Chapter 4
RELAY ALGORITHM COMPARISON USING THEORETICAL NETWORK MODELS

4.1 Introduction

Armed with the detailed knowledge gained from Chapter 2 and Chapter 3 pertaining to system fault theory and two of the numerical relays in use on the Eskom transmission system, this chapter is focused on doing some single-phase-to-earth fault comparison studies between the relays. The focus is on understanding how to compare the results obtained from the different algorithms of the two relays.

For the benefit of the student and others that may want to use it, Matlab routines were created from basic theory to simulate single-phase-to-earth system faults. The aim was to gain a thorough understanding of how the different system parameters of resistance and reactance influences power flow, fault levels and the measured values of current and voltage at the relay measuring position. All the steady-state parameters of the small system modelled for this purpose can easily be altered. A-phase-to-earth faults can be simulated at 10% intervals successively and the results for all faults simulated presented in graphical and text format. A comparison of these simulations have also been done using the PowerFactory system simulation software and are shown in this chapter in various tabular and graphical formats.

Relay algorithm result comparisons will firstly be done using a simple radial network. Section 4.3 will cover similar comparisons, but using a complex network. The impact that capacitive charging, direction of load-flow and remote end in-feed has on the distance protection algorithms discussed in Chapter 3 are evaluated. Comparisons between the generic apparent impedance algorithm and those for the different distance relays are shown in tabular and graphical format. A detailed comparison for fault analysis using relay algorithm results in the apparent impedance domain versus the loop impedance domain is done and recommendations are made for future fault analysis.

The first section on radial simulations will show that the Matlab simulation, which was developed from basic principles ignoring all capacitive quantities, can be used to determine the effect of fault resistance and load on a distance protection relay. It will also show that the impact of the system capacitive quantities cannot be ignored. Section 4.2 will also show that the relays have different algorithm responses under radial load conditions.

Section 4.3 on complex networks will focus on the impact of a remote in-feed/source on distance relay reach measurements. Differences between the results obtained from Matlab and PowerFactory simulations as well as apparent versus loop impedances are shown.

4.2 Radial network

This section applies the theory discussed in Chapter 2 on a typical radial network and demonstrates what role a connected load could play on the voltages and currents measured at the relaying point (see Figure 4.2). For this purpose and to obtain fast results a simulation routine using a typical Newton-Raphson load-flow solution was created in Matlab based on the simple network shown in Figure 4.2. The Matlab routines are included on CD (Appendix K), and are appended to this dissertation. Since the interest was focused towards understanding the impact of load current superimposed on the single-phase-to-earth fault current, the capacitive components of the circuit was ignored in the Matlab simulation. It is understood that the results obtained by ignoring the capacitive elements will not reflect an actual system condition. The results obtained from the Matlab simulations will be compared with simulation studies done in an official network simulation package illustrating the differences. Appendix J contains files with the relevant simulation results for reference.

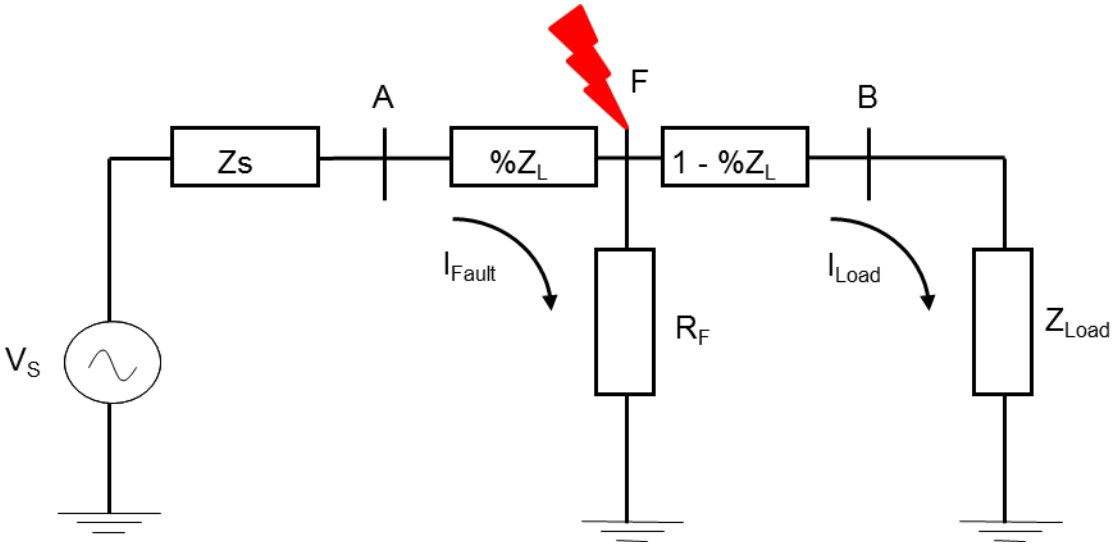

Figure 4.1: Simple radial network

Using Thevenin's super positioning theorem the sequence networks for the radial network in Figure 4.1 are represented in Figure 4.2. Figure 4.2(a) represents the pre-faulted network with pre-fault voltage at point F in the network. This pre-fault voltage becomes the driving voltage according to Thevenin's theorem during the fault, and is connected between the earth (neutral point) and the point of fault in Figure 4.2(a). Figure 4.2(b) shows the source voltage short-circuited as per Thevenin's theorem, and the pre-fault voltage reversed in order to obtain the correct direction of fault current. The pre-fault load current and the fault current can now be added together to obtain the total flow of current in all the branches during the fault (see Figure 4.2(c)).

The network in Figure 4.1 can now be represented by the positive-, negative- and zero sequence networks. The theory discussed in Chapter 2, with specific reference to Figure 2.38(b), with delta or star-connected loads can be applied. The earthed star-connected load referred to in Figure 2.38(a) is different from normal loads and will contribute to faults involving earth return depending on the load impedance. It should be noted that in transmission systems the loads are either delta or un-earthed star connected, and are mostly situated on the low voltage side of a transformer. Only the impact of these types of loads on relay performance will be evaluated. Earthed equipment in the transmission system includes transformers, generators, synchronous condensers and shunt devices such as reactors and capacitors banks. Generators and synchronous condensers are normally situated on the low voltage side of star-delta transformers resulting in high X/R ratios that impact feeder protection and associated high voltage equipment such as current transformers differently. System faults, close-up to generation, will result in much longer dc-offset decay times due to the high X/R-ratios. Long dc-offset decay times will negatively impact current transformer response and therefore secondary measurements. Strong frequency swings as a result of system faults are also more apparent close to sources of generation than further away. No further attention will be given to dc-offset phenomenon and frequency swings as a result of system faults. The impedance reach analysis that follows has been based on a delta or star-connected load, where the sequence networks as represented in Figure 2.38(b) were used.

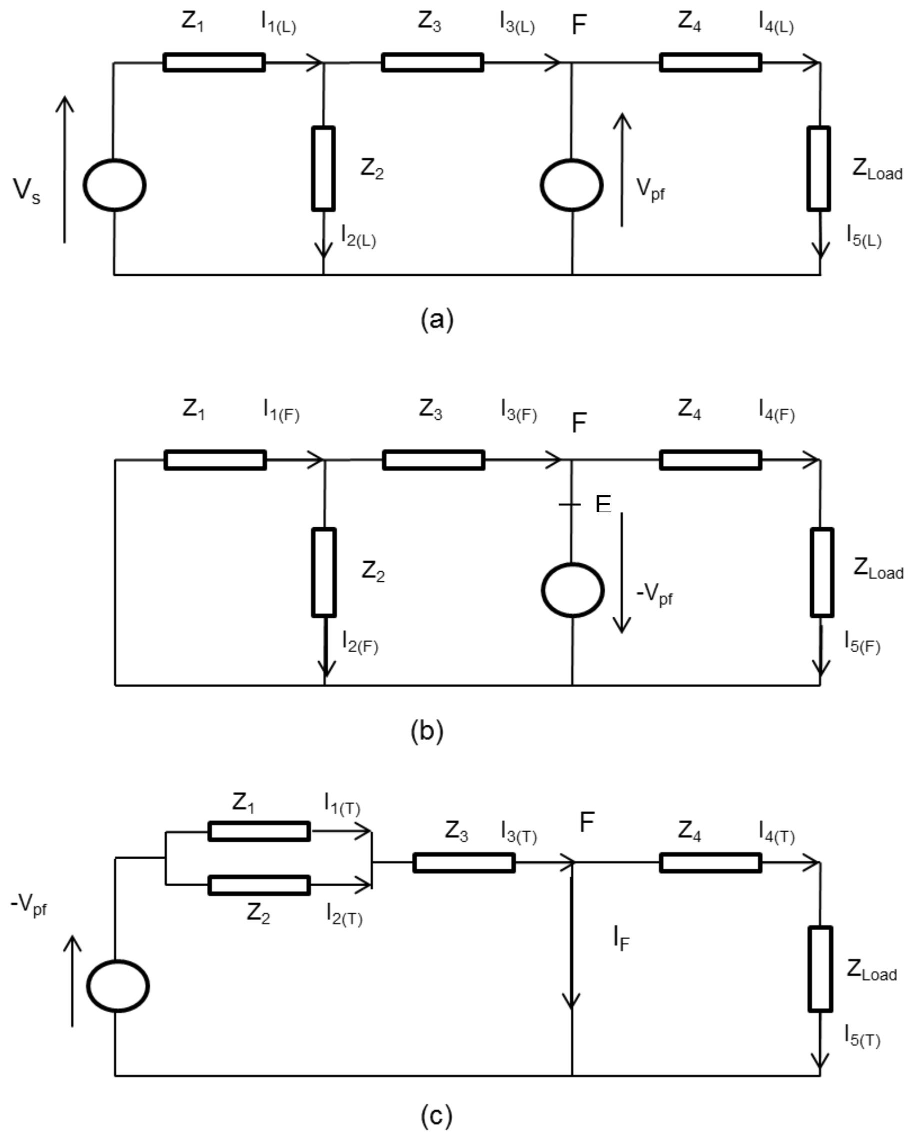

Figure 4.2: Thevenin's super positioning theorem [5]

For the purpose of evaluating the impact of external influences such as capacitive charging and direction of load-flow on distance protection the 400 kV, 401.3 km Bacchus – Droërivier series compensated line was chosen. The surrounding network was reduced to equivalent sources for simplicity. The series capacitor was by-passed in the simulations due to the expected voltage reversal indicative of series compensation. Figure 4.3 shows the reduced network used in the study, with 500 MVA (constant impedance load) load-flow results. All three bus voltages together with angles are shown including the generated active (P) and reactive (Q) power, the power transferred across the line and the power absorbed by the load at the remote end of the line.

The bus information is shown from top to bottom as the voltage V_A and angle of V_A. External Grid (1) generated 518.6 MW whilst consuming 28.74 Mvar of reactive power resulting in current through the line of 0.74 kA. As indicated above, the network has been reduced for ease of use, flexibility and reference. The illustrated network was successfully utilized in both radial and complex configurations. A complex configuration being defined as a multiple source and loads network with sources and loads situated on both ends of the protected overhead line. For the purpose of the studies the line was modelled using the latest parameters used by Eskom. These differ somewhat from those that were used when the original protection settings were calculated, with the biggest difference being in the value of the zero sequence resistance. The model was therefore created with the line positive sequence impedance of $Z_1 = 9.034 + j129.4\ \Omega$, and the zero sequence impedance of $Z_0 = 154.4 + j438.7\ \Omega$. The normal and complex values of K_0 are respectively given by 0.879 and 0.819 – j0.317. A validation comparison was done between results obtained from Matlab and PowerFactory for currents and voltages obtained based on an applied load of 500 MVA (see Table 4.1).

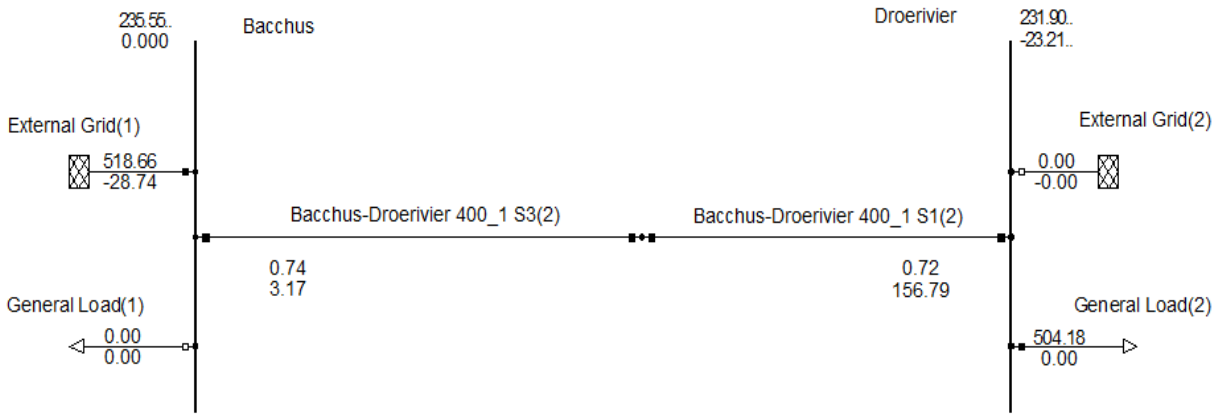

Figure 4.3: Bacchus - Droërivier reduced network diagram

Table 4.1: 500 MVA Load-flow comparisons

Voltages/ Currents	**Currents and Voltages based on 500 MVA Load**	
	Matlab	**PowerFactory**
Va	235.56 kV ∠0.00	235.559 kV ∠0.00
Vb	235.56 kV ∠-120.00	235.559 kV ∠-120.00
Vc	235.56 kV ∠120.00	235.559 kV ∠120.00
Ia	0.66627 kA ∠-21.463	0.73354 kA ∠3.1692
Ib	0.66627 kA ∠-141.46	0.73354 kA ∠-116.831
Ic	0.66627 kA ∠98.537	0.73354 kA ∠123.169

The difference in the current values in Table 4.1 can be attributed to the capacitive charging currents of the overhead conductor as modelled in the PowerFactory software. Charging currents, with no load connected, of I_A = 0.360 kA ∠89.738, I_B = 0.360 kA ∠-30.262 and I_C = 0.360 kA ∠-150.262 was obtained from simulation. Adding these currents to those obtained from the Matlab simulation results give 0.633 kA ∠10.59, 0.633 kA ∠-109.4 and 0.633 kA ∠130.6. Although a perfect match was not obtained the correlation is clear. This rather small difference was considered insignificant, since fault currents are the most dominant during system fault events. Single-phase-to-earth faults were simulated along the line as indicated at point F in Figure 4.1. Results obtained from these studies with Matlab and PowerFactory are shown in Table 4.2 to

Table 4.5. These results show voltage, current and impedance values obtained for bolted phase-to-earth and resistive faults along the line for different load conditions.

