IMPACT OF SERIES COMPENSATION ON THE PERFOMANCE OF DISTANCE PROTECTION ON ESKOM TRANSMISSION GRID

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DECLARATION

I ....Sihle Qwabe........................ declare that

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I would like to acknowledge my family and my friends for the support they have given through motivation that pushed me into completing this document.

Also I would like to acknowledge my research supervisors Dr. B.S. Rigby and Mr. Anura Perera for the support they gave.

ABSTRACT

Modern transmission systems are becoming heavily loaded. In addressing this issue Eskom has been installing series capacitors in their power transmission grids for the purposes of ensuring improved system stability, increased transmittable power, reduced transmission losses, enhanced voltage control and more flexible power flow control. Environmental concerns are also addressed at a fraction of the cost when compared to the alternative. However, with the utilization of series capacitors and their over-voltage protection devices typically the Metal Oxide Varistors and Spark Gaps when installed on transmission lines, several problems are created for the distance protection relays. This is because series capacitors when used on transmission lines can have serious effects on the performance of distance relay protection. This is because of the change of impedance seen by the distance relay since the electrical impedance measured by the relay is no longer a unique correspondence of the physical distance from the relay location to the point of fault when the protection of the series capacitors comes into play. The research results will show that, because of subsynchronous oscillations and voltage inversion phenomena as a result of series compensation, can cause distance protection's zone 1 directional elements to operate incorrectly, more specific to internal faults which may appear as external faults and external faults which may appear as internal faults.

The research will be investigating some of the challenges that are encountered by the distance protection relays when protecting a transmission line incorporating series capacitors. In answering the research question: *"What are the issues associated with the utilization of series capacitors on the Eskom Transmission grid to the performance of distance protection?"* the Digsilent PowerFactory software simulator package will be utilized to achieve the desired objectives. Other research projects have looked into the research question at hand utilizing the physical REL 531 relays and a real time model of the Eskom Hydra South Network, a system that supplies power to the Western Cape. In this research the author will be looking at the ability of Digsilent and its REL 531 Models to repeat and confirm the same conclusions, before considering possible alternative solutions.

The Muldersvlei-Bacchus and Bacchus-Droerivier lines forming part of the Eskom Hydra South Network were selected as the area of focus. The decision to select these two particular mentioned lines as the area of focus was because the studies will be able to cover impact of external series capacitors to both the performance of the relays on lines that are series compensated and those that

are not. The performance of the relays will involve analyzing the impact of series capacitors on the relays for faults before and after series capacitors.

The research will also be investigating the possibility of utilizing the current supervised zone 1 configuration, which has recently been introduced on some Eskom distance protection relays as a solution, to overcome the impact of series capacitors on the performance of the distance protection relays.

CONTENT

LIST OF ILLUSTRATIONS

GLOSSARY

Current Supervised Zone 1	CSZ1
Current Transformers	CTs
Digsilent Simulator Language	DSL
Droerivier	Dro
Faults after Series Capacitor	F
Faults before Series Capacitor	G
Metal Oxide Varistors	MOVs
Muldersvlei	Mul
Spark Gaps	SG
Series capacitors	SCs
Single line to ground	SLG
Permissive over-reach	POR
Permissive under-reach	PUR
Power Swing Blocking	PSB
Proteus	Prot

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INTRODUCTION

Modern transmission systems are becoming heavily loaded, which consequently conveys the benefit of the utilization of the series capacitors on the Eskom power transmission grids. It has been effectively proven by a number of researchers all over the world that by having series compensation as a feature on power transmission grids, that it is undoubtedly one of the cheapest and simplest ways of ensuring that the transmission system has improved stability, increased transmittable power , reduced transmission losses, enhanced voltage control and more flexible power flow control [4, 5, 7]**.** Environmental concerns are also addressed when compared to the alternative. However, the utilization of series capacitors (SCs) and their overvoltage protection devices typically Metal Oxide Varistors (MOVs) and/or Spark Gaps (SGs) when installed on transmission lines, create several problems [7] for the protective relays i.e. distance relay protection.

The addition of series compensation can have serious effects on the performance of the protection system more especially on distance relay protection relating to the change of impedance seen by the relay since the electrical impedance measured by the relay is no longer a unique correspondence of the physical distance from the relay location to the point of fault when the protection of the series capacitors comes into play.

The document discusses some of these challenges that are encountered by the distance protection relays when protecting transmission lines incorporating series capacitors. The research will involve utilizing the Digsilent PowerFactory simulating package to set up a simplified version of the network as existing on the Eskom Transmission grid for testing the performance of distance protection relays, the protection of series capacitors and that of protection of lines adjacent to the series compensated lines. The distance protection relays that will be studied are relay models that are provided within the PowerFactory Package.

CHAPTER I

1. Distance Protection

1.1 Distance Protection Philosophy

Distance protection is a non-unit system of protection, with capabilities of providing both primary and back-up protection facilities within a single relay. The distance protection scheme can easily be modified into a 'unit' system of protection by combining it with a signaling channel in this form it is eminently suitable for the protection of important transmission lines. In Eskom transmission, distance protection schemes are supplied with signaling channels always.

Distance protection relaying is designed to measure line impedance since the impedance of a transmission line is proportional to its length. Operation of the relay must only occur for faults occurring between the relay location and up to the set reach point. This is accomplished by arranging for the relay to have a balance point between operation and restraint at the selected reach point. Figure 1-1 illustrates the concept of the distance protection philosophy.

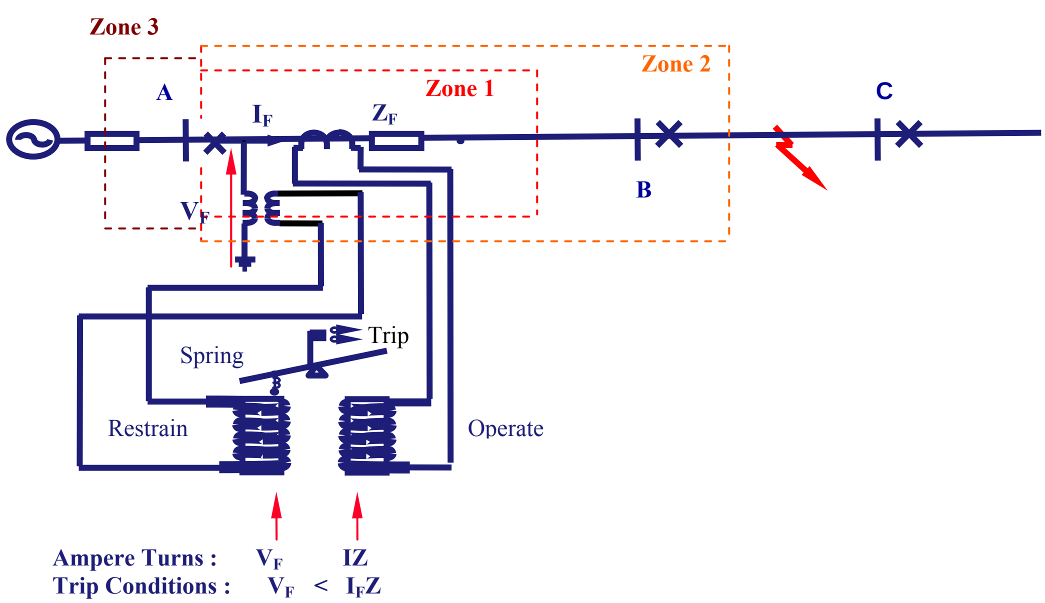


Figure 1-1 Distance Protection Philosophy [11]

The balance point on the distance protection relaying is defined by the zone reach settings of the relay. Thus, the relay either operates or restrains depending on whether the measured impedance up to the point of fault is respectively less than, or greater than, the relay reach setting. The reach setting is adjustable to minimum and maximum relay design limits to ensure that the relay is suitable for application on lines of varying length [2, 8].

1.2 Distance Zones of Protection

A typical distance protection relay consists of a number of zones of protection, the reach for each being determined by its reach setting. The zone reach is usually set as a percentage of the parameters of the line being protected. The distance protection relaying does not only provide the primary protection for the protected line, but also provides time delayed back-up protection for both the protected and adjacent lines as well.

In distance relaying the primary protection is provided by the underreaching (set to reach less than the impedance of the line) zone 1 reach elements, which operates only for faults occurring in the direction of the protected line. The back-up protection is offered by one or more zones of overreaching (set to reach more than the impedance of the line) elements, these being zone 2 and 3 reach elements. In Eskom transmission zone 3 elements are always set to reverse reach (look behind the protected line) with its reach setting such that it always overreaches the remote zone 2. This is to ensure protection security in cases of “weak in feed”. The underreaching zone 1 elements are by philosophy set to issue a trip output instantaneously whenever they measure a fault to be within their reach as such a fault can only have occurred on the protected line [2]. The ideology of the zones of protection is well illustrated in Fig. 1-2.

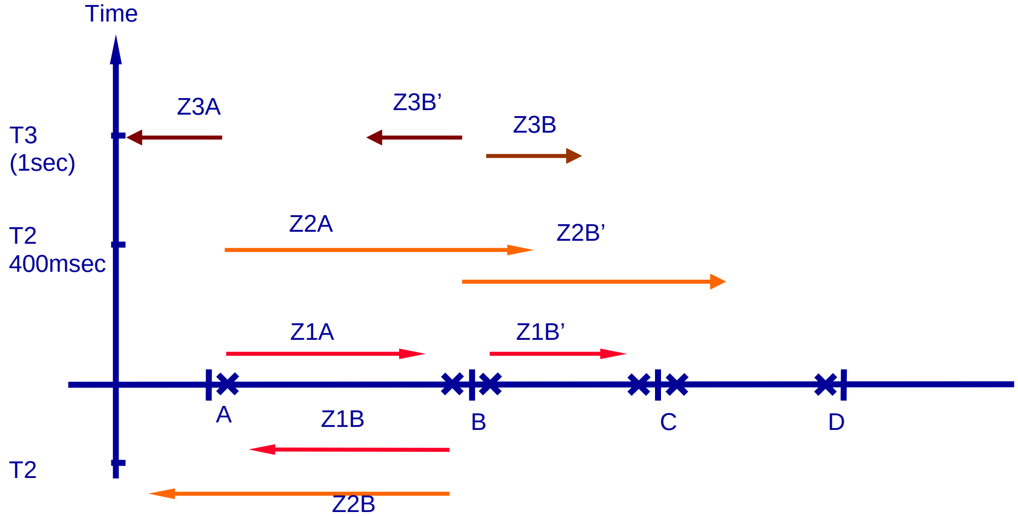


Figure 1-2 Distance Zones of Protection [11]

Any Zone element whose forward reach extends beyond the remote end of the line, or which reaches in the reverse direction, can only be permitted to issue a trip output signal to the associated circuit breaker after a pre-set time delay. This is to ensure protection scheme security and to avoid loss of discrimination with the primary protection on the adjacent line(s). The timers on the overreaching zones will be started on fault detection by the relay. When a fault falls within a particular zone's reach, and that zone element fails to operate to clear the fault after a set time has elapsed, the tripping time of the relay will be extended to that of the next zone. Figure 1-3 illustrates the concept of the distance protection zone timers. Removal of the fault from the system before the time delays have expired will cause the timers to reset, preventing operation of the overreaching zones.

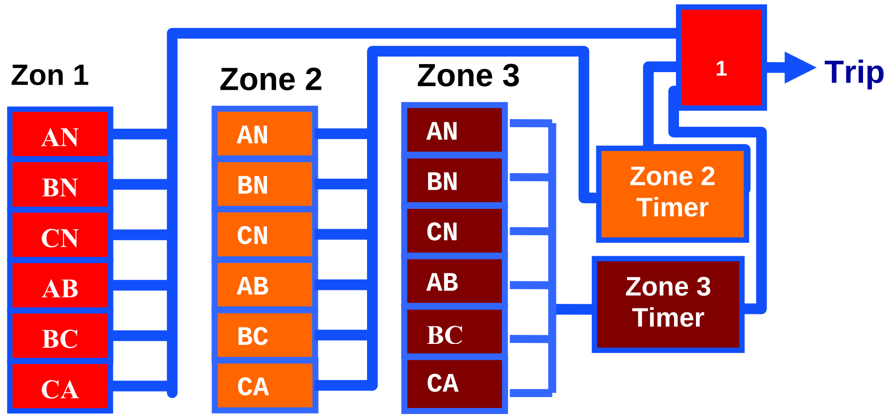


Figure 1-3 Distance Protection scheme Block Diagram [11]

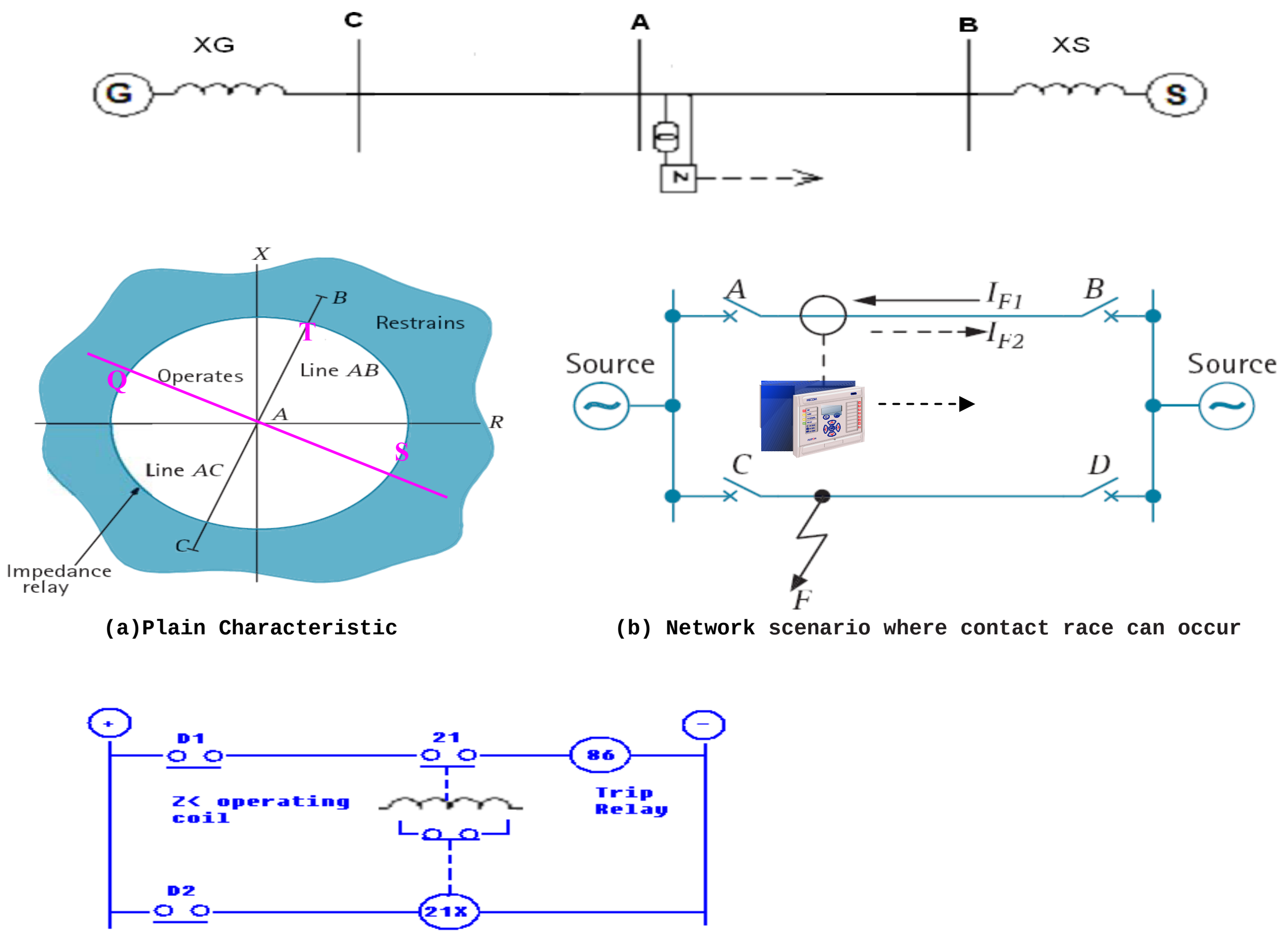
1.3 Distance Relay Characteristics

1.3.1 Plain Characteristic

The characteristic shape of the operation zones for distance relaying has been developed throughout the years. Figures 1-4, 1-5 and 1-6 depict an overview of the generations of the distance protection relay characteristics, with Fig. 1-4 (a), illustrating the first generation of the operating characteristic which is basically a circle centred at the origin of the co-ordinates in the R/X plane of the impedance relay. The radius the circle represents the instantaneous zone reach of the distance protection which is generally set to cover 80 to 90% of the protected line AB. This type of relay is therefore non-directional (i.e. it will operate for all faults of the protected line AB falling within the boundary of the protected circled area and also having the same effect to the adjacent line AC) and as a result requires a directional element to give the relay the discriminating quality.

The straight line QAS on the *R*/*X* diagram illustrated in Fig. 1-4 (a) represent the impedance characteristic of a directional control element, thus the semicircle AQTS depicts the combined characteristic of the directional and impedance relay. The characteristic would restrain operation for all faults falling outside the characteristic semi-circle. However, discrimination that is offered by directional elements provided by a separate unit from that of a distance protection may not provide reliable discrimination. To show how the reliability of such a scheme can be compromised, a power transmission network arrangement depicted in Fig. 1-4 (b) is considered as an example system.
If a fault occurs at F close to C on the parallel line CD, the directional unit D1 and D2 contacts shown in Fig. 1-4 (c) will restrain operation due to current I_{F1} flowing in the reverse direction at relay A. D2 is connected in series with the impedance auxiliary relay, so that when this unit is not energized its contact short-circuits the main impedance relay's coil, thus restraining the operation of

the impedance unit for the out of zone fault. If this control was not included, the under reaching impedance element could operate prior to circuit breaker C opening. When breaker C opens a current reversal from I_{F1} to I_{F2} is experienced at A, causing the directional unit D1 and D2 contacts to energize, while at the same time the impedance relay contact would be opening as the fault now appears to be out of the instantaneous zone's reach. This could result in the incorrect tripping of the healthy line if the directional unit D1 contact operates before the impedance unit contact resets. This phenomenon is referred to as the "contact race" [18].



(a)Plain Characteristic

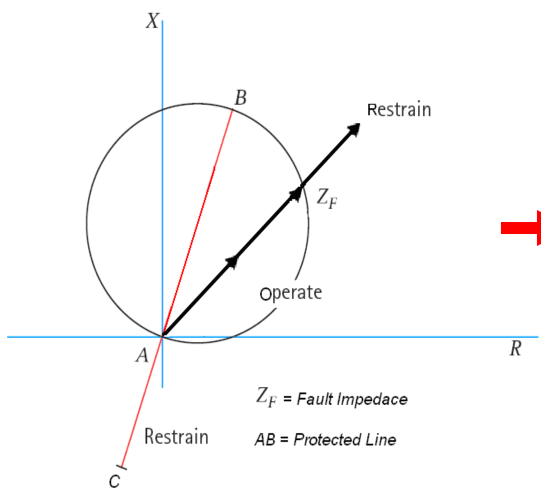
(b) Network scenario where contact race can occur

(c) Combined use of directional/impedance relays

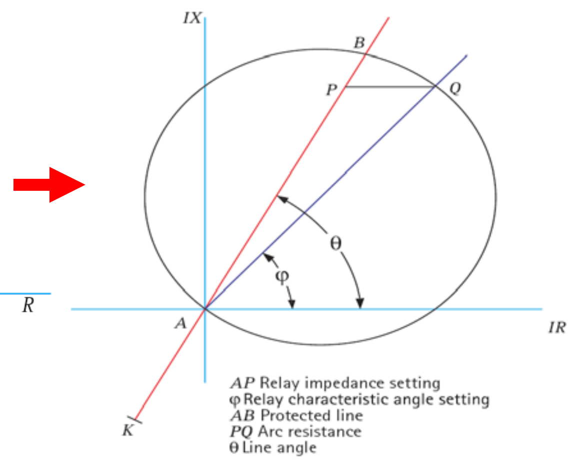
Figure 1-4 Plain Distance Relay Characteristics [18]

1.3.2 Mho Characteristic

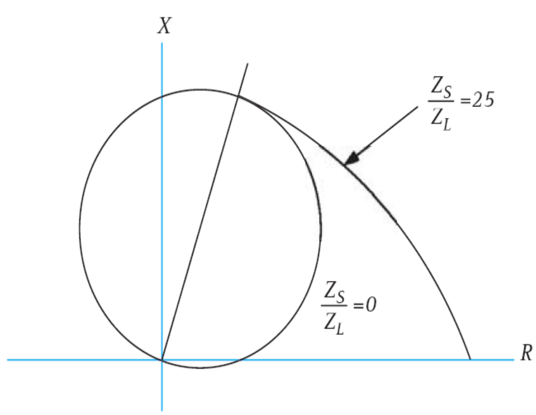
Directional control is an essential discrimination quality for a distance relay, to make the relay non-responsive to faults falling outside the protected line [18]. In trying to overcome the setback of the probability of the plain characteristic operating for faults behind the relay, a second generation of distance protection was developed where the oversized circle of the plain characteristic was reduced and its origin offset from the origin of the R/X co-ordinate plane, resulting in the mho relay characteristic [18] as illustrated in Fig. 1-5 (a).



(a) Mho Characteristic



(b) Increased arc resistance coverage



(c) Fully Cross Polarized Mho Characteristic

Figure 1-5 Mho Distance Relay Characteristics [18]

The impedance element of the mho characteristic is therefore directional and as such will only operate for faults in the forward direction, meaning it will only be protecting line AB and consequently eliminating the “contact race” setback that is a probability with the plain characteristic distance relaying used together with separate directional control elements. This is achieved by the addition of the polarizing signal [18].

However, the mho distance relaying characteristic has got inherent reliability weaknesses of its own, in that it is affected by arc resistance more than the plain distance characteristic. Since the line protected with distance protection is made up of resistance and inductance (i.e. Z = R + jXL), it is to be noted that its reach point setting will vary with the fault angle as the impedance measurement will not be constant for all angles. Now under an arcing fault condition, or an earth fault involving additional resistance, such as tower footing resistance or a fault through vegetation (i.e. line PQ refer to Fig. 1-5 (b)), the value of the resistive component of the fault impedance will increase which as a result will cause the fault angle to change. The relay which now sees a characteristic angle (RAQ) that is less than the line angle (RAB), will cause the mho relay characteristic to under-reach under these resistive fault conditions.

Generally it is normal to set the relay characteristic angle setting (φ) to be less than the line angle setting (θ), as this will allow for a small amount of fault resistance to be catered for without causing the relay to under-reach. The resulting characteristic is as illustrated in Fig. 1-5 (b), where AB represents the length of the line being protected. With φ set less than θ, the actual amount of line protected *AB*, would equate to the relay setting value *AQ* multiplied by cosine (θ- φ). The effect of arc resistance is really not significant when the application is on long overhead lines carried on steel towers with overhead earth wires, as a result this usually can be neglected. However, on short overhead lines the effect of arc resistance is more significant, and in cases where the protected line is of wood-pole construction without earth wires the effect is even more significant. This is because the earth fault resistance reduces the effective earth-fault reach of a mho Zone 1 element to such an extent that the majority of faults are detected in Zone 2 time [25]. This is because when the line used is of “wood-pole construction without earth wires”, the line angle “θ” is usually large and as such causes the instantaneous zone reach not to have adequate coverage along the resistive axis of the R/X plain. This problem however, can be eliminated by the use of relays with a fully cross-polarized mho characteristic or by using the third generation of “quadrilateral characteristic” relays. The fully cross-polarized mho relays, is a mho relay which opens out its mho characteristic along the R axis as illustrated in Fig. 1-5 (c). The degree of the resistive reach enhancement depends on the ratio of the source impedance to the relay reach (impedance) setting as shown in Fig. 1-5 (c).

Another setback with mho characteristic relays is that of reduced reliability to operate correctly for close-up (zero voltage) faults. This would be the case where the characteristic directional element, would have no polarizing voltage to allow the relay to operate. The utilization of cross-polarized mho relays is one way of ensuring correct mho element response for zero-voltage faults. In this scheme a percentage of the voltage from the healthy phase(s) is added to the main polarizing voltage as a substitute phase reference which, as a result, maintains the directional properties of the mho characteristic relays. The technique is most advantageous for close-up three-phase faults, where for this type of fault no healthy phase voltage reference is available and application of this scheme offers a synchronous phase reference for variations in power system frequency before or even during a fault by using the phase voltage memory system application. As cross-polarisation is achieved from memory system application or from healthy phase(s) reference, the mho resistive expansion will occur during a balanced three-phase fault as well as for unbalanced faults. For this reason the mho resistive expansion will restrain under load conditions, where there would be no phase shift between the measured voltage and the polarizing voltage [18].

1.3.3 Quadrilateral characteristic

The quadrilateral characteristic forms a polygonal shape as illustrated in Fig. 1-6. The characteristic uses directional reach elements and is provided with adjustable reactive and resistive reach settings that are set independently on the R/X plane. Some of the applications, advantages and disadvantages of the quadrilateral characteristic are discussed in the next section.

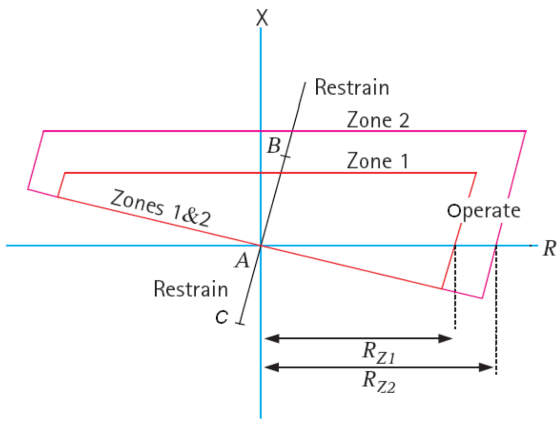


Figure 1-6 Quadrilateral Distance Relay Characteristics [18]

1.3.4 Quadrilateral Distance Applications

1.3.4.1 Short Line Application

Short transmission lines like the one on an R-X diagram depicted in Fig. 1-7, are generally associated with low impedance values, causing the line impedance to be electrically very far from the expected maximum load, as a result, this would challenge the measurement accuracies of mho distance relays. Generally the mho distance relay ground elements are equipped with a natural ability to expand and accommodate more of the resistive component (*Rf)* and this ground element expansion is proportional to the source impedance (*Zs*) as shown in Fig. 1-7. This however creates difficulties for mho characteristic elements when required to detect general faults that are even without arc resistance. This is because if the tower footing resistances are in the range of line impedances, this will add to Rf, causing the relay to under-reach. The situation is negatively amplified if the source impedance (Zs) is very small. Moreover, the situation for phase fault detection is similar to that of ground fault detection in short line applications. If the expected arc resistance is approximately the same magnitude as the transmission line impedance, the mho phase fault detecting elements will also experience problems [26].

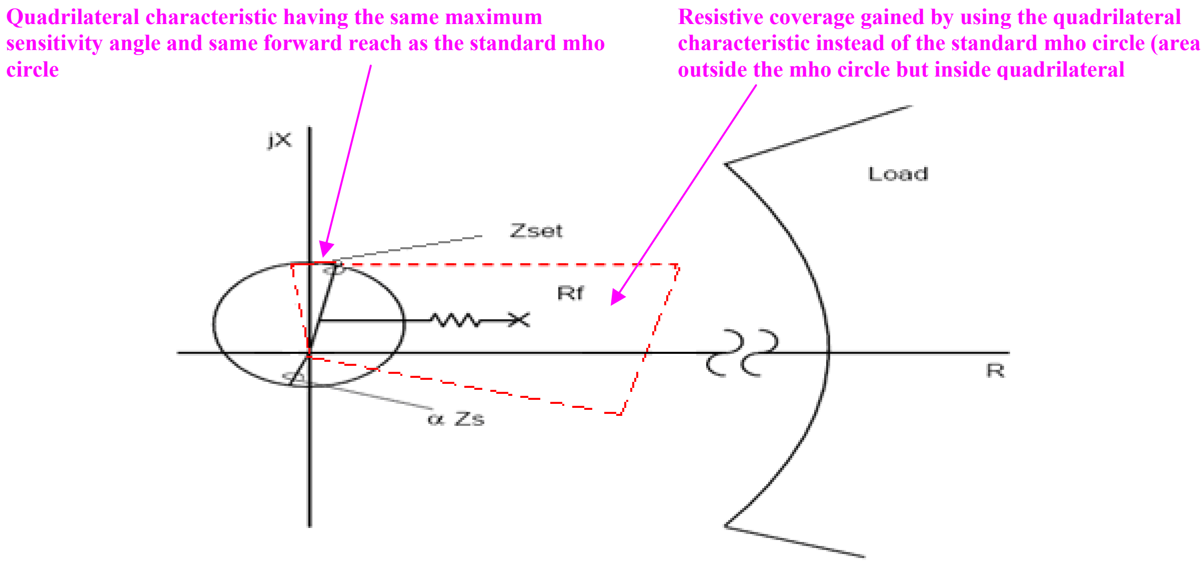


Figure 1-7 Short line apparent impedance [26]

The problem of under-reaching endured with mho characteristic protection as a result of arc resistance and or fault resistance to earth that tends to contribute to the highest values of fault resistance is therefore eliminated with the use of quadrilateral characteristic, since this relay's ground elements can provide a larger margin to accommodate "Rf" by allowing an independent settable maximum zone resistive reach setting. However, the use of a quadrilateral phase distance element with extended resistive fault sensitivity is vulnerable to the probability of tripping under heavy static load or power swings. It is therefore often necessary in practice to limit the resistive reach coverage of quadrilateral distance elements. There are a couple of limitations that are recommended by [16] in practice when setting the quadrilateral characteristic reach elements, and these will be discussed in the sections to follow in this chapter. Nevertheless, even with these limitations the performance of the quadrilateral relay is still a better option when compared to mho relays.

1.3.4.3 Load Encroachment Supervision Application

In traditional "mho" characteristic relays, increasing the reach setting of the ground elements in order to improve resistive fault sensitivity generally increases the relay's chances of picking up and tripping on load. When a transmission line is heavily loaded and inductive in nature, the traditional mho protection relay is not only susceptible to respond to system transient swings, but also may detect steady-state load. A number of alterations in the relay's zone characteristic have been developed over the years to try and reduce the setback of the sensitively set zone reach elements undesirably responding to load conditions. To mention a few, some of the alterations have included: the variations in zone positioning, characteristic angle adjustment; offsetting characteristics; Lens and other variations in zone shapes. The fundamentals of the mentioned relay alteration methods will not form part of the discussions of this document as these methods have been shown by [26, 27] to generally always result in a significant loss of the impedance plane coverage whenever loadability is improved. However, an alternate means of preventing, or even eliminating completely, a distance zone's response to transient or steady state load conditions has been to supervise its operation with other distance elements [26, 27], hence this document will only be discussing this method.

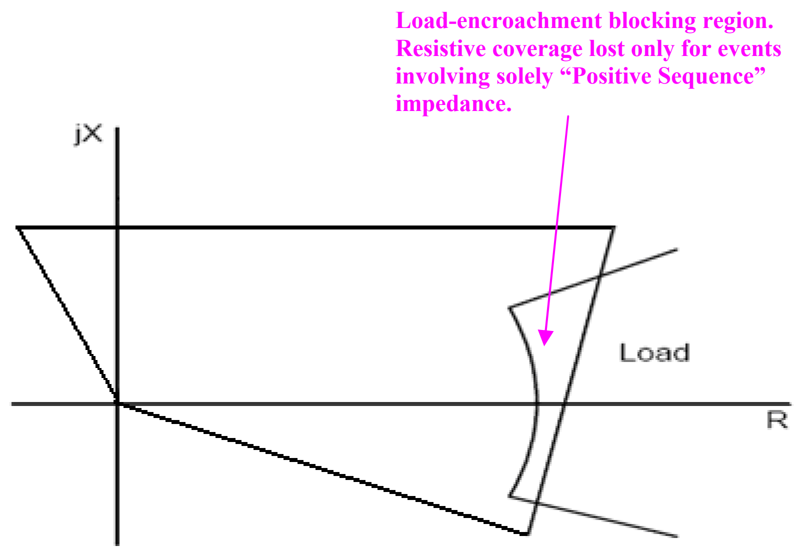


Figure 1-8 Load encroachment characteristic for quadrilateral distance elements

The load-encroachment characteristic is one feature that some of the modern distance relaying packages offer as a method of discriminating between a general load and an actual fault condition. Since loads in transmission systems are in general, primarily balanced three phase loads, supervisory restrictions are placed only on the operation involving the 3-phase distance elements, and not on operation involving single phase to ground, two phase fault, and double phase-to-ground faults [27]. The load-encroachment has the ability to define general load regions as illustrated in Fig. 1-8. The supervision operating point of the load impedance in the blocking region (refer to Fig.

1-8) will clearly identify load conditions and result in only a minimal portion of resistive 3-phase faults (corresponding to positive sequence impedance) that will be missed. "The relay calculates the positive sequence elements from the measured phase quantities, and from them calculates the magnitude and phase angle of the positive sequence impedance. If the measured positive sequence impedance lies within a defined load region, the 3-phase distance element is blocked from operating" [27]. It is to be noted that such faults are a very unlikely probability in transmission systems.

1.3.4.2 Power Swing Blocking Application

When power flows through power systems, there are transient oscillations that take place which can cause unnecessary line trips, which can in turn lead to networks being exposed to undesirable stability problems. Stability requirements demand that transmission lines remain in the power system during power system oscillations. Power swing blocking (PSB) is a distance relay application which monitors the power swings occurring on the network being protected and tries to determine whether they are of a stable or unstable nature. This is the way in which the PSB distinguishes if the impedance trajectories seen by a relay at that point in time, are associated with a genuine fault condition or just a general power swing condition.

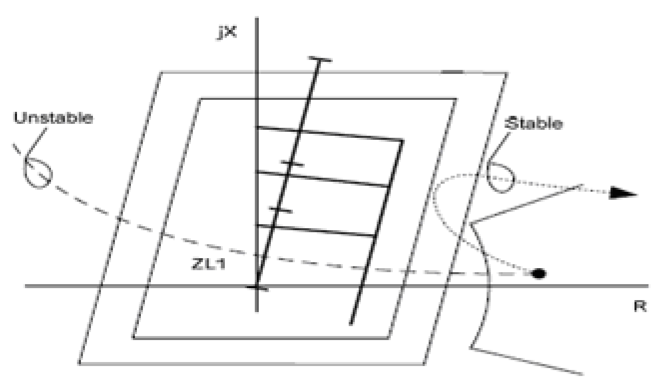


Figure 1- 9 Traditional dual-zone out-of-step characteristic [27]

If the oscillations are contained within a maximum oscillation envelope and are damped over time, the power swings are said to be stable. Meanwhile, if the power swings are not damped over time, the power swings are said to be unstable [26]. The PSB measuring elements generally incorporate two zones inserted between the load and tripping characteristics. Some relays use a starter and/or zone 4 for the detection of power swings. To differentiate between fault operating phenomena and a power swing condition, the time difference between the outer and the inner zone characteristics picking up (starter and zone 4) is measured [16]. Now the out-of-step detection techniques generally take advantage of the slower speed movement of the apparent impedance trajectory through the characteristic R-X plane for power swing conditions (the inner zone operates after a set time delay (2 to 5 cycles) with reference to the outer zone), while if the impedance trajectory is due to a power system fault, both zones will pick-up almost instantaneously. A traditional PSB scheme is illustrated in Fig. 1-9. All unwanted distance relay protection operations during power swing conditions should be blocked on transmission systems. The modern generation of distance relays are designed with technology that is capable of detecting a genuine fault condition during power swings and releases blocking to isolate the fault. However, in the old generation relays that do not have the facility to detect faults during power swings, only the instantaneous tripping zone has to be blocked if it is possible to do so.

The outer PSB zone must not encroach the load characteristic with a minimum of 50% margin (1.5*ZPSB <ZLoad) [16]. In cases where this requirement cannot be met, an adequate compromise of engineering judgment should be used to set the inner and outer zones, as well as the resistive reach of the quadrilateral element.

1.3.4.4 Single-Pole Trip Application

Transmission systems are required to perform single pole tripping in cases where lines experience single phase to ground faults. This is a common standard in transmission systems that the protection schemes have a functionality of tripping and isolating the only unhealthy phase when a line is experiencing a single phase to ground fault, while the network still maintains synchronization via the other two healthy phases. The rationale is that during the open single pole interval, if the fault was of passive type, the arc is allowed to deionise and a reclosing command can be sent to the breaker to reclose and bring the phase back to service. However, during the open-pole interval, the power system gets unbalanced causing negative and zero-sequence currents to flow. This causes major issues for distance elements as current polarization attained with zero-sequence currents and/or negative-sequence currents is not reliable [27]. This is because negative-sequence currents and zero-sequence currents will have different directions depending on the load flow direction during this condition. However, distance elements of mho relays when polarized with positive-sequence voltage, is one application that can be used to assure system stability during open-pole intervals and can also assure protection reliability when required to detect system faults during open-pole intervals [28]. Unfortunately, with quadrilateral schemes, the phase and ground elements should be disabled when an open-pole condition is detected. However, high-speed quadrilateral distance elements implemented with incremental quantities do not need to be disabled during this condition [27].

