement to correctly determine directionality. This memory control impedance measurement is independently set to ensure coverage for faults that can cause voltage reversal. It also has a high-speed measurement function, which is not impacted to the same extent as normal impedance measurement devices. The normal and high-speed underreaching zone 1 elements does however need to be carefully set to not cause overreach due to the line reactance compensation and harmonic oscillations caused by the series capacitor during system faults [20].

The relay removes the faulty phase voltage measurements from the positive sequence voltage filter to stabilize the polarizing voltage against phase angle changes due to voltage reversal on all faulted phases. Memory voltage is used for stabilization during the first 100 ms of a close-up three-phase fault. Should the fault condition continue, directionality is sealed in and no further directional measurement is allowed until after the fault has been cleared and the impedance measurements have reset [20].

Reactive and resistive reach setting limitations for positive and zero sequence are relevant, and these are given in Eq. (3.87) to Eq. (3.90). These reach setting limitations are used by the relay to determine the ranges within which to cater for the

dynamics associated with series capacitors during system fault conditions. The resistive reach algorithms for the phase-to-earth and phase-to-phase loops take into account the line reactance as well as the zone 2 fault resistance setting [20].

$$X1PP = X1PE = 2 \cdot X_C \cdot K \tag{3.87}$$

$$X0PE = 1.6 \cdot X_C \cdot K \tag{3.88}$$

$$RFPE \geq 1.1 \cdot (0.34 \cdot X_C \cdot K + RFPE_{ZM2}) \tag{3.89}$$

$$RFPP \geq 1.1 \cdot (0.68 \cdot X_C \cdot K + 0.68 \cdot X1PP + RFPP_{ZM2}) \tag{3.90}$$

$$K = \frac{(I_1 + I_2)}{I_1} \tag{3.91}$$

where

$X_C \cdot K$ = *maximum capacitive reactance the relay can be exposed to*

K = *capacitor reactance enlarging factor for remote in-feed of fault current*

I_1 = *Current measured by protection*

I_2 = *remote in-feed current*

3.3.6.2 Voltage reversal

The normal impedance measurement of the relay is influenced by voltage reversal, capacitor enlargement due to remote end in-feed and sub-harmonic oscillations. Voltage reversal can cause a false fault condition in that a voltage zero point can result on the protected or adjacent lines [20]. This possibility needs to be carefully evaluated and any instantaneous zones reach needs to be reduced accordingly. The following example shows how the protection of a series compensated line can be treated.

Considering a distance protection relay at substation A in Figure 3.22, with a three-phase fault on the other side of the series capacitor on the next line. A three-phase fault is chosen, since it is considered to have the biggest impact for voltage reversal. The reactive inductance of the capacitor, the length of line between substation B and

the capacitor bank and the magnitude of the in-feed I_2 will dictate whether voltage reversal will occur as well as the magnitude of the voltage reversal. The capacitive reactance enlargement factor K can be determined with the use of Eq. (3.91). Voltage reversal will cause an effective zero voltage at some point in the system that presents itself to the impedance protection as a fault condition [20].
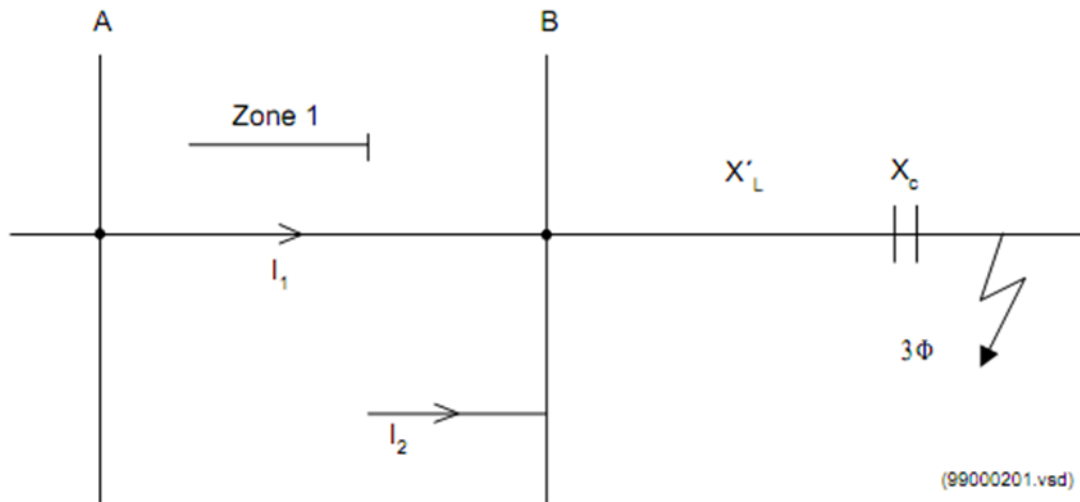
Figure 3.22: Network with Series Capacitor [20]