Table 4.2: Results comparison for radial network

Voltages/ Currents	**Simulated currents and voltages with no load and zero Fault resistance**							
	Matlab				**PowerFactory**			
	20%	**50%**	**80%**	**100%**	**20%**	**50%**	**80%**	**100%**
Va **Ang**	173.56 -1.529	206.13 -0.726	216.26 -0.476	219.87 -0.387	154.28 -2.507	193.12 -1.406	205.99 -0.950	210.76 -0.753
Vb **Ang**	237.15 -119.98	236.32 -119.99	236.06 -119.9	235.96 -119.9	236.94 -121.81	236.47 -121.21	236.24 -120.95	236.13 -120.80
Vc **Ang**	234.69 120.33	235.14 120.15	235.28 120.1	235.33 120.08	241.44 121.15	239.48 120.78	238.62 120.60	238.18 120.51
Ia **Ang**	3.625 -77.56	1.722 -76.76	1.129 -76.51	0.918 -76.49	2.929 -76.431	1.367 -72.478	0.8477 -69.783	0.6558 -68.316
Ib **Ang**	0.00 33.69	0.00 71.57	0.00 33.69	0.00 45	0.3796 -42.674	0.3854 -42.859	0.3832 -41.403	0.3789 -40.00
Ic **Ang**	0.00 45	0.00 71.57	0.00 45	0.00 45	0.4292 -143.65	0.4289 -142.78	0.4203 -143.42	0.4115 -144.20
In **Ang**	3.625 -77.56	1.7223 -76.76	1.1294 -76.51	0.9181 -76.49	3.4158 -79.533	1.8587 -79.066	1.3219 -79.413	1.112 -79.699

The comparison between results obtained from Matlab and PowerFactory for the different relay algorithms was done to highlight any possible impact caused by capacitive charging current on the accuracy of the calculation/measurement. Note that there are no currents present in the Matlab simulation for the B-phase and C-phase for the radial network with no load connected as reflected in Table 4.2. The different relays have different approaches towards impedance measurement. It is important to note that relay A (7SA513) uses different factors for its resistive and reactive reaches to reduce the loop impedance ($Z = V_A/I_A$) measured to an apparent impedance (Z_{ap}) value. The constants (K_R) and K_X) for relay A derived from

Eq. (3.29) and Eq. (3.30) in this example can then be calculated as shown in Eq. (4.1)and Eq. (4.2).

$$K_R = \left(1 + \frac{R_E}{R_L}\right) = 6.3641 \tag{4.1}$$

$$K_X = \left(1 + \frac{X_E}{X_L}\right) = 1.79704 \tag{4.2}$$

Relay B uses a constant derived from Eq. (3.48) for both the resistive and reactive reaches and is calculated as shown in Eq. (4.3).

$$1 + K_N = 1 + \frac{1}{3} \cdot \left(\frac{Z_0 - Z_1}{Z_1}\right) = 1.819199 - j0.317368 \tag{4.3}$$

Table 4.3 to Table 4.5 provides an interesting comparison between the generic apparent impedance algorithm and those for the different distance relays. According to the simulation results, relays using the generic equation with normal K0, and relays A (7SA513) and B (REL531), using the complex value of K0, will all have different reach capabilities for both resistive and reactive reaches. Comparing the relays in this way, using the apparent measured impedance, provides the analyst with the wrong impression however. Relay A for example uses, as discussed in Chapter 3, section 3.2.6, Eq. (3.31), a fault resistance reduction technique to determine the apparent fault impedance. A correct analysis of this relay's resistive reach can therefore only be made by subtracting the percentage line resistance to the point of fault and then multiplying the remainder with 1 + RE/RL.

Table 4.3: Results comparison using the Generic impedance equation

Fault Resistance	Apparent relay reach no-load condition							
	Generic equation (normal Ko)							
	Matlab Results				PowerFactory Results			
	20%	50%	80%	100%	20%	50%	80%	100%
0 Ω	6.121 + j24.75	15.3 + j61.88	24.48 + j99.0	30.60 + j123.75	6.52 + j25.19	17.06 + j62.19	27.66 + j99.09	34.94 + j124.93
10 Ω	11.44 + j24.75	20.63 + j61.88	29.81 + j99.0	35.93 + j123.75	11.57 + j25.24	22.06 + j62.24	32.85 + j99.07	40.44 + j124.86
20 Ω	16.77 + j24.75	25.95 + j61.88	35.13 + j99.0	41.25 + j123.75	16.62 + j25.20	27.05 + j62.22	38.05 + j99.00	45.94 + j124.70
30 Ω	22.09 + j24.75	31.27 + j61.88	40.45 + j99.0	46.57 + j123.75	21.67 + j25.09	32.05 + j62.14	43.25 + j98.86	51.43 + j124.47
40 Ω	27.41 + j24.75	36.59 + j61.88	45.78 + j99.0	51.89 + j123.75	26.71 + j24.91	37.05 + j61.98	48.45 + j98.65	56.93 + j124.17

Using the 40 Ω fault at 100% reach obtained with the Matlab simulation, which gave 15.32 Ω (Table 4.4) apparent resistive coverage, subtracting the line resistance of 9.034 Ω and multiply the answer with $1 + R_E/R_L$ will give an actual fault resistance coverage of 40 Ω. Similar calculations are possible for the generic and relay B measurements using the multiplication factor $1 + K_0$. The problem is that the exact position of fault is seldom known, which renders this approach rather useless.

Using the Matlab results, the different relay algorithms provided respective impedances of 51.89 + j123.8 Ω, 15.32 + j129.4 Ω and 30.37 + j133.1 Ω for the 40 Ω fault at 100% of line length, with the generic equation providing the largest resistive value of 51.89 Ω (see Table 4.3, Table 4.4 and

Table 4.5). Since the line resistance is only 9.03 Ω, the question that now remained is, how to compare the results from the different relay equations. Multiplying the Matlab results with the relevant relay multiplication factors (1 + abs(K_0)), (1 + R_E/R_L), (1 + X_E/X_L) and (1 + K_0) respectively for the generic relay, relay A and relay B we obtain the following resultant values in Ω per loop;

Generic relay

$$Z_{gen} = (51.89 + j123.75)\cdot\left(1 + \left|0.8192 - j0.31737\right|\right)$$
$$Z_{gen} = 97.475 + j232.46$$

Ω per loop

Relay A (7SA513)

$$Z_{relA} = 15.32\cdot K_r + j129.37\cdot K_x$$
$$Z_{relA} = 15.32\cdot 6.3641 + j129.37\cdot 1.79704$$
$$Z_{relA} = 97.498 + j232.483$$

Ω per loop

Relay B (REL531)

$$Z_{relB} = (30.37 + j133.09)\cdot\left(1 + K_0\right)$$
$$Z_{relB} = (30.37 + j133.09)\cdot\left(1 + \left(0.8192 - j0.31737\right)\right)$$
$$Z_{relB} = 97.488 + j232.479$$

Ω per loop

where

Z_{gen} = Impedance calculated with generic equation

Z_{relA} = Impedance calculated with the equation for relay A

Z_{relB} = Impedance calculated with the equation for relay B

It is obvious from the impedance results obtained for the different relays that a correct reach analysis can be made using an ohm per loop reference. Considering therefore, the possibility of misinterpreting the results of the studies listed in Table 4.3 to

Table 4.5, it would be advisable to do these types of reach comparisons in the impedance loop domain. Somewhat different results, which clearly show the impact that the capacitive components of the overhead transmission line have on the different relay algorithms, are obtained when using the results from the all-inclusive PowerFactory simulations. These results are given by $Z_{gen} = 106.9 + j233.3\ \Omega$, $Z_{relA} = 90.68 + j245.2\ \Omega$ and $Z_{relB} = 97.55 + j244.0\ \Omega$ respectively. The lines loop impedance as used in this model can be shown to be $Z_{Line(Loop)} = 57.49 + j232.5\ \Omega$.

The apparent measured impedances for relays A and B are graphically represented in Figure 4.4 and Figure 4.5, whilst the loop measured impedances are shown in Figure 4.6 and Figure 4.7 as determined from the simulated results obtained from Matlab and PowerFactory software respectively. Figure 4.4 provides a clear distinction between the apparent impedances obtained for relays A and B, with only the same apparent impedance being obtained for bolted faults. Figure 4.5 shows a deviation between the apparent impedances for the two relays for bolted faults as obtained with the PowerFactory simulations. Since no deviation was obtained for the same faults using the Matlab simulation, the deviation obtained using the PowerFactory results was attributed to the capacitive network components not modelled in the Matlab simulation.

A significantly different picture emerges when the results calculated in the loop domain is evaluated. The loop domain calculations for no-load conditions, provided in Table 4.6 and Table 4.7 and graphically illustrated in Figure 4.6 and Figure 4.7, showed an exact match for both relays associated with all relevant fault resistances using the Matlab simulation. Relatively small deviations between the relays can be observed in Figure 4.7 with results obtained from PowerFactory simulations. These deviations can only be attributed to the effect of the overhead transmission lines capacitive components on the relay algorithms.

Table 4.4: Apparent reach comparison for relay A

Fault Resistance	Apparent relay reach no-load condition							
	7SA513 equation							
	Matlab results				PowerFactory results			
	20%	50%	80%	100%	20%	50%	80%	100%
0 Ω	1.807 + j25.87	4.517 + j64.68	7.227 + j103.49	9.034 + j129.37	1.828 + j26.57	4.56 + j61.19	7.099 + j106.29	8.75 + j134.55
10 Ω	3.378 + J25.873	6.088 + j64.68	8.798 + j103.49	10.61 + j129.37	3.24 + j26.78	5.89 + j66.57	8.42 + j106.75	10.12 + j135.05
20 Ω	4.95 + j25.87	7.66 + j64.68	10.37 + j103.49	12.18 + j129.37	4.652 + j26.97	7.216 + j66.942	9.751 + j107.194	11.49 + j135.54
30 Ω	6.52 + j25.87	9.23 + j64.68	11.94 + j103.49	13.75 + j129.37	6.065 + j27.139	8.55 + j67.29	11.08 + j107.63	12.87 + j136.0
40 Ω	8.09 + j25.87	10.80 + j64.68	13.51 + j103.49	15.32 + j129.37	7.48 + j27.28	9.88 + j67.61	12.412 + j108.05	14.25 + j136.45

Table 4.5: Apparent reach comparison for relay B

Fault Resistance	Apparent relay reach no-load condition							
	REL531 equation							
	Matlab results				PowerFactory results			
	20%	50%	80%	100%	20%	50%	80%	100%
0 Ω	1.807 + j25.87	4.517 + j64.68	7.227 + j103.49	9.034 + j129.36	1.758 + j26.554	4.383 + j66.156	6.118 + j106.08	6.73 + j134.11
10 Ω	7.141 + j26.804	9.85 + j65.613	12.56 + j104.42	14.37 + j130.3	6.833 + j27.593	9.419 + j67.33	11.38 + j107.35	12.32 + j135.51
20 Ω	12.48 + j27.73	15.19 + j66.54	17.89 + j105.35	19.70 + j131.23	11.94 + j28.562	14.48 + j68.449	16.68 + j108.594	17.95 + j136.84
30 Ω	17.81 + j28.67	20.52 + j67.48	23.23 + j106.28	25.04 + j132.16	17.07 + j29.455	19.58 + j69.495	22.01 + j109.765	23.62 + j138.08
40 Ω	23.15 + j29.596	25.86 + j68.41	28.57 + j107.21	30.37 + j133.09	22.23 + j30.27	24.71 + j70.47	27.37 + j110.86	29.33 + j139.26

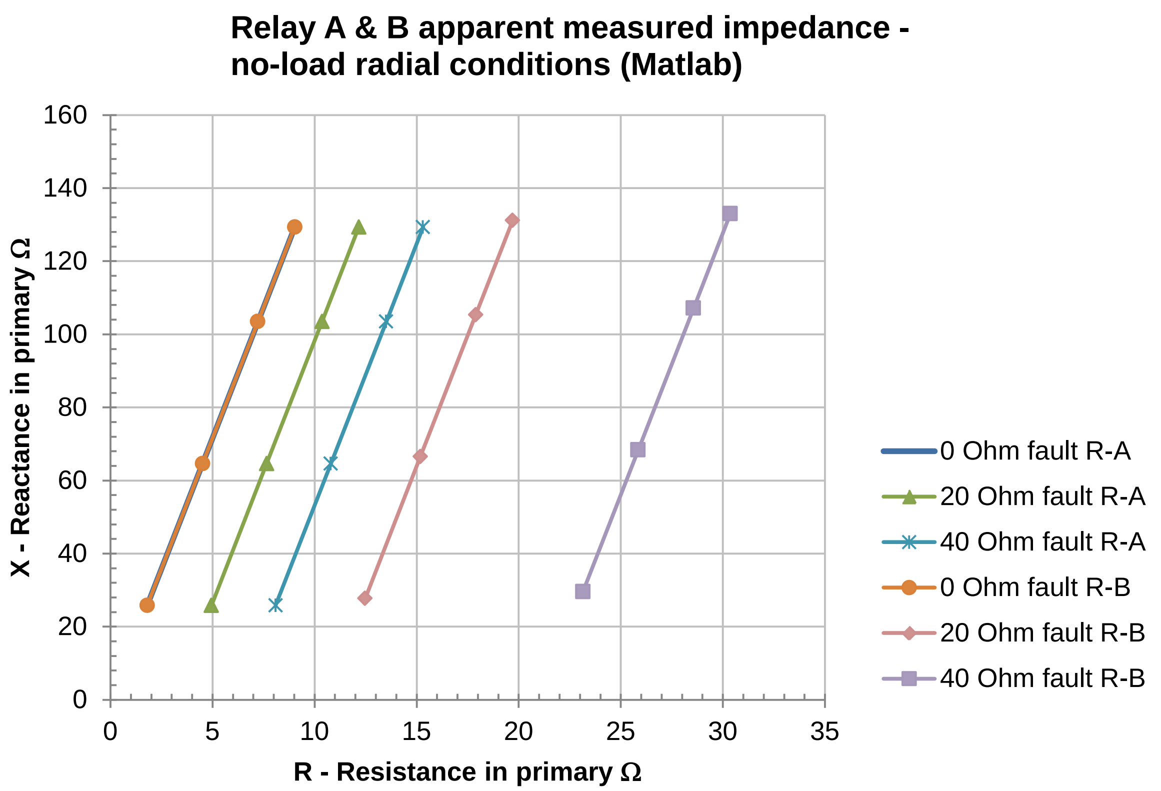

Figure 4.4: Apparent measured impedance at different fault locations for relays A and B (Matlab)