1.4 Permissive Distance protection Schemes

Both permissive under-reach (PUR) and permissive over-reach (POR) protection schemes are being used on the Eskom transmission network. Both their performances will be reviewed, findings will be analyzed and compared.

The main disadvantage of the unit protection schemes is their limitation in providing back-up protection to the adjacent line section. A distance scheme is capable of providing back-up protection but it does not provide high-speed tripping protection for the whole line length and the circuit breakers do not trip simultaneously at both ends for the end zone faults. The instantaneous tripping on distance schemes is only realized via zone 1 which only covers 80% of the line protected with the remaining 20% of the line faults cleared at 400ms via Zone 2.

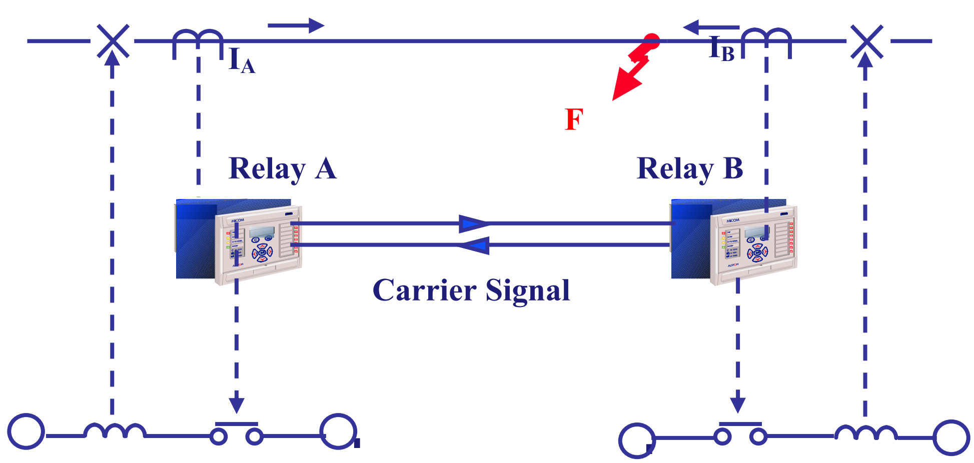


Figure 1-10 Permissive Distance Protection Scheme [11]

Now this is not acceptable, the most desirable protection scheme would be the scheme that presents both the features of the 'unit protection' and those of distance protection as far as the protection of long distance transmission lines is concerned. This ideology is not necessarily impossible, it can be achieved by interconnecting the distance protection relays at both ends of the line that is being protected with carrier signals. Such schemes provide instantaneous tripping as well as back-up protection. Fig. 1-10 illustrates how the unit and back-up protection can be attained with the utilization of carrier signals when protecting a transmission line.

Fig. 1-11 illustrates a protection system of transmission line AB and sections of adjacent lines on either side of the line. The line is protected by distance protection relaying at either end. The protection is aided with permissive signals that are exchanged between the relays over a dedicated communication channel, as illustrated in Fig. 1-12 and 1-14 i.e. PUR and POR schemes respectively. The distance protection relaying elements at either end of line AB are set to detect all internal faults, as well as external faults within the relay's Zone reach element settings. Both the distance protection relays at substation A and B are set and configured as discussed in Section 1.2.

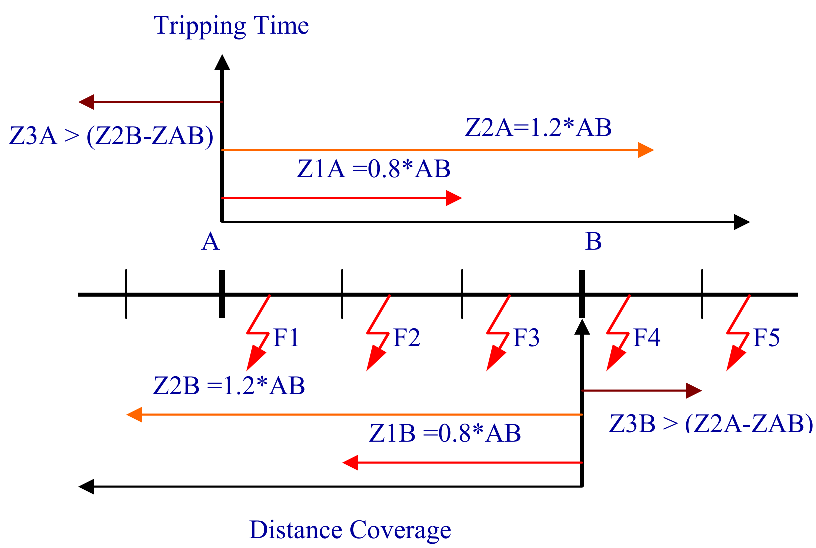


Figure 1-11 Permissive Over/Under reaching Scheme [6]

1.4.1 Permissive Under-Reaching Scheme

In ensuring that the basic line protection requirements, sensitivity, reliability, stability and fast operation are attained, PUR is one of the permissive schemes used by Eskom Transmission on the distance protection relaying. In this scheme (PUR), it is the under-reaching elements of Zone 1 that send a permissive signal to the remote end on occurrence of an in-zone internal line fault.

1.4.1.1 Principle of Operation

The distance tripping units of the under reaching element(s) (zone 1) are set short (typically 80% - 90%) of the remote line terminals. The standard for zone 1 setting being 80% for Eskom Transmission and operating time is instantaneous under fault conditions. The over reaching distance protection fault detector element(s) (Zone 2) are set at 120% of the line impedance thus over-reaching the line terminals and its operating time is normally set at 400ms. When an internal fault occurs on the protected line, take the case of fault ‘F1’ and ‘F3’ in Fig. 1-11, the distance tripping under reaching element(s) at associated local substation(s) (Zone1) will pick up, trip the local associated circuit breaker while simultaneously sending a permissive trip signal to the remote end terminal. A circuit breaker trip will occur at the remote end terminal only when the corresponding Zone 2 distance fault detector element(s) pick up and the permissive signal is received. This operation will take place nearly instantaneously resulting in breakers at both ends operating almost simultaneously. Fig. 1-12 illustrates the PUR Scheme signal sending arrangement.

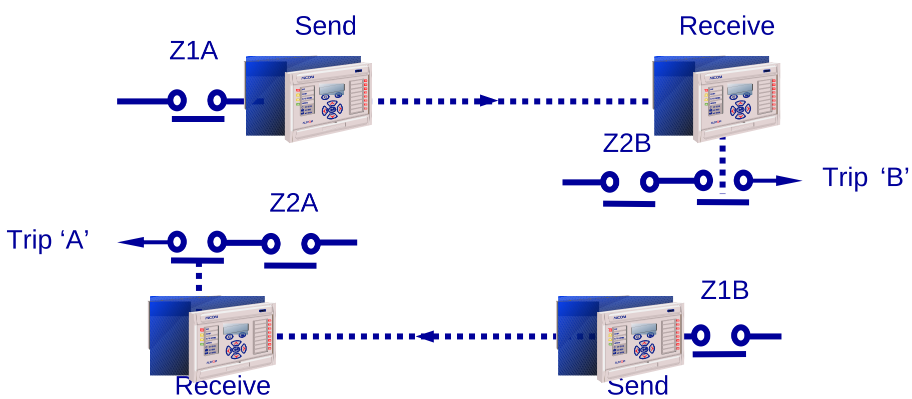
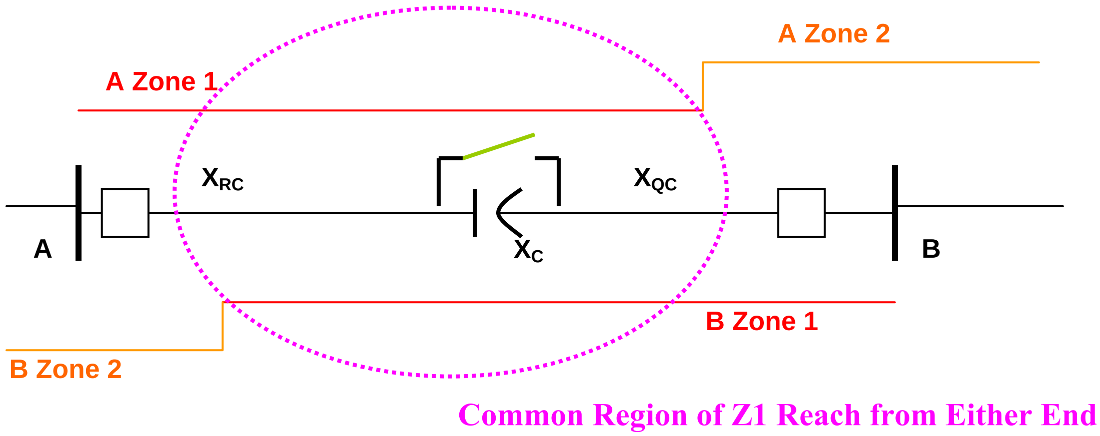


Figure 1-12 PUR Scheme signal Sending Arrangement [11]

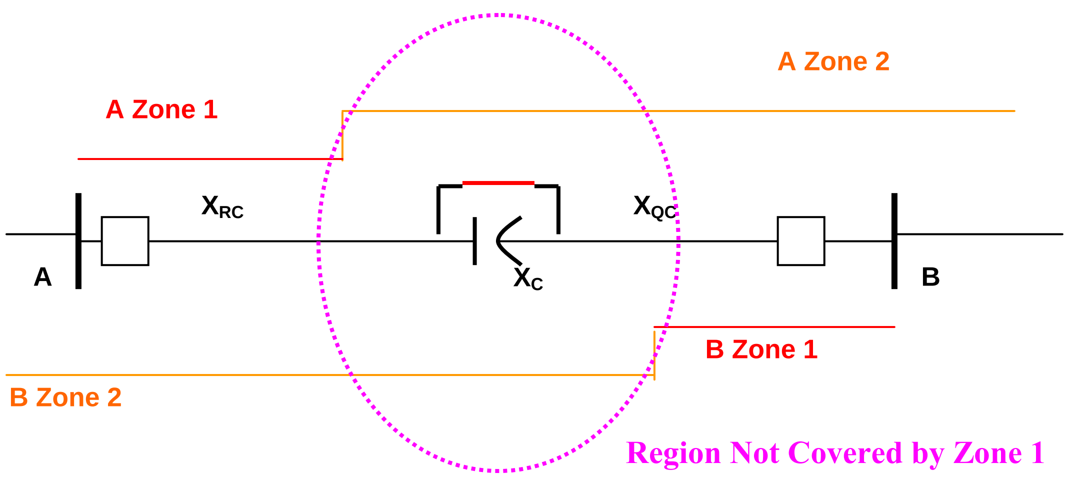
1.4.1.2 PUR Scheme Drawback

Permissive Under Reaching protection has a serious drawback that makes the POR scheme a more suitable distance protection permissive scheme for protection of series compensated transmission lines. In order to explain the drawback of the PUR scheme on a transmission link that is series compensated, an experimental study performed by reference [4] is now considered, where the power transmission link between substation A and B, depicted in Fig. 1-13 was considered as a case study.

The primary protection is provided by a zone set to reach less than the impedance of the line, hence the zone elements are termed under-reaching elements. In Eskom Transmission as has been mentioned before the zone 1 reach elements are usually set to “look” at typically 80% to 90% of the total line length that is being protected, with about 60% coverage of zone 1 reach protection at either end being common as illustrated in Fig. 1-13 (a), while Fig. 1-13 (b) illustrated the PUR scheme drawback.



(a)



(b)

Figure 1-13 Zone 1 Reach Before and After Capacitor Bypass [4]

As it has been mentioned that the zone 1 reach is usually set short (typically 80% - 90%) of the remote end of the line under normal conditions. We let h_R be the reach of the relay at A with the capacitor in service. As a result,

$h_R = 0.9(X_{RC} + X_{QC} - X_C)$ (1.1)

$h_R = 0.9(X_L - X_C) = 0.9(1\text{-}k)$

Where:

$X_L = (X_{RC} + X_{QC})$ (1.2)

k = Degree of Compensation Range of k = (0 – 0.6)

We then assume that the protection setting engineer decides on Zone 1 reach setting to reach 0.9 of the line AB illustrated in Fig. 1-13. Now we also assume that the total line reactance X_L is 1.0 and the degree of compensation is 0.7. With the series capacitor being in service the total end-to-end line reactance is 0.3 and the reach setting is 0.27.

The reach setting is adequate if we are considering the series capacitor (SC) to be in service. Now the PUR scheme drawback comes into play when the capacitor is completely bypassed, remember that the reach setting is still set at 0.27, as a result, the instantaneous zone 1 reach coverage is not even reaching up to the center of the line as illustrated in Fig. 1-13 (b). This results in approximately 46% gap in the center region of the line that was supposed to be covered by the instantaneous reach elements but is now only covered by overreaching elements of zone 2, thus, resulting in delayed clearing of faults that fall within this gap. This means all faults falling within the illustrated region in Fig. 1-13 (b) will be cleared with Zone 2 time delay of 400ms. This is unacceptable for protection of important transmission lines. This is because it has been discovered that multiphase faults on a transmission line close to a power generating station are very dangerous to the power system's stability as these faults have a high probability of causing the generators to go into an out of step condition if these faults are not cleared in 200ms [14]. As a result, the permissive under-reaching schemes are not recommended for the protection of series compensated lines.

1.4.2 Permissive Over-Reaching Scheme

POR is another permissive scheme preferred by Eskom Transmission protection Engineers/Technicians on the distance protection relaying. In this scheme (i.e. POR), it is the over-reaching elements of Zone 2 that send a permissive signal to the remote end on occurrence of an in-zone internal line fault.

1.4.2.1 Principle of Operation

When an internal fault occurs on the protected line and the distance POR scheme is utilized, the operation ideology of the scheme will be better explained by going through the case fault(s) 'F1' and 'F3' in Fig. 1-11. The distance tripping under reaching element(s) of zone 1 will pick up, trip the associated breaker instantaneously, while the over reaching element(s) of Zone 2 at associated local substation(s) pick up and send a permissive trip signal to the remote end terminal. A circuit breaker trip will occur at the remote end terminal only when the corresponding Zone 2 distance fault detector elements pick up and the permissive signal is received. This operation will take place nearly instantaneously resulting in breakers at both ends operating almost simultaneously. Fig. 1-14 illustrates the POR scheme signal sending arrangement.

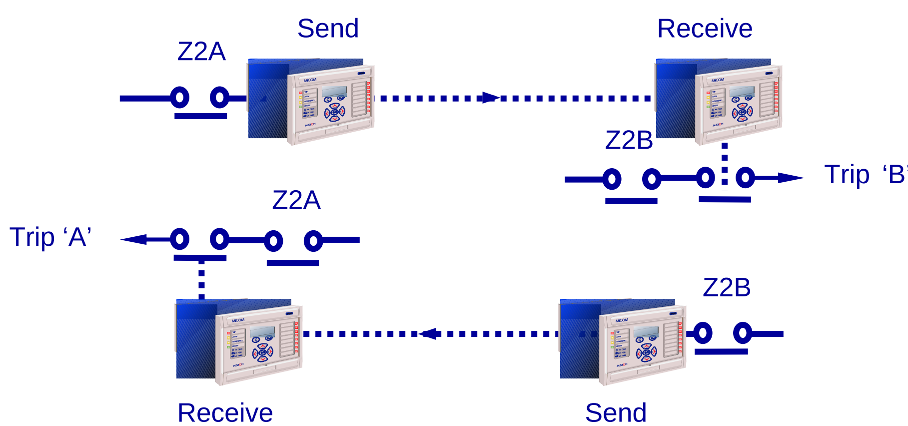


Figure 1-14 POR Scheme signal Sending Arrangement [11]

For both PUR and POR schemes, a fault located in position 'F2" in Fig. 1-11, this fault is within the middle portion of the line AB, tripping of the breakers at both ends without requiring any permissive signal will occur due to the overlapping of the under-reaching elements (zone 1), allowing the circuit breakers at both ends to trip instantaneously without delay.

1.4.3 Scheme Back-up Protection To Adjacent Lines

Faults 'F4' and 'F5' on the adjacent line shown on Fig. 1-11 are taken care of by the adjacent line's first line of defense protection, this being distance protection zone 1 elements and/or differential unit protection and should be cleared instantaneously. In the case of failure on the adjacent line protection, back-up protection in the form of zone 2 of substation A is expected to clear the fault in this location (i.e. the first 20% of the adjacent line), of course this fault would be cleared on zone 2 time delay setting of 400ms.

Zone 3 elements at substation B would operate if the zone 2 elements at the remote-end were to under-reach the faults at F4/F5, if and only if the fault persists for the zone 3 time delay setting of 1 second [6].

1.4.4 POR Scheme on Series Compensated Lines

In Eskom Transmission the POR scheme is a preferred choice for protection of series compensated lines. This scheme in Eskom Transmission is designed such that it uses zone 2 elements for fault detecting, since the reach of zone 2 extends well beyond the series compensated line still even when the SC has been bypassed. Figure 1-15 and 1-16 respectively illustrate the impact of series compensation to the performance of the distance POR protection scheme when the series capacitor is completely bypassed and when in service. The intention here is to show some of the advantages and disadvantages of utilizing the POR scheme for protection of series compensated lines, thus conveying the reasons why the scheme is a preferred choice.

It has been mentioned in earlier sections that it is normal practice in Eskom Transmission to set zone 2 reach such that it extends 20% beyond the remote end of the protected line (AB). This setting is such that it ignores the series capacitor, considering it as though it were completely bypassed as illustrated in Fig. 1-15. Moreover, if we now consider a case where the series capacitor is brought back into service, because of the negative reactance that the SC introduces to the line, the overreaching zone 2 is seen to reach even further into the adjacent lines as illustrated in Fig. 1-16. This is as a result of the reduced line impedance as seen by the relay since the line now appears to be shorter than what it really is. The extent to which zone 2 will overreach is strongly depended on the level of series compensation and the physical position of the SC relative to the measuring transformers.

The advantages of the POR scheme include: (1) since the scheme utilizes the overreaching zone 2 which its resistive reach coverage normally extends well beyond that of zone 1 for earth fault detection (refer to Fig. 1-6), it offers more resistive reach coverage for high resistance faults when compared to the PUR scheme that uses the underreaching zone 1 for the same purpose; (2) at all times whether the SC is bypassed or when not, the whole line is still protected with high-speed tripping operating protection as zone 2 reach covers the line completely in either SC status. However, the extension of zone 2 beyond the protected line might be considered a security risk as the local line protection is also 'looking' at faults falling outside the protected line (AB). In consequence, the local protection may race with the adjacent line protection and may possibly trip incorrectly for adjacent line faults. Fortunately, since the scheme utilizes the permissive over-reaching transfer trip logic (POTT) on relays on either end of the protected line, the security of the relays is maintained. This is because in this scheme, when a relay on one end detects a fault to be within its reach, it must also receive a trip permissive signal from the remote end relay before a trip signal can be issued [4].

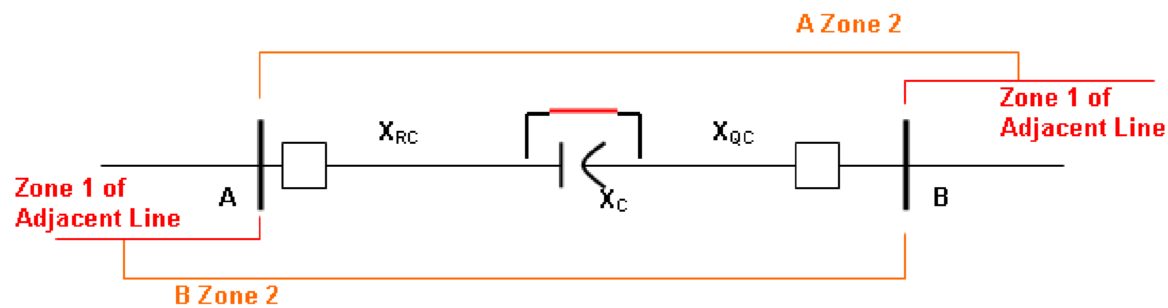


Figure 1-15 Zone 2 Reach When Series Capacitor is Bypassed

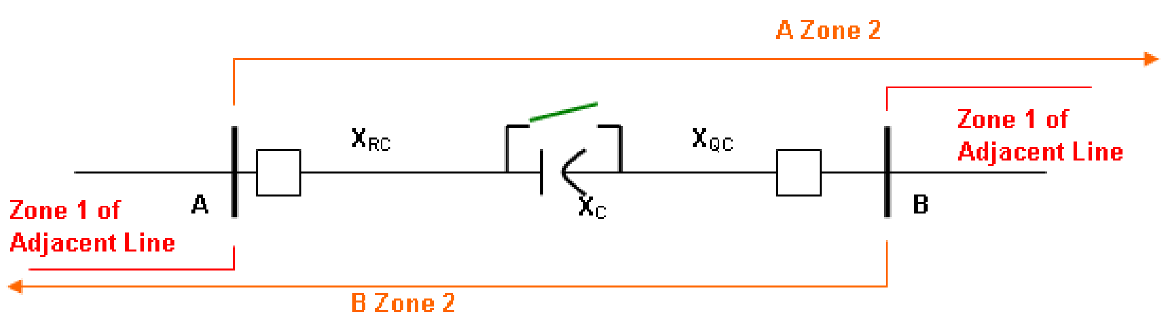


Figure 1-16 Zone 2 Reach When Series Capacitor is not Bypassed

However, the utilization of the POR scheme, introduces inherent reliability weaknesses which may result in the scheme not being able to execute high-speed tripping for faults falling within Zone 2 reach because:

a) The signal from the remote end is not received, possibly as a result of channel failure or relay failure, in consequence, causing the genuine in-zone internal line fault to be cleared in zone 2 time (400ms): since most of the time in Eskom Transmission, zone 1 on series compensated lines is switched off.
b) The breaker at the remote terminal is open.
c) The source behind the remote terminal is weak,

In such scheme applications, to reduce the identified risks requires: that the scheme communication channels be duplicated**;** use of current reversal guard and weak infeed logic to reliably detect in-zone internal line faults. However, it is to be noted that some of the above mentioned POR scheme reliability weaknesses, not only apply to series compensated line application but also to lines which are not compensated.

1.4.4.1 Current Reversal Guard

To explain the ideology of security problems that the POR scheme is subjected to as a result of current reversal when used for protection on parallel lines, a simple network illustrated in Fig 1-17 was considered as a case study. In parallel lines, the fault current distribution changes when circuit breakers open sequentially to clear a fault. As one line terminal opens, the current distribution change can cause the directional distance relay elements to see the fault in the opposite direction to which the fault was initially detected [16]. This can cause the POR scheme to maloperate by tripping the healthy line as a result of 'contact race' between one set of directional reach elements where one set is still trying to reset while the others are picking up.

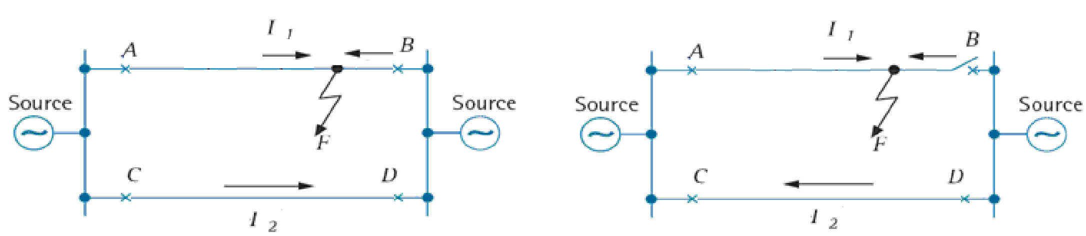


Figure 1-17 POTT Scheme Applied to Parallel Lines [18]

Consider a case where a fault occurs in Line 1(L_1) as shown in Fig. 1-17. Initially, the directional elements on relay B will correctly identify the fault, causing the associated breaker B to trip and open as it detects the fault to be within its Zone 1 reach. On breaker B opening, the fault current direction on Line 2 (L_2) will change direction from the original flow (C to D) to reverse (D to C).

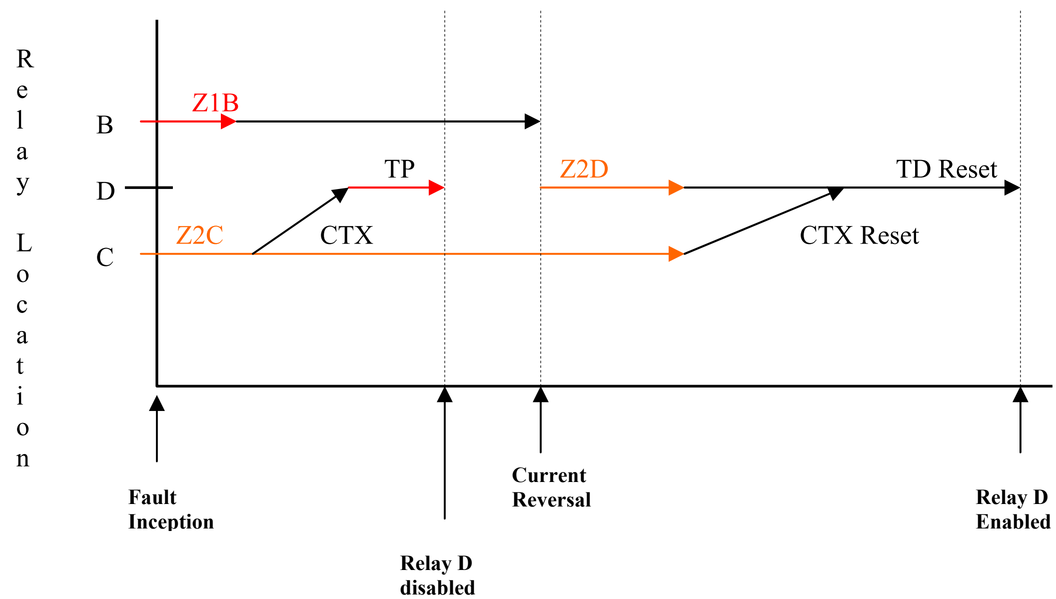


Figure 1-18 Current-Reversal Guard Timing Sequence [16]

The current reversal guard sequence diagram illustrated in Fig. 1-18 shows how the relays in the healthy line are prevented from incorrect operations due to the sequential opening of circuit breakers in the faulted line and the instance in the cycle at which this takes place. The current reversal guard is initiated when the healthy line relay at C receives a permissive trip signal from D the instant the current flow is reversed (D to C flow direction), but does not have zone 2 elements operated. A delay on pick-up ('TP', which is recommended by Eskom transmission to equate to 30ms, as this is the maximum channel operating time) in the current reversal guard timer is necessary in order to allow time for the zone 2 elements to operate, if they are to do so if the fault was indeed an internal fault. Once the current reversal guard timer has been initiated, the healthy line relay D transfer trip is inhibited. The reset of the guard timer is initiated by either the loss of signal or by the operation of zone 2 elements. A time delay TD for reset of the current reversal guard timer is required because, if the zone 2 elements of the relay at D were to operate before the permissive trip signal from the relay at C has reset, this could cause the relay on the healthy line to maloperate. [16]

1.4.4.2 Weak Infeed Tripping

The “weak infeed” tripping is an additional application found in most modern distance protection relays using the POR schemes to facilitate high speed tripping operations for faults falling beyond the zone 1 reach, of the protection of the strong source substation and close to a substation without sufficient fault current contributions to facilitate local protection operation or when the remote end breaker is opened. The weak infeed ideology is illustrated in Fig. 1-19.

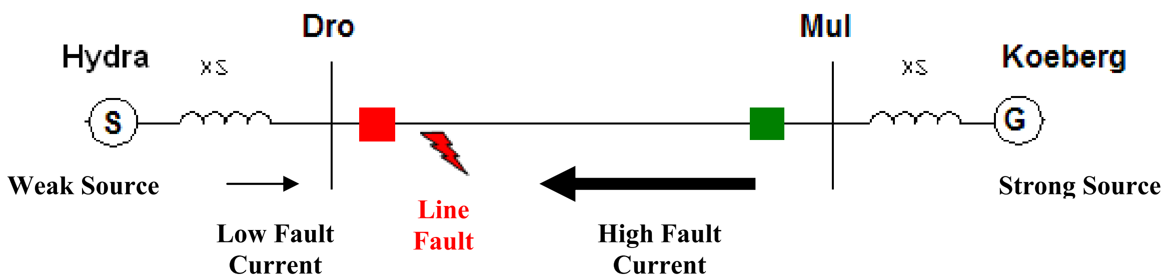


Figure 1-19 Weak Infeed Condition during in zone Line Fault

Consider the case illustrated in Fig. 1-19, a fault falling outside the zone 1 reach of the strong source substation and very close to the weak source substation. The relay at “Mul” will pick-up and isolate the local breaker while at the same time sends a carrier to the remote substation “Dro” as there is sufficient current at this substation to operate the protection relays, but because there is not sufficient fault current at “Dro” (i.e. $I_F < 100$ to 250mA on the secondary side of the CTs), the relay at this substation will not operate to clear and isolate the local breaker. To improve security of the above condition the weak infeed function is used.

To ensure reliable operation of the weak infeed function the following conditions must be met [16]:

a) Forward measuring elements at the weak source substation have not operated
b) Strong source forward measuring elements have operated and permissive carrier signal sent.
c) Weak source has received the permissive carrier signal
d) Permissive carrier signal sent from strong source relay to weak source relay if fault is beyond the weak source substation (illustrated in Fig. 1-20).

To prevent incorrect tripping in the case of reverse faults, the reverse blocking elements (zone 3) at weak source end have to block the weak infeed operation. Figure 1-21 shows a general logic diagram of the operation of the weak infeed operating condition. Moreover, to further improve scheme security, some of the modern relays are now being developed with additional features highlighted in dotted line in the weak infeed logic illustrated in Fig. 1-21.

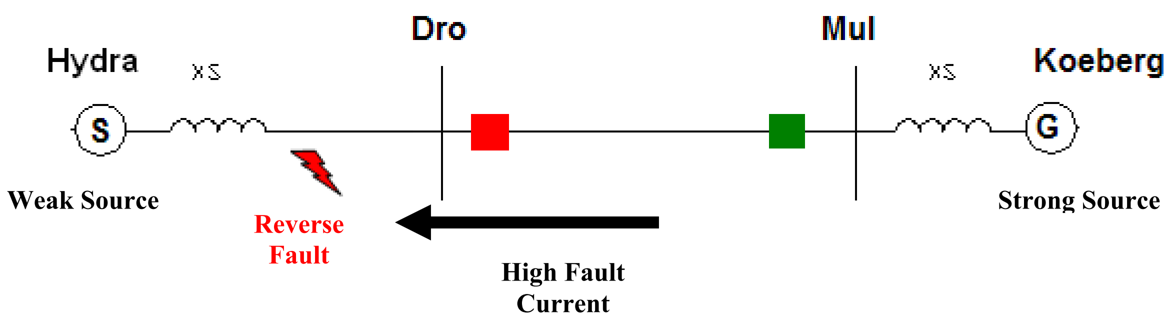


Figure 1-20 Reverse Fault Behind Weak Infeed Source

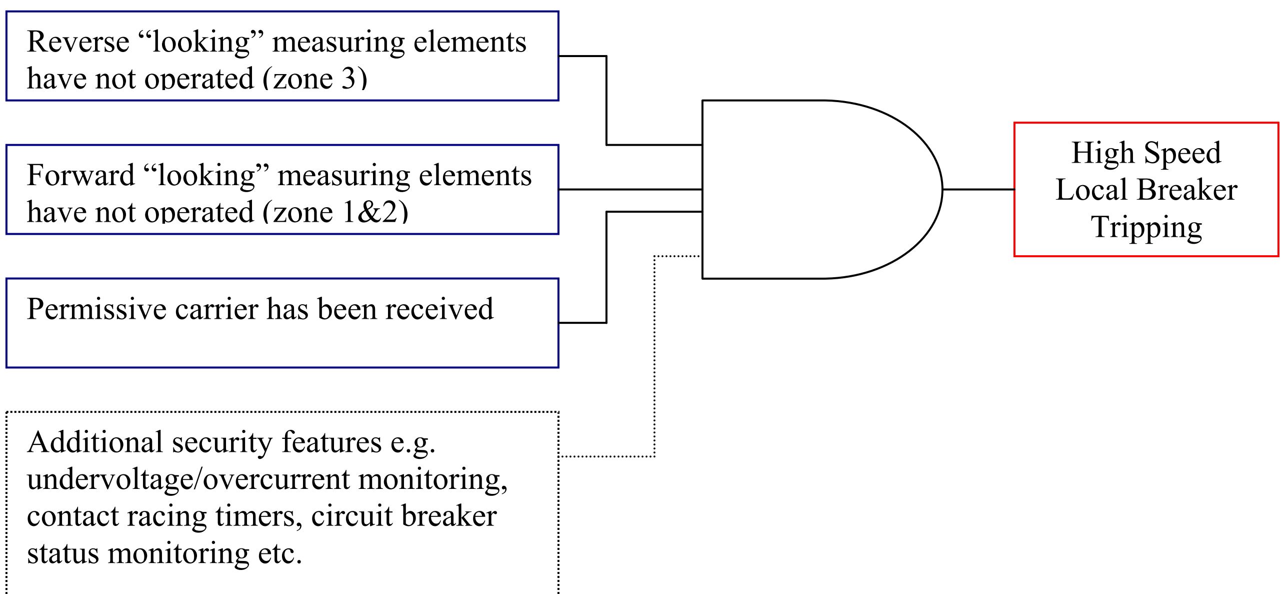


Figure 1-21 Weak Infeed Carrier Start Logic [16]

If all the conditions are satisfied in the weak infeed carrier start logic, then the relay will trip high-speed even though the distance elements at the weak source have not detected a fault.

1.4.5 Final Comparison Remarks on PUR and POR schemes

a) If selectable modern relays are utilized, zones with the furthest resistive reach should be used for permissive tripping. This will ensure the best coverage for high resistance faults. This means the POR scheme as it utilizes Zone 2 to send permissive tripping signals has a more reliable/dependable factor when compared to the PUR scheme.

b) Under-reaching schemes cannot be depended upon to provide adequate primary protection since the capacitor's own protection (i.e. removing and/or shorting the capacitors) will result in a section of the line which will have no instantaneous tripping coverage at all (discussion in Section 1.3.1.2). So, it is with this result that the permissive under-reaching schemes are not recommended for the protection of series compensated lines.

c) Although the POR scheme has superior performance for high resistance faults and protection of series compensated lines when compared to the alternative, it runs a risk of lack of reliability/dependability if it were to lose its communication channels, same goes for the PUR. This risk requires that the scheme communication channels be duplicated**.** Most of the phase electromechanical and early electronic relays on the Eskom Transmission grid are of PUR scheme. The present standard, since the introduction of static phase two relays, is of the POR intertripping scheme.

1.5 Distance Relay Settings

The previous sections presented discussions on the fundamentals of the distance protection operating philosophies and the type of schemes used on distance protection. This section will be discussing the fundamental setting philosophies followed by [16] when using the distance protection relays for protecting their important transmission lines. The REL 531 distance protection relays will be used as point of reference on the discussions as these will be the studied relays on answering the research question at hand. The decision to use these relays was for the purposes of analyzing the impact of SC on the performance of the relays as closely as possible to what would be in the field, since these particular relays are the most used on Eskom transmission lines.

1.5.1 Background of the REL 531 relay

The REL 531 protection relay is a high-speed distance protection relay suitable for use on series compensated networks for the purposes of protecting, monitoring and controlling overhead lines. It can also be used as back up protection to the adjacent lines and or transformers to the line being protected. The scheme utilizes a third generation distance protection characteristic i.e. the “quadrilateral characteristic”, which consists of five independent operating zones.The characteristic uses directional reach elements and is provided with adjustable reactive and resistive reach settings that are set independently on the R/X plane, each comprising three measuring elements for phase to earth (Ph-E) faults and /or three measuring elements for phase-to-phase (PH-PH) faults [20].

The minimum protection requirements for a line protected with distance protection is to have at least two forward reaching zones, one under-reaching zone and one over-reaching zone, these being zone 1 and zone 2 respectively. It is normal practice for protection engineers to try as much as possible to follow manufacturer’s recommendation when protection settings are to be calculated. One of the recommendations that are followed by [16] is to also include a third zone which is usually zone 3. This zone could either be forward reaching, reverse reaching and or could be set to be non directional [16]. However, as has been mentioned in Section 1.2 of this chapter, zone 3 in Eskom Transmission is always configured to reverse reach to cater for special circumstances such as ‘weak infeed tripping’.

Since the studies that will be conducted in answering the research question will be involving looking at the performance of zone 1 and zone 2, only these two zone settings will be discussed in this document.