Should the voltage reversal occur on the line between substation A and substation B and fall within the instantaneous underreaching zone 1 reach an unnecessary trip command to the breaker at substation A will be issued. Directional polarization that is normally implemented for series compensated lines together with the normal distance protection will prevent the protection at substation B from operating [20].

3.3.6.3   Sub harmonic oscillation

The possibility of sub harmonic oscillations has already been mentioned before. The impact of sub harmonic oscillation on an underreaching zone is shown in Figure 3.23.

The degree of series compensation (C) in Figure 3.23 is given by [20]

$$C = \frac{X_C}{X_1}$$

(3.92)

where

X_C = *series capacitor reactance*

$X1$ = *total positive sequence reactance from the source to the fault*

A three-phase fault at the remote terminal of the series capacitor needs to be evaluated to determine the worst-case impact on the impedance protection. Sub-harmonic oscillations, which are the result of dynamic interaction between the series capacitor installation and the network, will necessitate further reduction of an underreaching instantaneous zone, which was already impacted in steady state as a result of the series compensation. Figure 3.23 illustrates the reduction curve provided by the relay manufacturer, which can be used to determine the required percentage reduction in zone reach. The value of (*p)* obtained from the graph represents the maximum settable reach, as a result of sub-harmonic oscillations, for an instantaneous underreaching zone. A detailed analysis of the sub-harmonic oscillation phenomenon was done under section 3.2.4 and shown in Figure 3.10 and Figure 3.11.
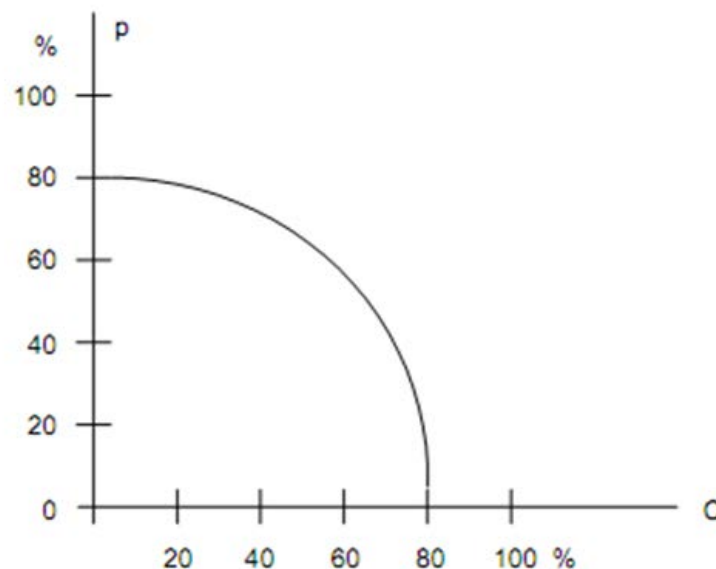
Figure 3.23: Sub-harmonic reduction curve [20]

The relay manufacturer has developed different algorithms, listed as (Eq. (3.93) to Eq. (3.98)), for relays in different system locations with respect to a series capacitor bank [20]. Zone suffixes (ZM_n, n = 1, 2, 3, 4, 5, 6) have been added to the equations

to provide better clarity (refer Eq. (3.81),   ,   ). Several different protection relay setting limitations are provided by the manufacturer for different relay positioning with respect to the position of the series capacitor bank. These limitation algorithms are shown here to provide detailed background for this system condition, some of which will be used in Chapter 5 during the fault analysis process where series capacitors are involved. These limitations are of crucial importance, since wrongly applied relay settings could cause unnecessary protection operations and possibly lead to supply interruptions. Positive sequence reactance reach limitations for phase-to-phase (X1PP) and phase-to-earth (X1PE) reaches, where the protection relay location is specifically qualified are given by [20]