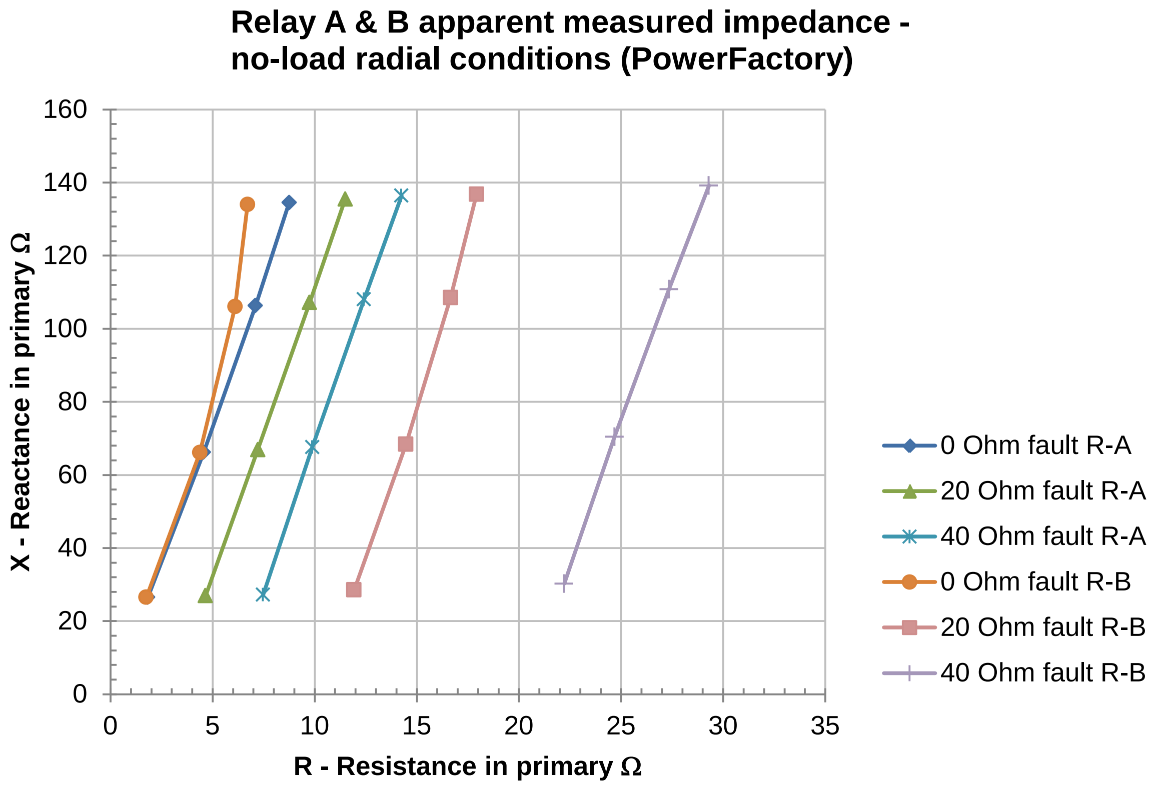

Figure 4.5: Apparent measured impedance at different fault locations for relays A and B (PowerFactory)

Table 4.6: Loop impedance measurements for relay A

Fault Resistance	**Loop relay reach no-load condition**							
	7SA513 equation							
	Matlab results				**PowerFactory results**			
	20%	**50%**	**80%**	**100%**	**20%**	**50%**	**80%**	**100%**
0 Ω	11.49 + j46.495	28.75 + j116.24	45.99 + j185.98	57.49 + j232.48	11.64 + j47.749	29.02 + j118.956	45.18 + j191.01	55.71 + j241.792
10 Ω	21.49 + j46.495	38.75 + j116.24	55.99 + j185.98	67.49 + j232.48	20.62 + j48.125	37.48 + j119.636	53.61 + j191.808	64.44 + j242.699
20 Ω	31.49 + j46.495	48.75 + j116.24	65.99 + j185.98	77.49 + j232.48	29.61 + j48.46	45.93 + j120.297	62.06 + j192.632	73.18 + j243.57
30 Ω	41.49 + j46.495	58.75 + j116.24	75.99 + j185.98	87.49 + j232.48	38.59 + j48.77	54.39 + j120.916	70.52 + j193.422	81.92 + j244.405
40 Ω	51.49 + j46.495	68.75 + j116.24	85.99 + j185.98	97.49 + j232.48	47.59 + j49.031	62.87 + j121.50	78.99 + j194.178	90.68 + j245.205

Table 4.7: Loop impedance measurements relay B

Fault Resistance	Loop relay reach no-load condition							
	REL531 equation							
	Matlab results				PowerFactory results			
	20%	50%	80%	100%	20%	50%	80%	100%
0 Ω	11.49 + j46.495	28.75 + j116.24	45.99 + j185.98	57.49 + j232.47	11.62 + j47.732	28.95 + j118.911	44.76 + j190.95	54.76 + j241.733
10 Ω	21.49 + j46.495	38.75 + j116.24	55.99 + j185.98	67.49 + j232.47	21.18 + j48.012	38.48 + j119.456	54.73 + j191.606	65.37 + j242.504
20 Ω	31.49 + j46.495	48.75 + j116.24	65.99 + j185.98	77.49 + j232.47	30.76 + j48.155	48.04 + j119.881	64.75 + j192.18	76.03 + j243.127
30 Ω	41.49 + j46.495	58.75 + j116.24	75.99 + j185.98	87.49 + j232.47	40.38 + j48.152	57.64 + j120.166	74.82 + j192.619	86.73 + j243.60
40 Ω	51.49 + j46.495	68.75 + j116.24	85.99 + j185.98	97.49 + j232.47	50.03 + j48.0	67.27 + j120.317	84.92 + j192.918	97.48 + j243.922

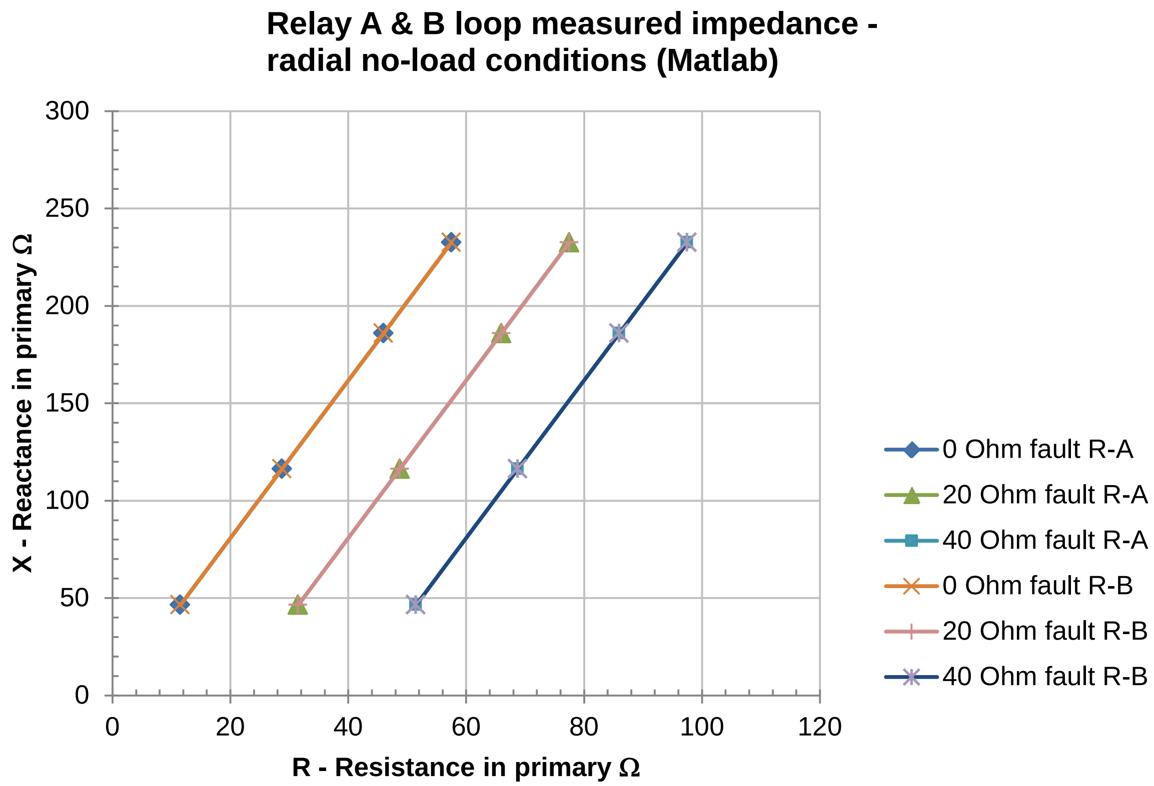

Figure 4.6: Loop measured impedance at different fault locations for relays A and B (Matlab)

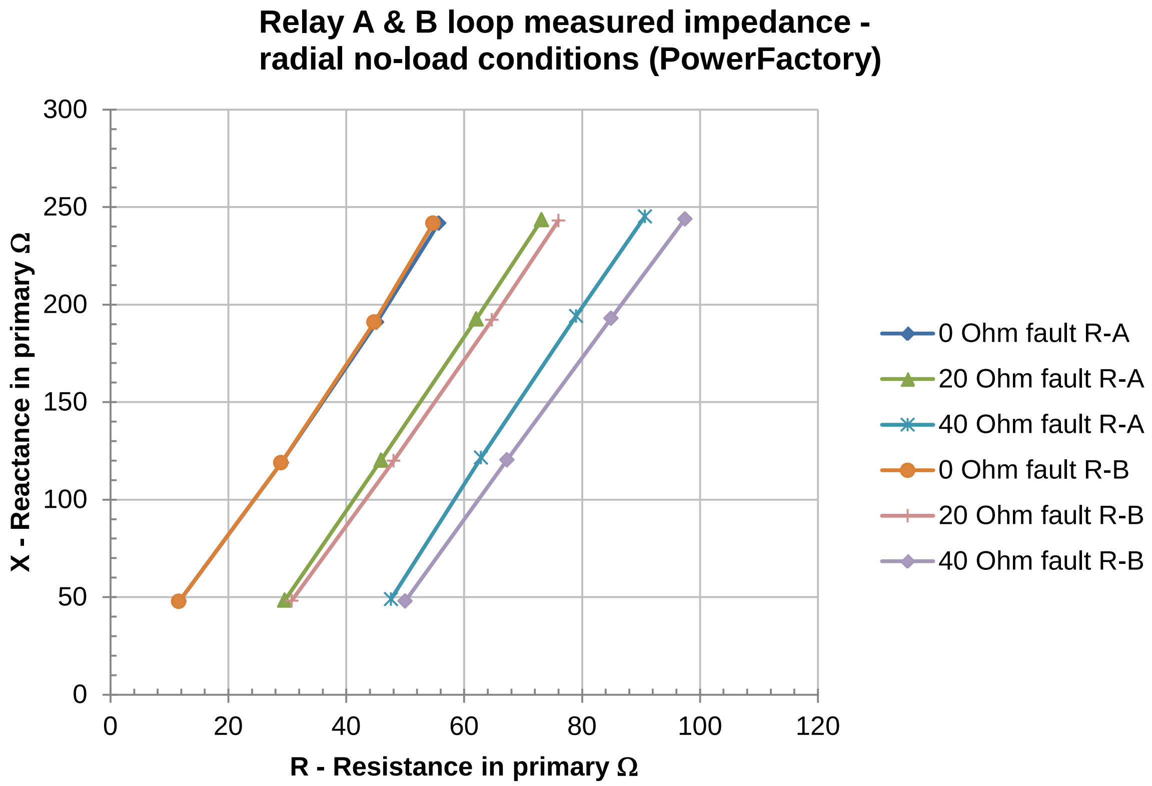

Figure 4.7: Loop measured impedance at different fault locations for relays A and B (PowerFactory)

Table 4.8, Table 4.9 and Table 4.10 provide a comparison between no-load (nL) versus load (L) export conditions on the measurement of a generic algorithm based relay, relay A and relay B for faults at 100% of line length. Figure 4.8 and Figure 4.9 gives a selective graphical representation of the PowerFactory results of

Table 4.9 and Table 4.10 illustrating an initial increase in the apparent impedance for close-up faults. Faults further down the line result in a reduction in the apparent impedance measured by relays A and B under load conditions.

A comparison is also made between the results obtained with the use of the Matlab routines and PowerFactory. The generic algorithm results shown in Table 4.8 are of academic value only, since it was never developed to reflect resistive and reactive results separately, but rather only an impedance value in terms of magnitude and angle. The apparent relay reach for relays using the generic algorithm is then best evaluated in this way.

No further attention will be given to the generic algorithm used with the K_o-factor with magnitude only in this dissertation. Relay B uses the generic algorithm with a complex K_o-factor, thus giving a complex answer that provides an apparent reach in terms of resistance and reactance.