1.5.2 Zone 1 Settings

As it was mentioned in Section 1.3, that there are certain limitations which are to be noted and or kept in mind when calculating the zone 1 settings. Following are [16] recommendations that will be followed in their listed order of priority when the zone 1 reach settings for the distance protection of the lines that will be under investigation are calculated. It is also to be noted that only the limitation that will be affecting the network section under investigation will be discussed.

a) Zone 1 is normally set to reach 80% of the positive sequence reactance of the line that is to be protected. This decision is taken to eliminate the risk of the Zone 1 protection over-reaching as a result of the probability of measuring errors that can rise from current transformers, voltage transformers, relays and inaccuracies in the line parameter data used. This is the most important limitation that is to be adhered to as settings greater than this recommendation (80%) could lead to a loss of discrimination with fast operating protection on the adjacent lines if the zone should over-reach.

b) Zone 1 may be reduced to below 80% reach when lines are series compensated. The extent to which this setting can be reduced will be dependent on the size and position of the SC; a safety margin curve for zone 1 setting discussed later in Section 3.3 is used to calculate this setting while catering for the limitation of SC.

c) When relays used for line protection are of modern technology, allowing for selection of resistive reach independently from other zones, as in the case of REL 531 relay, it is advisable to ensure that the ground elements of zone 1 cover at least a resistance of 20 ohms primary, refer to Fig. 1-22. This was an engineering decision that was taken by [16] based on the transmission line fault history investigations, where most ground fault resistance records proved to be in the range of 1 to 20 Ohms, with the majority of the faults being in the order of lower Ohm levels. However, fault resistance levels of up to 50 Ohms and above are also a possibility but rarely experienced [21].

d) Zone 1 must not encroach the load characteristic with a minimum of 50% margin. Usually this requirement is automatically covered once other zones with greater reaches are selected, since they also have to meet this requirement. In cases where individual selection of the resistive coverage is used, the following equation is used:

$1.5 \times Z1 < Z_{LOAD}$

Where:

Z1 = Zone 1 resistive reach

$Z_{LOAD} = Ze$

Where:

$Ze = V_{Line}$ / Line emergency load current

e) Zone 1 is set without any intentional time delay which in Eskom Transmission is normally set to operate instantaneously.

1.5.3 Zone 2 Settings

As in the case of zone 1 settings, there are also certain limitations that govern the reliability and security of zone 2 when zone 2 settings are calculated. Following are [16] recommendations that will be followed in their listed order of priority when the zone 2 reach settings for the distance protection of the lines that will be under investigation are calculated. Also for zone 2 setting calculations only the limitation that will be affecting the network section under investigation will be discussed.

a) The minimum allowable setting for zone 2 reach is 120% of the positive sequence reactance of the line to be protected. This decision is taken to ensure full coverage of the line, thus catering for the 20% that is not covered by zone 1 and also offers an allowance for the measuring errors mentioned in the previous section, in consequence, should the relay under-reach, full line protection coverage will still be maintained.

b) Zone 2 must not encroach the load characteristic with a minimum of 50% margin, the ideology is depicted in Fig. 1-22. In cases where individual selection of the resistive coverage, the following equation is used: $1.5 \times Z2 < Z_{LOAD}$.

f) When relays used for line protection are of modern technology, allowing for selection of resistive reach independently from other zones, it is advisable to ensure that the ground elements of zone 2 cover a maximum fault resistance reach and should not be less than 20 ohms primary, refer to Fig. 1-22.

g) Zone 2 is set with an intentional time delay which in Eskom Transmission is normally set to 400ms.

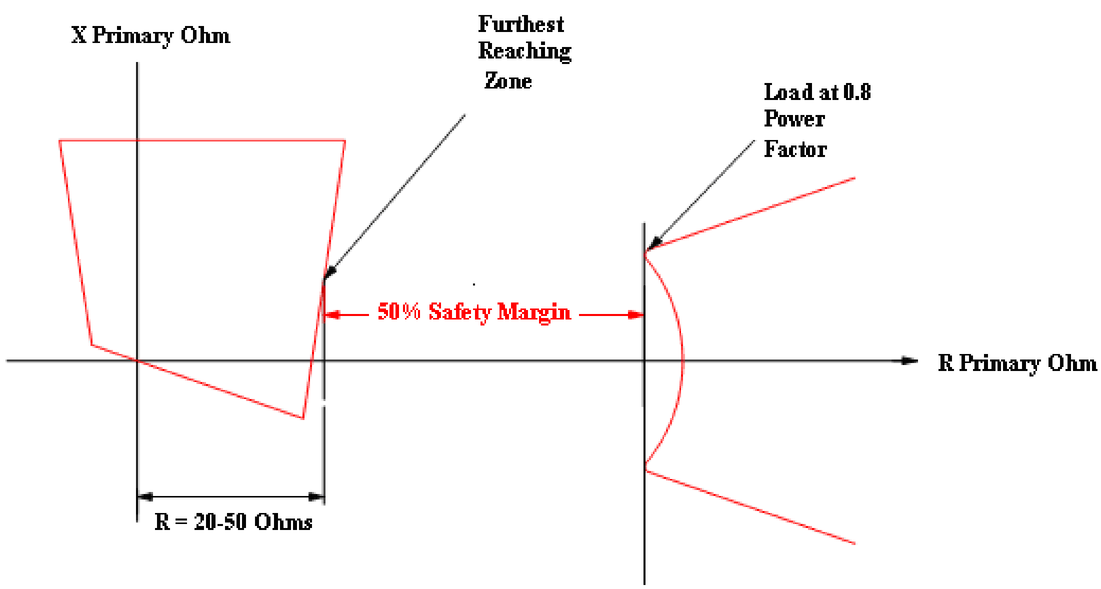


Figure 1-22 Distance Relay Setting Considerations [16]

CHAPTER II

2. Series Compensation

2.1 Series Compensation of Transmission Lines

Modern transmission systems are becoming heavily loaded, which consequently conveys the benefit of the utilization of the series capacitors on the Eskom power transmission grids. It has been effectively proven by a number of researchers all over the world that by having series compensation as a feature on power transmission grids, it is undoubtedly one of the cheapest and a simplest ways of ensuring that the transmission system has improved stability, increased transmittable power, redu ced transmission losses, enhanced voltage control and more flexible power flow control. Environmental concerns are also addressed when compared to the alternative [4, 5, 7].

The amount of line compensation is usually represented as a percentage of the line inductive reactance that is compensated with series capacitors. In Eskom Transmission the series compensation values for lines are usually within the ranges of 20 – 60 percent [17].

2.1.1 Improved Power Transfer Capability

With regards to power transfer capability, the active power transfer from one system to another is given by the following expression:

$$P = (V_1 * V_2 \sin\delta)/X \qquad (2.1)$$

$$X = X_L (1 - k) \qquad (2.2)$$

$$k = X_{c/} X_L \qquad (2.3)$$

Here, "V_1" and "V_2" represent the magnitudes of the voltages at either end of the transmission line, whereas "δ" represents the angular difference of the said voltages, X_L is the reactance of the line, X_c represents the reactance of the series capacitor and k is the degree of compensation. The setup is illustrated in Fig.2-1.

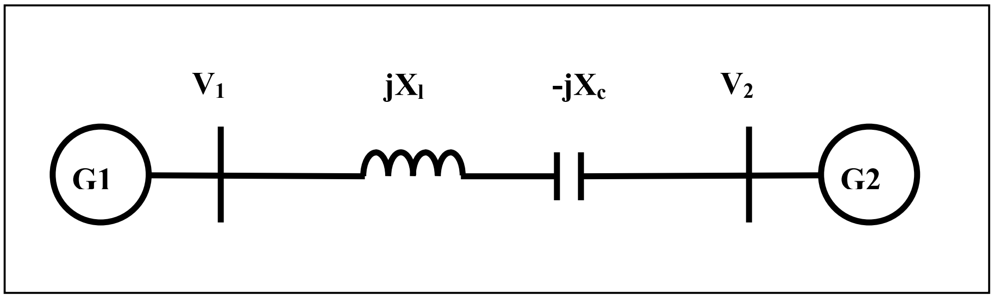


Figure 2-1 Power Transmission Line with Series Capacitor

From equation (2.1) it is evident that by introducing series capacitors (see equation (2.2)) on the interconnecting transmission line, this action would introduce a negative reactance to the positive reactance on the non-compensated line [5], consequently, reducing the overall line reactance and therefore increasing the amount of active power that can be transferred for a given transmission angle δ.

On proving the phenomenon of increasing power transfer capability on a network by mere introduction of series compensation on a transmission link, an experimental study performed by [5] was followed, where the power transmission line depicted in Fig. 2-1 was considered as a case study. The study involved analysis on how the transmitted power varies with the size of the series capacitor, where it was assumed that the magnitude of the voltage at the sending bus to be V_1 [kV] and that the magnitude of the voltage at the receiving bus to be V_2 [kV].

Furthermore, it was assumed that the electrical phase angle between the voltage at the sending and the voltage at the receiving end to be δ [degrees]. Furthermore, it was assumed that the series reactance of the power transmission line is equal to X_L [Ω] and that the series resistance of the line is zero. Finally, it was assumed that the reactance of the series capacitor is Xc [Ω].

The conclusion attained [5] was proven to be correct, as the study involved keeping all system parameters constant and only varying the degree of compensation i.e. k=0.0, k= 0.5 and finally k=0.7. The results attained are demonstrated graphically in Fig. 2-2 where it is illustrated that a 70% series compensated line shown in Fig. 2-1 will have a better power transfer capability compared to the same line if it were 50% or even 0% series compensated.

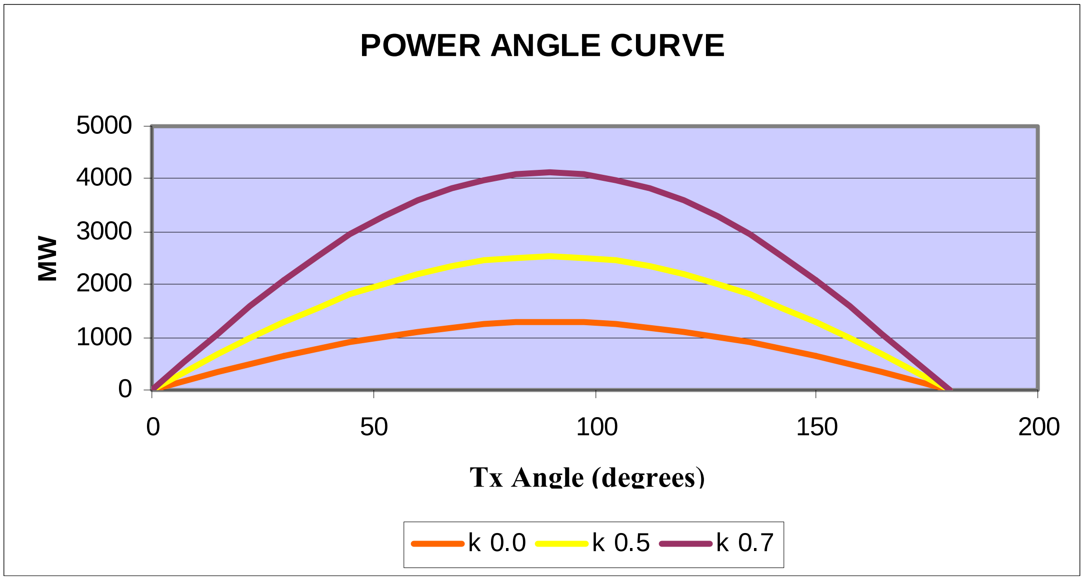


Figure 2-2 Power Transmission Curves for the Line

2.2 Series Capacitor Protection

Series capacitors have proven to be a very important element economically with regards to long distance power transmission. One of the most crucial considerations as far as the design and application of these devices has been over-voltage protection. The traditional Spark Gaps (SG) protected the series capacitors installed before the mid 1970s [3], this scheme bypasses the series capacitors to avoid over-voltages. Though there are still SGs in the Eskom Transmission Network, they are now being phased out with the metal oxide varistor protection. Fig. 2-3 shows the survey statistics of the SC protection on the Eskom Hydra South Network. The survey done by Eskom Transmission [13] conveyed that 50% of SG series capacitor over voltage protection still exists on the Hydra South Network, while also about 50% of the remaining SC are protected with MOVs. About three new projects are in place to install series capacitors and it has not been decided what will be used for SC protection on these particular circuits, these being the following:

a) Iziko 1 Hydra Poseidon Line circuit 01

b) Iziko 2 Hydra Poseidon Line circuit 02

c) Serumular 1 Beta Delphi Line circuit 01

A complete survey attained from [13] of the SC on the Eskom Hydra Network is as shown in Appendix A.

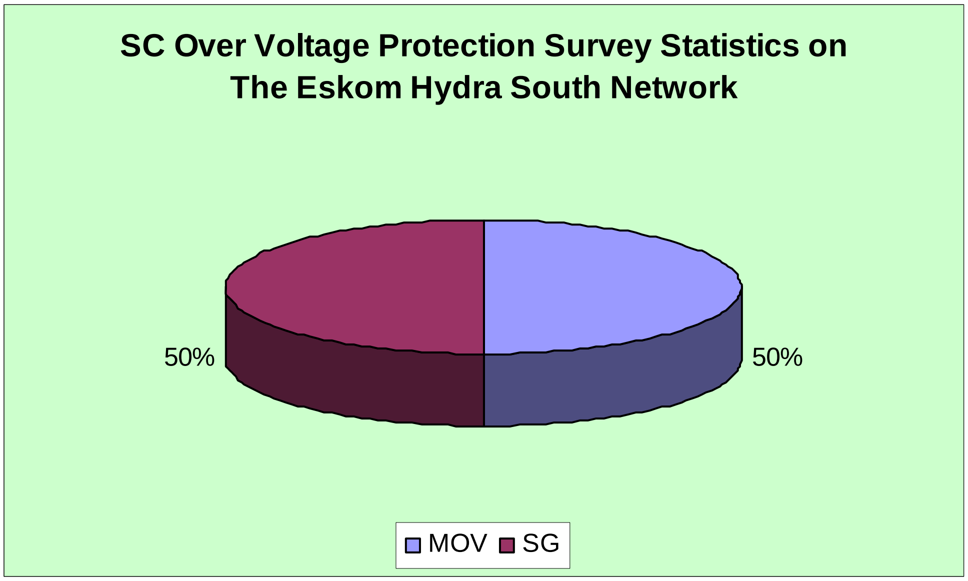


Figure 2-3 SC Protection Survey Statistics on the Eskom Hydra South Network [13]

The problems of distance protection relaying on series compensated lines are promoted even further with the utilization of these over-voltage protection schemes i.e. SG and/or MOV schemes. Spark Gaps (introducing a varying resistance component), Metal Oxide Varistors (introducing a varying and nonlinear resistance), [5] or even a circuit breaker which closes during faults creating a bypass around the capacitor for high fault currents, thus, introducing uncertainty into the relay calculations.

2.2.1 Spark Gaps

Fig. 2-4 shows a typical series capacitor protected by the spark gap scheme consisting of the basic following elements: the Spark Gap and the by-pass switch. The spark gap protection is connected directly in parallel with the series capacitor that it is protecting.

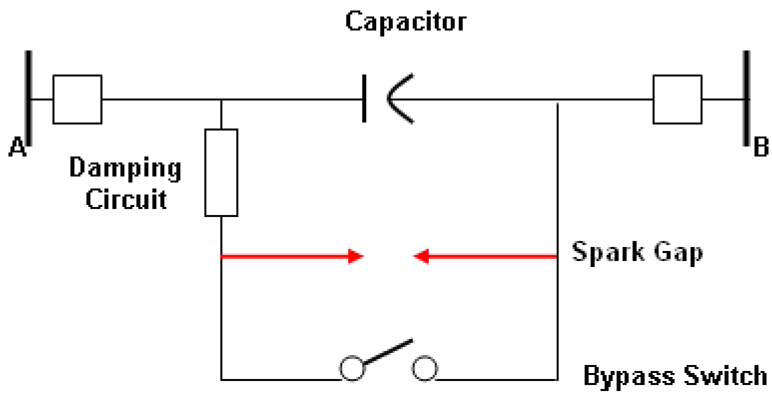


Figure 2-4 Typical Spark Gap Scheme for Over-voltage Protection

2.2.1.1 Principle of Operation

During a power system fault, the spark gap is self triggered and will flash over when the voltage across the series capacitor exceeds a threshold value. A by-pass switch will be operated by closing for all extended current flow through the arcing spark gap, thus, completely bypassing the series capacitor. The damping circuit is incorporated in the circuit for the sole purpose of limiting the discharge current and absorbing the energy stored in the high-level charged series capacitor.

The series capacitor is reinserted into the system by opening the by-pass switch. The protection and control will issue a reinserting command of the SC when the fault has been cleared, this will be attained by opening the by-passing switch after a certain time interval has elapsed, this is to allow the gap to deionize and ensuring that the SG withstand voltage has been regained. If the attempt for reinsertion is made too soon, it is likely to cause re-ignition of the ionized SG, especially when the line current is high. A de-ionizing time in the range of 200-300 ms is generally necessary [4, 5]. The gap scheme is sufficient for many applications, however, when fast reinsertion following disconnection of external fault is required (i.e. less then 100ms after fault clearing), the relatively long deionization time of the gap is a drawback [4].

2.2.2 Metal Oxide Varistors

"MOVs for over voltage protection are derived from their unique conduction properties and ability to remain stable under continuous energization even after repeated surge duties. Metal Oxide Varistors display a non-linear conduction mode that is highly desirable for overvoltage protection. The resistive intergranular molecular boundaries between the conductive zinc-oxide grains and the rare metal additives become conductive under sufficient electrical field stress. Very simply, after a certain threshold voltage is reached, small increase in electrical stress causes a drastic increase in conduction current. This 'non-linear' resistive behavior supports the application of the system voltage with very low leakage current, yet maintaining a remarkably constant voltage during high current surges. This method of overvoltage protection provides a number of benefits that include instantaneous reinsertion without transient, lower capacitor protective levels, greater reliability and lower maintenance" [12].

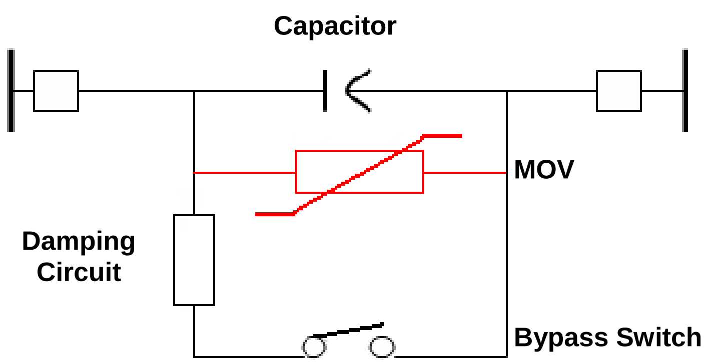


Figure 2-5 Typical Gapless MOV Scheme for Overvoltage Protection

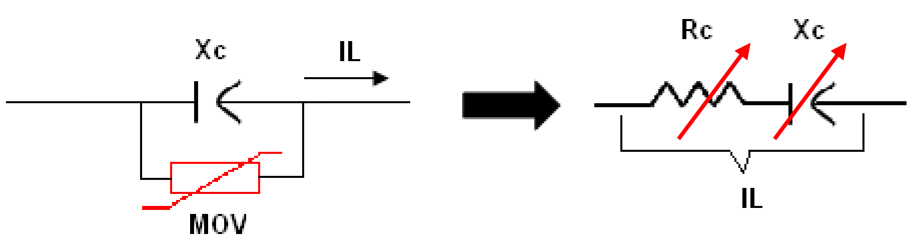


Figure 2-6 Capacitor/Varistor Goldsworthy equivalent model

2.2.2.1 Principle of Operation

Fig. 2-5 shows a typical series capacitor protected by the MOV scheme consisting of the basic following elements: the MOV, the damping circuit, and the by-pass switch. The MOV protection is connected directly in parallel with the series capacitor that it is protecting. The non-linear resistance characteristic of the MOV material shown in Fig. 2-7 makes it ideal for direct connection to the capacitor [9] and for voltage limitation. According to Goldsworthy model [9], the apparent impedance of the SC and MOV combination, as a function of the current flowing in the line can be represented in the equivalent circuit shown in Fig. 2-6. The series impedance model is shown in Fig. 2-8, where the resistance and the capacitive reactance are nonlinear and are a function of normalized capacitor bank current I_{LN} expressed in per unit, where one per unit I_L is the capacitor bank rms current rating at which the MOV begins to conduct [4]. Therefore, for bank currents below the SC protective level (“The protective level is the level of fault current at which MOV start conducting” [14]), the series circuit is a constant capacitive reactance which equates to its full SC rating. The moment the MOV protective level is exceeded, the MOV current will increase rapidly as shown in Fig. 2-7. At this point the effective circuit series impedance decreases and the current is diverted from the SC to the MOV. Now when currents much larger than the protective level flow through the MOV, the capacitive reactance gets less than 5% of its rated value but there is still a small value of the capacitive reactance component within the resistor/capacitor arrangement [4].

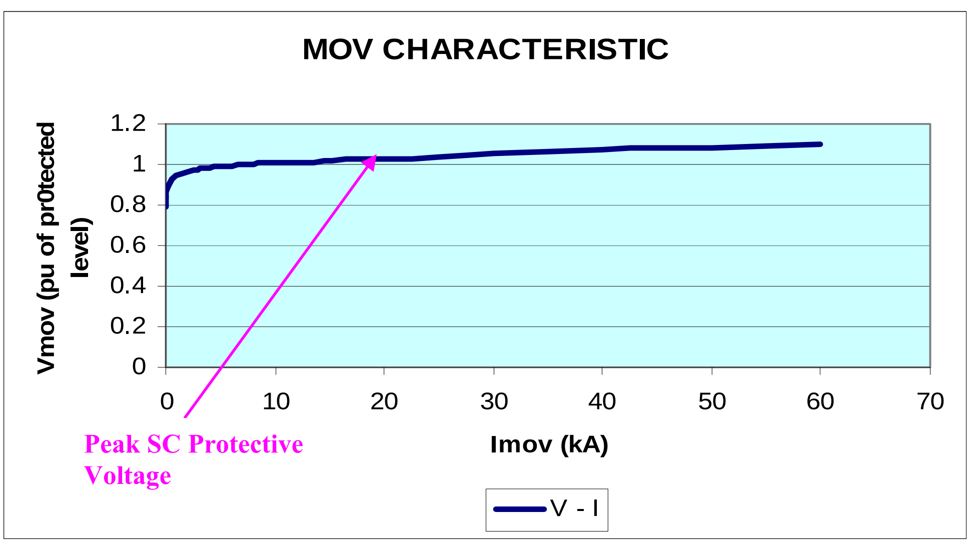


Figure 2-7 Non-linear resistance characteristic of the MOV

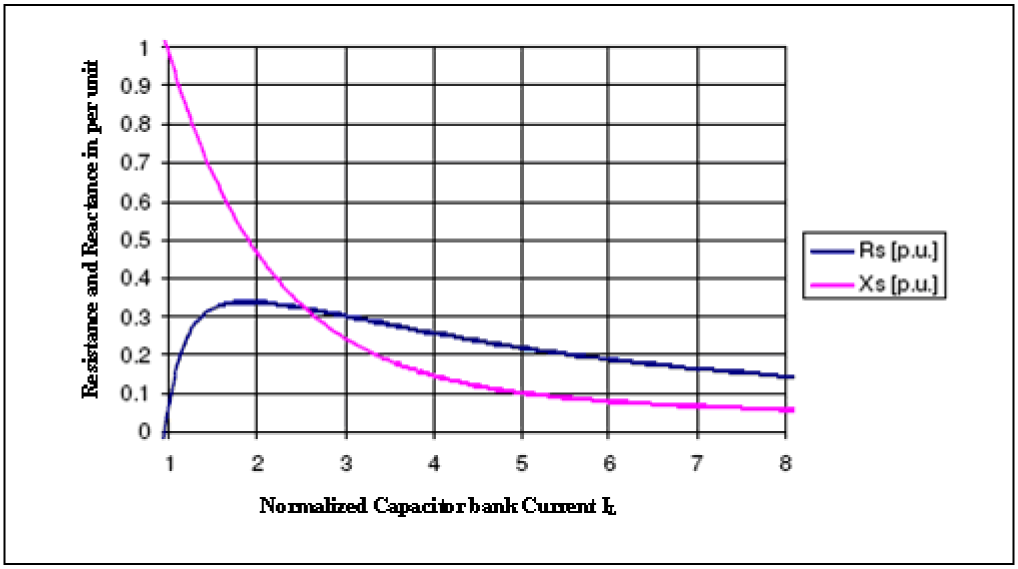


Figure 2-8 Non-linear Resistance and Reactance of the Varistor-Protected Series Capacitor Bank as a Function of Normalized Bank Current [23]

In the event of a power system fault, the excessive high currents will flow though the SC causing the MOV to conduct and absorb energy. When the maximum allowable MOV energy threshold is reached, the bypass switch will be operated by closing, thus, completely bypassing the series capacitor and the MOV connected in parallel to it. The damping circuit that is connected in series with the triggered bypass gap consists of a current limiting reactor, a resistor and a varistor in parallel with the reactor as illustrated in Fig.2-9, and has the following purpose: the resistor is there to add damping to the capacitor discharge current and thus quickly reduces the voltage across the capacitor after bypass operation, while the varistor is utilized for the purpose of avoiding the fundamental frequency losses in the damping resistor during steady state operations [5].

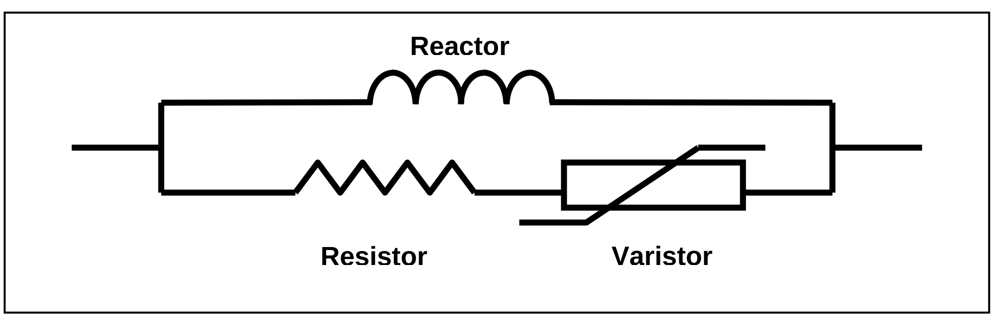


Figure 2-9 Typical Damping Circuit Arrangement

2.2.3 Final Comparison Remarks on SG and MOV schemes

a) The SG overvoltage scheme is a sufficient scheme for protection of series capacitors but when fast reinsertion is a requirement for external fault (i.e. less than 100ms after fault clearing), the scheme's considerable delay in deionizing the arc gap is a drawback, and it is with this reason that the MOVs are considered a logical option in overcoming the drawback [4].

b) For the same specified overvoltage protection application the SGs are relatively a cheaper option in comparison to the MOVs.

2.3 Effects of Series Capacitors and its Protection

The addition of series compensation can have serious effects on the performance of the protection system more especially on distance protection relaying relating to the change of impedance seen by the relay. This is because under transient conditions the impedance seen by the relay is no longer a unique correspondence of the physical distance from the relay location to the point of fault. The level of impact is greatly dependent on the line parameters, series capacitor size and its location.

2.3.1 Behavior of Non Series Compensated line and its Protection

A typical transmission line constructed without series capacitors shown in Fig. 2-10, has a linear relationship where the impedance of the line is directly proportional to its length, with the relationship between the two represented by equation 2-4. Fig.2-10 depicts the apparent impedance of a non series compensated power line as a function of distance viewed from the relay location.

$$Z_{LINE} = (R_{LINE} + jX_{LINE}).\ L_{LINE} \qquad (2.4)$$

Where:

L_{LINE} = Line length in km.
R_{LINE} = Line resistance in Ω/km.
X_{LINE} = Line reactance
in Ω/km.

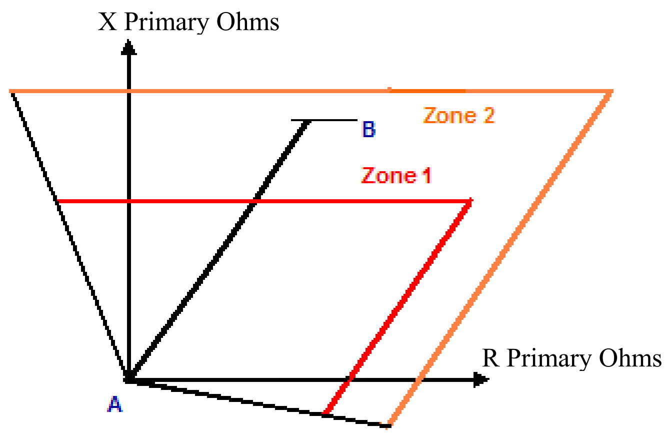


Figure 2-10 Apparent Impedance for Non Series Compensated lines

Predominantly the power transmission lines are inductive, as a result, the internal fault currents in such a network will cause phase currents flowing from a terminal into a protected line to lag the source voltage, with the assumption that the reference direction of the relay currents is from the busbar into the protected line. The phenomenon is illustrated in Fig.2-11. In most cases phase comparison systems usually take the in-phase currents for internal faults and out-of-phase for external faults. Now with the introduction of SC in the system, this can change these basic relationships known to protection relaying, more especially for faults before and after the SC that can give rise to voltage and current reversals [5]. Voltage and current reversals are the two problematic phenomena that challenge the relay logic in positively identifying faults on the transmission line [4]. As a result the reliability and security of the distance protection relaying is compromised.

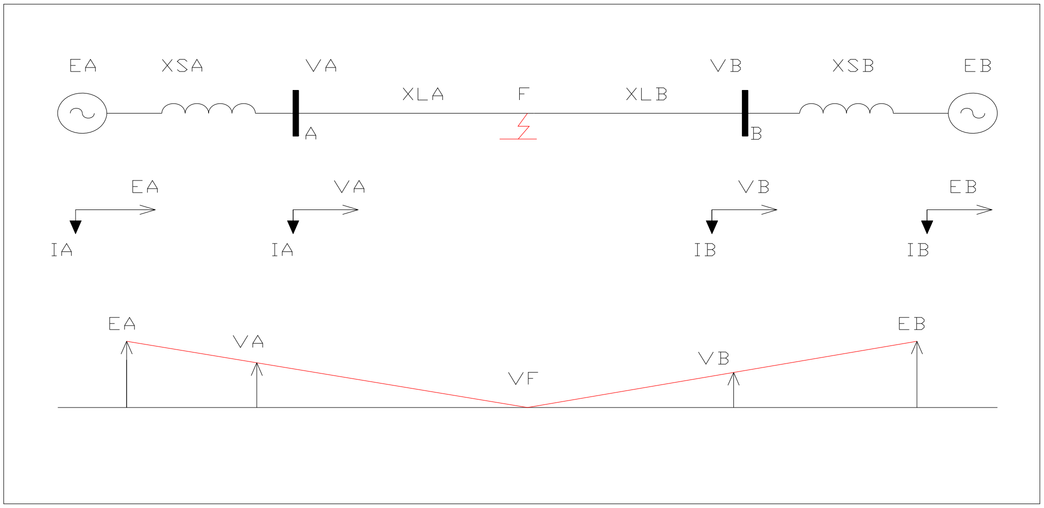
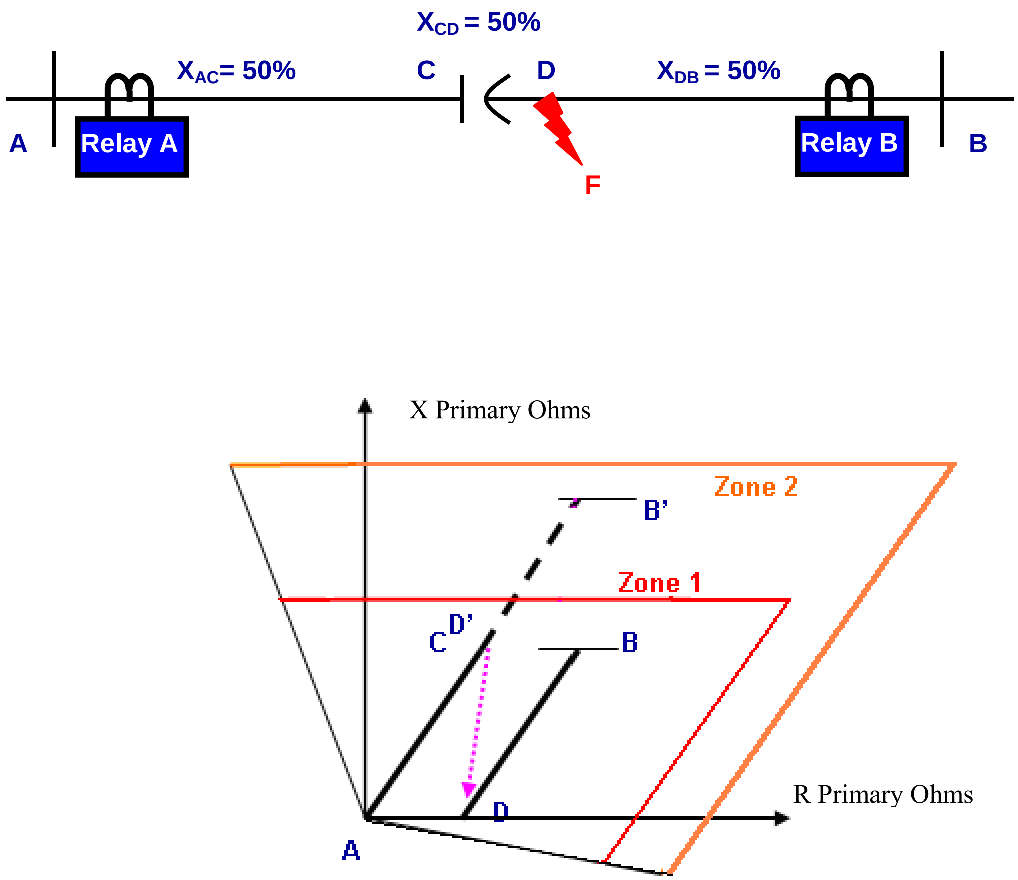


Figure 2.11 Fault Currents in Non Series Compensated lines [5]

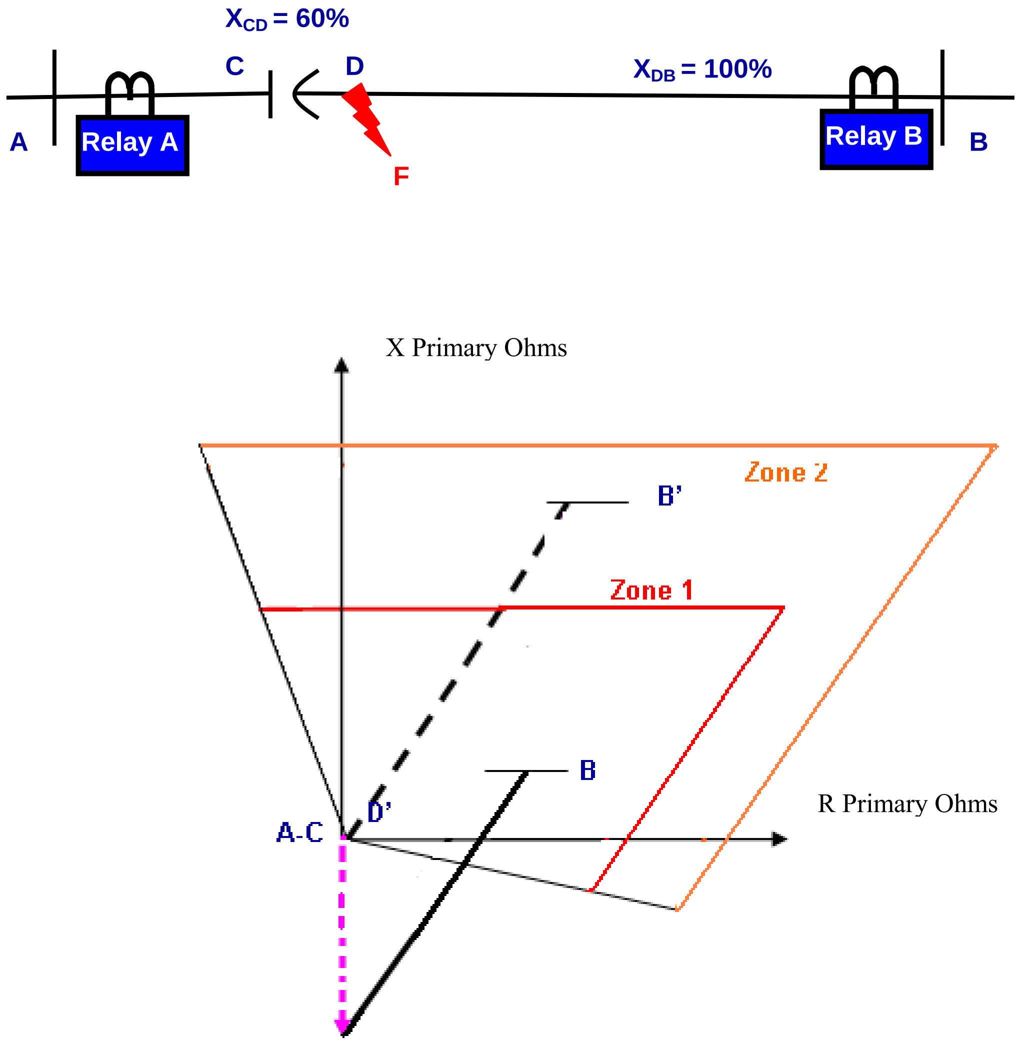
2.3.2 Behavior of Series Compensated line and its Protection

Fig.2-12 (a) and (b) illustrate the apparent impedance seen by the relay at position A when a 50% and 60% of series compensation is applied at the middle and end of the line respectively. Faults beyond the SCs appear to be closer when a 50% SC is not completely bypassed while for the 60% series compensation at the end of the line, the relay sees the fault in the reverse direction, as a result, the under-reaching elements of the distance relay ‘Zone1’ operate erroneously for faults outside its reach. This is because the impedance seen by the relay is no longer a unique correspondence of the physical distance from the relay location to the point of fault.