Protection on non-compensated lines not facing series capacitor

$$X1PP_{ZM1} = X1PE_{ZM1} = \frac{X_1 \cdot p}{100}$$

(3.93)

Protection on non-compensated lines facing series capacitor

$$X1PP_{ZM1} = X1PE_{ZM1} = \left(X_1 - K \cdot X_{neg}\right) \cdot \frac{p}{100}$$

(3.94)

Protection on series compensated lines

$$X1PP_{ZM1} = X1PE_{ZM1} = \left(X_1 - X_C\right) \cdot \frac{p}{100}$$

(3.95)

The zero sequence reactance (X0PE) for the above conditions needs to be adjusted in a similar way, and can therefore be set in accordance with

$$X0PE_{ZM1} = \frac{X_0 \cdot X1PE_{ZM1}}{X_1}$$

(3.96)

Zero sequence reactance reach limitations, where the protection relay location is specifically qualified, are given by [20]

Protection on non-compensated lines but affected by series capacitor and compensated line with series capacitor not within the normal reach of zone 1

$$X0PE_{ZM1} = \frac{X_0 \cdot X1PE_{ZM1}}{X_1}$$

(3.97)

Protection on compensated line with series capacitor within the normal zone 1 reaches

$$X0PE_{ZM1} = \frac{X_0 \cdot (X1Z1 + X_C)}{X_1}$$

(3.98)

where

K = *enlarging factor due to remote in-feed*

X_{neg} = *resulting capacitive reactance of compensated line with fault on remote capacitor terminal*

X_C = *Series capacitor reactance*

In some cases the resultant value of the phase-to-phase or phase-to-earth reactance (X1PP or X1PE) will be a negative value, which is an indication that the underreaching zone 1 must be de-activated. Similar limitations exist for the phase-to-phase (R1PP), phase-to-earth (R1PE) and zero sequence (R0PE) resistive reaches of the relay. These are given in Eq. (3.99) to Eq. (3.101) [20].

For non-compensated lines affected by series compensation and compensated lines with series capacitor not within the normal zone 1 reach Eq. (3.99) is valid.

$$R1PP_{ZM1} = R1PE_{ZM1} = \frac{R_1 \cdot X1PP_{ZM1}}{X_1}$$

(3.99)

For compensated line with series capacitor within the normal zone 1 reach Eq. (3.100) and Eq. (3.101) is used.

$$R1PP_{ZM1} = R1PE_{ZM1} = \frac{R_1 \cdot (X1PP_{ZM1} + X_C)}{X_1}$$

(3.100)

$$R0PE_{ZM1} = \frac{R_0 \cdot X0PE_{ZM1}}{X_0}$$

(3.101)

The zone 1 reach at substation A, shown in Figure 3.22, will need to be reduced in accordance with Eq. (3.94), for protection relay located on a non-compensated line, since the series capacitor is positioned within the forward reach of the relay. Remember that this seemingly overreach of the zone 1 reach of the relay at substation A is caused by the in-feed at substation B, which causes an enlarging effect on the capacitive reactance of the series capacitor. The position of the series capacitor on line B- also plays a large role. The closer it is positioned to substation B the greater the impact would be on the zone 1 reach limitation at substation A. The relay's fault resistive reach is limited by the minimum load impedance as well as the reactive reach set for the zone. The minimum load impedance, $Z_{LOADMIN}$ has been defined by Eskom transmission as the minimum allowable healthy system phase voltage of 0.85 p.u. divided by the maximum phase current of 1.5 p.u. The fault resistive reach limitations for sub-harmonic oscillations has been given by [20].

$$RFPE_{ZM1} \leq 0.83 \cdot \left(2 \cdot X1PE_{ZM1} + X0PE_{ZM1} \right)$$ (3.102)

$$RFPE_{ZM1} \leq 0.8 \cdot Z_{LOADMIN}$$ (3.103)

$$RFPP_{ZM1} \leq 3 \cdot X1PP_{ZM1}$$ (3.104)

$$RFPP_{ZM1} \leq 1.6 \cdot Z_{LOADMIN}$$ (3.105)