Table 4.8: Comparison of no-load versus 500 MVA load export for end-of-line fault on generic relays

Fault Resistance	Apparent relay reach 500 MVA load export condition			
	Generic equation – K_o (magnitude only)			
	Matlab results		PowerFactory results	
	No-load	500 MVA load	No-load	500 MVA load
0 Ω	30.604 + j123.75	26.723 + j120.08	34.916 + j124.874	28.157 + j121.719
10 Ω	35.927 + j123.75	31.085 + j119.22	40.412 + j124.799	32.552 + j120.825
20 Ω	41.251 + j123.75	35.328 + j118.41	45.909 + j124.648	36.825 + j119.927
30 Ω	46.574 + j123.75	39.458 + j117.65	51.404 + j124.418	40.979 + j119.125
40 Ω	51.897 + j123.75	43.479 + 116.94	56.896 + j124.111	45.021 + j118.121

Table 4.9: Comparison of no-load versus 500 MVA load export for end-of-line fault on relay A (7SA513) are tabled below

Fault Resistance	Apparent relay reach			
	7sa513 equation			
	Matlab results		PowerFactory results	
	No-load	500 MVA load	No-load	500 MVA load
0 Ω	9.034 + j129.37	9.034 + j129.37	8.75 + j134.55	8.55 + j135.368
10 Ω	10.61 + j129.37	10.53 + j129.01	10.12 + j135.05	9.88 + j135.512
20 Ω	12.18 + j129.37	12.02 + j128.66	11.49 + j135.54	11.22 + j135.63
30 Ω	13.75 + j129.37	13.49 + j128.33	12.87 + j136.0	12.542 + j135.734
40 Ω	15.32 + j129.37	14.951 + j128.02	14.25 + j136.45	13.85 + j135.82

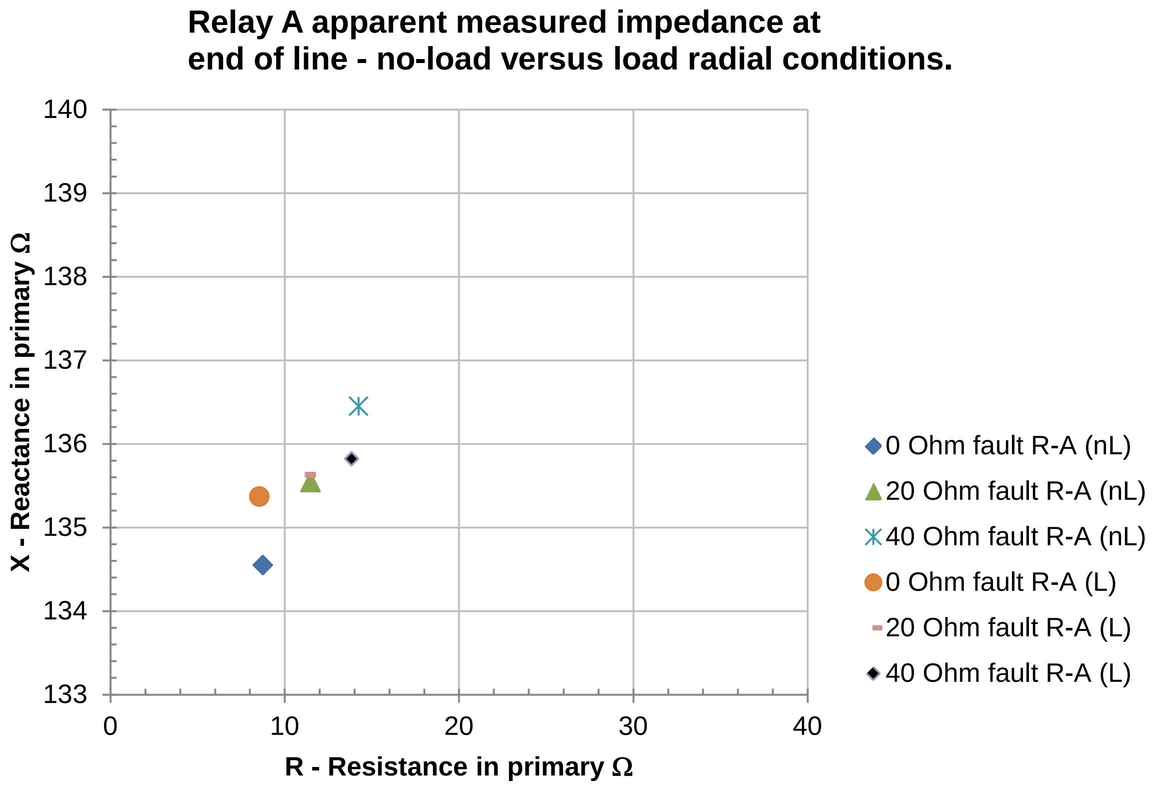

Figure 4.8: Relay A, no-load versus load measurement for radial condition

Table 4.10: Comparison of no-load versus 500 MVA load export for end-of-line fault on relay B (REL531) are tabled below

Fault Resistance	Apparent relay reach			
	REL531 equation			
	Matlab results		PowerFactory results	
	No-load	500 MVA Load	No-load	500 MVA Load
0 Ω	9.034 + j129.36	9.034 + j129.37	6.73 + j134.11	5.87 + j135.56
10 Ω	14.37 + j130.3	13.971 + j128.98	12.32 + j135.51	11.13 + j135.41
20 Ω	19.70 + j131.23	18.759 + j128.61	17.95 + j136.84	16.24 + j135.21
30 Ω	25.04 + j132.16	23.404 + j128.27	23.62 + j138.09	21.22 + j134.95
40 Ω	30.37 + j133.09	27.913 + j127.95	29.33 + j139.26	26.06 + j134.64

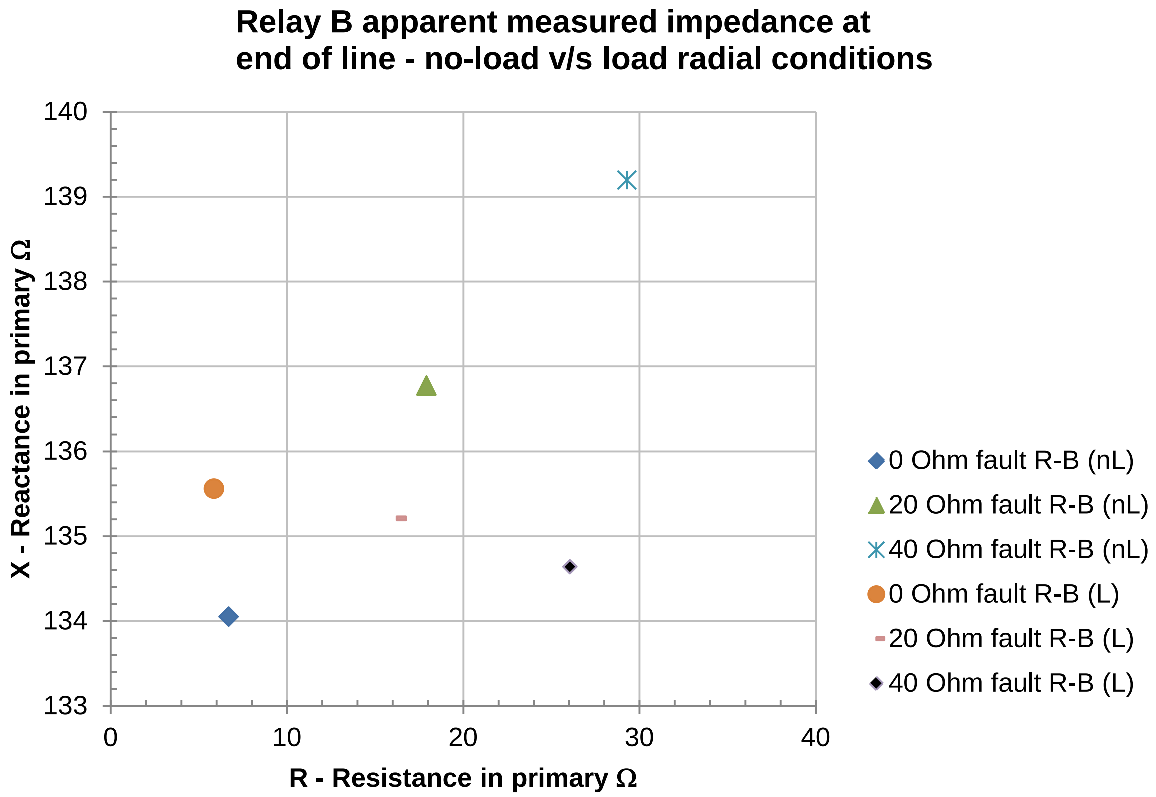

Figure 4.9: Relay B, no-load versus load measurement for radial condition

The impedance results for relays A and B shown in Figure 4.8 and Figure 4.9 indicates a simular tendency towards increased reactive measurement for increasing resistive end-of-line faults for radial no-load system conditions. During load conditions however relay A and B showed an increase in reactive measurement for a bolted fault with reduction in the reactive measurements for increasing resistive faults. When compared to the actual line reactance of 129.4 Ω, both relays has a tendency to underreach for the line-end fault under the conditions simulated. The impact of which is much greater for relay B than for relay A.

Figure 4.10 provides a clear comparison of apparent impedances measured by the relays. This comparison provides an interesting relationship and highlights a phenomenon of an increasing inductive reach for relay A versus a decreasing inductive reach for relay B for the same faults as measured in the apparent impedance domain. The same phenomena can be seen when evaluating the measured impedances in the loop domain as shown in Figure 4.11.

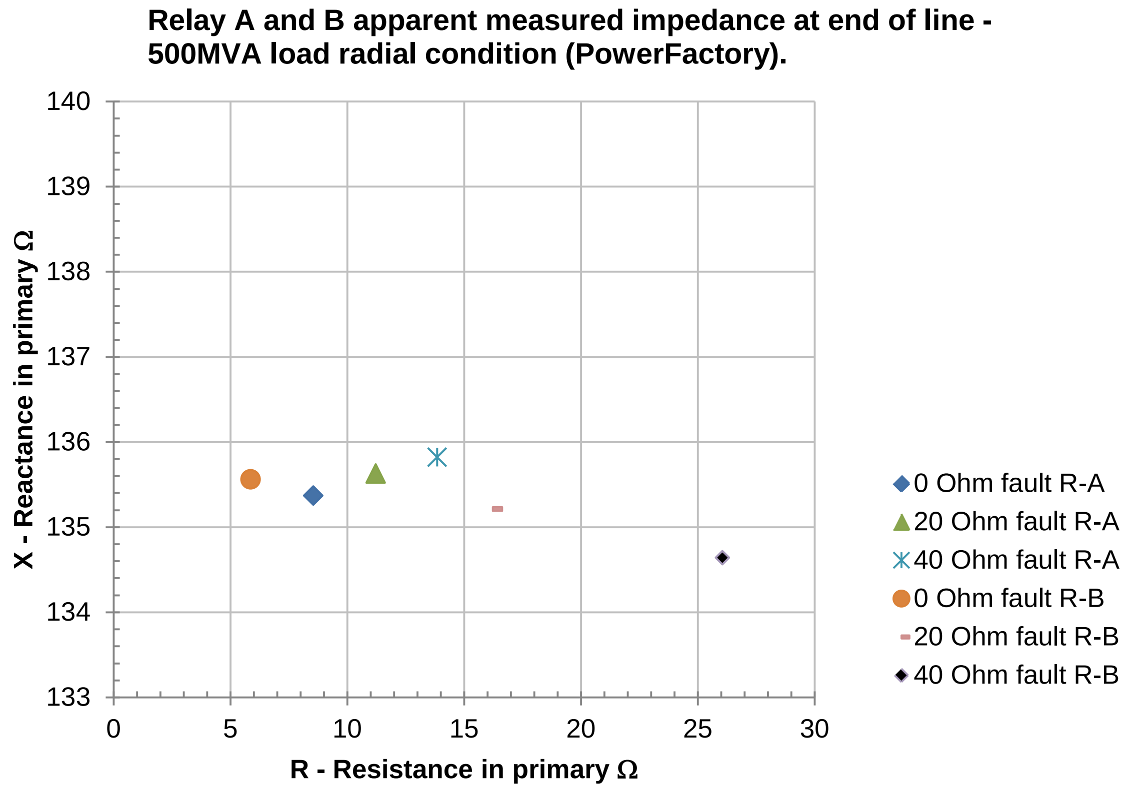

Figure 4.10: Apparent measured impedance comparison for relay A and B

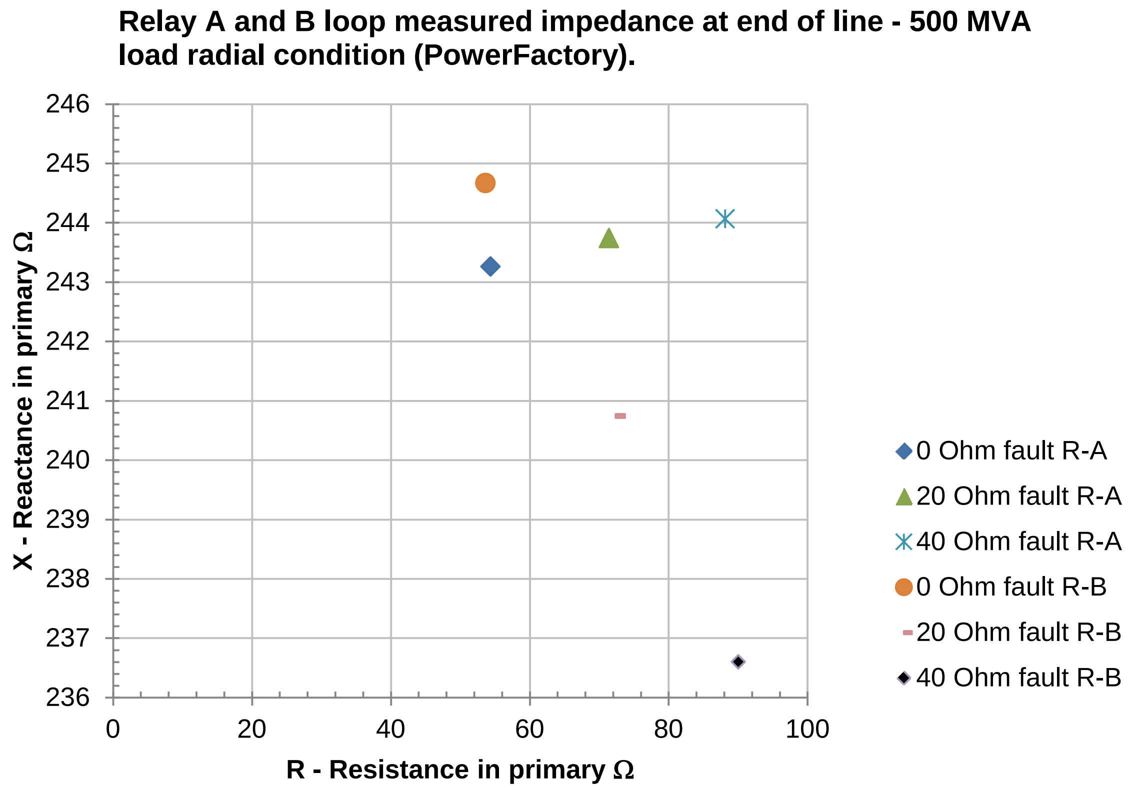

Figure 4.11: Relays A and B loop impedance measurements for end line faults

Whilst this section has shown that the Matlab simulation, which was developed from basic principles ignoring all capacitive quantities, can be used to determine the effect of fault resistance and load on a distance protection relay, it has also shown that the impact of the capacitive quantities for long lines cannot be ignored. The relays have also been shown to have somewhat different responses under radial load conditions.