(a)

Figure 2-12 Apparent Impedance for Series Compensated lines



(b)

Figure 2-12 (continued) Apparent Impedance for Series Compensated Lines

2.3.3 Voltage Inversion

Voltage inversion is defined as the change of the voltage phase angle by 180 degrees [15]. With reference to a transmission line depicted in Fig. 2-13 below, when assuming that the SC overvoltage protection is not conducting, the voltage inversion phenomena can be represented by equation 2.5.

$$X_{LA} < X_C < (X_{LA} + X_{SA}) \qquad (2.5)$$

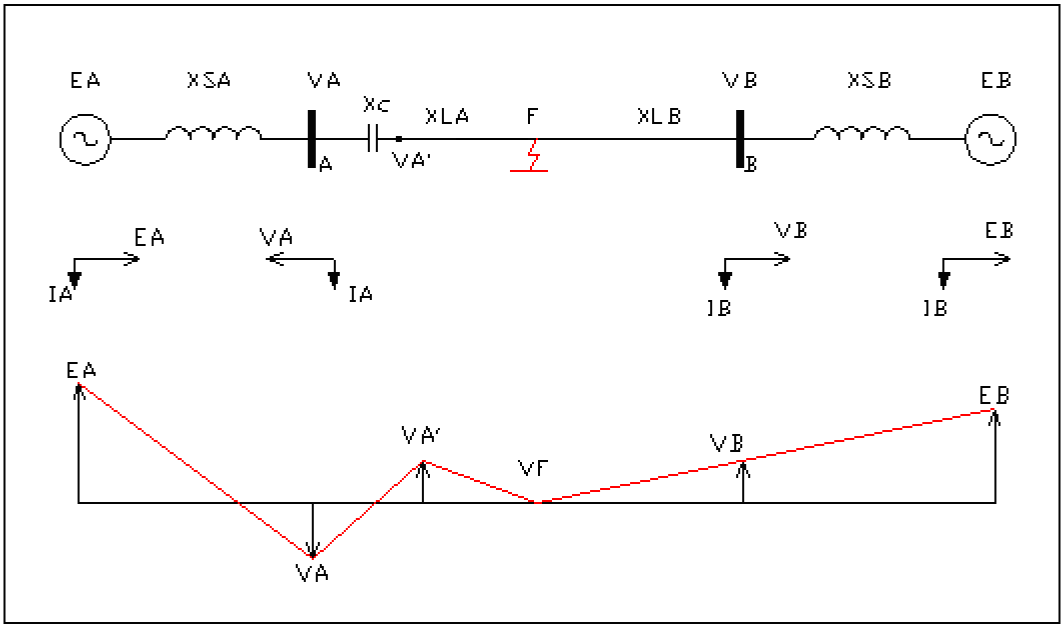


Figure 2-13 Voltage Inversion Phenomenon [5]

The phenomenon occurs as a result of the relay at Substation A, looking forward into the line and seeing the impedance to the point of fault as capacitive ($X_C > X_{LA}$) rather than inductive ($X_C < X_{LA}$), causing the voltage measured at the relay point to be capacitive (i.e. the fault current leads the measured voltage at relay A by 90˚)

Referring to Fig. 2-13, a three phase fault just in front of the SC, if we assume the arrangement of ($X_C > X_{LA}$), VA and VA' voltages will be 180 degrees out of phase, with VA' being the normal voltage for forward faults and VA voltage reversed in reference to VA' voltage [15]. This means for a fault condition depicted in Fig. 2-13, in order for the distance protection relays located at Substation A to correctly identify the fault for what it is, a forward fault, then line side voltage data VA' should be utilized by the relay. The phenomenon is thus referred to as voltage inversion and or voltage reversal, as the relay will proclaim a reverse fault on the adjacent line as a forward fault if VA bus side voltage is used.

2.3.4 Current Inversion

The phenomenon occurs on series compensated lines when a line experiences an internal fault as depicted in Fig. 2-14, with one side of the equivalent system from a point of fault being capacitive (i.e. left side of fault in Fig. 2-14, when ($X_{SA} < X_C$)), and the other equivalent system side (right side of fault in Fig. 2-14) being inductive.

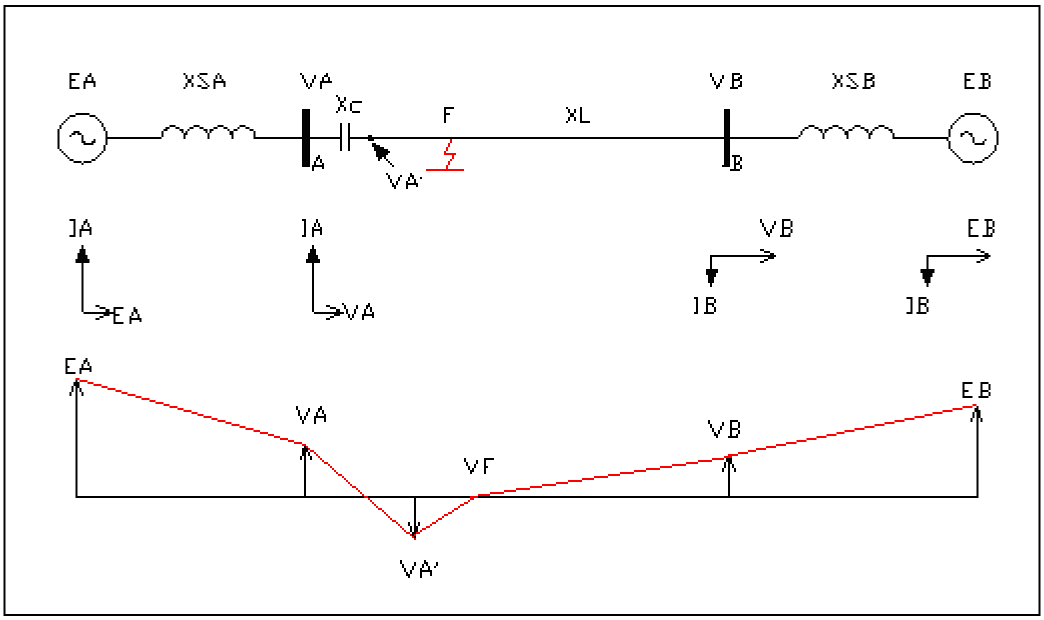


Figure 2.14 Current Inversion Phenomenon [15]

With bus "B" system section being inductive, current I_B will lag voltage V_B by 90 degrees, while the bus "A" system section is capacitive, current I_A will lead voltage V_A by 90 degrees. As a result the two currents will be 180 degrees out of phase. It goes without saying that this will create problems for distance protection relaying, since when declaring an internal fault both currents need to be in phase [5, 15, 24].

Current reversals are associated with high degrees of line compensation that result in high fault currents [4]. The problem is easily resolved by the mere utilization of SC overvoltage protection devices (MOVs and SGs) discussed in Section 2.2. Under high current line fault conditions the overvoltage protection device will conduct and absorb energy in case of "MOV", and when the voltage across the series capacitor exceeds a threshold value, the SC will be completely bypassed by the overvoltage protecting devices connected parallel to it. In reference to Fig. 2-14 setup, this action will cause the capacitor reactance to be reduced and or even removed, as a result the SC system section becomes inductive and completely eliminating the possibility of the current reversal phenomenon.

On this note, this makes the current inversion phenomenon a highly unlikely occurrence in compensated networks. However, in cases of high resistance faults, the low fault currents will prevent the overvoltage series capacitor protection devices from operating, hence, allowing the occurrence of the current inversion phenomenon.

CHAPTER III

3. System Under Study

3.1 System Layout

Fig. 3-1 shows the expanded Hydra South Network section with relays under investigation. The rest of the entire Eskom Hydra South Network is as shown in Appendix B. The system supplies power to the Western Cape and is interconnected between two power stations, these being Koeberg a strong source and Hydra a weak source. It encompasses a couple of long heavily series compensated 400 kV transmission lines, which include Bacchus-Proteus, Proteus-Droerivier and Muldervlei-Droerivier lines. The mentioned lines have a great impact to the performance of the relays under investigation which are located at Muldervlei-Bacchus line, a non-series compensated 109km long 400kV transmission line, with the second relay located on the Bacchus-Droerivier line, a 402km long and 60% series compensated 400kV transmission line. The MOV characteristics of the series compensated lines of the area of focus for the studies of this research are shown in Appendix D.

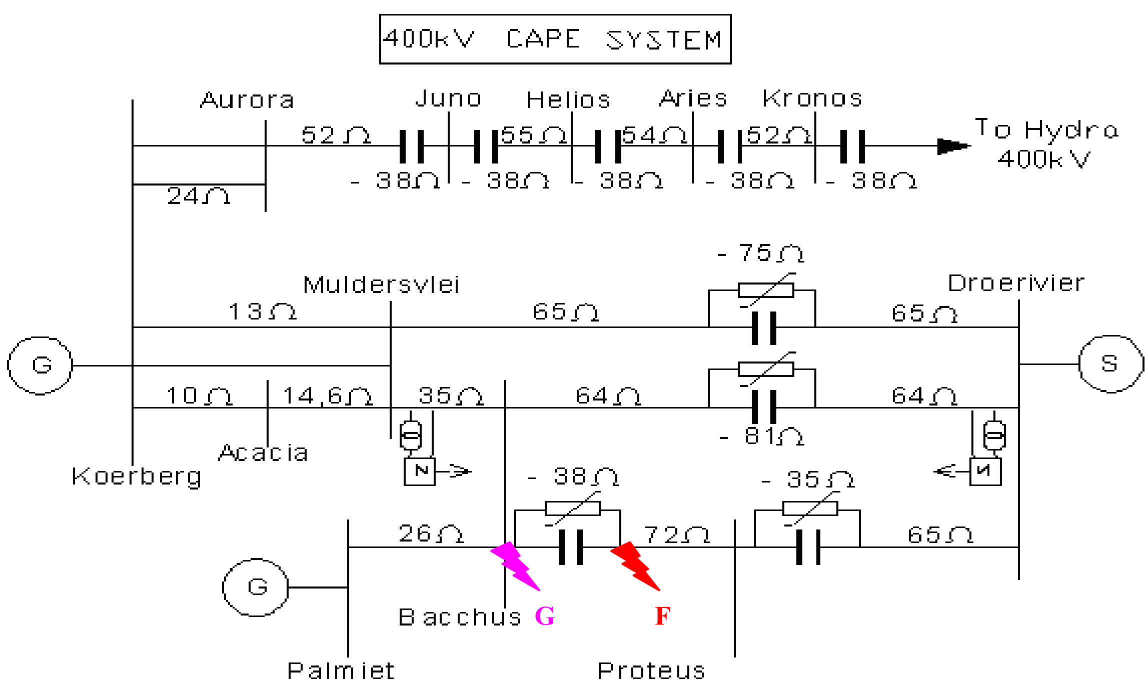


Figure 3-1 Hydra South Network section with fault positions and relays under investigation [14]

The network topology was modeled on the Digsilent PowerFactory simulator with every line represented using lumped parameter model. This was because when investigating setting calculations and relay performance analysis, lumped model of the line parameters is normally sufficient and very much recommended by Eskom System Operator. All line series capacitors which included their over-voltage MOV protection were modeled as closely as possible to what is on the field. The only setback in the PowerFactory simulator as far as SCs are concerned, is that the model does not include the SC bypass breakers. Thus, for the objectives of this dissertation, the bypass breakers were modeled manually across the SCs for the purposes of analyzing performance of the relays if the SCs were completely bypassed during dynamic fault conditions. The SC bypass breaker relay model was designed utilizing the Digsilent Simulator Language (DSL) function in PowerFactory to simulate the bypassing of both the SC and the MOV when the maximum MOV energy threshold is reached.

Also the entire network could not be modeled on the student version package that was utilized for these studies as the package is limited to a specific number of nodes/buses (31) that can be simulated. Some of the network sections were replaced with an equivalent Thevenin circuit in a form of external grids, these included: all plant behind the Hydra busbar; all plant behind the Koeberg busbar and all plant behind the Palmiet busbar including the Palmiet – Bacchus line; the set up is illustrated in Appendix C.

The protection in the Muldersvlei – Bacchus (Mul-Bac) and Bacchus – Droerivier (Bac-Dro) lines in the studies made use of the Digsilent model of the REL 531 distance protection relays.

Lastly relay zone impedance reach settings were also performed in accordance to the Eskom's System Operator distance relay protection setting philosophies. This was for the purposes of analyzing the impact of SC on the performance of the relays as faithfully as possible to conditions that would be experienced in the field.

3.2 Studies Performed

In answering the research question the relays on the Mul-Bac and Bac-Dro lines were selected as the area of focus. The decision to select these two particular mentioned lines as the area of focus was because the studies will be able to cover impact to both the performance of the relays with lines that are series compensated and those that are not.

The performance of the relays was analyzed by applying faults at point F and G in the study case model to simulate and analyze the impact of series compensation on the relays located at Muldersvlei and Droerivier for faults before and after series capacitors respectively. Point ‘F’ is immediately behind the Bacchus series capacitor bank in the adjacent Bacchus – Proteus (Bac-Prot) line as illustrated in Fig. 3-1. Point ‘G’ is immediately in front of the Bacchus series capacitor bank, terminated on the Bacchus busbar. For faults located at these points immediately before and after the SC (again refer to Fig. 3-1), the relays on the Mul-Bac and those at Bac-Dro lines are not supposed to operate for these faults. However, due to the phenomenon mentioned in Section 2.3, such a fault (point F) could appear in zone 1 of the relay at either Muldersvlei or Droerivier. On the EMT dynamic study analysis performed, which were focusing mainly on the network topology shown in Fig. 3-1, the results conveyed that not only does such a probability exist, but that the fault would appear behind the relay at Muldersvlei [1] and at Droerivier, while for a fault located at point G, the underreaching zone elements at Muldersvlei and Droerivier could not see this fault.

3.3 Relay Setting Calculations

In the studies performed, all the settings were calculated utilizing a REL 531 setting calculating programme developed by ref. [20]. This programme utilizes the primary side line parameter data and converts this information into secondary data, the programme than uses this converted data to calculate the relay settings, while at the same time caters for the limitations discussed in section 1.5.

The normal recommended settings were first calculated on the program for each line of focus in the research without concern for the effects of the limitations within the line to be protected itself and or on adjacent lines. In each case of the lines under investigation, these being Mul-Bac and Bac-Dro lines, this meant that the zone 1 reach of the relays was set to 80% of the line length. The programme than allowed the settings to be calculated catering for the limitations which in the case of the Bac-Dro line, the zone 1 reach setting was reduced as the line is series compensated, this action was taken to cater for the subharmonic oscillations caused by series capacitors under fault conditions. Zone 1 was then set as a percentage reach to the actual fault according to the safety margin curve for zone 1 setting shown in Fig. 3-2.

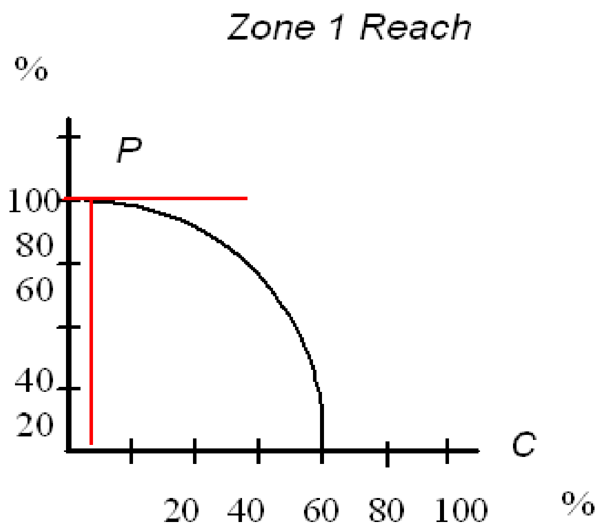


Figure 3-2 Safety margin for zone 1 setting [20]

Where:

C = Xc/X1, degree of compensation

X1 = Total positive sequence reactance from the source to the series capacitor

P = Maximum allowable reach for the underreaching zone.

C = Xc/X1

P is read from graph in reference to C

Zone 1 reach = (X1 – Xc)*P/100

Note: The reach equates to 17.89% of the (Bac-Dro) physical uncompensated line reactance.

The setting programme therefore gives more than one set of setting results, one that's catering for normal case situation and followed by a result for each and every limitation that the system is affected by. In the case of the investigation for the objectives of this document, only the normal case setting and series compensation limitations discussed in section 1.5.2 were considered. Adequate zone 1 settings were then selected within the calculated options on the basis that the reach setting must not be less than the minimum requirement (20 ohms) and also ensuring maximum possible resistive reach coverage (50 ohms) for the high resistance faults while at the same time making sure that the zone reaches do not encroach on the load. The same principle was followed for the setting of zone 2. The calculated line settings for Mul-Bac line are shown in Appendix E, while those of Bac-Dro line are shown in Appendix F, both settings are also summarized in Table 3-1 and Table 3-2 respectively. Fig. 3-3 and 3-4 demonstrate how the above relay calculated settings are configured on the Digsilent Power Factory program.

Parameter	Zone 1		Zone 2		Unit	Discription
	Primary	Secondary	Primary	Secondary		
X1PP	26.82	11.80	40.48	17.81	Ω/ph	Positive sequence reactive reach of the distance protection zone 1 for Ph-Ph faults.
R1PP	2.14	0.94	3.20	1.41	Ω/ph	Positive sequence line resistance included in the distance protection zone 1 for Ph-Ph faults.
RFPP	45.45	20.00	50.00	22.00	Ω/loop	Resistive reach of the distance protection zone 1 for Ph-E faults.
TPP	0.00	0.00	0.40	0.40	S	Time delayed trip operation of the distance protection zone 1 for Ph-Ph faults
X1PE	27.00	11.88	40.48	17.81	Ω/ph	Positive sequence reactive reach of the distance protection zone 1 for Ph-E faults.
R1PE	2.14	0.94	3.20	1.41	Ω/ph	Positive sequence line resistance included in the distance protection zone 1 for Ph-E faults.
X0PE	96.61	42.51	144.91	63.76	Ω/ph	Zero sequence line reactance included in distance protection zone 1 for Ph-E faults.
R0PE	26.73	11.76	40.11	17.65	Ω/ph	Zero sequence line resistance included in the distance protection zone 1 for Ph-E faults.
RFPE	45.45	20.00	50.00	22.00	Ω/loop	Resistive reach of the distance protection zone 1 for Ph-E faults.
TPE	0.00	0.00	0.40	0.40	S	Time delayed trip operation of the distance protection zone 1 for Ph-E faults

Table 3-1 Summarized Mul-Bac line Relay Settings [19]

Parameter	Zone 1		Zone 2		Unit	Discription
	Primary	Secondary	Primary	Secondary		
X1PP	22.64	9.96	191.80	84.39	Ω/ph	Positive sequence reactive reach of the distance protection zone 1 for Ph-Ph faults.
R1PP	8.64	3.80	15.99	7.04	Ω/ph	Positive sequence line resistance included in the distance protection zone 1 for Ph-Ph faults.
RFPP	45.45	20.00	50.00	22.00	Ω/loop	Resistive reach of the distance protection zone 1 for Ph-E faults.
TPP	0.00	0.00	0.40	0.40	S	Time delayed trip operation of the distance protection zone 1 for Ph-Ph faults
X1PE	22.64	9.96	191.82	84.40	Ω/ph	Positive sequence reactive reach of the distance protection zone 1 for Ph-E faults.
R1PE	8.64	3.80	16.00	7.04	Ω/ph	Positive sequence line resistance included in the distance protection zone 1 for Ph-E faults.
X0PE	272.98	120.11	655.09	288.24	Ω/ph	Zero sequence line reactance included in distance protection zone 1 for Ph-E faults.
R0PE	77.48	34.09	185.39	81.57	Ω/ph	Zero sequence line resistance included in the distance protection zone 1 for Ph-E faults.
RFPE	45.45	20.00	50.00	22.00	Ω/loop	Resistive reach of the distance protection zone 1 for Ph-E faults.
TPE	0.00	0.00	0.40	0.40	S	Time delayed trip operation of the distance protection zone 1 for Ph-E faults

Table 3-2 Summarized Bac-Dro line Relay Settings [19]

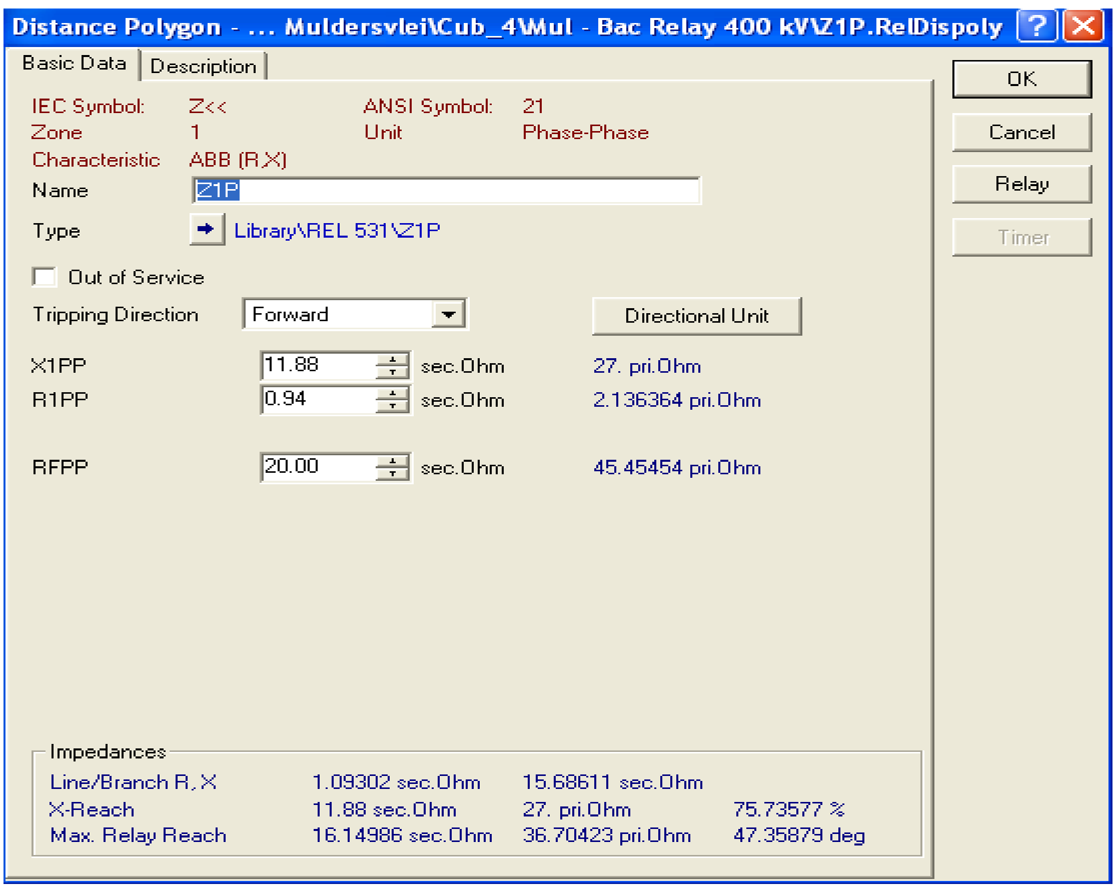


Figure 3-3 Zone 1 Phase to Phase Muldersvlei Relay window setting display

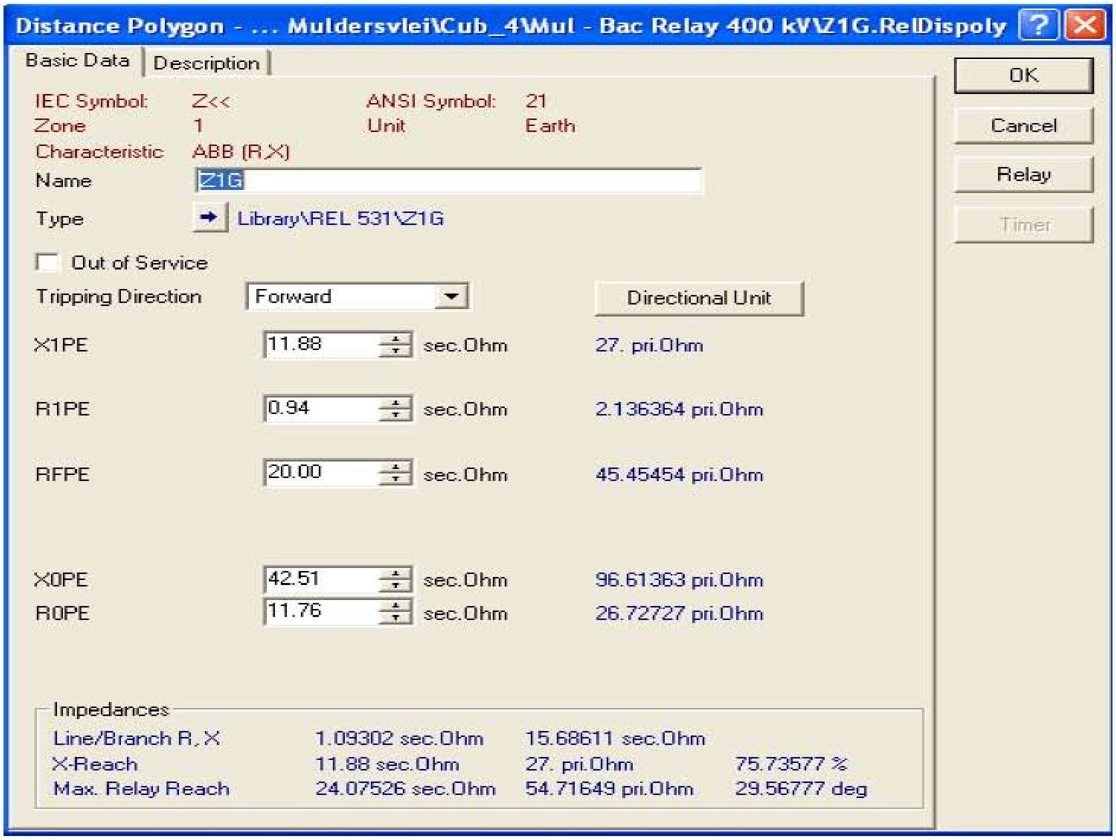


Figure 3-4 Zone 1 Phase to Earth Muldersvlei Relay window setting display

3.4 Response of Relay at Muldersvlei for a fault at ‘G’

PowerFactory simulator was utilized to perform a study of investigating the impact of series compensation on the performance of distance protection of the transmission lines for faults located before the SC. Fig. 3-5 shows the dynamic impedance analysis of the response of the relays at Muldersvlei for the study where a three phase fault was placed at point G, a point immediately in front of the Bacchus SC. The results show that for a three phase fault EMT study performed, the under reaching zone 1 elements do not “see” the fault in their reach, as the impedance loci of all three phases do not enter the zone 1 polygon characteristic area of the relays at Muldersvlei, hence the relay not tripping. However, the zone 2 reach elements do see the fault, as a result, the fault is cleared in zone 2 time. This proves correct relay configuration as by principle the region where the fault was placed is covered by zone 2 for backup protection purposes as discussed in earlier chapters.

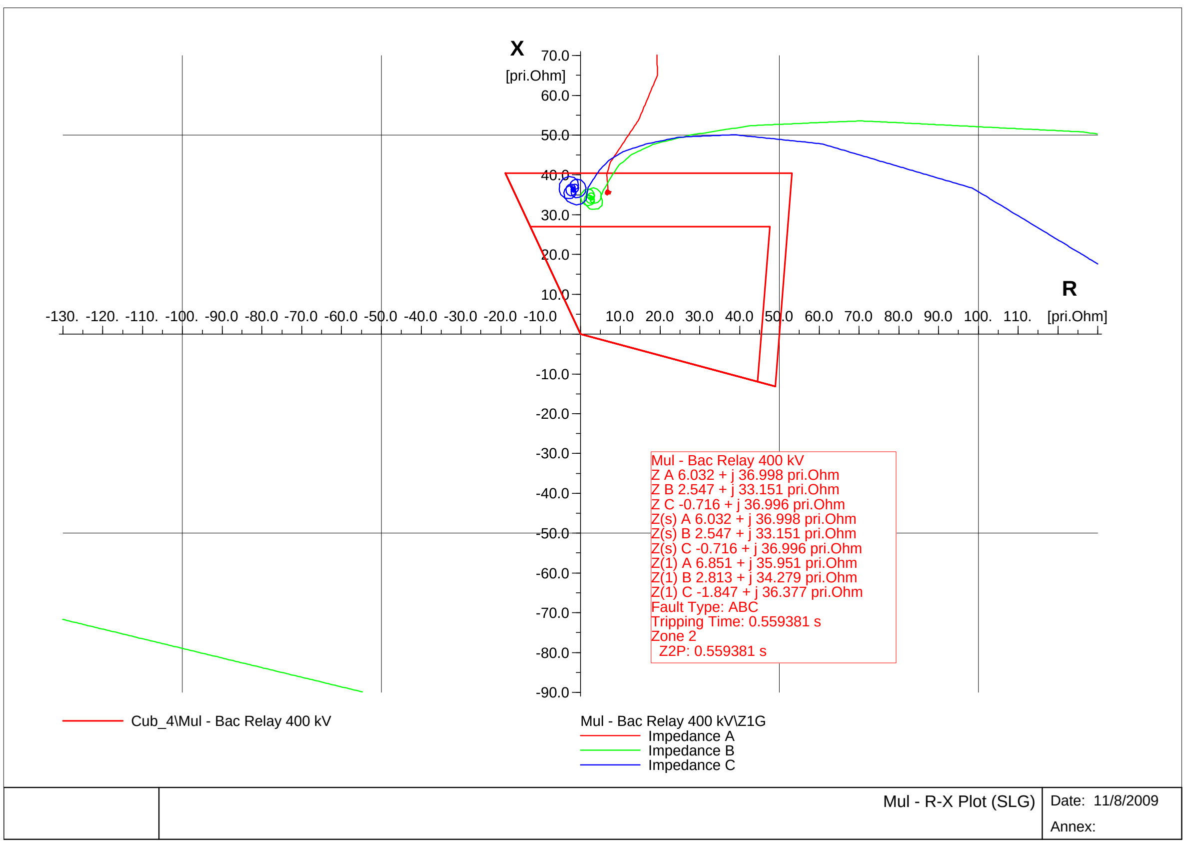


Figure 3-5 Response of relay at Muldersvlei for a three phase fault in front of the SC.

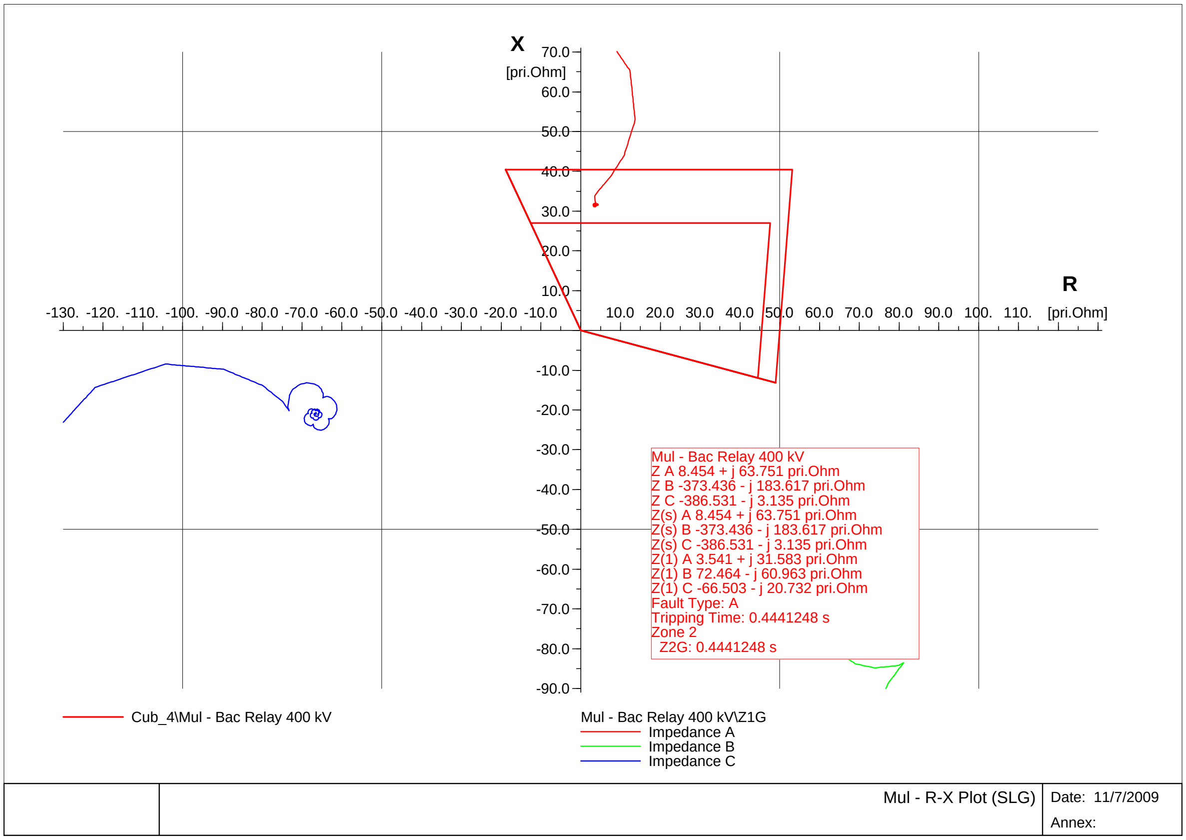


Figure 3-6 Response of relay at Muldersvlei for a SLG fault in front of the SC

Fig. 3-6 depicts the dynamic impedance analysis of the response of the relay at Muldersvlei for a single phase to ground fault at point G. The results again show that the underreaching zones of the relay at Muldersvlei do not “see” the fault in their reach for a single phase to ground fault as the faulted phase impedance does not enter the zone 1 polygon characteristic area, hence the zone 1 elements not tripping for this fault. However, also as in the case of the three phase fault, the zone 2 reach elements do see the fault, as a result, the fault is cleared in zone 2 time.

3.5 Response of Relay at Droerivier for a fault at 'G'

As for the studies performed at Muldersvlei for a fault at point G, similarly, PowerFactory simulator was utilized to perform a study of investigating the impact of series compensation on the performance of distance protection of the transmission lines and this time focusing on the Droerivier relay.

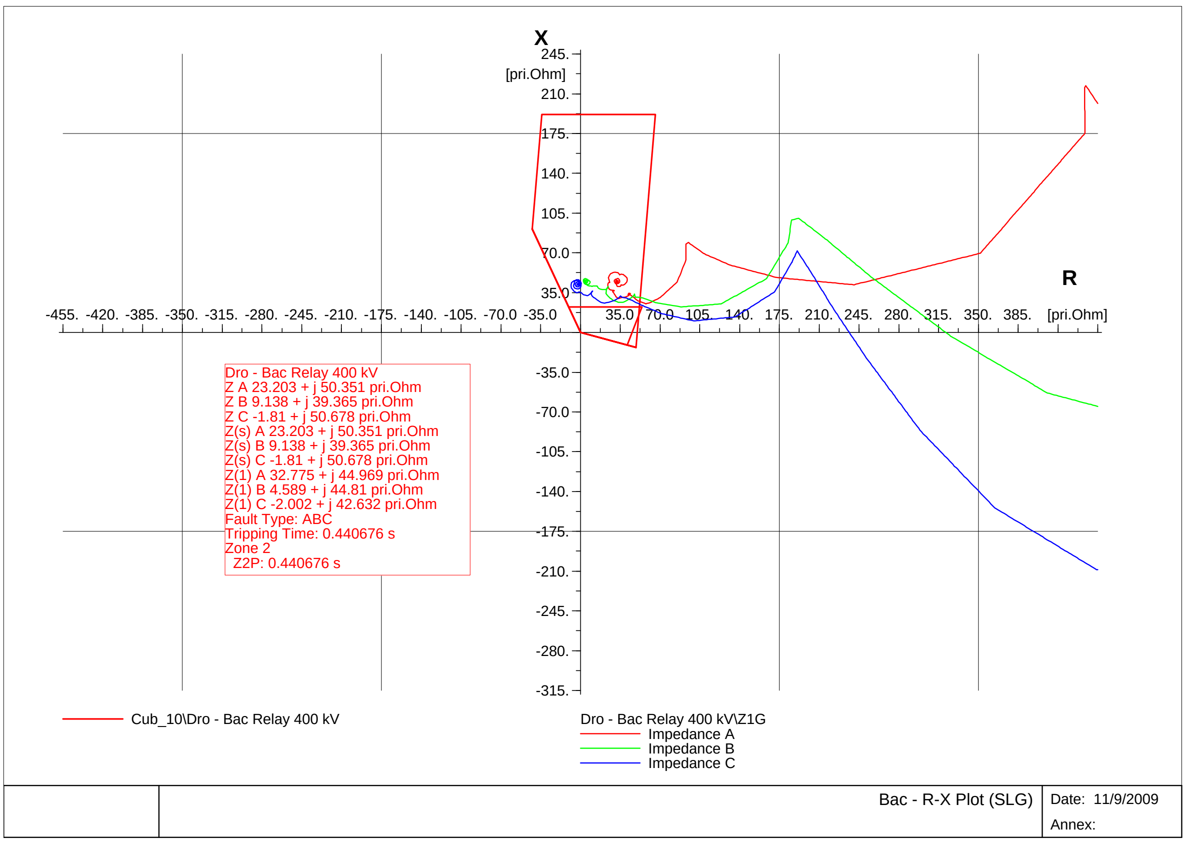


Figure 3.7 Response of relay at Droerivier for a 3-Phase fault in front of the SC

Fig. 3-7 depicts the dynamic impedance analysis of the response of the relay at Droerivier for the study where a three phase fault was placed at point G, a point immediately in front of the Bacchus SC. The study shows that for a three phase fault EMT study performed, the under reaching zone 1 elements do not "see" the fault in their reach as the impedance loci of all three phases, do not enter the zone 1 polygon characteristic area of the relay at Droerivier hence the relay is not tripping for this fault. However, it is noted that the fault impedance locus passes very close to the under-reaching zone 1, and well inside the over-reaching zone 2, as a result, the fault is cleared in zone 2 time. This conveys the importance of the decision taken to reduce the reach of the under-reaching zone elements from the normal setting of 80% to cater for the negative reactance that is introduced by the series capacitors on the Bacchus-Droerivier line, since it can be seen from Fig. 3-7 that should the zone 1 reach not have been reduced, the zone 1 elements would have over-reached for this external fault due to the impedance of the line that is no longer a unique correspondence to the physical distance from the relay location to the point of fault.