Besides the impact that the series capacitor reactance has on the underreaching zone 1 reach, the overreaching zone as well as the reverse reaching zone needs special attention. It is essential that the zone 2 reach detects all faults on the line being protected, with or without the series capacitor in service. This is of paramount importance on lines with reduced zone 1 coverage. For this reason the manufacturer recommends a setting for X1PP and X1PE of 150% of the lines positive sequence reactive impedance (X_1).

$$X1PP_{ZM2} = X1PE_{ZM2} = 1.5 \cdot X_1$$ (3.106)

The resistive and zero sequence reactance values for zone 2 are set in accordance with the ratio X1PP$_{ZM2}$/X$_1$, whilst the normal limitations are valid for the fault

resistance settings RFPP and RFPE. Special care must be exercised for the reverse zone, since total coverage of the remote end overreaching zone 2 element for permissive overreaching schemes must be ensured at all times. The reactive and resistive reach is dependent on the remote end zone 2 reaches $X1PP_{ZM2}$ and $X1PE_{ZM2}$ and are given by [20]

$$X1PP_{ZM3} \geq 1.2 \cdot X1PP_{ZM2} - 0.5 \cdot \left(X_1 - X_C \right) \tag{3.107}$$

$$X1PE_{ZM3} \geq 1.2 \cdot X1PE_{ZM2} - 0.5 \cdot \left(X_1 - X_C \right) \tag{3.108}$$

All the other zone 3 setting reaches (RFPP, RFPE, X0PE) are set in accordance to the line data and in the correct relationship with the reactance settings. A multiplication factor of $X1PP_{ZM3}$/X1 also needs to be used to ensure that R/X limitaions of the relay are not exceeded, whilst the normal load encroachment limitations must also be considered. Setting, for example, the remote end zone 2 reactive reach to 150% of the line's positive sequence reactance, would require the local relay's reverse reactive reach $X1PP_{ZM3}$ and $X1PE_{ZM3}$ to be set to at least 1.2 * ($X1PP_{ZM2}$(remote end) – X1) and 1.2 * ($X1PE_{ZM2}$(remote end) – X1) respectively.

3.3.6.4   High-speed function

The high-speed function only has a dynamic characteristic that cannot be verified using steady state characteristic location methods as with normal distance zone characteristics. Since the focus of this document is on steady state measurements only limited exposure will be given to this function. The high-speed measurement elements are individually settable for reactance and resistance for both phase-to-earth and phase-to-phase measurement loops. The generic characteristic is illustrated in Figure 3.24 [20]. The high-speed characteristic is a combination of a mho and quad characteristic as shown in Figure 3.24.

The relay manufacturer claims that series compensation and the effects associated with it during system disturbances, has very little impact on the high-speed underreaching zone due to the reaction time of between 10 ms to 15 ms of this function. Energy stored in the series capacitor requires time to influence the fault

current and voltage, therefore only limited reduction of the high-speed underreaching zone reach is required. The high-speed function has predefined criteria for operation of the phase-to-earth and phase-to-phase measurement loops. These can be represented by Eq. (3.109) to Eq. (3.123) as provided by [20].
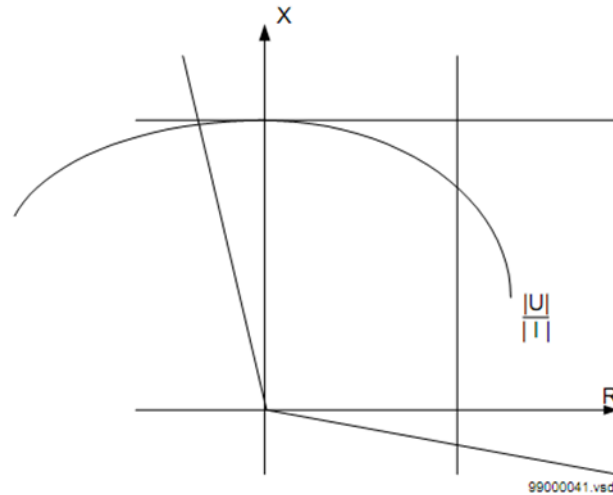
Figure 3.24: High-speed operation characteristic [20]