The following section on complex networks will focus on the impact of a remote in-feed/source on distance relay reach measurements. Differences between the results obtained from Matlab and PowerFactory simulations as well as apparent versus loop impedances will be shown.

4.3 Complex network

In order to do impedance calculations at any given point in a complex multi-source network, it is paramount to reduce such a network to a simplified network with a single voltage source at the fault position, unless bus impedance matrix solution methods are used. This replacement voltage source, as already mentioned under section 4.1, is the equivalent of the voltage that existed at the fault position in steady state just prior to the fault. An example network with a single-phase-to-earth fault at point F is shown in Figure 4.12. Currents in all branches of the network have been labelled in correlation with the branch impedances.

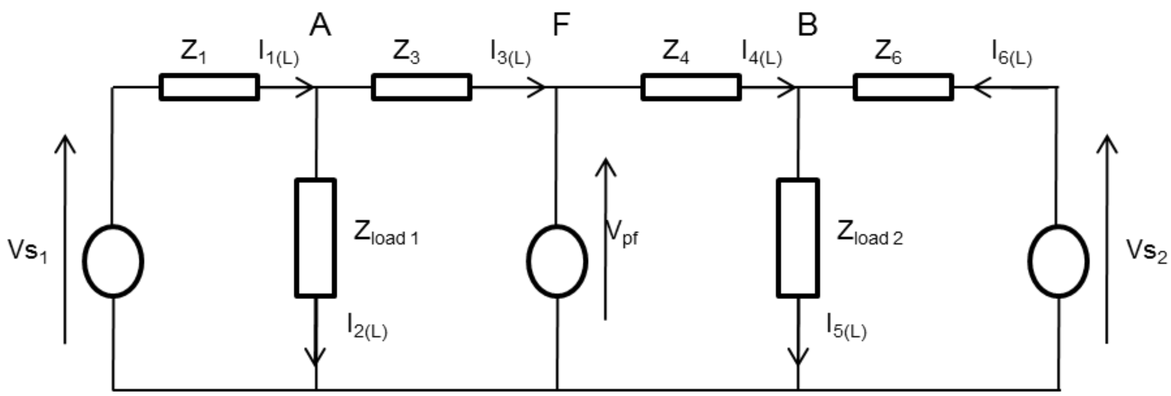

Figure 4.12: Multi-source network with fault at point F

This network can now be represented in its positive, negative, and zero sequence networks as shown in Figure 4.13. Note that the load connection has been left open in the zero sequence circuit to illustrate an ungrounded star or delta connected load. This connection would be closed for an earthed-star connected load. Further reduction simplification is possible, but was not done for illustration purposes.

The sequence networks were used to develop the Matlab routines that were also referred to in the section covering radial networks. The sequence components have been labelled with the appropriate suffixes to distinguish between positive (1), negative (2) and zero sequence (0) components. The impact of the remote end in-feed will be evaluated during simulated single-phase-to-earth fault conditions on the overhead transmission line between busbar A and B as depicted in Figure 4.12. It is a known fact that remote in-feed causes normal impedance relays to underreach due to their limited algorithm abilities.

Numerical techniques have however introduced several benefits and enhancements to counteract this phenomenon. An attempt is therefore made to sensitize the reader to the level of improvement that has been achieved in counteracting the influence of load.

Figure 4.14 and Figure 4.15 show the load-flow results obtained from PowerFactory and Matlab for a multi-source system with a 500 MVA load connected at the Droërivier busbar. Results comparison for single-phase-to-earth faults at 100% of line length, for this condition, are shown in Table 4.11 and Table 4.12. These faults have been simulated along the entire line length at 10% intervals as was done in the previous section, to determine the impact of remote end in-feed. The simulation results are graphically represented in Figure 4.16, Figure 4.17, Figure 4.18 and Figure 4.19, whilst an impedance comparison between the relays is shown in Figure 4.20 and Figure 4.21. The comparative graphs of Figure 4.20 and Figure 4.21 highlight the differences in the apparent impedances measured for the two relays.

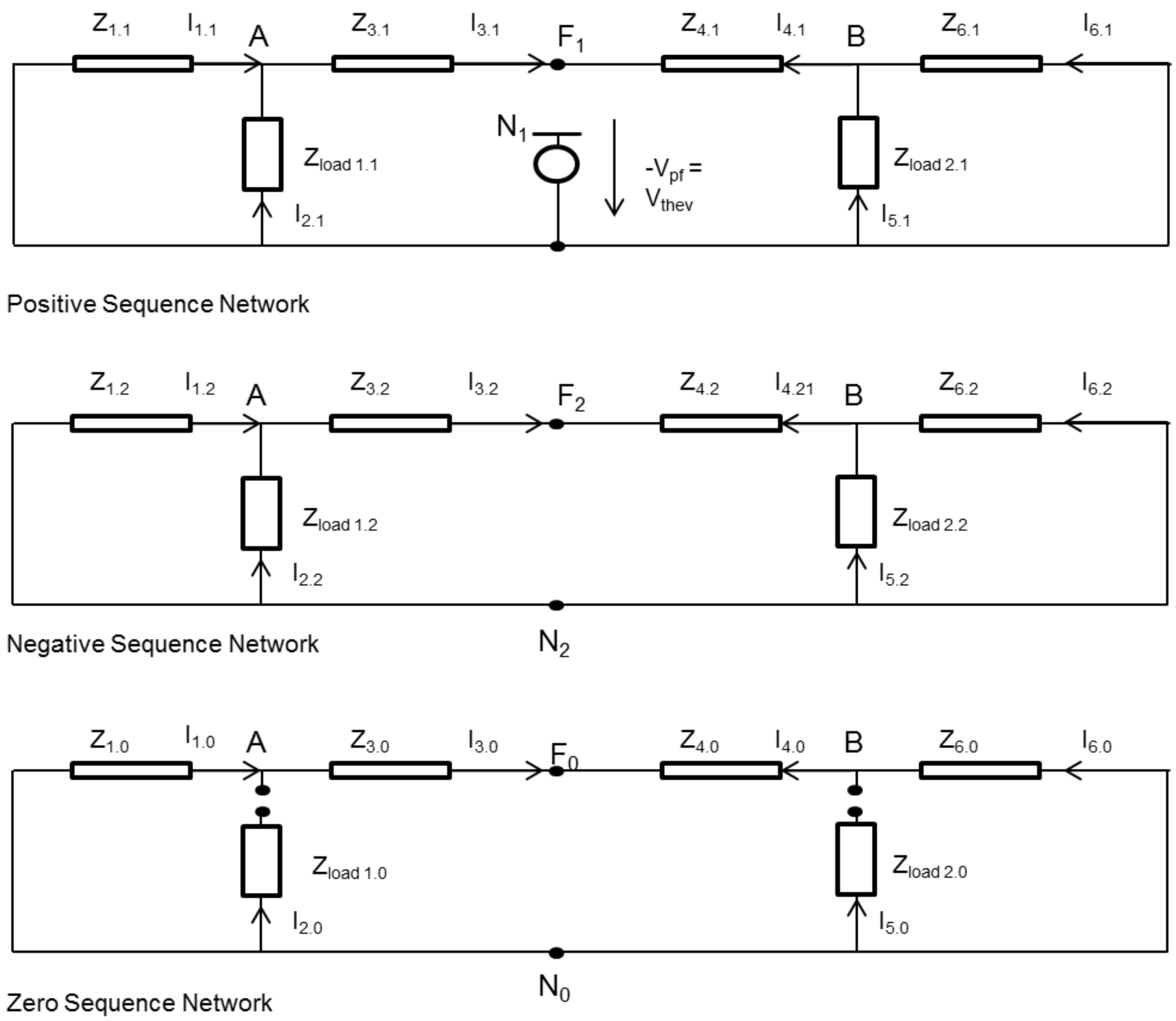

Figure 4.13: Multi-source, multi-load sequence network

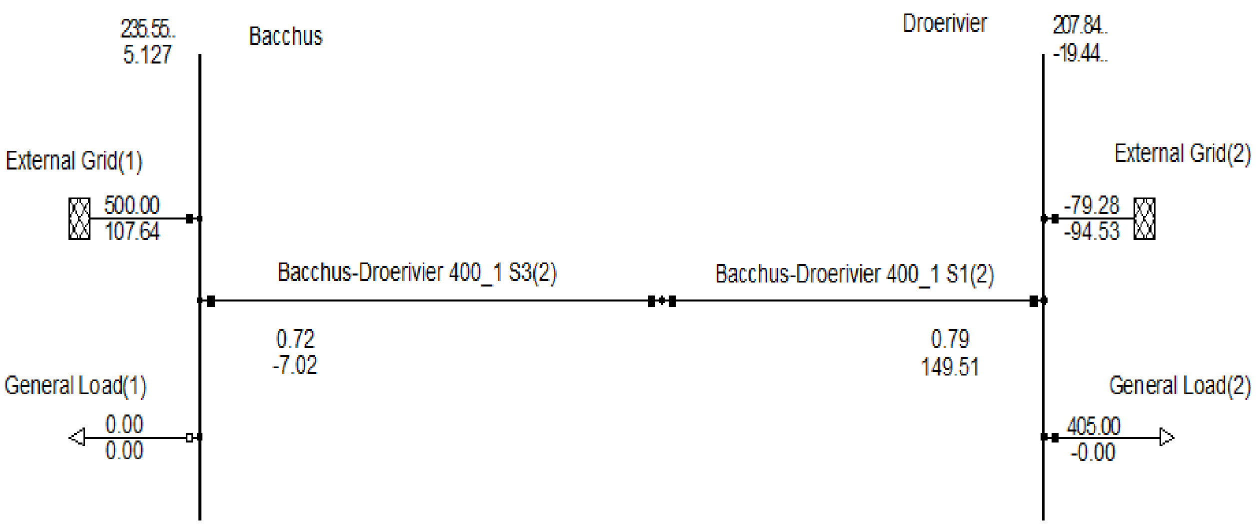

Figure 4.14: PowerFactory load-flow results from multi-source system

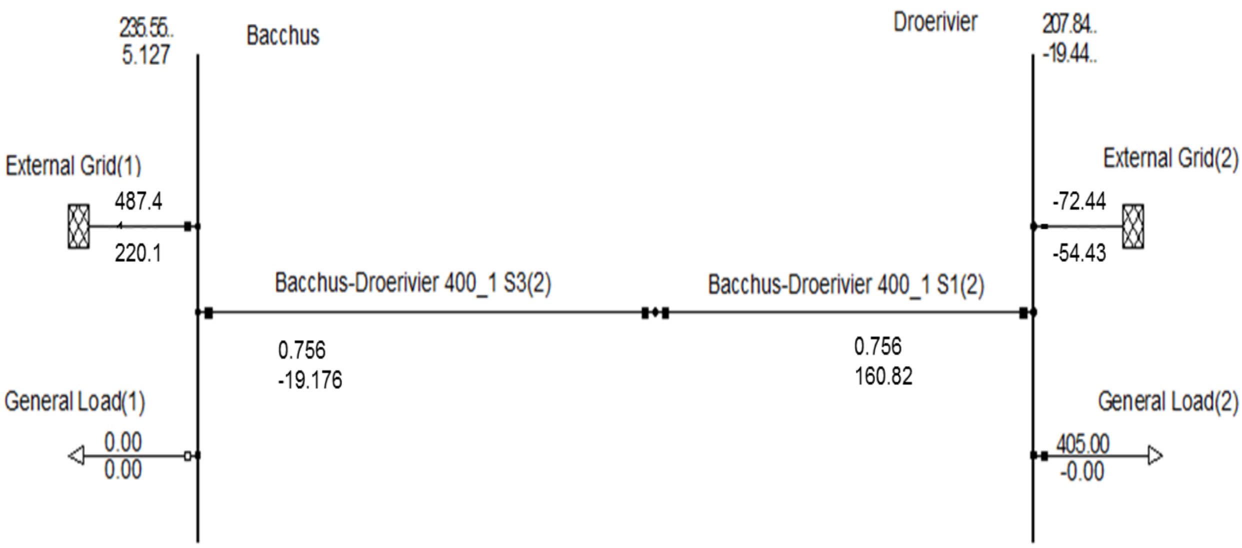

Figure 4.15: Matlab load-flow results from multi-source system

Table 4.11: Remote end in-feed influence on apparent relay A reach

Fault Resistance	Apparent relay reach – 500 MVA load export condition							
	7SA513 equation							
	Matlab results				PowerFactory results			
	20%	50%	80%	100%	20%	50%	80%	100%
0 Ω	1.807 + j25.87	4.52 + j64.68	7.23 + j103.49	9.03 + j129.37	1.81 + j26.49	4.49 + j66.15	6.95 + j106.79	8.8 + j136.82
10 Ω	3.78 + j25.74	7.49 + j64.094	13.55 + j101.2	38.05 + j111.78	3.76 + j26.41	7.37 + j65.72	12.9 + j104.87	28.88 + j123.92
20 Ω	5.74 + j25.636	10.42 + j63.596	19.63 + j99.35	62.44 + j103.19	5.69 + j26.33	10.21 + j65.32	18.64 + j103.16	46.69 + j114.78
30 Ω	7.67 + j25.57	13.29 + j63.18	25.49 + j97.868	82.8 + j98.977	7.59 + j26.28	12.99 + j64.96	24.17 + j101.61	62.57 + j108.02
40 Ω	9.57 + j25.54	16.11 + j62.83	31.12 + j96.68	99.9 + j97.06	9.48 + j26.23	15.73 + j64.62	29.5 + j100.22	76.75 + j102.83