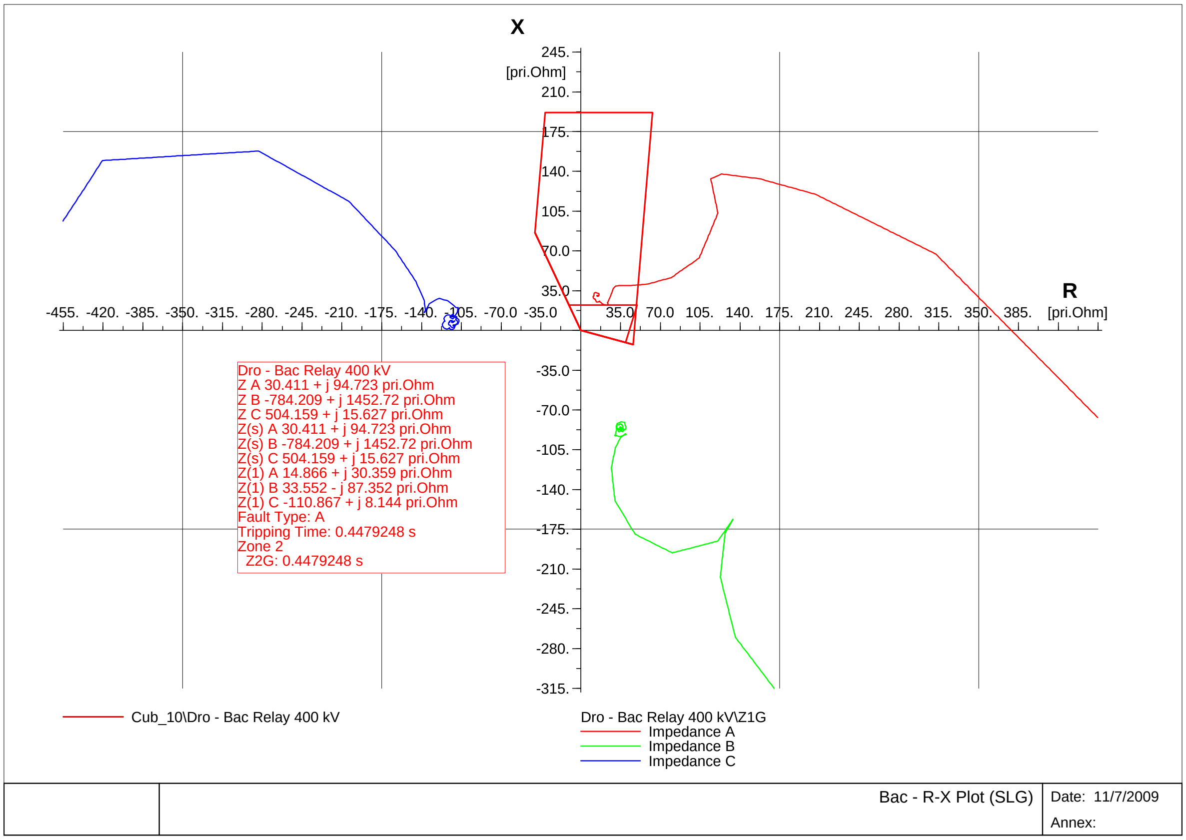
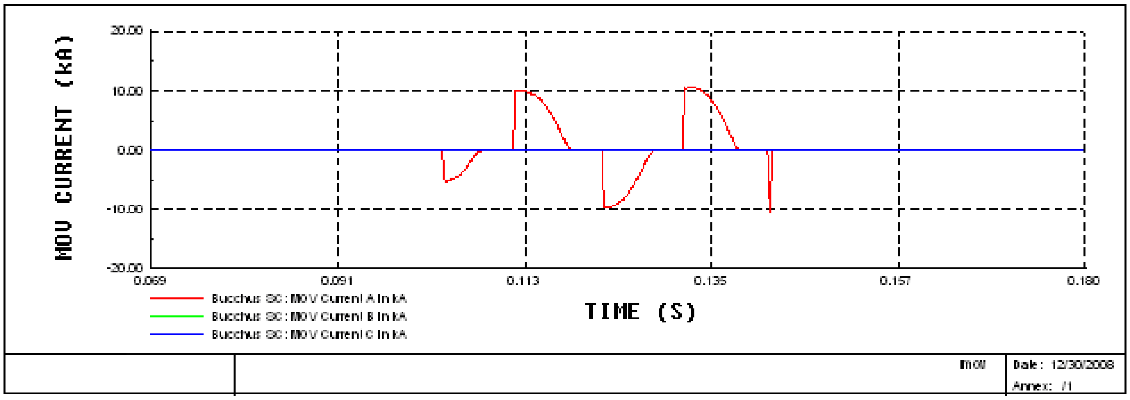


Figure 3-8 Response of relay at Droerivier for a SLG fault in front of the SC

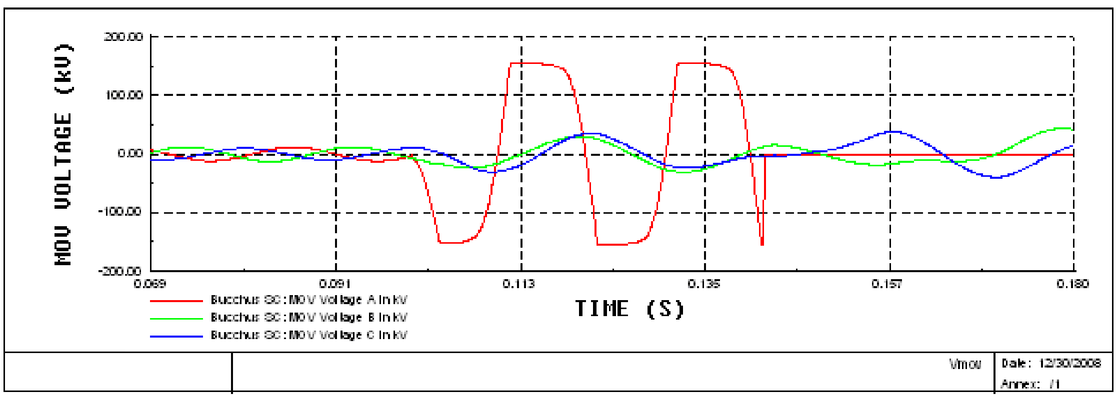
Fig. 3-8 depicts the dynamic impedance analysis of the response of the relay at Droerivier for a single phase to ground fault at point G. The results again show that the underreaching zone of the relays at Droerivier do not "see" the fault in their reach for a single phase to ground fault as the faulted phase impedance does not enter the zone 1 polygon characteristic area of the relay, hence the relay is not tripping for this fault. However, as in the case of the response of the relay at Droerivier for a three phase fault in front of the SC, the same can be noted for a single phase fault. The phase fault impedance locus passes very close to the under-reaching zone 1 and passes well inside the over-reaching zone 2, as a result, the fault is cleared in zone 2 time. This goes to show that should the zone 1 reach not have been reduced to cater for the series compensation, the zone 1 would have overreached for this external fault due to the impedance of the line that is no longer a unique correspondence to the physical distance from the relay location to the point of fault.

3.6 MOV Response for Faults In front and Behind SC

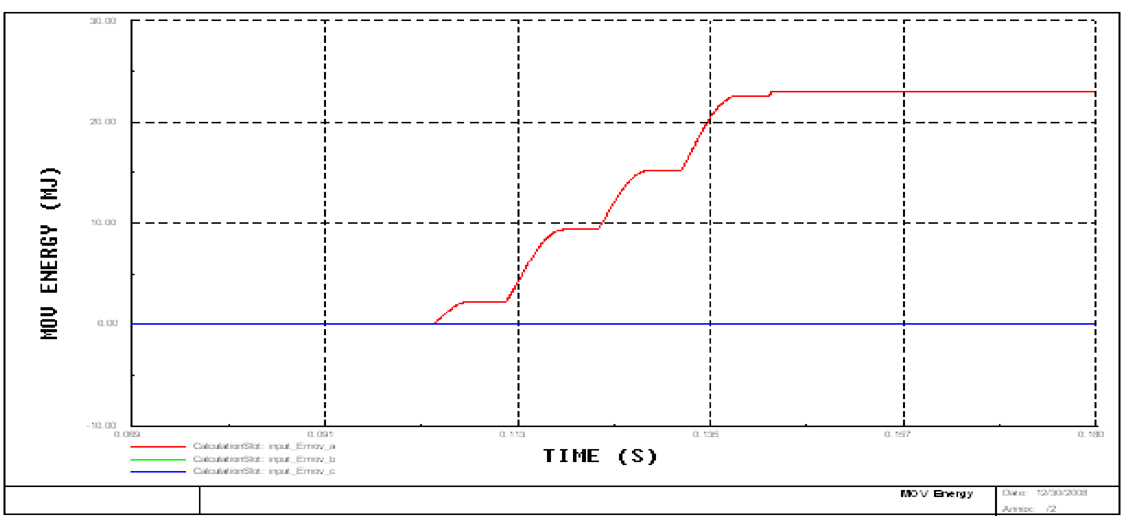
Fig. 3-9 and 3-10 depicts the behavior of the SC protection 'MOV' illustrating current, voltage and energy respectively on the Bacchus SC for both a three-phase fault and a single-phase to ground fault at point F, as obtained from the PowerFactory simulation model of the studied system.



(a) MOV Current

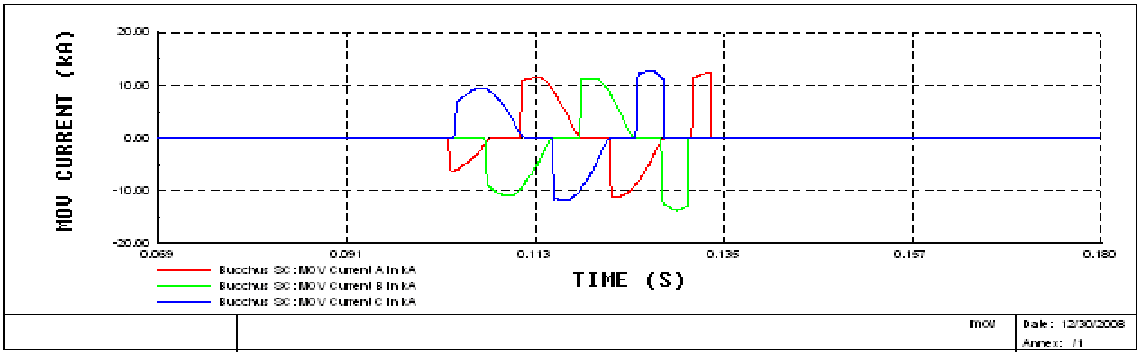


(b) MOV Voltage

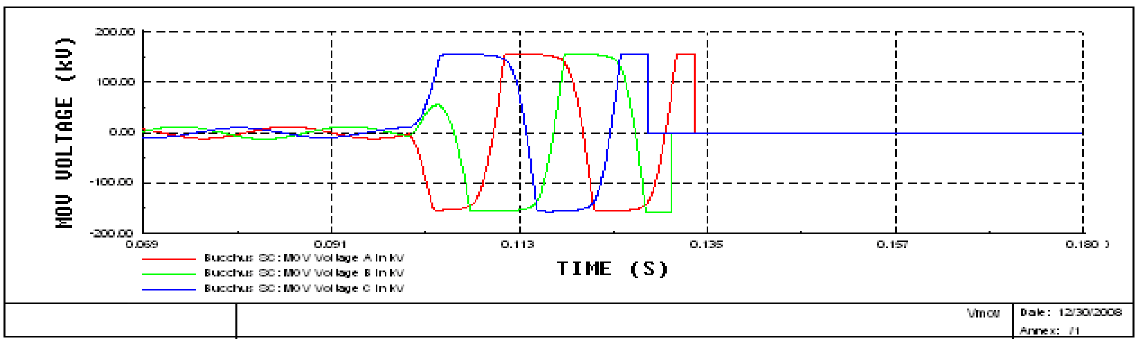


© MOV Energy

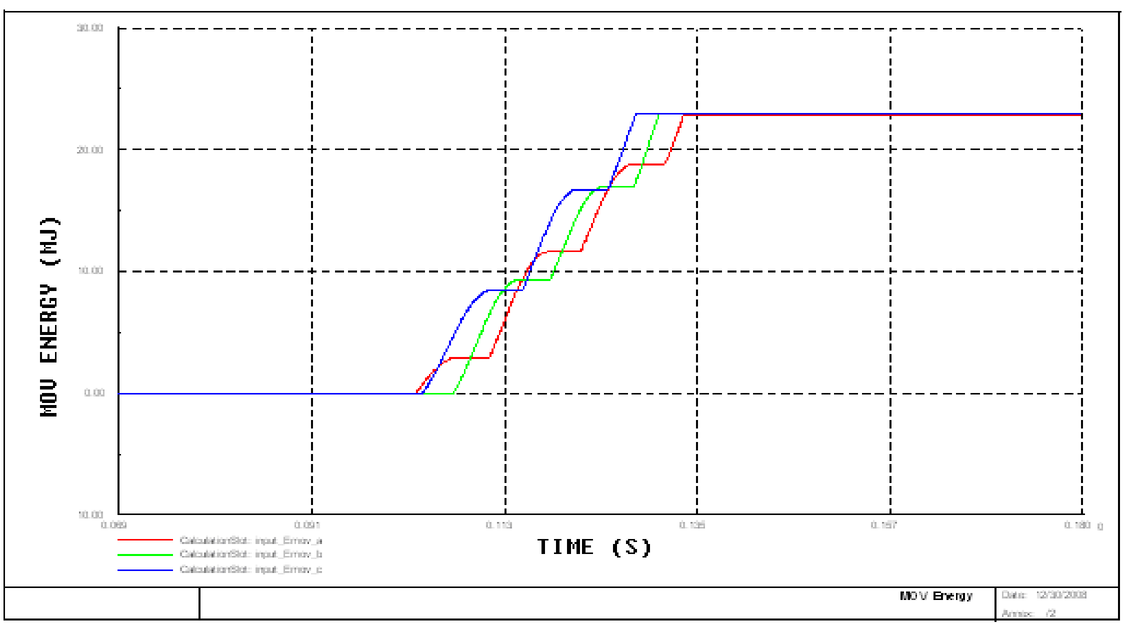
Figure 3-9 MOV Current, Voltage and Energy during a SLG Fault behind the SC



(a) MOV Current



(b) MOV Voltage



(c) MOV Energy

Figure 3-10 MOV Current, Voltage and Energy during a 3-Phase Fault behind the SC

For a single phase to ground fault located immediately behind the SC as illustrated in Fig. 3-1, the results depicted in Fig. 3-9 (a) depict the MOV current in the faulted phase conducting for two cycles at 10kA. While for a three phase fault at the same fault location, the results depicted in Fig. 3-10 (a) show the MOV phase currents conducting for one and a half cycles at approximately 12kA. It is at this instant when the effective capacitive reactance at Bacchus will be reduced, with an additional resistive impedance component introduced as a result of the MOV conduction [1].

Fig. 3-9 (c) and Fig. 3-10 (c) depict the MOV energy absorbed during a simulated single and three phase fault(s) behind the SC. In both instances the energy accumulated in the MOV of each faulted phase(s) behaves as per MOV and bypass breaker principles discussed in section 2.2.2.1: the energy increases till the MOV allowable threshold (23MJ) is reached, following which the bypass breaker bypasses both the SC and the MOV.

During the simulation of the single and three phase fault(s) behind the Bacchus SC, the results respectively depicted in Fig. 3-9 (b) and Fig. 3-10 (b), in both instances showed the series capacitor voltage being limited to approximately 157 kV due to the high fault currents endured on the system very close to the SC. As has been discussed in Section 2.2.2, that when high fault currents are endured on the system nearby the SC, the protective MOV will start conducting current and on reaching the protective voltage threshold, the effective SC reactance is then reduced. Subsequently, when the MOV energy absorbed reaches its maximum and the bypass breaker is closed then the SC is completely bypassed.

3.7 Response of Relays at Muldersvlei for a fault at 'F'

PowerFactory simulator was utilized to perform a study of investigating the impact of series compensation on the performance of the distance protection on the transmission lines. Fig. 3-11 shows the dynamic impedance analysis of the response of the relay at Muldersvlei for the study where a three phase fault was placed at point F, a point immediately behind the Bacchus SC. The results show that for a three phase fault EMT study performed, the under reaching zone 1 elements picks up and trips for this fault as the impedance loci of all three phases enters the zone 1 polygon characteristic area, passing through and settles in the zone 2 polygon characteristic area of the relay at Muldersvlei. This is as a result of the reduced impedance of the line seen by the relay at Muldersvlei that is no longer a unique correspondence of the physical distance from the relay location to the point of fault due to series compensation. Figure 3-12 depicts the dynamic impedance of phase A of the series capacitor as seen by the relay at Muldersvlei for a 3-Phase fault behind the Bacchus SC with (a) and (b) representing the resistance and reactance respectively.

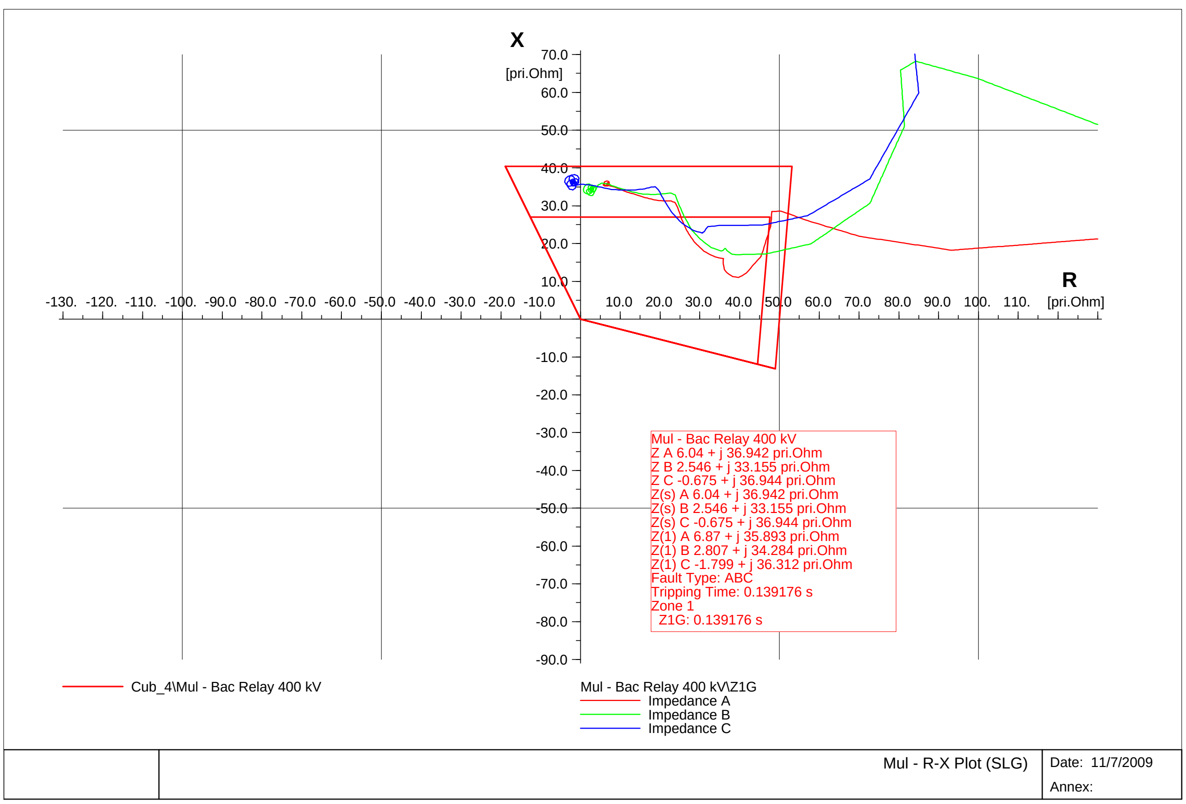
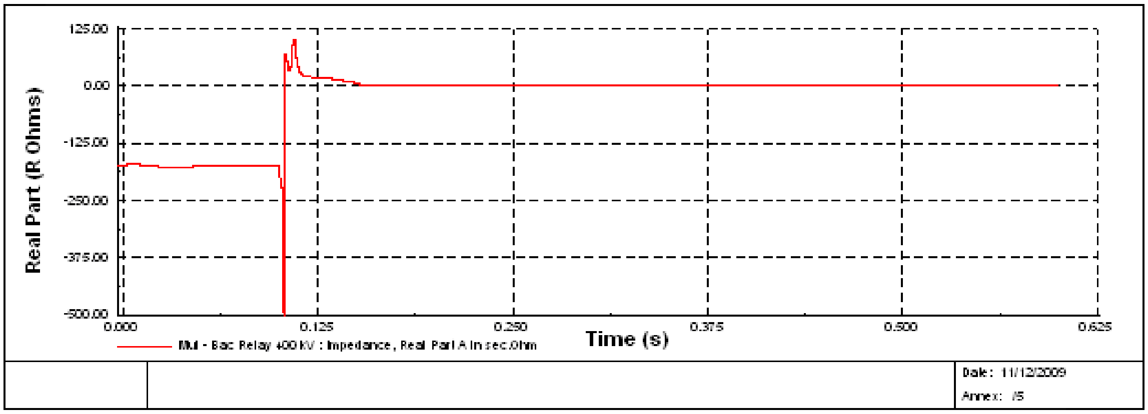
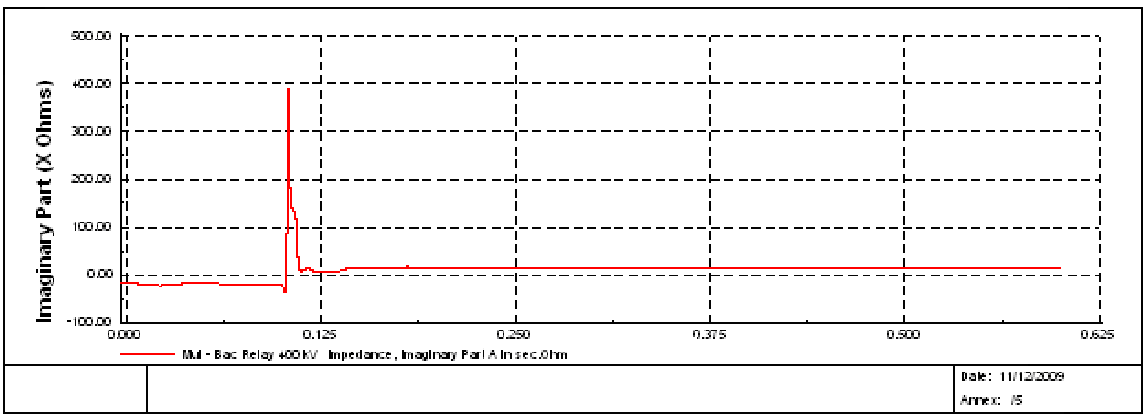


Figure 3-11 Response of relay at Muldersvlei for a 3-Phase fault behind the SC



(a) Resistance



(b) Reactance

Figure 3-12 Single Phase Impedance seen by the relay at Muldersvlei for a 3-Phase fault behind the SC

Fig. 3-13 depicts the dynamic impedance analysis of the response of the relays at Muldersvlei for a single phase to ground fault at point F. The results again show that the underreaching zone of the relays at Muldersvlei picks up and trips on single line to ground fault as the faulted phase impedance enters the zone 1 polygon characteristic area, passing through and settles in the zone 2 polygon characteristic area of the relay at Muldersvlei. This is as a result of the reduced impedance of the line seen by the relay that is no longer a unique correspondence of the physical distance from the relay location to the point of fault due to series compensation. Figure 3-14 depicts the dynamic impedance of phase A of the series capacitor as seen by the relay at Muldersvlei for a single line to ground fault behind the Bacchus SC with (a) and (b) representing the resistance and reactance respectively.

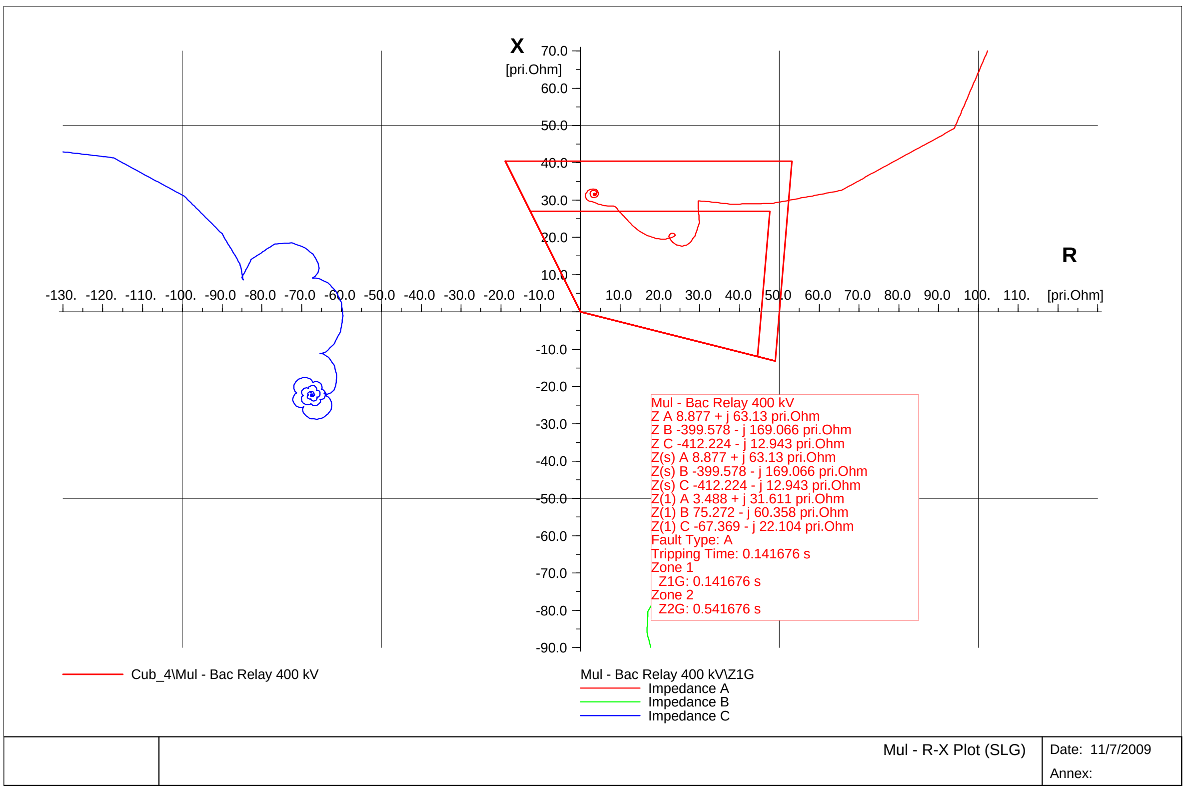
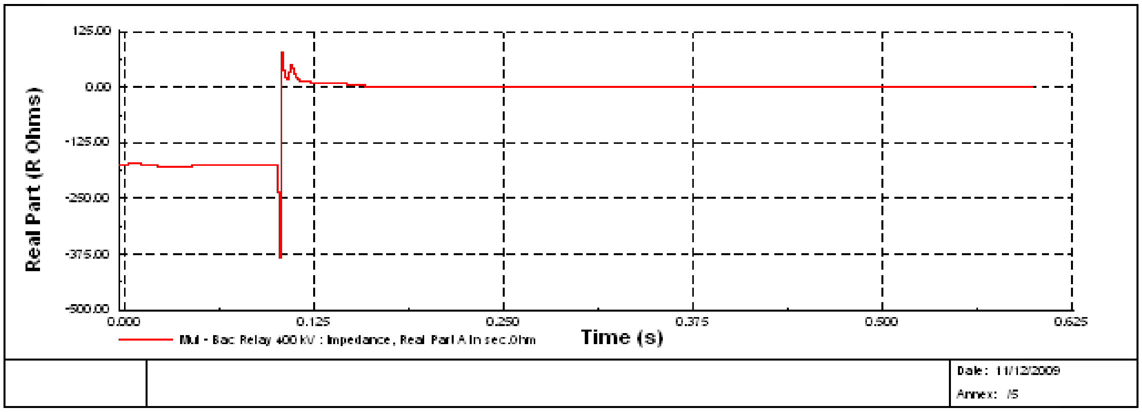
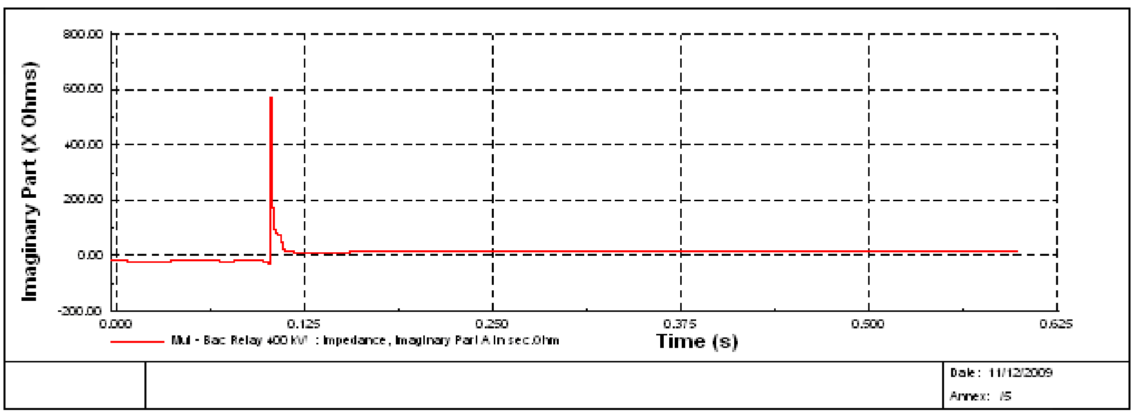


Figure 3-13 Response of relay at Muldersvlei for a SLG fault behind SC



(a) Resistance



(b) Reactance

Figure 3-14 Single Phase Impedance seen by the relay at Muldersvlei for a SLG fault behind the Bacchus SC

To try and overcome this setback, other power system protection researchers/engineers [14] have been known to recommend three possible solutions: firstly, reducing the zone 1 reach element settings below the level of encroaching faulted impedances. This is practical to a certain extent but in the case of the analytical studies performed for the relays at Muldersvlei, this action of reducing the zone 1 reach settings will not add value as the faulted impedances invades a considerable area on the polygon characteristic of zone 1. Say for instance the reach setting of the under reaching zone were to be reduced in the case of SLG fault on Muldersvlei relays; approximately 50% of phase to phase element reach will have to be reduced, meaning about 70% (considering the 20% that was not covered in the first state) of the line will not be protected on zone 1 protection. As for the case of three phase faults at Muldersvlei, the faulted impedance locus invades most of the zone 1 characteristic polygon area, allowing no possibility to reduce the reach settings. Consequently, it is the author's recommendation that the zone1 reach must be switched off.

Secondly, in trying to overcome the setback of incorrect tripping as a result of subsynchronous oscillations and or voltage inversion phenomena due to series compensation on the adjacent lines, Eskom System Operations and Planning Engineers [14] have recently introduced an alternative configuration of the "current supervised zone 1" (CSZ1) on the Eskom distance protection relays. Based on the dynamic and analytical studies performed, by the author, the phenomenon was proved not to be a possible solution for these specific relays under investigation. The detailed studies that lead to this conclusion are discussed in greater detail in Chapter 4.

Thirdly and the author's recommendation, to overcome instances where reducing reach settings is not possible, the underreaching zone 1 reach elements have been recommended to be disabled altogether. However this option has a defect on its own where instantaneous tripping for faults falling within the zone 1 reach of the protected line can only be achieved via the aid of telecommunication (POR scheme discussed in Section 1.3.2), and if there should be failure in the communication channels, which is a probability, this would mean the faults will now be cleared in zone 2 time delay of 400ms, needless to say that this is unacceptable in Eskom transmission for reasons that have been discussed in earlier sections, but this option proves to be a better option compared to the alternative.

3.8 Response of Relay at Droerivier for a fault at 'F'

As for the studies performed at Muldersvlei, similarly, PowerFactory simulator was utilized to perform a study of investigating the impact of series compensation on the performance of the distance protection on the transmission lines and this time focusing on the Droerivier relay.