Residual current limitation for the phase-to-earth loop

$$|I_N| > 0.2 \cdot I_r \tag{3.109}$$

and

$$|I_N| > 0.2 \cdot \max\left[\left||\overline{I_{L1}}| - |\overline{I_{L2}}|\right|, \ \left||\overline{I_{L2}}| - |\overline{I_{L3}}|\right|, \ \left||\overline{I_{L3}}| - |\overline{I_{L1}}|\right|\right] \tag{3.110}$$

Difference in phase current and residual current for the phase-to-phase loops

$$\Delta\left|\overline{I_{L1}} - \overline{I_{L2}}\right| > 0.5 \cdot I_r \tag{3.111}$$

$$\Delta\left|\overline{I_{L2}} - \overline{I_{L3}}\right| > 0.5 \cdot I_r \tag{3.112}$$

$$\Delta\left|\overline{I_{L3}} - \overline{I_{L1}}\right| > 0.5 \cdot I_r \tag{3.113}$$

and

$$\left| \overline{I_N} \right| < 0.4 \cdot \max \left[\left| \overline{I_{L1}} - \overline{I_{L2}} \right|, \quad \left| \overline{I_{L2}} - \overline{I_{L3}} \right|, \quad \left| \overline{I_{L3}} - \overline{I_{L1}} \right| \right]$$

(3.114)

where

I_r = terminal rated current

I_{Ln} (n = 1, 2, 3) = corresponding phase currents

The reactive and resistive measurements for the phase-to-earth measuring elements are determined using the line model equation Eq. (3.115) [20].

$$V_{L1} = L \cdot \frac{dI_{L1}}{dt} + L_N \cdot \frac{d_{IN}}{dt} + R_{FN} \cdot I_N$$

(3.115)

where

L = positive sequence inductance

L_N = line earth return inductance for high-speed zone

R_{FN} = the loop resistance for high-speed zone

Although Eq. (3.115) is claimed to be accurate and caters for line impedance coupled voltage and current transients, non-coupled transients caused through capacitive voltage transformer measurements can result in extensive overreach if adequate voltage filtering is not done. The operation of the high-speed function does not allow enough time to perform sufficient filtering and therefore the manufacturer employs yet another algorithm (Eq. (3.116)) in an attempt to limit erroneous reactive measurement. This algorithm is however sensitive to impedance coupled voltage and current transients, whilst it caters well for the non-coupled transients. The combination of the two algorithms (Eq. (3.115) and Eq. (3.116)) therefore provides a good solution [20].

$$\frac{\left| V_{L1} \right|}{\left| I_{L1} \right|} < \left(X + X_{NH} \right)$$

(3.116)

where
X = the set positive sequence reactance for high-speed zone
X_{NH} = the set earth return reactance for high-speed zone

For phase-to-phase measuring elements, the same limitations in terms of coupled and non-coupled transients exists, and therefore a similar route as for the phase-to-earth elements was followed. Eq. (3.117) and Eq. (3.118) has been used to define the line model and stabilizing measurement algorithms [20].

$$V_{L1-L2} = L \cdot \frac{d}{dt}(I_{L1} - I_{L2}) + R_F \cdot (I_{L1} - I_{L2})$$ (3.117)

$$\frac{|V_{L1} - V_{L2}|}{|I_{L1} - I_{L2}|} < X$$ (3.118)

3.3.7   Impact of fault resistance

3.3.7.1   Normal distance function

The relay has independent settable resistive reaches for each protection measurement zone, applicable to phase-to-phase (RFPP) and phase-to-earth (RFPE) faults, which allows for high resistive coverage with the communication aided overreaching zone. Fault resistance, which is a combination of arc-resistance, tower footing resistance and resistance associated with the tower construction, plays a major role in the performance of impedance relays, whether in a phase-to-phase or phase-to-earth fault loop. Although the tower and tower footing resistance needs to be within a utilities specification, these do change and should be measured to determine an average resistance value for a line. The resistance associated with the fault arc, can be calculated with the use of the Warrington equation [20].