Table 4.12: Remote end in-feed influence on apparent relay B reach

Fault Resistance	Apparent relay reach – 500 MVA load export condition							
	REL513 equation							
	Matlab results				PowerFactory results			
	20%	50%	80%	100%	20%	50%	80%	100%
0 Ω	1.807 + j25.87	4.52 + j64.68	7.23 + j103.49	9.034 + j129.37	1.73 + j26.58	4.25 + j66.38	6.0 + j107.27	7.78 + j137.32
10 Ω	8.39 + j26.41	14.04 + j64.26	25.8 + j100.08	67.98 + j111.88	8.43 + j27.06	13.96 + j65.9	24.76 + j103.63	56.09 + j120.09
20 Ω	14.69 + j26.997	22.97 + j64.02	42.19 + j97.68	107.3 + j105.64	14.85 + j27.54	23.09 + j65.48	41.41 + j100.54	91.59 + j109.06
30 Ω	20.74 + j27.627	31.37 + j63.939	68.66 + j96.03	134.9 + j103.71	21.01 + j28.00	31.7 + j65.12	56.27 + j97.89	118.7 + j101.52
40 Ω	26.53 + j28.295	39.27 + j63.98	69.7 + j94.93	155.3 + j103.56	26.93 + j28.47	39.82 + j64.79	69.63 + j95.6	140.1 + j96.11

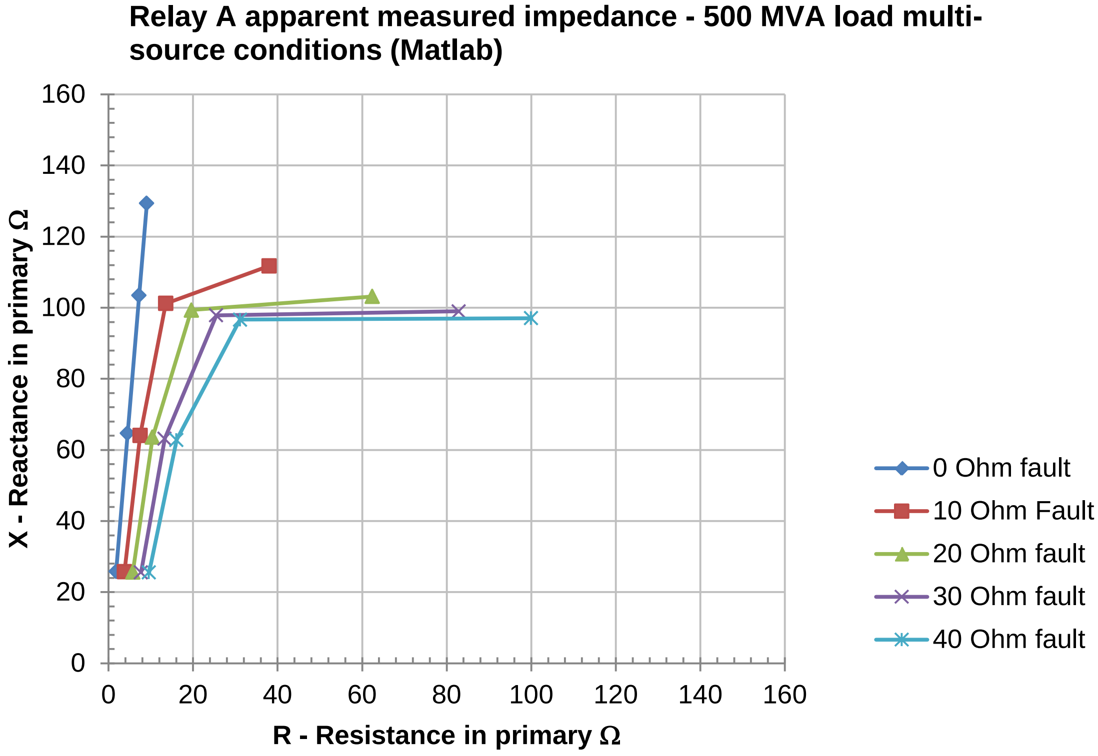

Figure 4.16: Apparent measured impedance at different fault locations of relay A under in-feed conditions

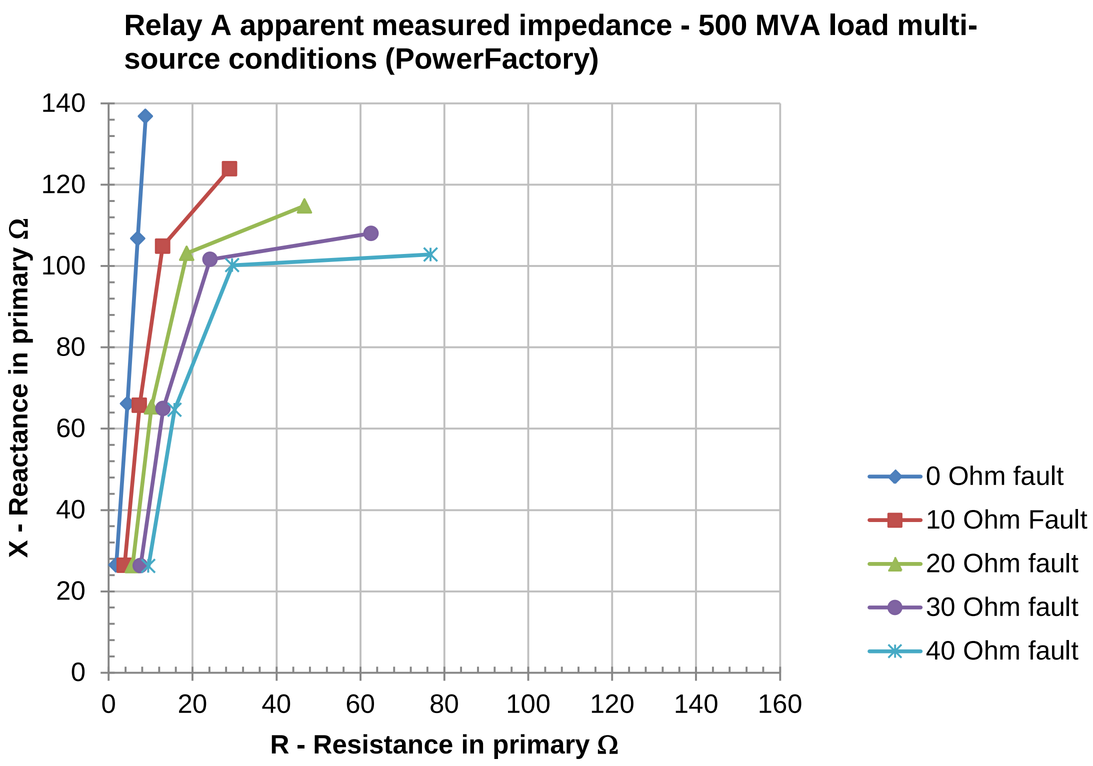

Figure 4.17: Apparent measured impedance at different fault locations of relay A under in-feed conditions

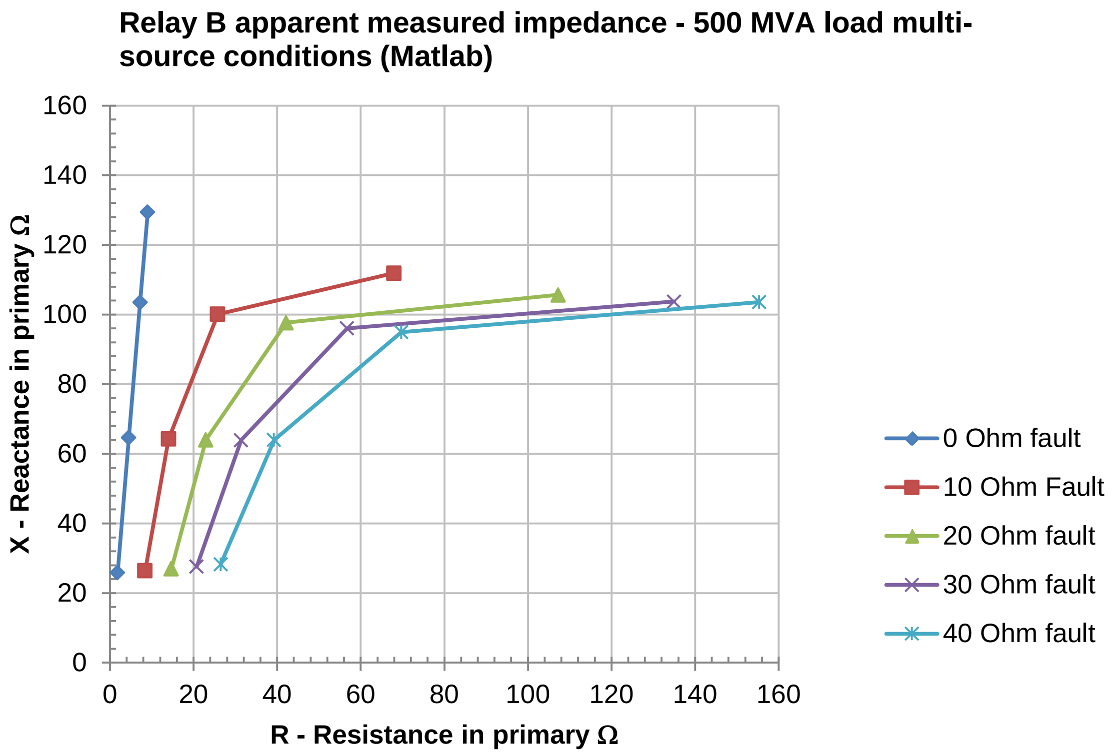

Figure 4.18: Apparent measured impedance at different fault locations of relay B under in-feed conditions

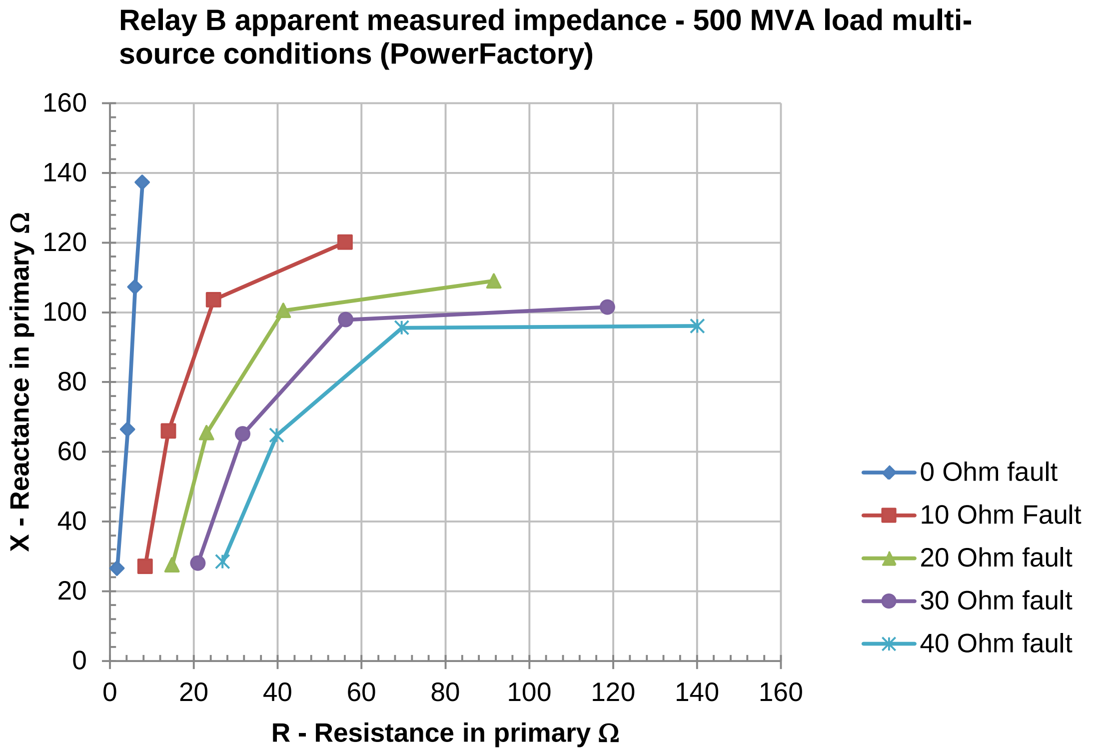

Figure 4.19: Apparent measured impedance at different fault locations of relay B under in-feed conditions

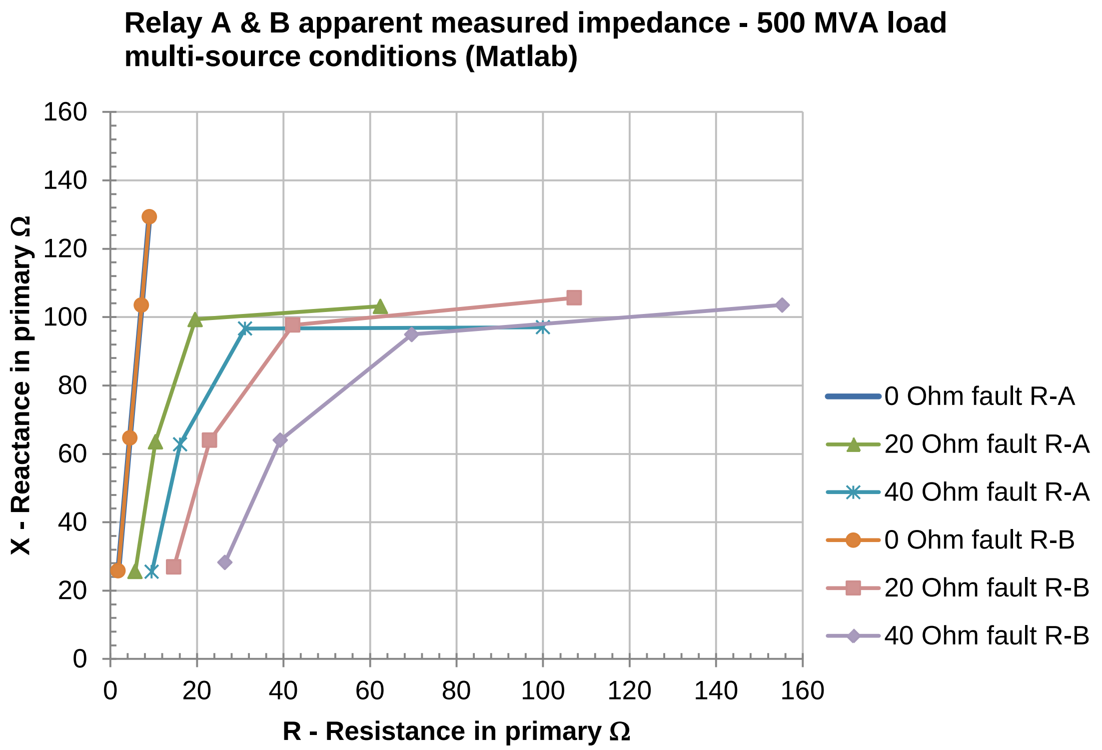

Figure 4.20: Apparent impedance comparison at different fault locations for relay A and B under in-feed conditions