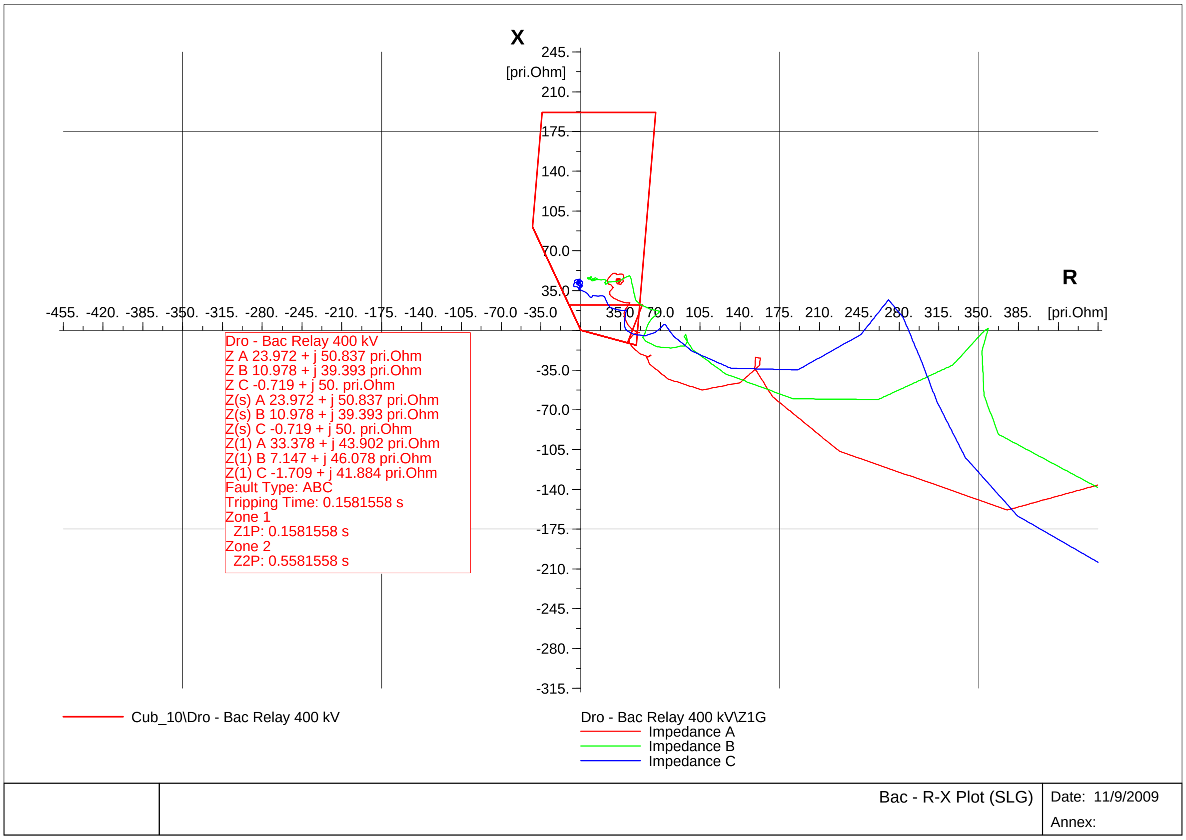
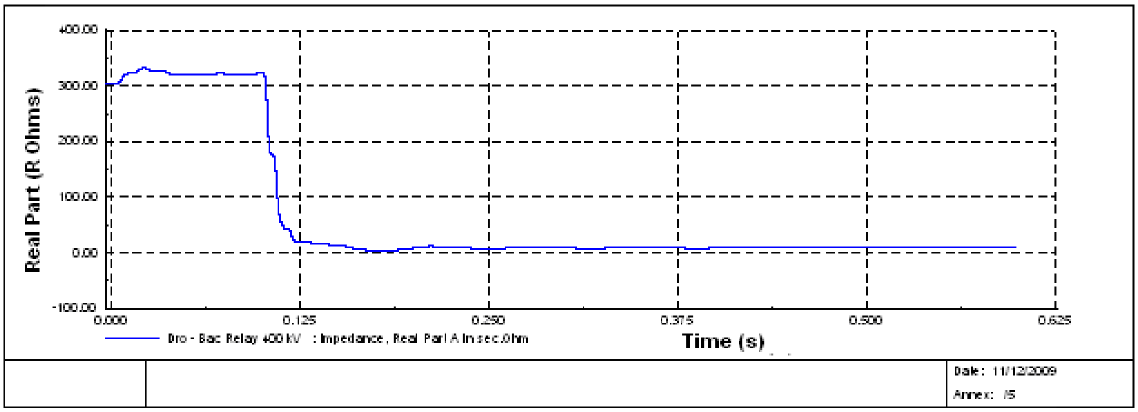
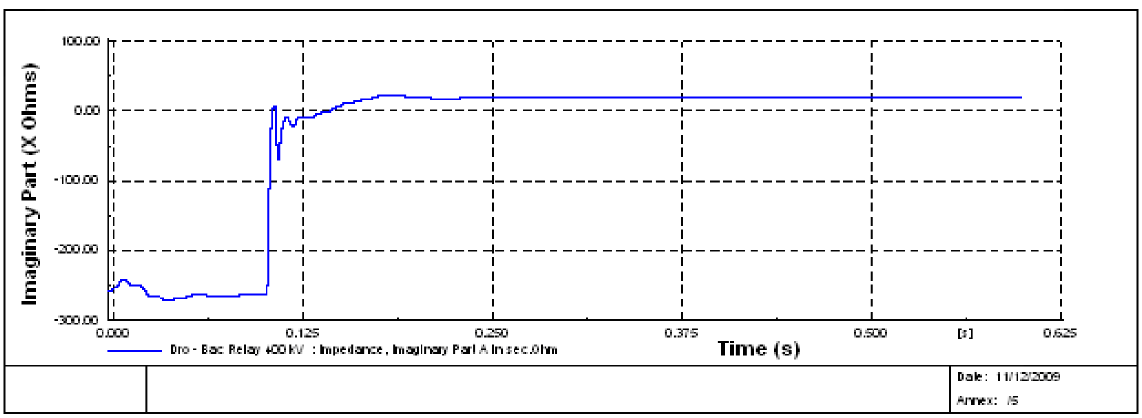


Figure 3-15 Response of relay at Droerivier for a 3-Phase fault behind the Bacchus SC

Fig. 3-15 depicts the dynamic impedance analysis of the response of the relays at Droerivier for the study where a three phase fault was placed at point F, a point immediately behind the Bacchus SC (refer to Fig. 3-1). The study shows that for a three phase fault EMT study performed, the under reaching zone 1 elements pick up and trip for this fault as the impedance loci of the red and blue phases enter the zone 1 polygon characteristic area, passing through and settling in the zone 2 polygon characteristic area of the relay at Droerivier. This is as a result of the reduced impedance of the line seen by the relay at Droerivier that is no longer a unique correspondence of the physical distance from the relay location to the point of fault due to series compensation. Figure 3-16 depicts the dynamic impedance of phase A of the series capacitor as seen by the relay at Droerivier for a three phase fault behind the Bacchus SC with (a) and (b) representing the resistance and reactance respectively.



(a) Resistance



(b) Reactance

Figure 3-16 Single Phase Impedance seen by the relay at Droerivier for a 3-Phase fault behind the Bacchus SC

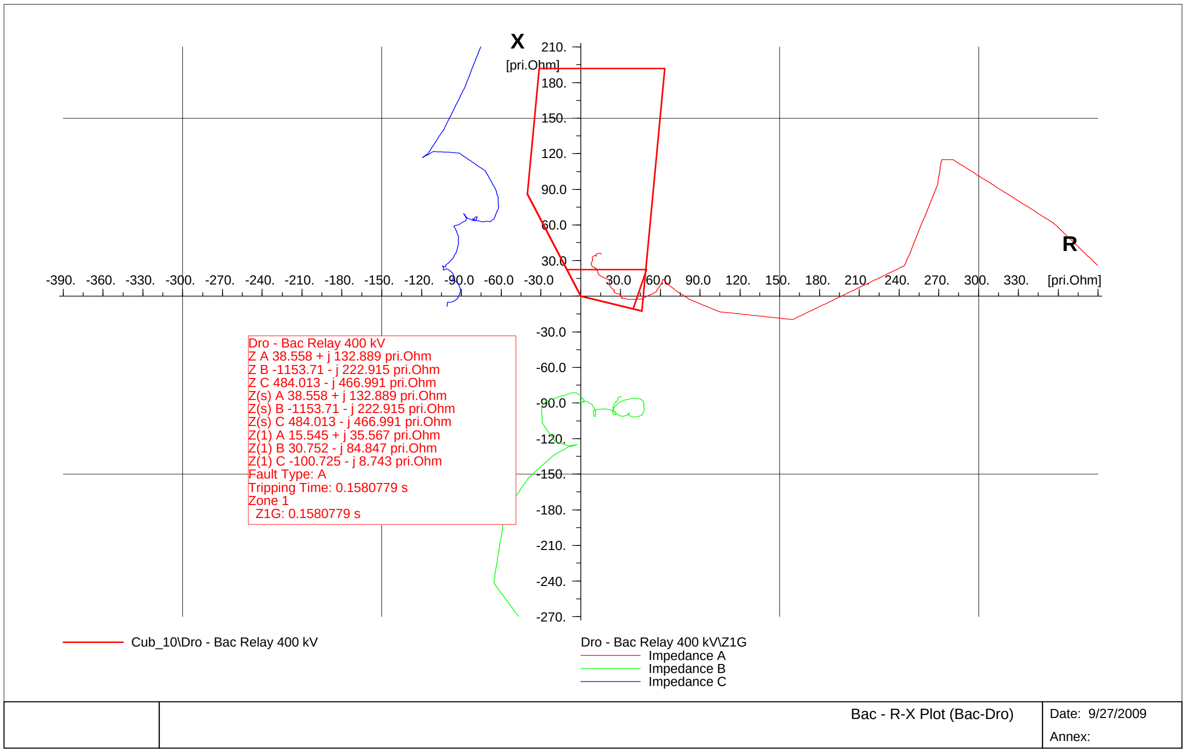
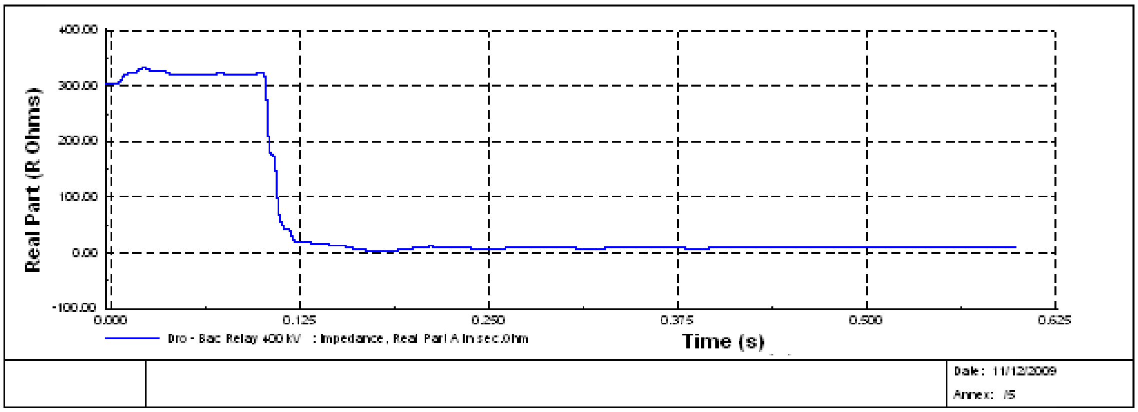


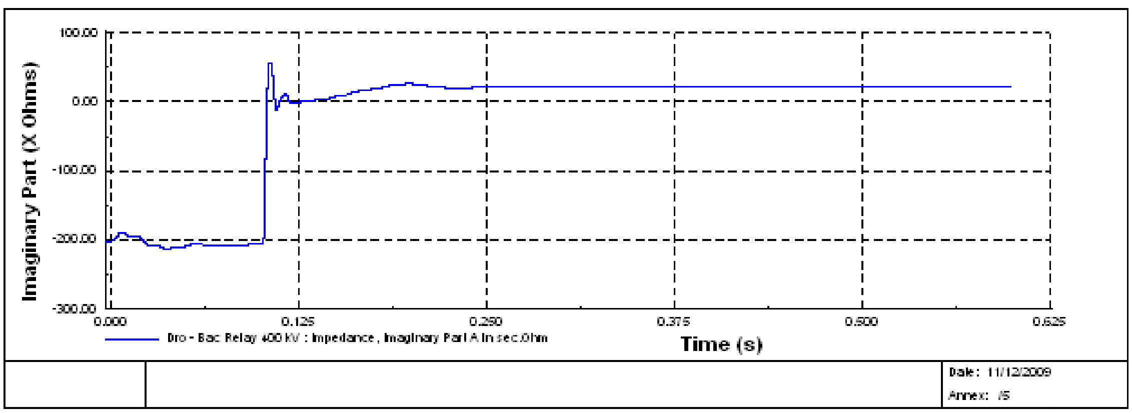
Figure 3-17 Response of relay at Droerivier for a SLG fault behind the SC

Fig. 3-17 depicts the dynamic impedance analysis of the response of the relays at Droerivier for a single phase to ground fault at point F. The results, similarly to the case of a three phase fault at the same fault location, show that the underreaching zone of the relay at Droerivier picks up and trips on single line to ground fault as the fault phase impedance locus enters the zone 1 reach characteristic area, passing through and settling in zone 2 characteristic area. This is as a result of the reduced impedance of the line seen by the relay at Droerivier that is no longer a unique correspondence of the physical distance from the relay location to the point of fault due to series compensation. Fig. 3-18 depicts the dynamic impedance of phase A of the series capacitor as seen by the relay at Droerivier for a single line to ground fault behind the Bacchus SC with (a) and (b) representing the resistance and reactance respectively.

It is also noted that despite the decision taken to reduce the reach setting of the underreaching zone 1 elements of the relay at Droerivier from the normal setting of 80% of the Bac-Dro line, for the purposes of catering for the negative reactance that is introduced by the Komsberg 1 series capacitors, in both fault studies performed (SLG and three phase faults behind the Bacchus SC), the under reaching zone 1 still overreaches. To try and overcome this setback, reducing the zone 1 reach setting even further would not add value, since the fault impedance loci invades most of the zone 1 characteristic area. It is with this reason that again the author recommends that the zone1 reach for the Droerivier relay be switched off.



(a) Resistance



(b) Reactance

Figure 3-18 Single Phase Impedance seen by the relay at Droerivier for SLG fault behind the Bacchus SC

CHAPTER IV

4. Current Supervised Zone 1

4.1 Background

Current supervised zone 1 is a distance protection relaying configuration that has recently been introduced to some Eskom series compensated networks. This is one way that was developed in trying to overcome the setback of incorrect trips on series compensated networks as a result of subsynchronous oscillations, voltage and current inversion phenomena due to series compensation within and or adjacent distance relaying protected lines.

Before CSZ1 configuration was considered for Eskom distance protection in order to overcome instances where reduced reach settings were not possible, the under reaching zone 1 reach elements had to be disabled altogether. However this option has a defect, since instantaneous tripping for faults falling within the zone 1 reach of the protected line can then only be achieved via the aid of telecommunication: if there should be failure in the communication channels, which is a probability, this would mean that the faults could then only be cleared in the zone 2 time delay of 400ms. Needless to say, that this again is unacceptable in Eskom transmission.

4.2 Current Supervised Zone 1 Operating Philosophy

Fig. 4-1 depicts a magnified Hydra South Network with a relay under investigation, which was studied to explain the ideology of the CSZ1 operating philosophy. This particular network was considered as a case study to explain the CSZ1 philosophy because this is an example of the kind of line where the philosophy has already been proven in [14] to work. This figure also shows a vector diagram of a SC conveying the high negative reactance that gets magnified by network infeed viewed by the relay protecting lines associated with SC. The effect is that the impedance locus falls within the zone 1 characteristic area of the relay at Muldersvlei for an external fault behind the SC at Bacchus. This has been proven by [14] especially for series capacitors located at midpoint of the line with MOV overvoltage protection out of service.

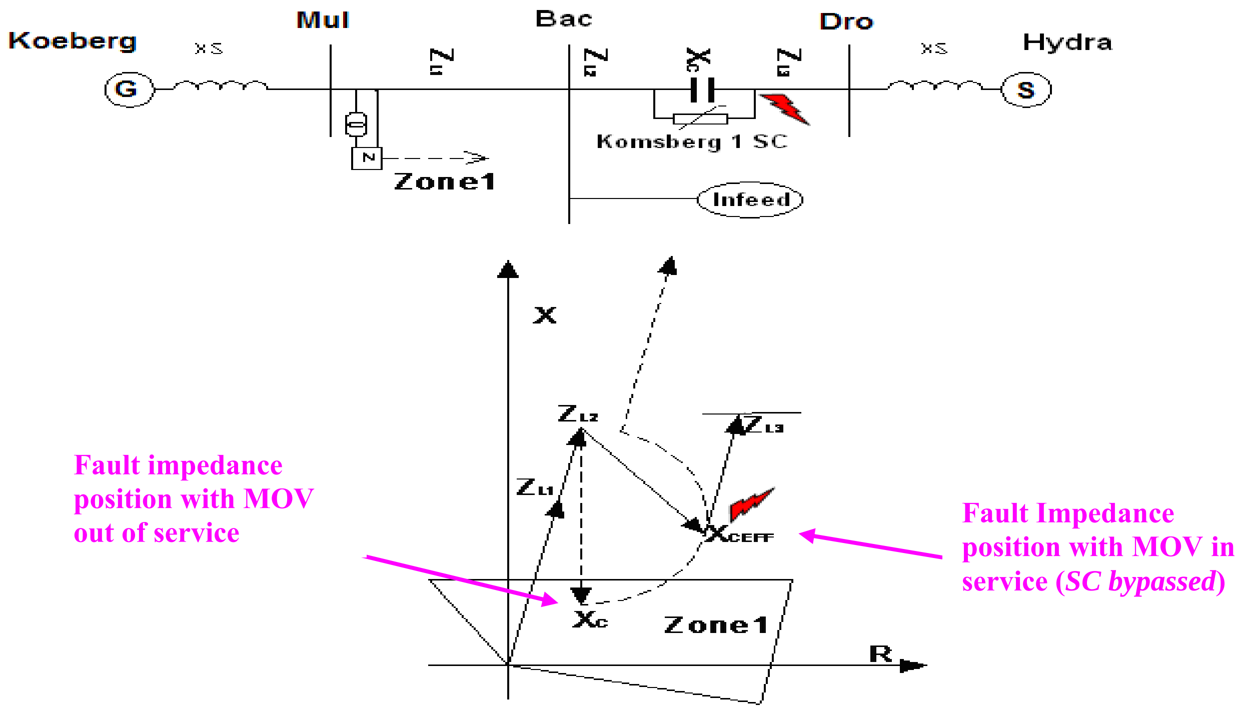


Figure 4-1 CSZ1 Impedance Vector Diagram [14]

The "Current supervised zone 1" philosophy works on condition that the MOV is conducting, by monitoring the fault current seen by the relay since the MOVs only conduct when there is sufficient current flowing through the SC. The conduction of MOVs during fault occurrence changes the impedance measured by the relays in the surrounding network, and this is the exact phenomenon with which the CSZ1 configuration is based upon. First step is to select the 'current level setting' with which the reach setting of zone 1 can be adjusted to in covering faults that would deliver the required fault current [14].

This current level setting by principle should not be less than 150% of the protective level of SCs electrically closest to the protected line. This selection equates to 150% of twice the full load rating of the SC [21]. The decision to use a standard current level setting of 150% of the MOV protective level, was an engineering decision by [14] based on the physical behavior of a conducting MOV discussed in section 2.2.2.1: that when bank currents much larger than the 'protective level' flow through the MOV, the capacitive reactance in the 'series R-X model' is reduced to less than 5% of its rated value, resulting in the circuit becoming mostly resistive. The impact is however reduced at lower currents flowing through the SC.

Now since the CSZ1 configuration's successful operation is based on the MOV conducting enough current to ensure SC bypass, a current level setting of 150% of the SC's protective level selected was shown to be sufficient on studies conducted by [14] to ensure that the MOVs are conducting. In some cases, such conduction of the MOV has been shown to be sufficient to ensure SC bypass, as a result causing the fault impedance locus to settle far away from the zone 1 characteristic area as illustrated in Fig. 4-1 and Fig 4-3. In Fig. 4-1, X_{CEFF} represents the effective reactance of the SC and its conducting MOV when the MOV is in service, while X_C represents the negative reactance of the SC. The actual value of reactance (X_{CEFF}) that the SC and the MOV together end up settling at, is greatly influenced by the fault current level [14].

To commit to a particular zone 1 reach setting to which zone 1 can be adjusted to in covering only for in-zone internal line faults, the procedure is to calculate RMS fault currents by simulating faults: (1) immediately in front of the measuring transformers; (2) at 80% of the line or in front of the SC if the line is mid-series compensated and (3) behind the electrically closest capacitors, with priority placed on the capacitors with the highest protective level. The rationale is that the protective level must ensure that in any system configuration, the impedance loci must not enter the instantaneous underreaching zone of relays under investigation with security margin for any fault behind SCs. EMT simulation studies are required when calculating these fault currents. This is because the studies conducted in EMT mode, also put into consideration the effect of subsynchronous oscillations and damping effects of the nonlinear MOVs [14]. Unfortunately, Digsilent PowerFactory simulator does not calculate EMT RMS fault currents.

However, the relays modelled in Digsilent PowerFactory get only the voltages and currents measured by the respective line measuring transformers, regardless whether one calculates EMT simulations or static short circuits studies [29]. So, since Digsilent PowerFactory is able to calculate RMS fault currents when conducting studies in static short circuit mode, static short circuit studies were conducted to calculate the fault currents on the above mentioned locations within the network section of interest shown in Fig. 3-1. The calculated fault currents were then evaluated relative to the current level setting selected, to which the reach setting of zone 1 can be adjusted to (examples will be shown in the next sections), in ensuring that the distance protection only issues high-speed tripping for in-zone internal line faults (assuming that when MOV is fully conducting for external faults behind the SC, the fault impedance loci will settle outside the instantaneous underreaching zone 1). It was however assumed on simulation studies conducted that since the MOV is inserted on the line associated with the relays under investigation: the current the relay will "see" will be reduced by the conduction of the MOV, with the impact extent to the relay calculations greatly dependent on the size and placement of the MOV relative to the measurement transformers.

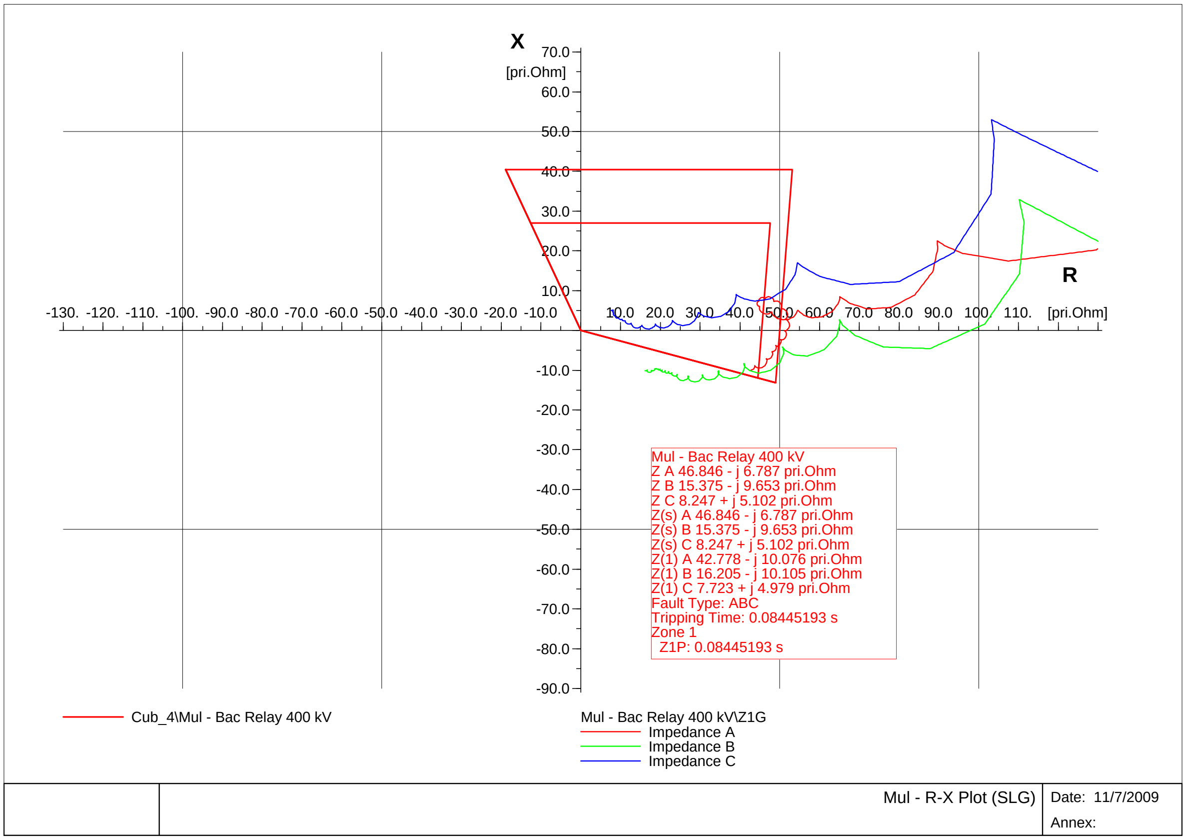


Figure 4-2 CSZ1 Response of the relay at Muldersvlei with MOV out of service

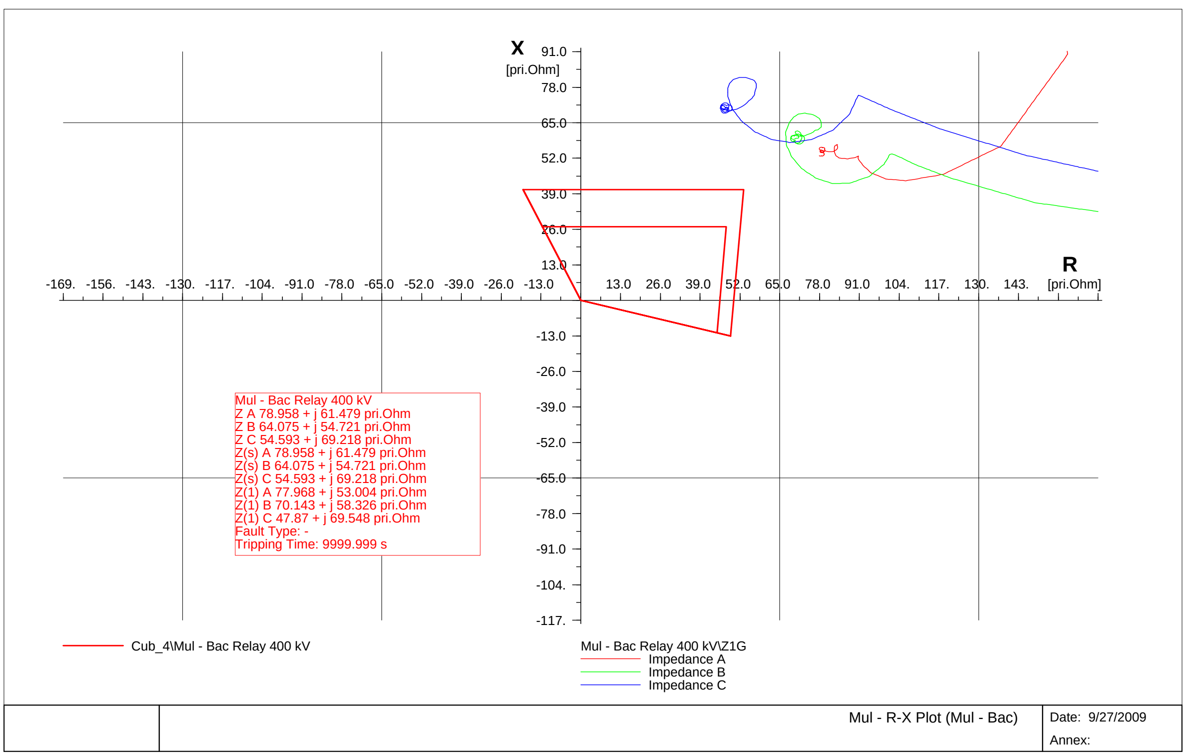


Figure 4-3 CSZ1 Response on relay at Muldersvlei with MOV in service

Figure 4-2 depicts the dynamic impedance analysis of the response of the relay at Muldersvlei for the study where a three phase fault was placed immediately behind the Komsberg 1 SC with the MOV out of service. The results indeed did show the impedance loci for all three phases settling inside the zone 1 characteristic reach area. Now for the same fault study that proved the above mentioned phenomena but now with the MOV put in service, the results depicted in Fig. 4-3 shows the impedance loci for all three phases settling far away from the zone 1 characteristic area. The simulation results in Fig. 4-2 and Fig. 4-3 agree with the findings in [14] for a similar type of line.

On investigating the probability of utilizing the CSZ1 configuration for the relay at Muldersvlei to eliminate the impact of external series compensation on the performance of the distance protection, the following static short circuit studies were performed to attain the RMS fault currents on the network depicted in Fig. 4-1. First the current level setting was selected to be 4.18kA (i.e. 150% of the Komsberg SC MOV protective level). On the three phase fault studies performed, the current seen by the relay for a fault just after the current transformers (CTs) at Muldersvlei was found to be 9.4kA and at 80% of the Mul-Bac line was found to be 4.2 kA. The currents seen by the relay get reduced as the fault moves down the line and the impedance to the point of fault increases; however, the current seen by the relay increases again for faults just behind the Komsberg 1 SC (5.7kA) due to the negative reactance the SC adds on the network.

Now if the CSZ1 logic were to be used, then whenever the zone 1 elements see a current that is equal to or greater than the selected current level setting of 4.18kA, they will pick up and trip instantaneously as this will mean that there is a fault between the Muldersvlei bus and 80% reach of the Mul-Bac protected line. This by principle is the normal zone 1 reach region. However, for a fault just behind the SC the current seen by the relay is also greater than the selected “protective level” of 4.18kA, but this does not present a problem since the fault current is sufficiently high to ensure that the MOV is conducting, which in turn ensures that the impedance seen by the Muldersvlei relay will lie outside its zone 1 polygon as seen in Fig. 4-3.

In other words even when the fault current seen by the relays at Muldersvlei exceeds that of the selected current level setting, the relay zone 1 reach elements will not trip for a fault just after the SCs since for the relay to trip under CSZ1 configuration, two conditions have to be met:

a) The relay fault current has to be equal to or greater than the selected current level setting.
b) The fault impedance has to be seen by the zone 1 reach elements.

If these two conditions are met, the security and reliability of zone 1 is sustained. The phenomenon philosophy in summary is as depicted in Fig. 4-4.

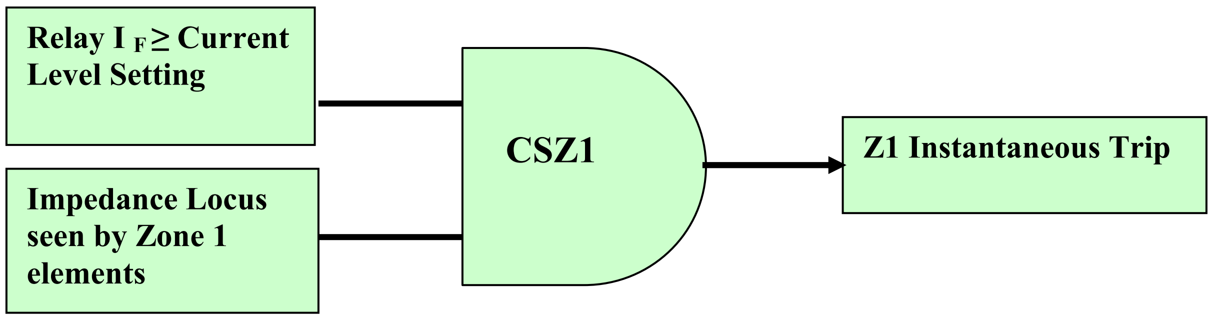


Figure 4-4 Current Supervised Zone 1 Logic

Furthermore, even when the evaluation of currents on the application of CSZ1 configuration on distance protection were to be disregarded, as certain assumptions were made on fault current calculations conducted in static short circuit mode. The actual fault study shown in Fig. 4-3 was conducted in full EMT mode and the results showed that for a fault immediately behind the Komsberg 1 SC, when the MOV is conducting, the reactance of the SC is reduced sufficiently such that the impedance loci is seen settling outside the instantaneous reaching zone 1. In consequence the application of the CSZ1 configuration in this study is shown to be adequate to ensure that the distance protection's security is maintained.

4.3 Impact of Bacchus SC on Current Supervised Zone 1

The previous section has shown that Current Supervised Zone 1 can be used to overcome the need to completely disable zone 1, at least for faults behind the external capacitor at Komsberg 1. In this section, the CSZ1 configuration was reviewed as a probable solution for faults behind the external capacitor at Bacchus. Since the CSZ1 works on fault current monitoring seen by the relay, in order to determine whether the SC's MOV is conducting, the first step that was taken in reviewing the CSZ1 configuration as a solution was to analyze the impact of series capacitors on the relays at Muldersvlei and Droerivier when the MOVs are conducting and when they are not, when a three phase fault is placed just behind the Bacchus SC.

4.3.1 Response of the Muldersvlei Relays with MOVs in and out of Service.

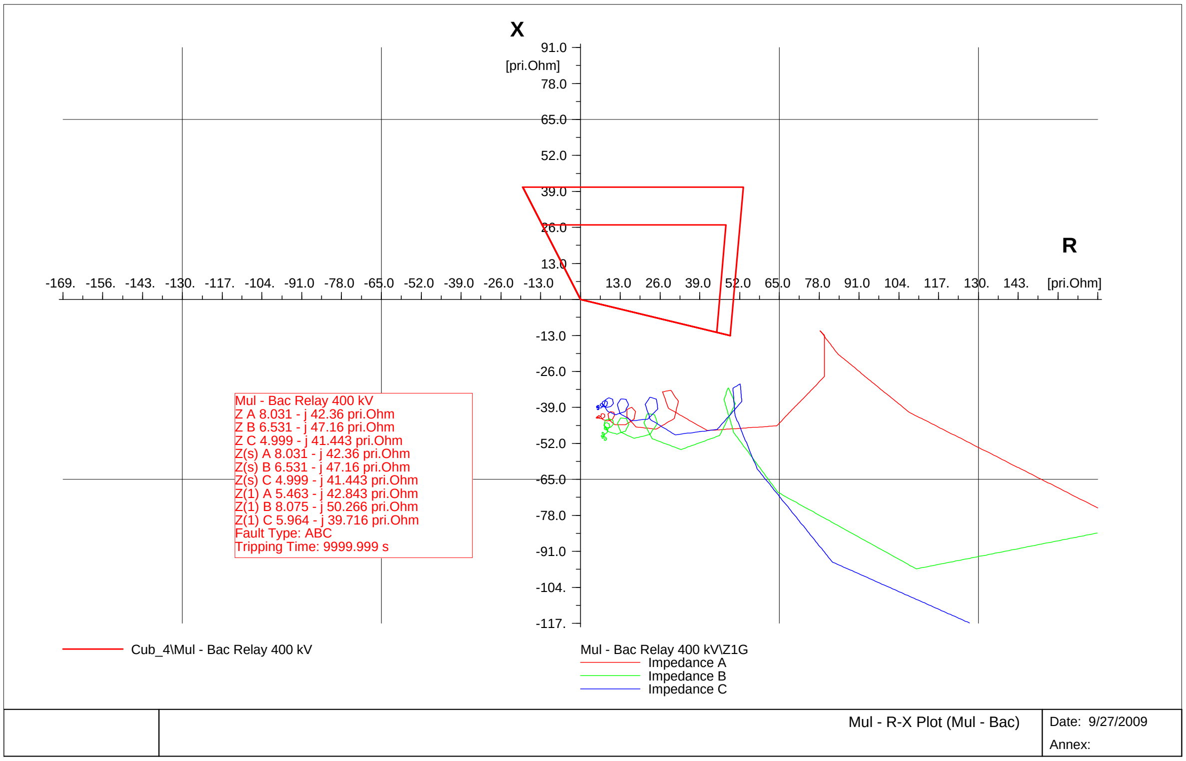


Figure 4-5 Response of relay at Muldersvlei with MOV out of service.

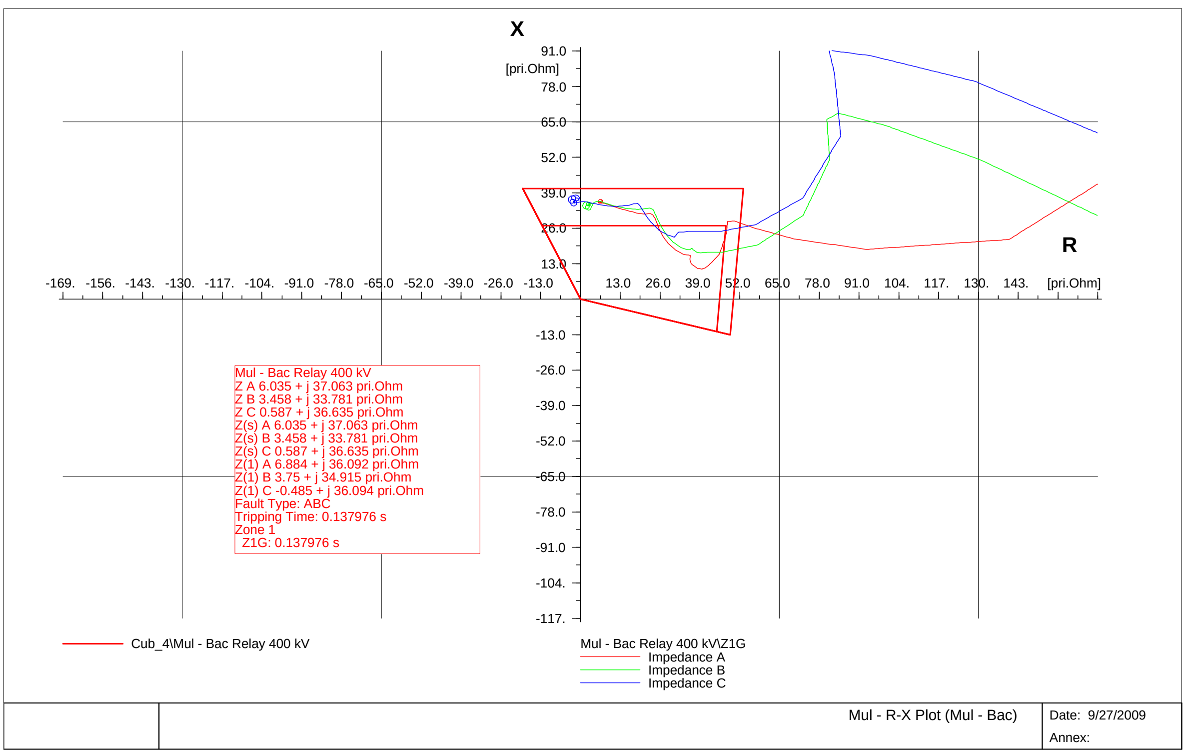


Figure 4-6 Response of relay at Muldersvlei with MOV in service.

Fig. 4-5 illustrates the response of the relays at Muldersvlei when the MOVs on the series capacitors at Bacchus were placed out of service. On performing the analytical studies to evaluate the impact of SC without MOVs conducting, a three phase fault was placed immediately behind the Bacchus SC. The response was that the fault impedance locus was seen settling outside the characteristic reach area of zone 1. The response of this study is also illustrated with a vector diagram shown in Fig. 4-7.

Fig. 4-6 illustrates the response of the relays at Muldersvlei when the same fault was applied but now with the MOV put back into service. The response was that the impedance locus was seen passing through zone 1 and settling right inside the zone 2 characteristic reach area of the relay at Muldersvlei. The response of this study is also illustrated with a vector diagram shown in Fig. 4-7.