$$R_{arc} = \frac{28707 \cdot L_{arc}}{I^{1,4}}$$ (3.119)

where

L_{arc} = length of the fault arc in meters

I = fault current in A

R_{arc} = Fault resistance in the arc

The maximum possible fault resistance coverage, as per manufacturer's definition, that could be safely set on the relay is a function of minimum load impedance and

the set reactive reach.   Eq. (3.120) to Eq. (3.123) provides the maximum settable limits for phase-to-earth and phase-to-phase fault resistance [20].

$$RFPE \leq 0.83 \cdot \left(2 \cdot X1PE + X0PE \right) \tag{3.120}$$

$$RFPE \leq 0.8 \cdot Z_{LOADMIN} \tag{3.121}$$

$$RFPP \leq 3 \cdot X1PP \tag{3.122}$$

$$RFPP \leq 1.6 \cdot Z_{LOADMIN} \tag{3.123}$$

For system conditions where the fault loop characteristic angle for phase-to-earth or phase-to-phase faults is not more than three times larger than the maximum load angle the following resistive fault limitations apply [20].

$$RFPE \leq 0.8 \cdot Z_{LOADMIN} \cdot \left[\cos \varphi - \left(\frac{2 \cdot R1PE + R0PE}{2 \cdot X1PE + X0PE} \right) \cdot \sin \varphi \right] \tag{3.124}$$

and

$$RFPP \leq 1.6 \cdot Z_{LOADMIN} \cdot \left[\cos \varphi - \frac{R1PP}{X1PP} \cdot \sin \varphi \right] \tag{3.125}$$

The fault resistance for the underreaching zone should also be limited to [20]

$$RFPE \leq 4.5 \cdot X1PE \tag{3.126}$$

It must be noted, that although mutual coupling does not form part of this document, mutual coupling on long, in service, parallel lines running in the same servitude or worse still, on the same tower structure will have a reduction in overreaching zone reaches due to the effect of the zero sequence mutual coupling.   The reduction factor for overreaching zones, which will be the greatest for single-phase-to-earth faults towards the end of the line, are given in Eq. (3.127) as [20]

$$\overline{K}_0 = 1 - \frac{\overline{Z}_{mo}}{2 \cdot \overline{Z}_1 + \overline{Z}_0 + \overline{Z}_{mo} + 3R_F}$$

(3.127)

Similar overreaching problems exist for underreaching zones when the parallel circuit is out-of-service and earthed both sides. Special care must therefore be taken to ensure that this system condition is evaluated and the relay is set in accordance with the manufacturer's specifications, or as the system dictates.

3.3.7.2   High-speed function

This function is only mentioned here for the sole purpose of complete coverage of the relay's functionality, and does not play a role in the purpose of this document. The high-speed function resistive setting requirements differ from the normal distance zones in that both the line resistance and the fault resistance must be included in a single resistive setting. The fault resistive coverage for both the phase-to-earth and phase-to-phase measuring elements on a per loop base are defined in Eq. (3.128) and Eq. (3.129).

$$R_F = RFPE - \left(p \cdot \frac{2 \cdot R_1 + R_0}{3} \right)$$

(3.128)

$$R_F = RFPP - p \cdot R_1 \cdot 2$$

(3.129)

where

R_F = *Fault resistance*

R_1 = *positive sequence line resistance*

R_0 = *zero sequence line resistance*

p = *per unit value of relay reach*

Resistive reach limits for the high-speed function of 0.8 and 0.6 * $Z_{LOADMIN}$ must be applied for the phase-to-earth and phase-to-phase loops respectively. The minimum load impedance ($Z_{LOADMIN}$) has been given under section 3.3.6 as the minimum allowable healthy system phase voltage of 0.85 p.u. devided by the maximum phase current of 1.5 p.u.