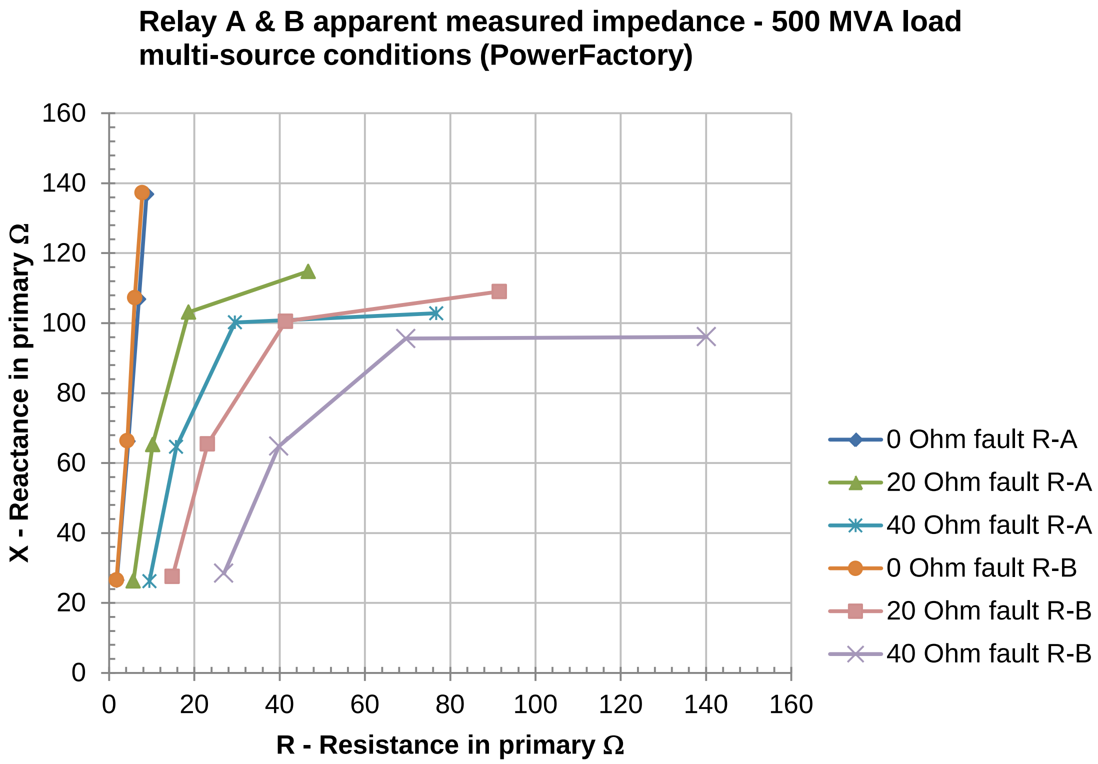

Figure 4.21: Apparent impedance comparison at different fault locations for relay A and B under in-feed conditions

The loop measurement results for these relays were then determined as previously discussed, provided in Table 4.13 and Table 4.14 and graphically represented in Figure 4.23 and Figure 4.24 respectively. Comparative graphical representation in the loop domain is also given in Figure 4.26 and Figure 4.27. Table 4.15 and Table 4.16 provide a comparison between calculated versus measured loop impedances using the respective relay algorithms and loop correction factors. Loop impedance to the point of fault inclusive of fault resistance is determined from the equation $Z_{Loop} = p(Z_1 + Z_N) + R_F$, derived from Eq. (3.41) where p is in per unit of distance to fault.

Table 4.13: Remote in-feed impact on loop impedance measurement for relay A.

Fault Resistance	Loop relay reach – 500 MVA load export condition							
	7SA513 equation							
	Matlab results				PowerFactory results			
	20%	50%	80%	100%	20%	50%	80%	100%
0 Ω	11.49 + j46.49	28.75 + j116.24	45.99 + j185.98	57.49 + j232.48	11.59 + j47.80	28.79 + j119.33	44.74 + j192.58	56.55 + j246.48
10 Ω	24.41 + j46.25	47.68 + j115.18	86.21 + j181.85	242.2 + j200.88	24.07 + j47.64	47.25 + j118.53	82.74 + j189.06	184.7 + j223.10
20 Ω	36.5 + j46.07	66.28 + j114.29	124.9 + j178.54	397.4 + j185.44	36.4 + j47.50	65.37 + j117.79	119.37 + j185.92	298.5 + j206.57
30 Ω	48.79 + j45.95	84.55 + j113.53	162.2 + j175.87	527.2 + j177.87	48.59 + j47.39	83.18 + j117.12	154.7 + j183.09	399.7 + j194.33
40 Ω	60.93 + j45.89	102.5 + j112.91	198.0 + j173.7	636.4 + j174.42	60.63 + j47.31	100.7 + j116.49	188.77 + j180.54	490.1 + j184.96

Table 4.14: Remote in-feed impact on loop impedance measurement for relay B

Fault Resistance	Loop relay reach – 500 MVA load export condition							
	REL531 equation							
	Matlab results				PowerFactory results			
	20%	50%	80%	100%	20%	50%	80%	100%
0 Ω	11.49 + j46.495	28.75 + j116.24	45.99 + j185.98	57.49 + j232.47	11.58 + j47.806	28.79 + j119.42	44.96 + j193.24	57.73 + j247.35
10 Ω	23.65 + j45.381	45.93 + j112.45	78.7 + j173.87	159.2 + j181.95	23.92 + j46.55	46.32 + j115.46	77.93 + j180.66	140.2 + j200.67
20 Ω	35.3 + j44.45	62.11 + j109.18	107.7 + j164.31	228.7 + j158.14	35.75 + j45.38	62.8 + j111.79	107.24 + j169.75	201.2 + j169.33
30 Ω	46.49 + j43.678	77.36 + 106.36	133.7 + j156.69	278.4 + j145.84	47.11 + j44.28	78.34 + j108.39	133.4 + j160.22	248.2 + j147.0
40 Ω	57.24 + j43.054	91.75 + j103.93	156.9 + j150.57	315.5 + j139.1	58.02 + j43.251	93.01 + j105.24	157.0 + j151.826	285.3 + j130.38

Table 4.15: Calculated versus measured relay loop reaches for relay A

Fault Resistance	Loop relay reach comparisson							
	7SA513 equation							
	Calculated loop impedance				Measured loop impedance			
	20%	50%	80%	100%	20%	50%	80%	100%
0 Ω	11.49 + j46.495	28.75 + j116.24	45.99 + j185.98	57.49 + j232.48	11.59 + j47.80	28.79 + j119.33	44.74 + j192.58	56.55 + j246.48
10 Ω	21.49 + j46.495	38.75 + j116.24	55.99 + j185.98	67.49 + j232.48	24.07 + j47.64	47.25 + j118.53	82.74 + j189.06	184.7 + j223.10
20 Ω	31.49 + j46.49	48.75 + j116.24	65.99 + j185.98	77.49 + j232.48	36.4 + j47.50	65.37 + j117.79	119.37 + j185.92	298.5 + j206.57
30 Ω	41.49 + j46.495	58.75 + j116.24	75.99 + j185.98	87.49 + j232.48	48.59 + j47.39	83.18 + j117.12	154.7 + j183.09	399.7 + j194.33
40 Ω	51.49 + j46.495	68.75 + j116.24	85.99 + j185.98	97.49 + j232.48	60.63 + j47.31	100.7 + j116.49	188.77 + j180.54	490.1 + j184.96

Table 4.16: Calculated versus measured relay loop reaches for relay B

Fault Resistance	Loop relay reach comparisson							
	REL531 equation							
	Calculated loop impedance				Measured loop impedance			
	20%	50%	80%	100%	20%	50%	80%	100%
0 Ω	11.49 + j46.495	28.75 + j116.24	45.99 + j185.98	57.49 + j232.48	11.58 + j47.806	28.79 + j119.42	44.96 + j193.24	57.73 + j247.35
10 Ω	21.49 + j46.495	38.75 + j116.24	55.99 + j185.98	67.49 + j232.48	23.92 + j46.55	46.32 + j115.46	77.93 + j180.66	140.2 + j200.67
20 Ω	31.49 + j46.49	48.75 + j116.24	65.99 + j185.98	77.49 + j232.48	35.75 + j45.38	62.8 + j111.79	107.24 + j169.75	201.2 + j169.33
30 Ω	41.49 + j46.495	58.75 + j116.24	75.99 + j185.98	87.49 + j232.48	47.11 + j44.28	78.34 + j108.39	133.4 + j160.22	248.2 + j147.0
40 Ω	51.49 + j46.495	68.75 + j116.24	85.99 + j185.98	97.49 + j232.48	58.02 + j43.251	93.01 + j105.24	157.0 + j151.826	285.3 + j130.38

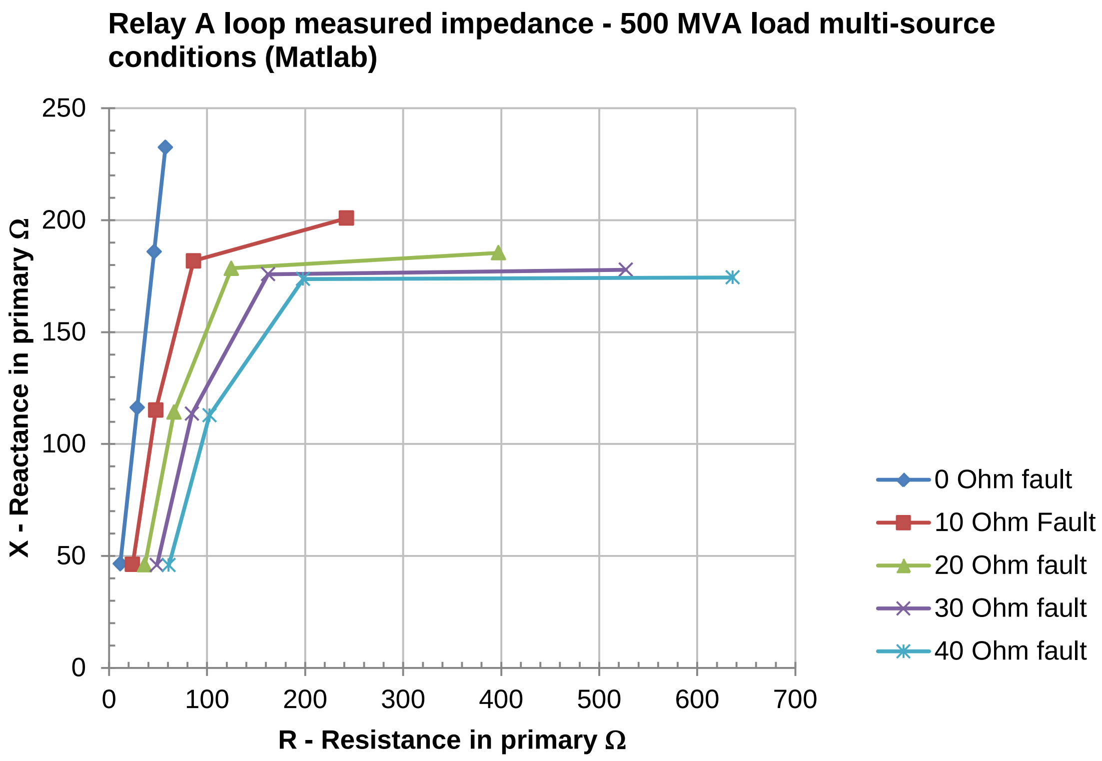

Figure 4.22: Loop impedance measurement at different fault locations for relay A under in-feed conditions