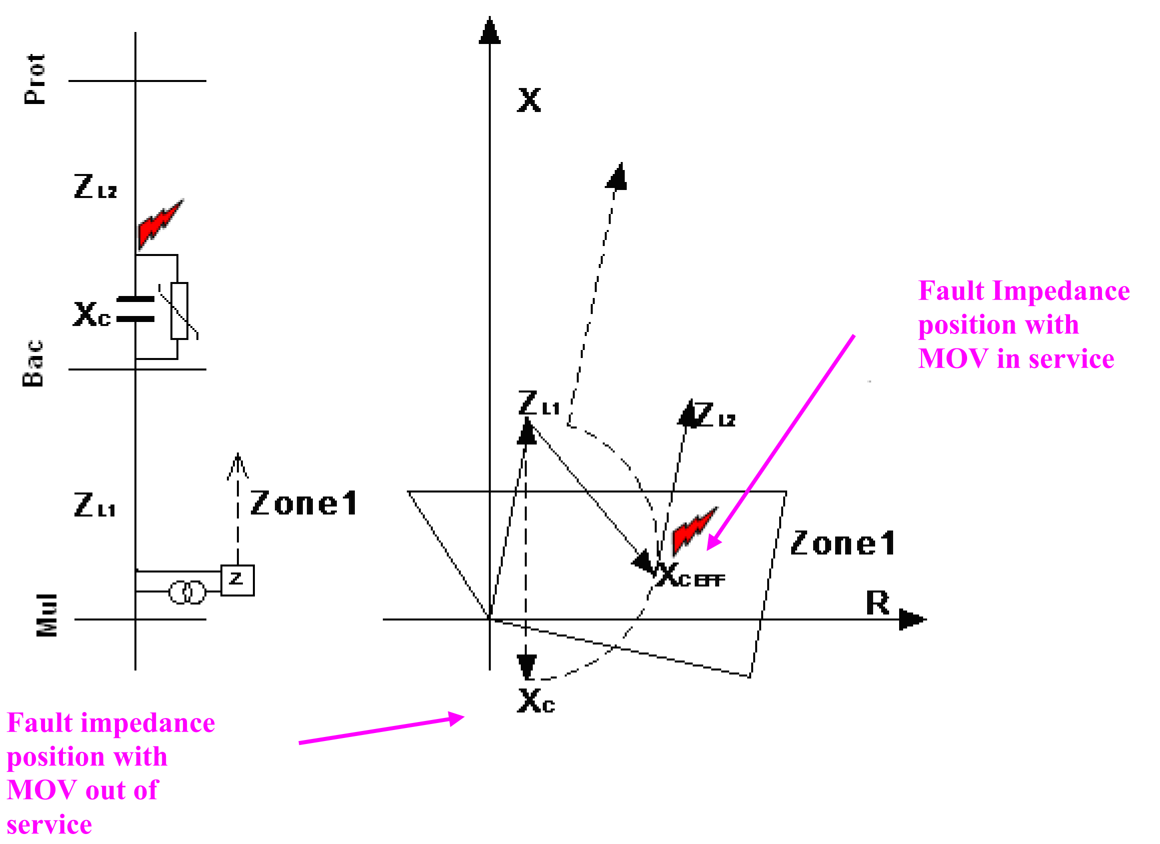


Figure 4-7 Muldersvlei Relay Response Vector Diagram

On investigating the probability of utilizing the CSZ1 configuration to eliminate the impact of series compensation on the performance of the distance protection for the relay at Muldersvlei, the following static short circuit studies were performed to attain the RMS fault currents on the network depicted in Fig. 4-7. On the studies performed, first the current level setting was selected to be 4.44kA (i.e. 150% of the Bacchus SC MOV protective level). The current seen by the relay for a fault just after the CTs at Muldersvlei was found to be 9.4kA and at 80% of the line was found to be 4.2kA. These fault level currents were recorded from the relay when the system was running in normal system configuration.

Now if the CSZ1 logic were to be used, then whenever the zone 1 elements see a current that is greater than or equal to 4.44kA they will pick up and trip instantaneously as that will mean the fault is between Muldersvlei bus and approximately 75% reach of the protected line. The decision to reduce the zone 1 reach to 75% of the line was as a result of the Muldersvlei line fault currents beyond the 75% reach point dropping below the selected current level setting of 4.44kA. But also for a fault just behind the Bacchus SC, where the current seen by the relay (6.48kA) is greater than the current level setting, this will cause the MOV to conduct, causing the impedance locus to pass through the zone 1 characteristic reach area as depicted in Fig. 4-7. Based on the CSZ1 logic illustrated in Fig. 4-4, the Muldersvlei relay will still overreach for faults behind the Bacchus SC since the logic governing inputs of the fault at this location meet the two conditions that constitute the instantaneous trip operation of the CSZ1 configuration (i.e. the relays at Muldersvlei "see" both the impedance locus in zone 1 and a fault current that is greater than the selected current level setting): the CSZ1 configuration will therefore not be a suitable solution for overreaching relay at Muldersvlei for faults behind the Bacchus SC, since the Zone 1 stability and security still cannot be attained.

As has been discussed in the earlier study that showed CSZ1 configuration application to be capable of maintaining distance protection's security: that even if the evaluation of currents on the application of CSZ1 configuration on distance protection at Muldersvlei were to be disregarded also in this case, as assumptions were made on fault current calculations conducted in static short circuit mode. The actual fault study shown in Fig. 4-6 was conducted in full EMT mode and the results showed that for a fault immediately behind the Bacchus SC, when the MOV is conducting, the reactance of the SC is reduced sufficiently such that the impedance loci is seen passing through the instantaneous reaching zone 1 resulting in the incorrect relay operation for an out of zone fault.

4.3.2 Response of the Droerivier Relay with MOVs in and out of Service.

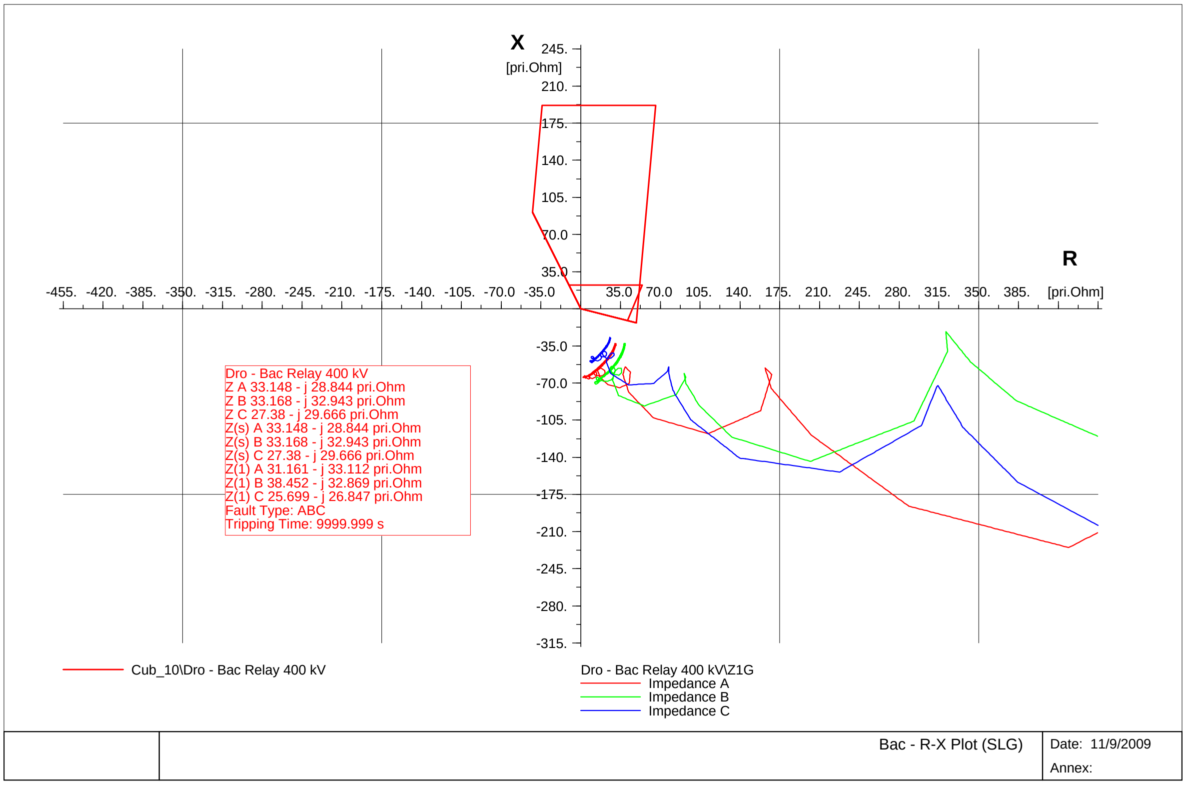


Figure 4-8 Response of relay at Droerivier with MOV out of service

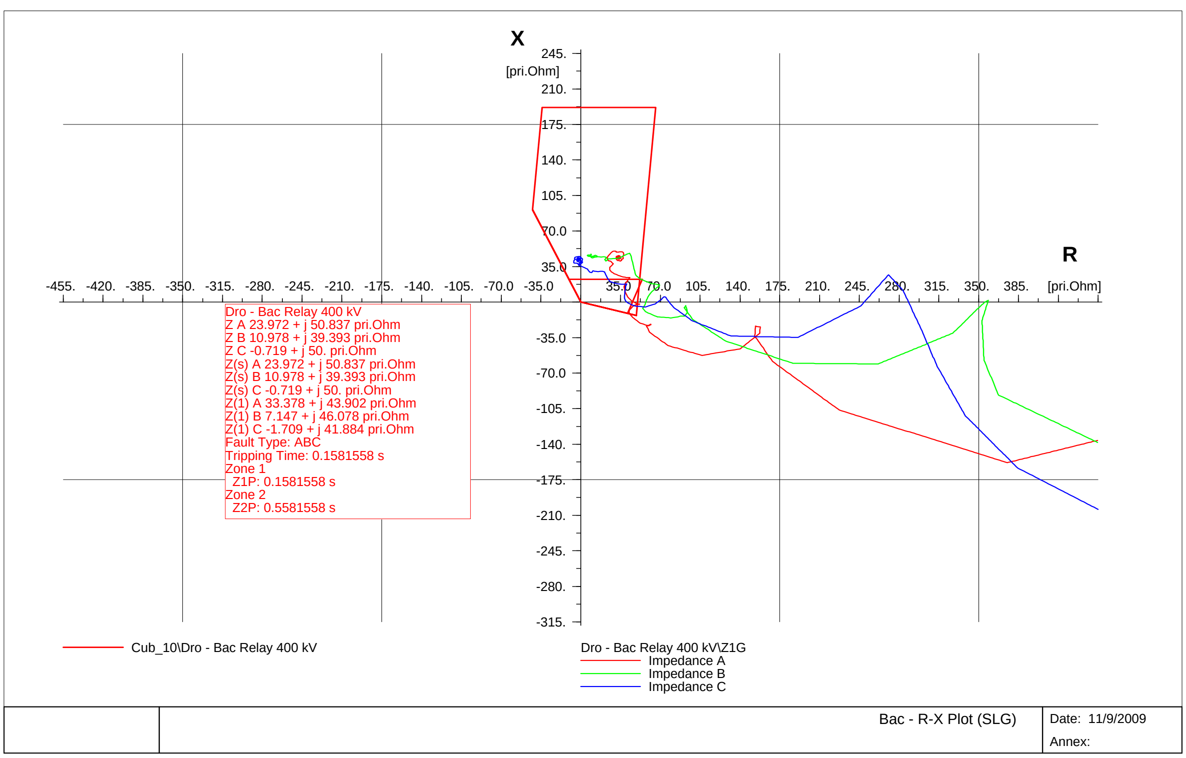


Figure 4-9 Response of relay at Droerivier with MOV in service

Fig. 4-8 illustrates the response of the relay at Droerivier when the MOVs were placed out of service. On performing the analytical studies to evaluate the impact of SC without MOVs conducting, a three phase fault was placed immediately behind the Bacchus series capacitor. The response was that the impedance loci as in the case of Muldersvlei relay, was also seen settling outside the characteristic area of zone 1. The response of this study is also illustrated with a vector diagram shown in Fig. 4-10.

Fig. 4-9 illustrates the response of the relays at Droerivier when the MOVs were put back into service. On performing the analytical studies to evaluate the impact of SC with MOVs conducting, the same three phase fault that was performed for the study where the MOVs were out of service was also conducted. The response was that the under reaching zone 1 element picks up and trips for this fault as the impedance loci of the red and blue phases enter the zone 1 polygon characteristic area, passing through and settling in the zone 2 polygon characteristic area of the relay at Droerivier. This is as a result of the reduced impedance of the line seen by the relay at Droerivier that is no longer a unique correspondence of the physical distance from the relay location to the point of fault due to series compensation. The response of this study is also illustrated with a vector diagram shown in Fig. 4-10.

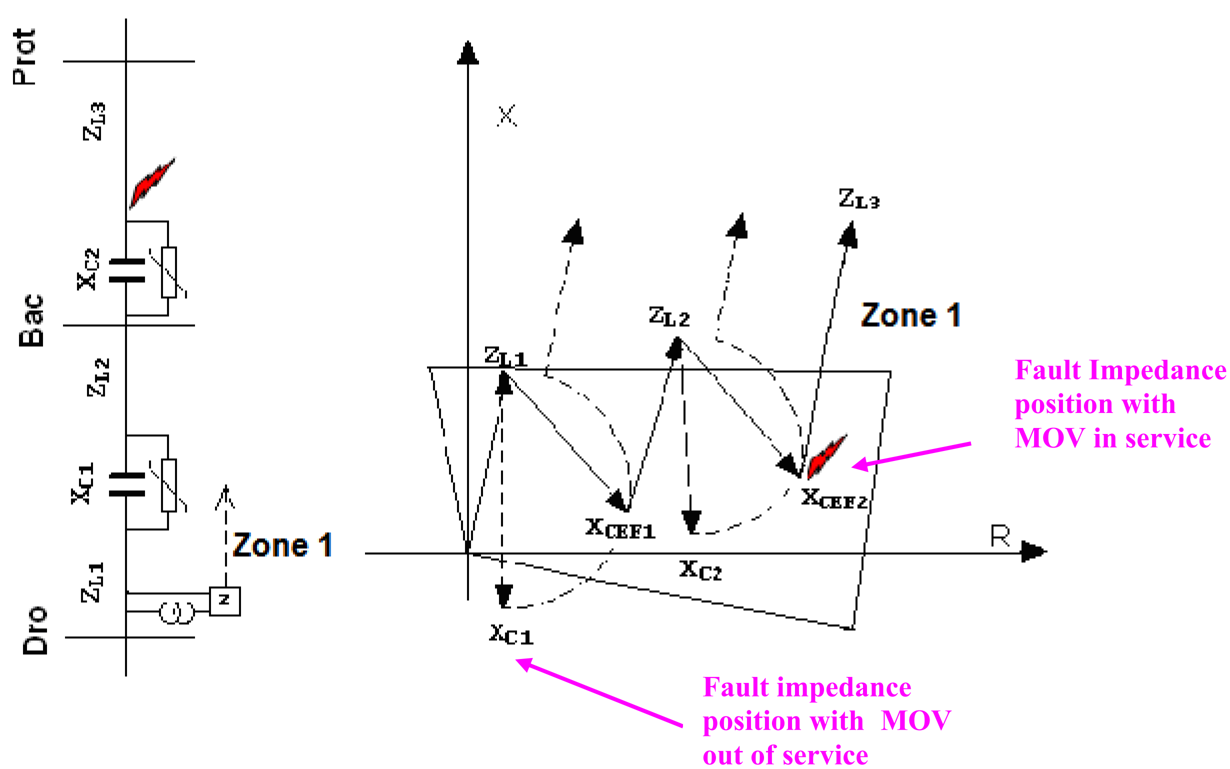


Figure 4-10 Droerivier Relay Response Vector Diagram

On investigating the probability of utilizing the CSZ1 configuration to eliminate the impact of series compensation on the performance of the distance protection for the relay at Droerivier, the following static short circuit studies were performed to attain the RMS fault currents on the network depicted in Fig. 4-10. On the studies performed, first the current level setting was selected to be 4.44kA (i.e. 150% of the Bacchus SC MOV protective level). The fault current seen by the relay just after the CTs at Droerivier was found to be 11.8kA and at 50% of the line, just in front of the Komsberg 1 SCs, was found to be 1.59kA. These fault level currents were recorded from the relay when the system was running in normal system configuration.

Now if the CSZ1 logic were to be used, then whenever the zone 1 elements see a current of greater than 4.44kA they will pick up and trip instantaneously as this will mean the fault is between Droerivier bus and approximately 25% reach of the protected line. The decision to reduce the zone 1 reach to 25% of the line was as a result of the Bac-Dro line fault currents beyond the 25% reach point dropping below the selected current level setting (4.44kA). But also for a fault just behind the Bacchus SC, where the current seen by the relay equates to 5.9kA and is greater than the current level setting, this will cause the MOVs to conduct causing the impedance locus to settle right inside the zone 1 characteristic reach area as depicted in Fig.4-10. Based on the CSZ1 logic illustrated in Fig. 4-4, as in the case of the Muldersvlei relays, the Droerivier relay will also still overreach for faults behind the Bacchus SC. This is because the logic governing inputs of the fault at this location meet the two conditions that will cause the instantaneous trip operation of the relay. As a result, the CSZ1 configuration will therefore also in this case not be a suitable solution.

Likewise, as in the case of Muldersvlei relay, even if the evaluation of currents on the application of CSZ1 configuration on distance protection of the relay at Droerivier were to be disregarded for reasons already discussed, the actual fault study shown in Fig. 4-9 was conducted in full EMT mode and the results showed that for a fault immediately behind the Bacchus SC when the MOV is conducting, the reactance of the SC is reduced sufficiently such that the impedance loci is seen passing through the instantaneous reaching zone 1, resulting in the incorrect relay operation for an out of zone fault.

Moreover, if we compare the performance of the relay at Muldersvlei for a fault immediately behind the Komsberg 1 SC (a series capacitor located at the center of the adjacent line of the one being protected), and that immediately behind the Bacchus SC (a series capacitor located on the busbar of the adjacent line of the one being protected). The impedance trajectories on simulation studies conducted, showed that the performance of the distance protection is indeed influenced by the location and size of the SCs.

CHAPTER V

5. Conclusion

It was shown that series capacitors do not have an impact on the performance of the distance protection relaying when a fault in an adjacent line is in front of the series capacitor. This was a conclusion reached based on the analytical and dynamic studies that were performed, where for faults immediately in front of the Bacchus series capacitor, the studies showed that the under reaching zone 1 elements at Muldersvlei and Droerivier do not “see” the fault in their reach. On both the three phase and single phase to ground faults, the impedance locus was not seen entering the zone 1 polygon characteristic area of these relays, but was settling in the zone 2 characteristic area which by principle is correct, since the section in front of the Bacchus series capacitor is covered on backup protection of zone 2 reach of both the relays at Muldersvlei and Droerivier.

However, in the case of the Droerivier relay for both single phase to ground and three phase faults, it was noted that the fault impedance locus was passing very close to the underreaching zone 1, and well inside the over-reaching zone 2. This conveyed the importance of the decision that was taken to reduce the reach setting of the underreaching zone elements from the normal setting of 80%, which was to cater for the negative reactance that is introduced by the Komsberg 1 series capacitor on the Bacchus-Droerivier line. If the reach of zone 1 had not been reduced, the zone 1 element would have overreached for the external faults in front of the Bacchus series capacitor due to the impedance of the line no longer being a unique correspondence to the physical distance from the relay location to the point of fault.

On the other hand for faults behind the external Bacchus series capacitor, the results shown agreed with those presented in other research projects that have looked into the research question at hand, but were utilizing the physical REL 531 relays and a real time model. The series capacitors do have a great impact on the performance of the distance protection relays, when a line or adjacent lines are compensated with series capacitors. The Muldersvlei to Bacchus line does not have series capacitors but was affected by the series capacitor of the adjacent line for both three phase and single phase to ground faults behind this external capacitor. This was a conclusion reached based on the analytical and dynamic studies that were performed, for faults immediately behind the Bacchus series capacitor. The studies showed that the under reaching zone 1 elements at Muldersvlei do “see” the fault in their reach as for both the three phase and single phase to ground faults, the impedance locus was seen entering the zone 1 characteristic area, picking up and tripping on these elements.

Droerivier zone 1 reach setting was reduced before performing the studies to cater for the negative reactance of the Komsberg 1 series capacitor within the Bacchus to Droerivier line. Needless to say that the distance protection at Droerivier was affected the same way as the Muldersvlei relays for both three phase and single phase to ground faults behind the Bacchus series capacitor on the adjacent line.

In trying to overcome the setback of overreaching zone 1 elements as a result of subsynchronous oscillations and voltage inversion phenomena due to the Bacchus series capacitors, the recently introduced alternative configuration of the "current supervised zone 1" for Eskom distance protection relays was reviewed as a possible solution. Based on the dynamic and analytical studies performed, the current supervised zone 1 configuration was first shown to work when considering the impact of series capacitors located at the midpoint of a line adjacent to the line being protected. The analysis was looking at utilizing the current supervised zone 1 configuration to improve security of the performance of the Muldersvlei relay for faults behind the Komsberg 1 series capacitor. This line was selected as a case study because it is an example of the kind of line where the current supervised zone 1 configuration philosophy has already been proven to work in previous studies.

However, the current supervised zone 1 configuration was also shown not to provide a solution for the relays at Muldersvlei and Droerivier for faults immediately behind the Bacchus series capacitor. This is because the logic criterion that governs the instantaneous trip operation of the CSZ1 configuration of the relays at Muldersvlei and Droerivier were met, where for a fault immediately behind the Bacchus series capacitor despite the MOV conducting, both relays under investigation still did "see" the impedance locus in their instantaneous operating underreaching zone 1. Hence, still the incorrect instantaneous trip operations of the relays for a fault on the adjacent line.

It is believed that current supervised zone 1 approach is not applicable to network configurations that involve end of line or bus-bar series compensation as this configuration is more likely to create the condition of voltage and current reversals. This is because there is no line impedance between the relay location and the series capacitors. Moreover this also impacts the adjacent line protection because of the negative reactance that is added to the adjacent line for faults behind the external bus-bar SC, the higher the degree of line compensation the worse the impact effects to the distance protection performance. To improve protection performance it is believed that transmission must do away with bus-bar compensation and start implementing middle of line series compensation to all of transmission networks.

It is thus the author's conclusion and recommendation that: (1) for both the distance protection schemes at Muldersvlei and Droerivier to maintain their security, the zone 1 reach elements are to be disabled altogether, since zone 1 protection of the line will always overreach and operate incorrectly for faults immediately behind the Bacchus series capacitor; (2) because of subsynchronous oscillations and voltage inversion phenomena as a result of series compensation, can cause distance protection directional elements to operate incorrectly, more specific to internal faults which may appear as external faults and external faults which may appear as internal faults; (3) to address the distance protection challenges associated with series capacitors, transient simulations, protection applications and performance testing is recommended to ensure dependable and secure protection schemes.

Based on the above mentioned findings, the results have shown that by utilizing the Digsilent PowerFactory software simulator package together with its relay models, transient simulations, protection application and performance testing to ensure dependable and secure protection schemes can be done with confidence. This is because the research findings attained concur with those of previous research work where the physical relays and real time models were utilized.

6. Further Work Recommended

The following problems should be considered for further wok:

a) Study impact if end of line series compensation is moved towards the middle of the line.
b) Test relays with source impedance variations.
c) Test relays with fault resistance variations
d) Digsilent SC/MOV model to be modeled with built-in bypass circuit breakers.
e) Study power system oscillations.

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APPENDIXES

APPENDIX A

Bank name	Reactance (ohm)	Rated current (A)	Bank rating = 3 * I^2 *Xc	Continuous	8 hours in 12 hours	30 minutes in 6 hours	10 minutes in 2 hours	Transmission Line Position	Over Voltage Protection Type
				Equivalent 400kV power rating					
				= $\sqrt{3}$ * I * 400kV	= 1,1 * continuous	= 1,35 * continuous	= 1,5 * continuous		
Komsberg no 1	81.8	1,703	712	1,180	1,298	1,593	1,770	Droerivier Muldersvlei no. 1	Gapless MOV
Komsberg no 2	74.8	1,703	651	1,180	1,298	1,593	1,770	Droerivier Bacchus no. 1	Gapless MOV
Bacchus	37.3	1,479	245	1,025	1,127	1,383	1,537	Bacchus Proteus no. 1	Gapless MOV
Proteus	34.9	1,479	229	1,025	1,127	1,383	1,537	Proteus Droerivier no. 1	Gapless MOV
Hydra	35	1,600	269	1,109	1,219	1,496	1,663	Hydra Droerivier no. 3	Spark Gap
Victoria 1 and 2	37.2	1,410	222	977	1,075	1,319	1,465	Hydra Droerivier no. 1 and 2	Spark Gap
Luckhoff no 1	43.68	2,000	524	1,386	1,524	1,871	2,078	Beta Hydra no. 1	Gapless MOV
Luckhoff no 2	47.48	2,000	570	1,386	1,524	1,871	2,078	Perseus Hydra no. 1	Gapless MOV
Luckhoff no 3	47.48	2,000	570	1,386	1,524	1,871	2,078	Perseus Hydra no. 2	Gapless MOV
Juno no 1	37.6	1,100	136	762	838	1,029	1,143	Juno Aurora no. 1	Spark Gap
Juno no 2	37.6	1,100	136	762	838	1,029	1,143	Juno Helios no. 1	Spark Gap
Helios	37.6	1,100	136	762	838	1,029	1,143	Helios Juno no. 1	Spark Gap
Aries	37.6	1,660	311	1,150	1,265	1,553	1,725	Aries Kronos no. 1	Spark Gap
Kronos	37.6	1,660	311	1,150	1,265	1,553	1,725	Hyrda Kronos no. 1	Spark Gap
Iziko 1	50.2	2,100	664	1,455	1,600	1,964	2,182	Hydra Poseidon no 1	To Be determined New Project
Iziko 2	50.2	2,100	664	1,455	1,600	1,964	2,182	Hydra Poseidon no 2	To Be determined New Project
Serumula 1	60.7	2,100	803	1,455	1,600	1,964	2,182	Beta Delphi no. 1	To Be determined New Project

Table A-1 Series Capacitor Data on the Eskom Hydra Network

APPENDIX B

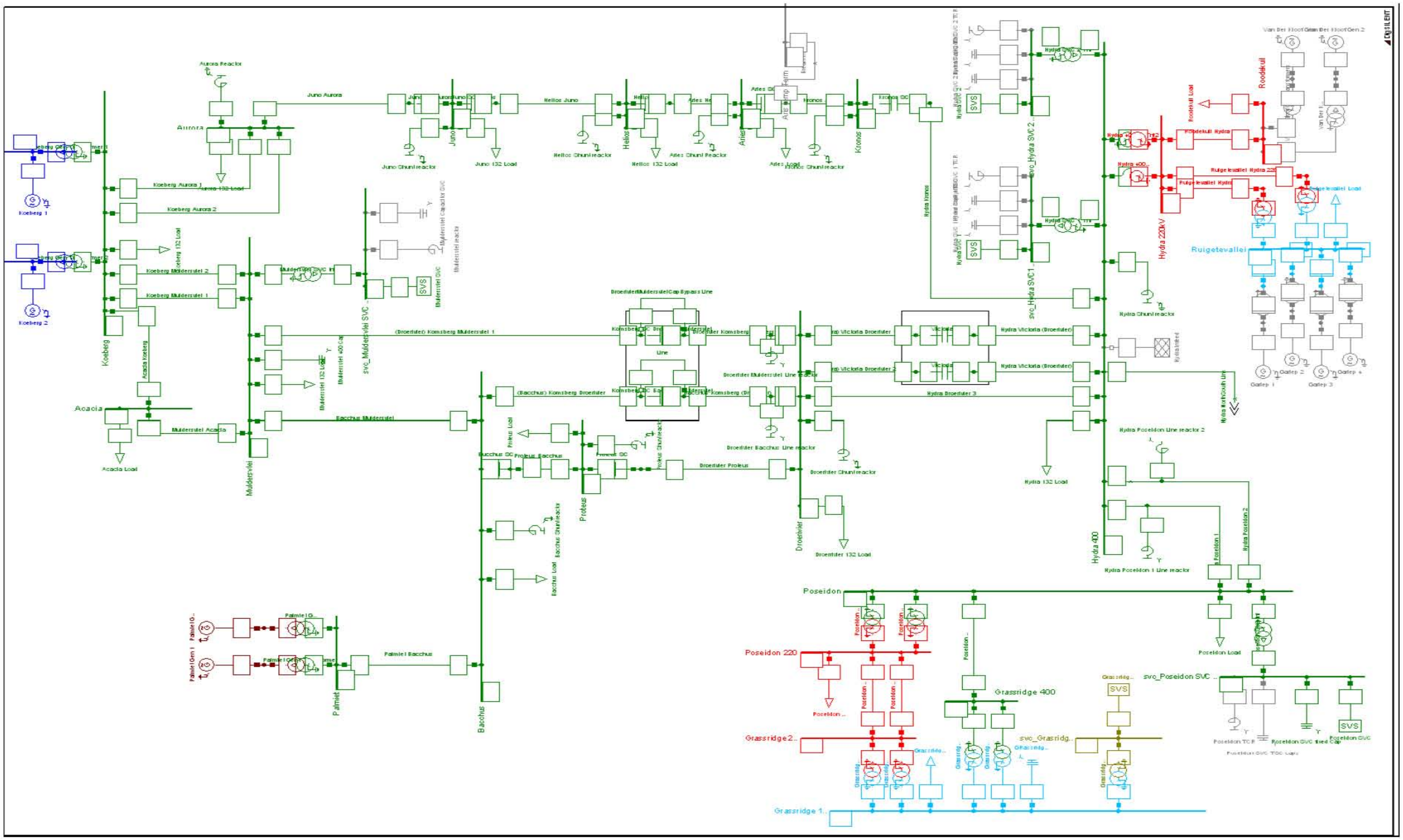


Figure B-1 Entire Eskom Hydra South Network

APPENDIX C

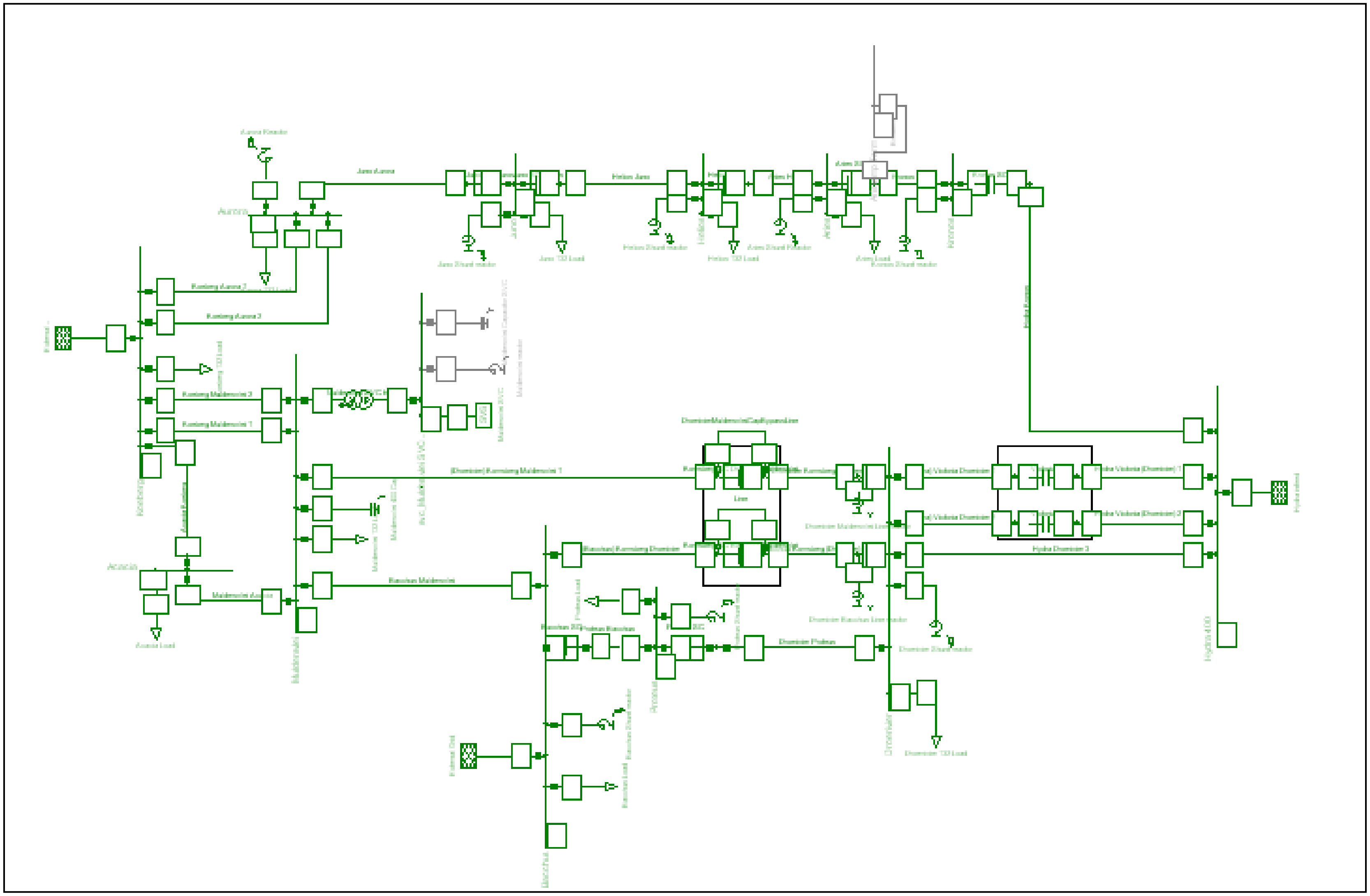


Figure C-1 Hydra South Network Sections Replaced with Equivalent Thevenin Circuit

APPENDIX D

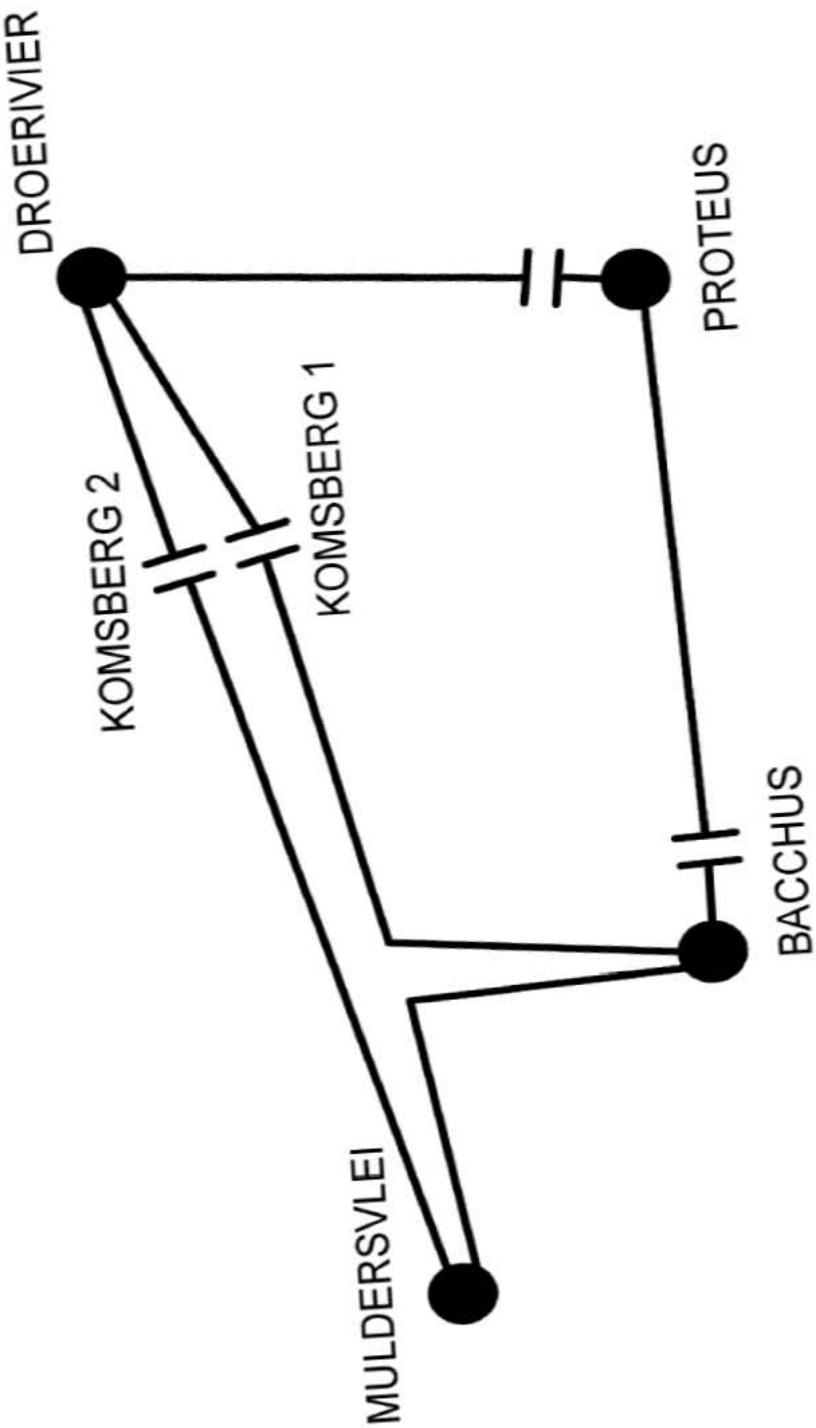


Figure D-1 Series Compensated lines Under Area of Focus

Bacchus 1 SC		Proteus 1 SC	
I (kA)	*U* (p.u. base 157.7 kV)	*I* (kA)	*U* (p.u. base 146.0 kV)
0.00031	0.786531896	0.00030	0.787326822
0.005	0.823931909	0.005	0.825368365
0.01	0.834374528	0.01	0.83582919
0.1	0.87545772	0.1	0.877054275
0.5	0.910969805	0.5	0.912734037
1.	0.926780208	1.	0.92857506
1.5	0.936887254	1.5	0.938763749
2.	0.944221304	2.	0.946112489
2.5	0.949949549	2.5	0.951852207
3.	0.954655653	3.	0.956567737
3.5	0.958652792	3.5	0.960572881
4.	0.962128796	4.	0.964055848
4.5	0.965205309	4.5	0.967138523
5.	0.967965679	5.	0.969904422
6.	0.972761036	6.	0.974709383
7.	0.976833982	7.	0.978790487
7.5	0.978662421	7.5	0.980622588
8.	0.98037591	8.	0.982339509
9.	0.98351077	9.	0.985480648
10.	0.986323492	10.	0.988299003
12.	0.991209794	12.	0.993195092
15.2	0.997494085	15.2	0.999479077
17.7	1.001551639	17.8	1.003695447
20.5	1.005480695	20.5	1.007481581
25.	1.010814491	25.	1.012825991
30.	1.01573971	30.	1.017761011
35.	1.019922642	35.	1.021952266
40.	1.023559983	40.	1.025596845
45.	1.02677911	45.	1.028822379
50.	1.029667296	50.	1.031716313
55.	1.033858517	55.	1.036898126
60.	1.039211753	60.	1.042267101

Appendix D (continued) MOV Characteristics of the Bacchus and Proteus Series Capacitors

Komsberg 1 SC		Komsberg 2 SC	
I (kA)	*U* (p.u. base 393.1 kV)	*I* (kA)	*U* (p.u. base 360.3 kV)
0.00011	0.786998372	0.00012	0.786989309
0.005	0.835951238	0.005	0.835708307
0.01	0.84816961	0.01	0.847923128
0.1	0.893411111	0.1	0.892973288
0.5	0.930380081	0.5	0.929815347
1.	0.94802507	1.	0.947449625
1.5	0.958501453	1.5	0.957919649
2.	0.966004701	2.	0.965418343
2.5	0.971865098	2.5	0.971275182
3.	0.976679773	3.	0.976086935
3.5	0.980769127	3.5	0.980173806
4.	0.984325323	4.	0.983727844
4.5	0.987474851	4.5	0.986873423
5.	0.99025248	5.	0.989673993
6.	0.99507751	6.	0.994496204
7.	0.999175352	7.	0.998591652
7.5	1.001014876	7.5	1.000430102
8.1	1.003070848	8.2	1.00281286
9.	1.005892346	9.	1.005304723
10.	1.008721781	10.	1.008132504
12.	1.013636803	12.	1.013044655
15.2	1.02004504	15.2	1.019449148
17.7	1.024194326	17.7	1.023596011
20.	1.029260478	20.	1.026935552
25.	1.042983386	25.	1.040627462
30.	1.054331528	30.	1.05194997
35.	1.06402252	35.	1.061619073
40.	1.07287561	40.	1.070066639
45.	1.081514249	45.	1.078588035
50.	1.089300697	50.	1.086353416
55.	1.096392678	55.	1.093426208
60.	1.10290746	60.	1.099923363

Appendix D (continued) MOV Characteristics of the Komsberg 1 and 2 Series Capacitors

APPENDIX E

SETTING OF THE
DISTANCE PROTECTION RELAY
REL 531

PROGRAM DEVELOPED BY:- ESKOM, PROTECTION SETTINGS & CO-ORDINATION TEAM.