3.3.8 Influence of load

The reactance measurement algorithm for the underreaching zone 1 compensates for the impact that load current has on the impedance measurement. The relay also has resistive reach limitations to compensate for load encroachment. The manufacturer has provided recommendations as shown in Eq. (3.130) and Eq. (3.131) [20].

$$Z_{LOADMIN} \leq \frac{V^2}{S}$$

(3.130)

$$RF_{Z1} \leq 3 \cdot X1_{Z1}$$

(3.131)

where

V = minimum phase-to-phase system voltage

S = maximum apparent load MVA

RF_{Z1} = zone 1 resistive limit

$X1_{Z1}$ = zone 1 reactive setting

The load impedance is also defined as a function of the system voltage and current. The worst case load impedance can therefore be calculated from the minimum voltage and the maximum load current. Eq. (3.132) represents the minimum load impedance under emergency load transfer conditions for a given line.

$$Z_{LOADMIN} = \frac{V_{MIN}}{\sqrt{3} \cdot I_{MAX}}$$

(3.132)

The fault resistance that could be covered by the distance relay is therefore limited firstly by the maximum load that can be transferred and secondly by limitations of the relay itself in terms of the maximum allowable R/X-ratio. For this relay the maximum R/X-ratio is equal to 3 as indicated in Eq. (3.131). The situation therefore arises where Eq. (3.132) dictates the maximum resistive reach and therefore forces the maximum settable resistive reach to a value less than the maximum limit as defined by Eq. (3.131).

3.3.9 Summary

The zone and phase selection elements of relay B that are applicable to this dissertation has been discussed in detail together with reach and reach limitation algorithms suggested by the relay manufacturer for different system conditions. The following facts requires consideration during relay setting and fault investigations:

- Independent zone reach and phase selection elements have to be set for each of the phase-to-earth and phase-to-phase zones.

- The reactive reaches are set in ohms/phase, whilst the resistive reaches are set in ohms/loop. This is an important fact to remember especially when attempting to co-ordinate with relays from a different manufacturer.

- The maximum possible fault resistance coverage that could be safely set on the relay is a function of minimum load impedance and the set reactive reach.

- The maximum allowable R/X-ratio is equal to 3 as indicated in Eq. (3.131).

- The relay has five distance zones of which only the first three have phase selective functionality capable of doing single-phase tripping.

- The manufacturer claims that correct directional determination for each measuring loop are ensured, even during evolving faults within complex network configurations.

- This relay has a dedicated directional control function for series compensated lines, which has been designed to cope with voltage reversal during system faults. Directionality is ensured through the use of a continuously synchronized memory and healthy phase polarized voltage. The relay uses a memorized positive sequence polarizing voltage controlled by an impedance measurement criteria to correctly determine directionality. This memory control impedance measurement is independently set to ensure coverage for faults that can cause voltage reversal.

- The normal impedance measurement of the relay is influenced by voltage reversal, capacitor enlargement due to remote end in-feed and sub-harmonic oscillations. Voltage reversal can cause a false fault condition in that a voltage zero point can result on the protected or adjacent lines. This

possibility needs to be carefully evaluated and any instantaneous zones reach needs to be reduced accordingly.

- The relay removes the faulty phase voltage measurements from the positive sequence voltage filter to stabilize the polarizing voltage against phase angle changes due to voltage reversal on all faulted phases. Memory voltage is used for stabilization during the first 100 ms of a close-up three-phase fault. Should the fault condition continue, directionality is sealed in and no further directional measurement is allowed until after the fault has been cleared and the impedance measurements have reset [20].

- The relay has a high-speed measurement function, which is not impacted to the same extent as normal impedance measurement devices. The normal and high-speed underreaching zone 1 elements does however need to be carefully set to not cause overreach due to the line reactance compensation and harmonic oscillations cause by the series capacitor during system faults [20].

- The high-speed function resistive setting requirements differ from the normal distance zones in that both the line resistance and the fault resistance must be included in a single resistive setting.

- The reactance measurement algorithm for the underreaching zone 1 compensates for the impact that load current has on the impedance measurement.

- The relay has resistive reach limitations to compensate for load encroachment.

- The number of reach limitations that needs to be adhered to under different system conditions can be confusing and requires careful consideration before being applied.

Whilst Chapter 3 attempted to provide detail about two of the numerical relays used on the Eskom transmission system, the next chapter will focus on doing a comparison between the two relays, with the sole aim of gaining a proper understanding of how to best use these relays on the system.