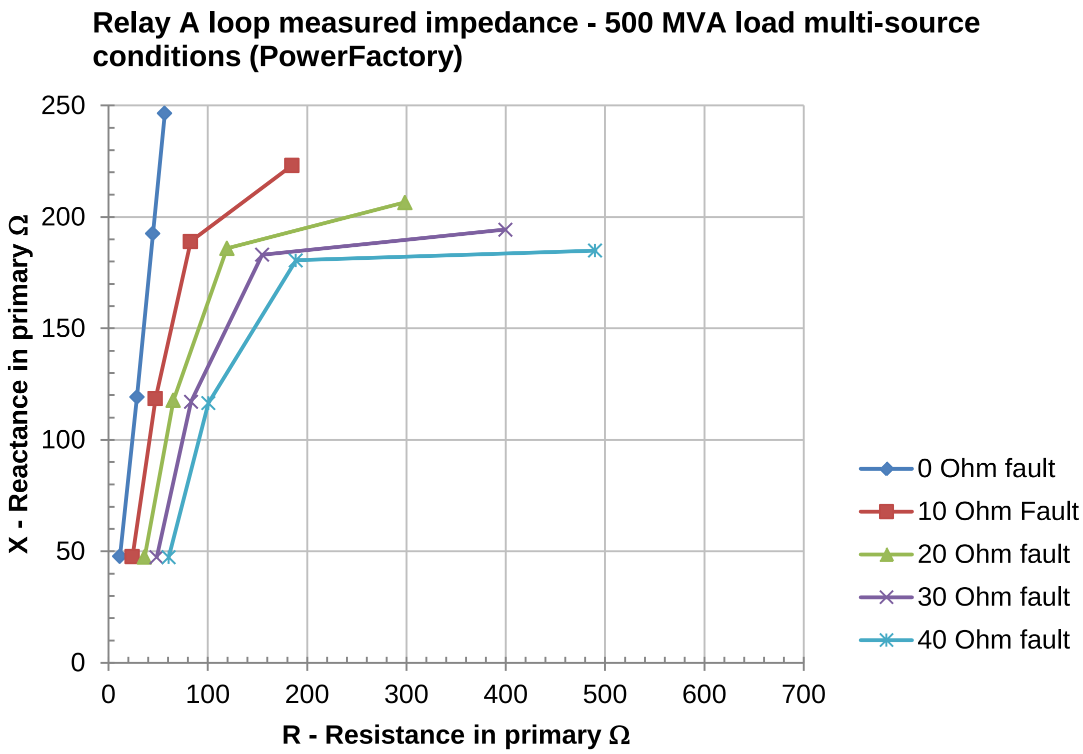

Figure 4.23: Loop impedance measurement for relay A under in-feed conditions

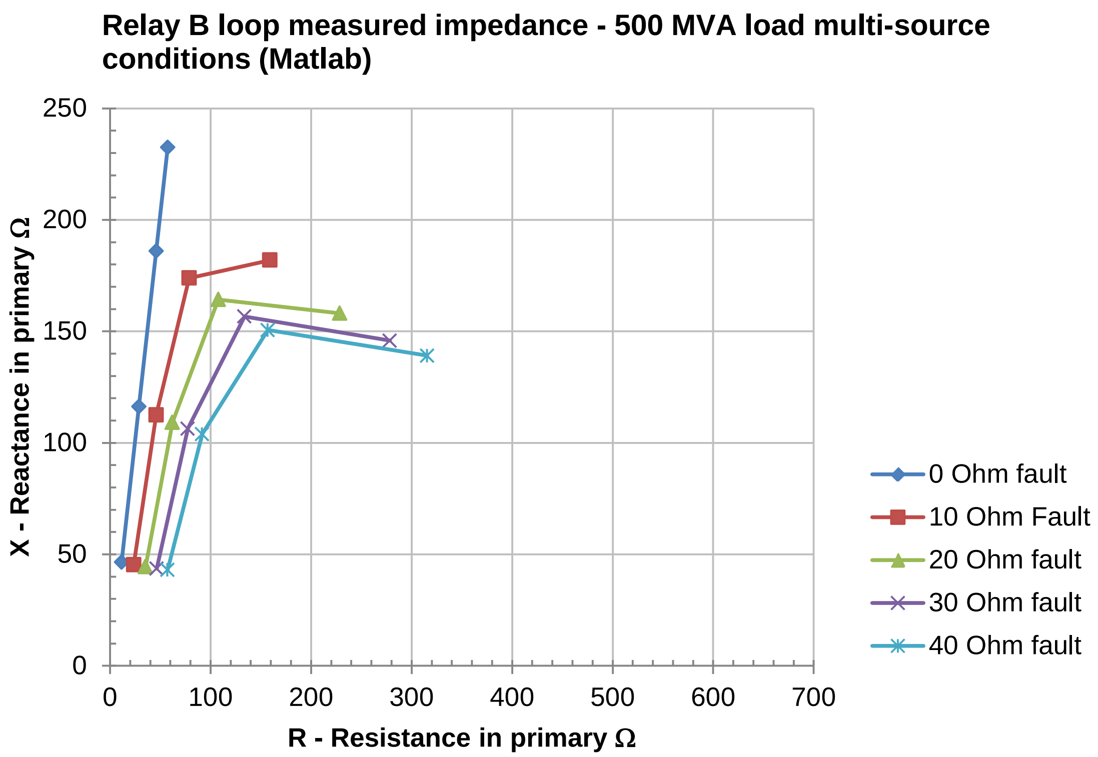

Figure 4.24: Loop impedance measurement for relay B under in-feed conditions

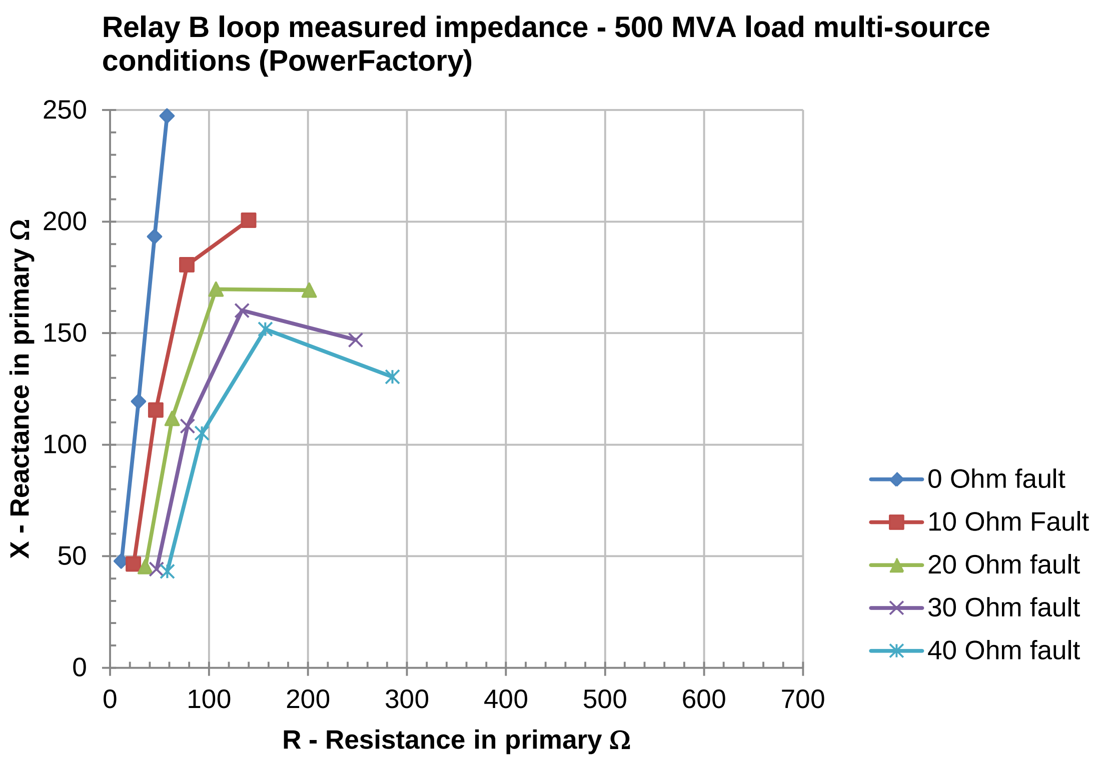

Figure 4.25: Loop impedance measurement for relay B under in-feed conditions

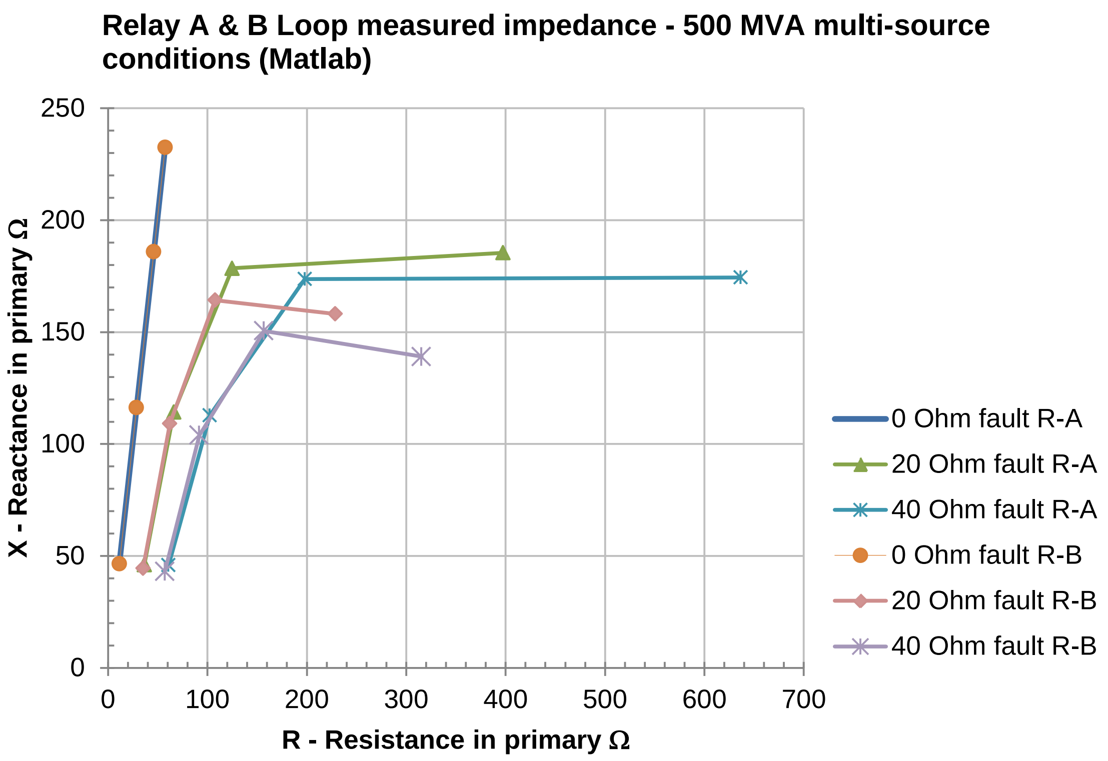

Figure 4.26: Loop impedance comparison for relays A and B under in-feed conditions

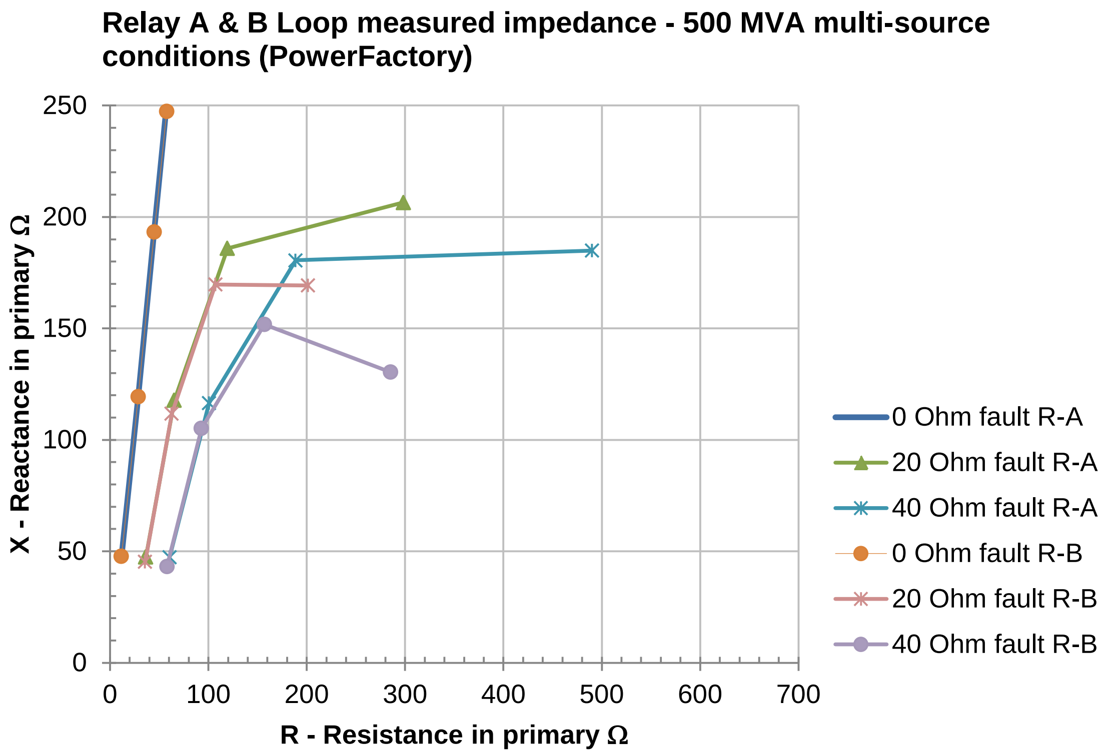

Figure 4.27: Loop impedance comparison for relays A and B under in-feed conditions

4.4 Conclusions

The comparison of results obtained from the Matlab and PowerFactory simulations has shown that differences in the overall responses of relay algorithms are comparable with or without taking the effect of the capacitive components of a network into account. The work done in this chapter has shown that load has an impact on the impedance measured by relays and that the response obtained from the different relay algorithms differ. Differences in the complexity of network analysis between radial and complex networks have been illustrated.

A detailed comparison between the apparent impedances calculated by the relays has been done and showed significant differences between the relays in resistive and reactive reaches (see Figure 4.20 and Figure 4.21). These results highlight the fact that attempting to compare different relay reaches on this basis are misleading and could result in wrong implementation. Evaluation of the same fault conditions in the loop domain provided significantly different results as has been shown in Figure 4.26 and Figure 4.27.

The most important message from the graphs portrayed in Figure 4.22 to Figure 4.27 is the close comparison obtained in the loop domain between relays A and B. Figure 4.26 and Figure 4.27 and Table 4.15 and Table 4.16 reflect a near perfect relationship for bolted faults. Deviations in the results obtained from the algorithms of the two relays are clearly as a result of the remote end in-feed, the magnitude of the resistive fault and the position of the fault in relation to that of the relays. This is in line with the theory discussed in previous chapters.

It has been illustrated that the two relay algorithms behave in a similar manner for all faults dependant on the distance to fault from the relay measurement position. Deviation between the relays, viewed in loop domain, only occur for resistive faults beyond 50% of the line length in relationship to the relays position of measurement. This illustrates that the differences in the relay measurements for high resistive faults in these locations could result in very different relay responses resulting in unexpected operations. Careful consideration must therefore be given when two relays with different measurement algorithms are to be used to provide impedance protection at the two ends of the same overhead line. The impedance loop domain will be further explored in Chapter 6 and Chapter 7 when the results of secondary injection testing on relay A and B will be discussed.

Chapter 5, will analyse in some detail some of the actual faults that occurred on the Eskom transmission system. The lessons learned from the previous chapters will be used for the analysis. Relay setting and recommendations made to enhance the relay operations during system faults are discussed in section 5.8.