STATION:	MULDERVLEI			**DONE BY :**	S. QWABE
CIRCUIT :	BACCHUS		FDR.:	**CHECKED:**	S. QWABE
VOLTAGE:	400	kV		**DATE :**	28-Aug-08
				DRAWING No.:	
SCHEME :	4FZ3100				
CT RATIO:	1600	/ 1		**Z ratio =**	0.44
VT RATIO:	400	kV / 110V		**Z base =**	1600 Ω

LINE PARAMETERS.:

Line length [km]	Conductor Type	90 º Th lim. [MVA]	Plant lim. [MVA]
109		2302	2302

R1	Ro	X1	Xo	B1	Bo
[p.u.]	[p.u.]	[p.u.]	[p.u.]	[p.u.]	[p.u.]
0.00167	0.02088	0.02108	0.07547	0.64649	0.43749

R1	Ro	X1	Xo	B1	Bo
Ωprim	Ωprim	Ωprim	Ωprim	Ωprim	Ωprim
2.67	33.41	33.73	120.75	1034.38	699.98

R1	Ro	X1	Xo	B1	Bo
Ωsec	Ωsec	Ωsec	Ωsec	Ωsec	Ωsec
1.17	14.70	14.84	53.13	455.13	307.99

	Z Line 1		**Z Line o**		**Zload min**	
	Ω	angle º	Ω	angle º	Ω	angle º
Primary	33.83	85.47	125.29	74.54	69.5	36.87
Secondary	14.89	85.47	55.13	74.54	30.58	36.87
ZE/ZL	0.901	Series Cap	0	Ω sec		

ZMn - DISTANCE PROTECTION.

The distance protection function in REL 531 line protection consists of five independent zones, each comprising three measuring elements for phase to earth (Ph-E) faults and /or three measuring elements for phase-to-phase (PH-PH) faults. It uses the **quadrilateral characteristic**, with the reactive and resistive reach settings being set independently on the Y and X axis respectively. The zones are set as percentages of the line parameters (RnZn and XnZn)
The directionality and operationality of the relay is determined by the settings below. Zones ZM1 - ZM4 are used for tripping. Zone ZM5 is used for switch onto fault purposes. ZM4 is also used in the power swing detection logic. ZM1, ZM2 and ZM4 are used as forward reaching zones whilst ZM3 is used as the reverse reaching zone. This is set in the relay's configuration tables and cannot be changed.

NOTE! **The interest of the studies under inverstigation are only base on Zone 1, therefore Zone 1 and 2 settings will be performed.**

Z General
Minimum operating current for forward directed distance protection zones.

Possible setting = [10 -30 % of I1b]

Set = **10%**

IminOp = 10%

DISTANCE ZONES.
ZONE 1
The zone 1 required reach must be set to 80 % of the line to be protected.

Operation mode and directionality of distance protection zone 1

Possible setting = [Off / Nonedirectional /Forward / Reverse]
Set = **Forward**

Operation = Forward

Settings for the phase-to-phase measurement

Operating mode for distance protection zone 1 for phase-to-phase faults

Possible setting = [Off / On]
Set = **On**

Operation PP = On

Positive sequence reactive reach of the distance protection zone 1 for Ph-Ph faults.

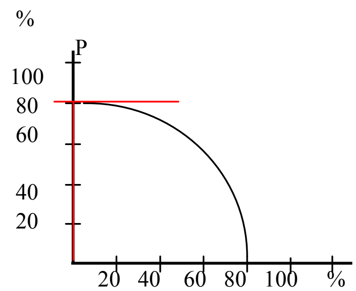
a) Normal Limit is 80% of Xline.

X1PP =	80%	*Xline
=	0.8 * 14.84	Ω /phase sec.
=	**11.88**	Ω /phase sec.

b) Series Compensation Limitation.

The zone 1 reach setting must be reduced if the line or adjacent lines are series compensated, due to the subharmonic oscillations caused by the series capacitor under fault conditions. Zone 1 can only be set as a percentage reach to the actual fault according to the curve shown below.

Is this line or the adjacent line series compensated?	N	[Y; N]
Is this line series compensated?	N	[Y; N]
Does this protection face the series capacitor?	N	[Y; N]



C = Xc/ X1 , degree of compensation.
X1 = Total positive sequence reactance from the source to the series capacitor.
P = Maximum allowable reach for the underreaching zone.
C

C =	Xc / X1(tot)
=	0 / 18.95
=	0.00%

Therefor from graph;

P = 80%

This option is not applicable.

X1PP =	X1* P/100		*, X1 = total line positive seq. Reactance.*
=	11.87	Ω /phase sec.	

Possible setting = [0.01 - 400 Ω /sec.]

Set =	**11.88**	Ω /phase sec.
X1PP =	**11.88**	Ω /phase sec.

NOTE: When the calculation of X1PP gives a negative value the zone 1 must be permanently blocked.

Positive sequence line resistance included in the distance protection zone 1 for Ph-Ph faults.
a) Normal Limit is 80% of Rline.

R1PP = 80% *Rline
= 0.8 * 1.17 Ω /phase sec.
= 0.94 Ω /phase sec.

b) Series Compensation Limitation.
This function is not applicable.

R1PP = (R1 *(X1PP - Xc))/X1 *; - Xc is used when Xc is entered as a negative value.*
= (1.17 * (11.88 + 0))/14.84
= 0.94 Ω /phase sec.

Possible setting = [0.01 - 400 Ω /sec.]
Set= **0.94** Ω /phase sec.

R1PP = 0.94 Ω /phase sec. Ohm/phase.

Resistive reach of distance protection zone 1 for Ph-Ph faults. This setting is based on the minimum of 3 * X1PP and 1.6 * minimum load. This setting could also be calculated using van Warringtons formulae considering remote end infeed and earth resistance.

Limit 1:

RFPP ≤ MIN(3 * 11.88 , 2*13.86) Ω /loop.
≤ 27.72 Ω /loop.

Limit 2 : This setting must cover a minimum fault of 20 ohms primary, unless restricted by the X1PP criteria. Remote end infeed must be considered. Do not set more than 50 ohms primary.

Possible setting = [0.01 - 400 Ω /sec.]
Set = **20** Ω /loop.

RFPP = 20 Ω /loop.

This setting provides a phase to phase fault resistance coverage of: **45.45** ohms prim.

Operating mode of time delayed trip for the distance protection zone 1 for Ph-Ph faults

Possible setting = [Off / On]
Set = **On**

Timer T1pp = On

Time delayed trip operation of the distance protection zone 1 for Ph-Ph faults

Possible setting = [0.00 - 60.000 s.]
Set= **0.000** s.

T1pp = 0.000 s.

Settings for the phase-to-earth measurement

Operating mode for distance protection zone 1 for phase-to-earth faults

Possible setting = [Off / On]
Set = **On**

Operation PE = On

Positive sequence reactive reach of the distance protection zone 1 for Ph-E faults.
a) Normal Limit is 80% of Xline.

X1PE = 80% *Xline
= 0.8 * 14.84 Ω /phase sec.
= 11.88 Ω /phase sec.

b) Series Compensation Limitation.
This option is not applicable.

X1PE = X1* P/100 *, X1 = total line positive seq. Reactance.*
= 11.87 Ω /phase sec.

Possible setting = [0.01 - 400 Ω /sec.]
Set= **11.88** Ω /phase sec.

X1PE = 11.88 Ω /phase sec.

NOTE: When the calculation of X1PE gives a negative value the zone 1 must be permanently blocked.

Positive sequence line resistance included in the distance protection zone 1 for Ph-E faults.

a) Normal Limit is 80% of Rline.
R1PE = 80% *Rline
= 0.8 * 1.17 Ω /phase sec.
= 0.94 Ω /phase sec.

b) Series Compensation Limitation.
This function is not applicable.

R1PE = (R1 *(X1PP + Xc))/X1
= (1.17 * (11.88 + 0))/14.84
= 0.94 Ω /phase sec.

Possible setting = [0.01 - 400 Ω /sec.]
Set= **0.94** Ω /phase sec.

R1PE = 0.94 Ω /phase sec.

Zero sequence line reactance included in distance protection zone 1 for Ph-E faults.
a) Normal Limit is 80% of Xline.

XoPE = 80% *Xoline
= 0.8 * 53.13 Ω /phase sec.
= 42.51 Ω /phase sec.

b) Series Compensation Limitation.
This function is not applicable.

XoPE = (XoL * (X1PP + Xc))/X1L - Xc , *X1 = total line positive seq. Reactance.*
= 42.53 Ω /phase sec.

Possible setting = [0.01 - 400 Ω /sec.]
Set= **42.51** Ω /phase sec.

XoPE = 42.51 Ω /phase sec.

Zero sequence line resistance included in the distance protection zone 1 for Ph-E faults.

RoPE = 80% *Roline
= 0.8 * 14.7004
= 11.76 Ω /phase sec.

Possible setting = [0.01 - 400 Ω /sec.]
Set= **11.76** Ω /phase sec.

RoPE = 11.76 Ω /phase sec.

Resistive reach of distance protection zone 1 for Ph-E faults. This setting is based on the minimum of 4.5 * X1PE and 0.8 * minimum load. This setting could also be calculated using the van Warrington formula considering remote end infeed and earth resistance.

a) Normal Limitation.

RFPE ≤ MIN(4.5 * 11.88 , 1.0*13.86)
≤ 13.86 Ω /loop.

b) Series Compensation Limitation.
This function is not applicable.
RFPE ≤ 0.83 *(2 * X1PE + XoPE)
≤ 0.83 *(2 * 11.88 + 42.51)
≤ 55.00

Possible setting = [0.01 - 400 Ω /sec.]
Set = **20** Ω /loop.

RFPE = 20 Ω /loop.

Operating mode of time delayed trip for the distance protection zone 1 for Ph-E faults

Possible setting = [Off / On]
Set = **On**

Timer T1PE = On

Time delayed trip operation of the distance protection zone 1 for Ph-E faults

Possible setting = [0.00 - 60.000 s.]
Set= **0.000** s.

T1PE = 0.000 s.

<u>ZONE 2.</u>

General zone setting parameters

Operation mode and directionality of distance protection zone 2

Possible setting = [Off / Nonedirectional /Forward / Reverse]
Set = **Forward**

Operation = Forward

Settings for the phase-to-phase measurement

Operating mode for distance protection zone 2 for phase-to-phase faults

Possible setting = [Off / On]
Set = **On**

Operation PP = On

a) The zone 2 required reach must be set to 120 % of the line to be protected.
b) Ensure coordination with remote end reverse reach.

Positive sequence reactive reach of the distance protection zone 2 for Ph-Ph faults.

<u>Limit 1:</u>
The zone 2 required reach must be set to 120 % of the line to be protected.

X1PP $\geq$ 1.2 * 14.84 Ω /phase sec.
X1PP **17.81** Ω /phase sec.

Positive sequence line resistance included in the distance protection zone 2 for Ph-Ph faults.

R1PP = 120% *Rline
= 1.2 * 1.17 Ω /phase sec.
= 1.41 Ω /phase sec.

Possible setting = [0.01 - 400 Ω /sec.]
Set= **1.41** Ω /phase sec.

R1PP = 1.41 Ω /phase sec.

Resistive reach of distance protection zone 2 for Ph-Ph faults.

Resistive reach of distance protection zone 2 for Ph-Ph faults. Manufacturer recommends the minimum of 3 * X1PP and 1.6 * minimum load. Since the NERC recommendation is used, the factor of 1.6 is ignored. This setting could also be calculated using the van Warrington formula considering remote end infeed and earth resistance.

RFPP ≤ MIN(3 * 17.808 , 2.0*13.86) Ω /loop.
≤ 27.72 Ω /loop.

Possible setting = [0.01 - 400 Ω /sec.]
Set = **22** Ω /loop.

RFPP = 22 Ω /loop.

This setting provides a phase to phase fault resistance coverage of: **50.00** ohms primary

Operating mode of time delayed trip for the distance protection zone 2 for Ph-Ph faults

Possible setting = [Off / On]
Set = **On**

Timer T2PP = On

Time delayed trip operation of the distance protection zone 2 for Ph-Ph faults

Possible setting = [0.00 - 60.000 s.]
Set= **0.4s**

T2PP = 0.4s

Settings for the phase-to-earth measurement

Operating mode for distance protection zone 2 for phase-to-earth faults.

Possible setting = [Off / On]
Set = **On**

Operation PE = On

Positive sequence reactive reach of the distance protection zone 2 for Ph-E faults.

X1PE = 17.81 Ω /phase sec. Set same as for phase-to-phase faults

Possible setting = [0.01 - 400 Ω /sec.]
Set= **17.81** Ω /phase sec.

X1PE = 17.81 Ω /phase sec.

Positive sequence line resistance included in the distance protection zone 2 for Ph-E faults.

R1PE = 1.41 Ω /phase sec. Set same as for phase-to-phase faults

Possible setting = [0.01 - 400 Ω /sec.]
Set = **1.41** Ω /phase sec.

R1PE = 1.41 Ω /phase sec.

Zero sequence line reactance included in distance protection zone 2 for Ph-E faults.

XoPE = 120% *Xoline
= 1.2 * 53.13 Ω /phase sec.
= 63.76 Ω /phase sec.

Possible setting = [0.01 - 400 Ω /sec.]
Set = **63.76** Ω /phase sec.

XoPE = 63.76 Ω /phase sec.

Zero sequence line resistance included in the distance protection zone 2 for Ph-E faults.

RoPE = 120% *Roline
= 1.2 * 14.7004 Ω /phase sec.
= 17.65 Ω /phase sec.

Possible setting = [0.01 - 400 Ω /sec.]
Set = **17.65** Ω /phase sec.

RoPE = 17.65 Ω /phase sec.

Resistive reach of distance protection zone 2 for Ph-E faults. This setting is based on the minimum of 4.5 * X1PE and 0.8 * minimum load. It must also fall inside the remote end reverse reach - ZM3.

1) Must not encroach on load.

RFPE ≤ MIN(4.5 * 17.808 , 1*13.86) Ω /loop.
≤ 13.86 Ω /loop.

2) Must fall inside the remote end reverse reach.

Remote reverse reach RFPE = 40.00 Ω /loop.
Therefor RFPE ≤ 32 Ω /loop.

Possible setting = [0.01 - 400 Ω /sec.]
Set= **32** Ω /loop.

RFPE = 32 Ω /loop.

Operating mode of time delayed trip for the distance protection zone 2 for Ph-E faults

Possible setting = [Off / On]
Set = **On**

Timer T2PE = On

Time delayed trip operation of the distance protection zone 2 for Ph-E faults

Possible setting = [0.00 - 60.000 s.]
Set= **0.4s** s.

T2PE = 0.4s s.

Directional Measuring Element - Zdir.

This function is to be used with series compensated lines, and is able to cope with the condition of voltage reversal. This function will be enabled on series compensated- and lines adjacent to series compensated lines, and is controlled by the faulty phase criteria.

Operation mode and directionality of distance protection directional element.

This function is only used for series compensated lines.

Possible setting = [Non-series compensated, Series compensated]
Set = **Non-Series Compensated**

Operation = Non-Series Compensated

Lower Angle of Forward directional characteristic.

These parameters define the position of the directional lines in the impedance plane. Default values of 15 and 25 degrees respectively for ArgDir an ArgNegRes should be used unless fault studies on long heavily loaded lines indicate a clear necessity for deviation from this. It needs to be noted that the reverse directionality will also be affected, since the reverse directional lines is a mirror image of the forward directional lines.

Set ArgDir = 15.00 Degrees

Possible setting = [5 - 45 degrees; 1 deg. steps]
ArgDir = **15.00 Degrees**

Upper Angle of Forward directional characteristic.

This setting is used to define the upper angle in the second quadrant. PSS/E results to be consulted when deciding to change this angle. 25 Degrees in the relay manual refers to 90 + 25 = 115 degrees.

Set ArgNegRes = 115.00 Degrees

Possible setting = [5 - 45 degrees; 1 deg. steps]
ArgNegRes = **115.00 Degrees**

APPENDIX F

SETTING OF THE
DISTANCE PROTECTION RELAY
REL 531

PROGRAM DEVELOPED BY:- ESKOM, PROTECTION SETTINGS & CO-ORDINATION TEAM.

STATION:	BACCHUS				**DONE BY :**	S. QWABE
CIRCUIT :	DROERIVIER		FDR.:		**CHECKED:**	S. QWABE
VOLTAGE:	400	kV			**DATE :**	28-Aug-08
					DRAWING No.:	
SCHEME :	4FZ3100					
CT RATIO:	1600	/ 1			**Z ratio =**	0.44
VT RATIO:	400	kV / 110V			**Z base =**	1600 Ω

LINE PARAMETERS.:

Line length	Conductor Type	90 º Th lim.	Plant lim.
[km]		[MVA]	[MVA]
402		1595	1595

R1	Ro	X1	Xo	B1	Bo
[p.u.]	[p.u.]	[p.u.]	[p.u.]	[p.u.]	[p.u.]
0.00666	0.07747	0.07991	0.27295	2.35383	1.70866

R1	Ro	X1	Xo	B1	Bo
Ωprim	Ωprim	Ωprim	Ωprim	Ωprim	Ωprim
10.66	123.95	127.86	436.72	3766.13	2733.86

R1	Ro	X1	Xo	B1	Bo
Ωsec	Ωsec	Ωsec	Ωsec	Ωsec	Ωsec
4.69	54.54	56.26	192.16	1657.1	1202.9

	Z Line 1		**Z Line o**		**Zload min**	
	Ω	angle º	Ω	angle º	Ω	angle º
Primary	128.3	85.24	453.97	74.15	100.31	36.87
Secondary	56.45	85.24	199.75	74.15	44.14	36.87
ZE/ZL	0.846	Series Cap	35.64	**Ω** sec		

Appendix F Droerivier Line Settings

<u>ZMn - DISTANCE PROTECTION.</u>

The distance protection function in REL 531 line protection consists of five independent zones, each comprising three measuring elements for phase to earth (Ph-E) faults and /or three measuring elements for phase-to-phase (PH-PH) faults. It uses the **quadrilateral characteristic**, with the reactive and resistive reach settings being set independently on the Y and X axis respectively. The zones are set as percentages of the line parameters (RnZn and XnZn)
The directionality and operationality of the relay is determined by the settings below. Zones ZM1 - ZM4 are used for tripping. Zone ZM5 is used for switch onto fault purposes. ZM4 is also used in the power swing detection logic. ZM1, ZM2 and ZM4 are used as forward reaching zones whilst ZM3 is used as the reverse reaching zone. This is set in the relay's configuration tables and cannot be changed.

NOTE! **The interest of the studies under inverstigation are only base on Zone 1, therefore Zone 1 and 2 settings will be performed.**

<u>Z General</u>
Minimum operating current for forward directed distance protection zones.

Possible setting = [10 -30 % of I1b]

Set = **10%**

IminOp = 10%

<u>DISTANCE ZONES.</u>
<u>ZONE 1</u>
The zone 1 required reach must be set to 80 % of the line to be protected.

Operation mode and directionality of distance protection zone 1

Possible setting = [Off / Nonedirectional /Forward / Reverse]
Set = **Forward**

Operation = Forward

Settings for the phase-to-phase measurement

Operating mode for distance protection zone 1 for phase-to-phase faults

Possible setting = [Off / On]
Set = **On**

Operation PP = On

Positive sequence reactive reach of the distance protection zone 1 for Ph-Ph faults.

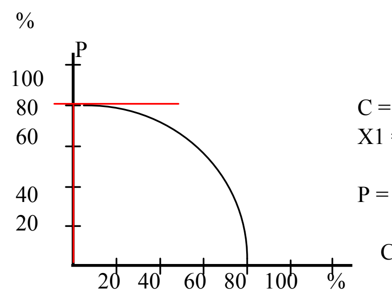
a) Normal Limit is 80% of Xline.

X1PP =	80%	*Xline
=	0.8 * 56.26	Ω /phase sec.
=	**45.01**	Ω /phase sec.

b) Series Compensation Limitation.

The zone 1 reach setting must be reduced if the line or adjacent lines are series compensated, due to the subharmonic oscillations caused by the series capacitor under fault conditions. Zone 1 can only be set as a percentage reach to the actual fault according to the curve shown below.

Is this line or the adjacent line series compensated?	Y	[Y; N]
Is this line series compensated?	Y	[Y; N]
Does this protection face the series capacitor?	Y	[Y; N]



C = Xc/ X1 , degree of compensation.
X1 = Total positive sequence reactance from the source to the series capacitor.
P = Maximum allowable reach for the underreaching zone.

C =	Xc / X1(tot)
=	35.64/56.26
=	63.35%

Therefor from graph;

P = 48%

Protection on compensated line facing capacitor.

X1PP =	(X1 - Xc) * P/100		*, X1 = total line positive seq. Reactance.*
=	9.96	Ω /phase sec.	

Possible setting =	[0.01 - 400 Ω /sec.]	
Set =	**9.96**	Ω /phase sec.

X1PP = 9.96 Ω /phase sec.

NOTE: When the calculation of X1PP gives a negative value the zone 1 must be permanently blocked.

Positive sequence line resistance included in the distance protection zone 1 for Ph-Ph faults.
a) Normal Limit is 80% of Rline.

R1PP = 80% *Rline
= 0.8 * 4.69 Ω /phase sec.
= 3.76 Ω /phase sec.

b) Series Compensation Limitation.
Protection on compensated line with series capacitor inside the normal reach of zone 1.

R1PP = (R1 *(X1PP - Xc))/X1 *; - Xc is used when Xc is entered as a negative value.*
= (4.69 * (9.95946 + 35.64))/56.26
= 3.80 Ω /phase sec.

Possible setting = [0.01 - 400 Ω /sec.]
Set= **3.80** Ω /phase sec.

R1PP = 3.80 Ω /phase sec. Ohm/phase.

Resistive reach of distance protection zone 1 for Ph-Ph faults. This setting is based on the minimum of 3 * X1PP and 1.6 * minimum load. This setting could also be calculated using van Warringtons formulae considering remote end infeed and earth resistance.

Limit 1:

RFPP ≤ MIN(3 * 9.95946 , 2*20.01) Ω /loop.
≤ 29.88 Ω /loop.

Limit 2 : This setting must cover a minimum fault of 20 ohms primary, unless restricted by the X1PP criteria. Remote end infeed must be considered. Do not set more than 50 ohms primary.

Possible setting = [0.01 - 400 Ω /sec.]
Set = **20** Ω /loop.

RFPP = 20 Ω /loop.

This setting provides a phase to phase fault resistance coverage of: **45.45** ohms prim.

Operating mode of time delayed trip for the distance protection zone 1 for Ph-Ph faults

Possible setting = [Off / On]
Set = **On**

Timer T1pp = On

Time delayed trip operation of the distance protection zone 1 for Ph-Ph faults

Possible setting = [0.00 - 60.000 s.]
Set= **0.000** s.

T1pp = 0.000 s.

Settings for the phase-to-earth measurement

Operating mode for distance protection zone 1 for phase-to-earth faults

Possible setting = [Off / On]
Set = **On**

Operation PE = On

Positive sequence reactive reach of the distance protection zone 1 for Ph-E faults.
a) Normal Limit is 80% of Xline.

X1PE = 80% *Xline
= 0.8 * 56.26 Ω /phase sec.
= 45.01 Ω /phase sec.

b) Series Compensation Limitation.
Protection on Non-compensated line facing series capacitor.

X1PE = (X1 - Xc) *P/100 *, X1 = total line positive seq. Reactance.*
= 9.96 Ω /phase sec.

Possible setting = [0.01 - 400 Ω /sec.]
Set= **9.96** Ω /phase sec.

X1PE = 9.96 Ω /phase sec.

NOTE: When the calculation of X1PE gives a negative value the zone 1 must be permanently blocked.

Positive sequence line resistance included in the distance protection zone 1 for Ph-E faults.

a) Normal Limit is 80% of Rline.
R1PE = 80% *Rline
= 0.8 * 4.69 Ω /phase sec.
= 3.76 Ω /phase sec.

b) Series Compensation Limitation.
Protection on compensated line with series capacitor inside the reach of zone 1.

R1PE = (R1 *(X1PP + Xc))/X1
= (4.69 * (9.95946 + 35.64))/56.26
= 3.80 Ω /phase sec.

Possible setting = [0.01 - 400 Ω /sec.]
Set= **3.80** Ω /phase sec.

R1PE = 3.80 Ω /phase sec.

Zero sequence line reactance included in distance protection zone 1 for Ph-E faults.
a) Normal Limit is 80% of Xline.

XoPE = 80% *Xoline
= 0.8 * 192.16 Ω /phase sec.
= 153.73 Ω /phase sec.

b) Series Compensation Limitation.
Protection on compensated line with series capacitor inside the normal reach of zone 1.

XoPE = (XoL * (X1PP + Xc))/X1L - Xc *, X1 = total line positive seq. Reactance.*
= 120.11 Ω /phase sec.

Possible setting = [0.01 - 400 Ω /sec.]
Set= **120.11** Ω /phase sec.

XoPE = 120.11 Ω /phase sec.

Zero sequence line resistance included in the distance protection zone 1 for Ph-E faults.

RoPE = 63% *Roline
= 0.63 * 54.538
= 34.09 Ω /phase sec.

Possible setting = [0.01 - 400 Ω /sec.]
Set= **34.09** Ω /phase sec.

RoPE = 34.09 Ω /phase sec.

Resistive reach of distance protection zone 1 for Ph-E faults. This setting is based on the minimum of 4.5 * X1PE and 0.8 * minimum load. This setting could also be calculated using the van Warrington formula considering remote end infeed and earth resistance.

a) Normal Limitation.

RFPE ≤ MIN(4.5 * 9.95946 , 1.0*20.01)
≤ 20.01 Ω /loop.

b) Series Compensation Limitation.

RFPE ≤ 0.83 *(2 * X1PE + XoPE)
≤ 0.83 *(2 * 9.95946 + 120.108173366513)
≤ 116.22

Possible setting = [0.01 - 400 Ω /sec.]
Set = **20** Ω /loop.

RFPE = 20 Ω /loop.

Operating mode of time delayed trip for the distance protection zone 1 for Ph-E faults

Possible setting = [Off / On]
Set = **On**

Timer T1PE = On

Time delayed trip operation of the distance protection zone 1 for Ph-E faults

Possible setting = [0.00 - 60.000 s.]
Set= **0.000** s.

T1PE = 0.000 s.

ZONE 2.

General zone setting parameters

Operation mode and directionality of distance protection zone 2

Possible setting = [Off / Nonedirectional /Forward / Reverse]
Set = **Forward**

Operation = Forward

Settings for the phase-to-phase measurement

Operating mode for distance protection zone 2 for phase-to-phase faults

Possible setting = [Off / On]
Set = **On**

Operation PP = On

a) The zone 2 requirement for series comp. lines or protection on lines affected by it is greater or equal to 150%
b) Ensure coordination with remote end reverse reach.

Positive sequence reactive reach of the distance protection zone 2 for Ph-Ph faults.

Limit 1:
The zone 2 requirement for series compensated lines or protection on lines affected by it is greater or equal to 150%
The safety factor of 150% are required due to operating speed requirements and possible underreaching.

$X1PP \geq 1.5 * 56.26$ Ω /phase sec.
84.39 Ω /phase sec.

Positive sequence line resistance included in the distance protection zone 2 for Ph-Ph faults.

R1PP = 150% *Rline
= 1.5*4.69 Ω /phase sec.
= 7.035 Ω /phase sec.

Possible setting = [0.01 - 400 Ω /sec.]
Set= **7.035** Ω /phase sec.

R1PP = 7.035 Ω /phase sec.

Resistive reach of distance protection zone 2 for Ph-Ph faults.

Resistive reach of distance protection zone 2 for Ph-Ph faults. Manufacturer recommends the minimum of 3 * X1PP and 1.6 * minimum load. Since the NERC recommendation is used, the factor of 1.6 is ignored. This setting could also be calculated using the van Warrington formula considering remote end infeed and earth resistance.

RFPP ≤ MIN(3 * 67.512 , 2.0*20.013: Ω /loop.
≤ 40.03 Ω /loop.

Possible setting = [0.01 - 400 Ω /sec.]
Set = **22** Ω /loop.

RFPP = 22 Ω /loop.

This setting provides a phase to phase fault resistance coverage of: **50.00** ohms primary

Operating mode of time delayed trip for the distance protection zone 2 for Ph-Ph faults

Possible setting = [Off / On]
Set = **On**

Timer T2PP = On

Time delayed trip operation of the distance protection zone 2 for Ph-Ph faults

Possible setting = [0.00 - 60.000 s.]
Set= **0.4s**

T2PP = 0.4s

Settings for the phase-to-earth measurement

Operating mode for distance protection zone 2 for phase-to-earth faults.

Possible setting = [Off / On]
Set = **On**

Operation PE = On

Positive sequence reactive reach of the distance protection zone 2 for Ph-E faults.

X1PE = 84.40 Ω /phase sec. Set same as for phase-to-phase faults

Possible setting = [0.01 - 400 Ω /sec.]
Set= **84.40** Ω /phase sec.

X1PE = 84.40 Ω /phase sec.

Positive sequence line resistance included in the distance protection zone 2 for Ph-E faults.

R1PE = 7.035 Ω /phase sec. Set same as for phase-to-phase faults

Possible setting = [0.01 - 400 Ω /sec.]
Set = **7.035** Ω /phase sec.

R1PE = 7.035 Ω /phase sec.

Zero sequence line reactance included in distance protection zone 2 for Ph-E faults.

XoPE = 150% *Xoline
= 1.5*192.16 Ω /phase sec.
= 288.24 Ω /phase sec.

Possible setting = [0.01 - 400 Ω /sec.]
Set = **288.24** Ω /phase sec.

XoPE = 288.24 Ω /phase sec.

Zero sequence line resistance included in the distance protection zone 2 for Ph-E faults.

RoPE = 150% *Roline
= 1.5*54.38 Ω /phase sec.
= 65.45 Ω /phase sec.

Possible setting = [0.01 - 400 Ω /sec.]
Set = **81.57** Ω /phase sec.

RoPE = 81.57 Ω /phase sec.

Resistive reach of distance protection zone 2 for Ph-E faults. This setting is based on the minimum of 4.5 * X1PE and 0.8 * minimum load. It must also fall inside the remote end reverse reach - ZM3.

1) Must not encroach on load.
RFPE ≤ MIN(4.5 * 84.4 , 1*20.01) Ω /loop.
≤ 20.01 Ω /loop.

2) Must fall inside the remote end reverse reach.

Remote reverse reach RFPE = 40.00 Ω /loop.
Therefor RFPE ≤ 32 Ω /loop.

Possible setting = [0.01 - 400 Ω /sec.]
Set= **22.00** Ω /loop.

RFPE = 22 Ω /loop.

Operating mode of time delayed trip for the distance protection zone 2 for Ph-E faults

Possible setting = [Off / On]
Set = **On**

Timer T2PE = On

Time delayed trip operation of the distance protection zone 2 for Ph-E faults

Possible setting = [0.00 - 60.000 s.]
Set= **0.4s** s.

T2PE = 0.4s s.

Directional Measuring Element - Zdir.

This function is to be used with series compensated lines, and is able to cope with the condition of voltage reversal. This function will be enabled on series compensated- and lines adjacent to series compensated lines, and is controlled by the faulty phase criteria.

Operation mode and directionality of distance protection directional element.

This function is only used for series compensated lines.
Possible setting = [Non-series compensated, Series compensated]
Set = **Series Compensated**

Operation = Series Compensated

Lower Angle of Forward directional characteristic.

These parameters define the position of the directional lines in the impedance plane. Default values of 15 and 25 degrees respectively for ArgDir an ArgNegRes should be used unless fault studies on long heavily loaded lines indicate a clear necessity for deviation from this. It needs to be noted that the reverse directionality will also be affected, since the reverse directional lines is a mirror image of the forward directional lines.

Set ArgDir = 15.00 Degrees

Possible setting = [5 - 45 degrees; 1 deg. steps]
ArgDir = **15.00 Degrees**

Upper Angle of Forward directional characteristic.

This setting is used to define the upper angle in the second quadrant. PSS/E results to be consulted when deciding to change this angle. 25 Degrees in the relay manual refers to 90 + 25 = 115 degrees.

Set ArgNegRes = 115.00 Degrees

Possible setting = [5 - 45 degrees; 1 deg. steps]
ArgNegRes = **115.00 Degrees**

BIOGRAPHY

Sihle Qwabe has been involved in high voltage engineering since 2003. He first started his career as a project engineer for Trans-Africa Projects where he was responsible for substation designs for Eskom Sub-transmission. In 2005 he then was appointed as settings engineer for Eskom Transmission. In 2006 he was appointed engineering projects manager for SAVCIO Holdings Pty Ltd. Since 2007 he has been with Richards Bay Minerals where he was appointed as a high voltage engineering specialist, where he is responsible for the quality of power supply, high voltage power system protection, high voltage switchgear reliability and responsible for all plant energy saving projects. His highest qualification is a Bachelor of Technology Degree in electrical engineering from the Durban Institute of Technology. Currently he is working on his Bachelor of Science (Honours) degree in Technology Management with the University of Pretoria. Sihle Qwabe is also registered as a Professional Engineering Technologist with the Engineering Council of South Africa.