
Chapter 7

CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

7.1 Conclusions

This research was started with the aim of providing answers to issues pertaining to the maloperation of some numerical protection relays for specific types of system faults. In most cases these faults were limited to single-phase-to-earth resistive faults. The following has been covered in this dissertation;

- i. An introduction into some of the actual distance protection relay maloperations.
- ii. Review of the fundamental principles concerning simple and complex overhead line impedance calculations.
- iii. Thorough exploration of the principles of overhead line inductance (impedance) calculations, covering aspects of dc- and ac-resistance, skin effect, skin depth, current density, spiralling- and transformer effect in ACSR-types of conductors. The meaning of conductor Geometric Mean Radius (GMR) and Geometric Mean Diameter (GMD) as well as calculation methods for GMR for single and bundle conductors were considered.
- iv. The impact that load impedance and different types of load could have on the impedance measured by distance relays as well as how this is analysed with the use of sequence networks.
- v. The principles of impedance relay measurements for two (7SA513 and REL531) of the numerical relays used on the Eskom transmission network were explored.
- vi. The relay algorithms used, method of fault detection, directional determination, tripping characteristics, impact of fault resistance, series compensation and the influence of load on impedance measurements were analysed and discussed.
- vii. Radial and complex theoretical network models created in Matlab and PowerFactory network simulation software were used to evaluate the impact of fault resistance and load on the generic impedance algorithm and the specific impedance algorithms of the two numerical relays being studied.

Most importantly the differences between the apparent impedances calculated by these algorithms were highlighted. A suggestion with proof of relevance, for the evaluation and/or comparison of results obtained from these algorithms in the impedance loop domain was made. Greater success with much less chance of misinterpretation of results was achieved during system fault evaluations and distance relay operation in the loop impedance domain, than was the case when using the apparent/positive sequence method.

- viii. Comparisons between results obtained with Matlab and PowerFactory were made. This work not only validates the routines generated in Matlab, but also highlights the impact of capacitive network components on the relays evaluated. Capacitive network components were not modelled in the Matlab routines.

From the differences in the results obtained from the relay algorithms for apparent impedance it became clear that these capacitive components impact the measurement algorithms of the two relays differently. The impact that the different compensation factors for the respective relays has on the final measurement was highlighted when the measured impedances were re-calculated into the loop domain. Both relays provided the exact same or comparative results with some exclusions during high resistive faults.

The study has shown that the impact of load current, capacitive charging current and the subsequent enlarging effect of remote end in-feed during resistive phase-to-earth faults must be evaluated when deciding on the most appropriate relay settings to be applied. Both relays have a tendency to overreach during load export conditions. A tendency to underreach in the resistive direction due to increased apparent fault resistance during remote end in-feed was also observed. The REL531 relay showed a significantly greater underreach in the resistive direction than the 7SA513 relay for the same faults (faults $> 0 \Omega$) when viewed in the apparent domain as was illustrated in Figure 4.20 and Figure 4.21. Put differently, the REL531 relay measures the fault to have a greater resistance than the 7SA513 relay ($R_{RB} \gg R_{RA}$). This role is reversed, although not in the same magnitude, for measurement in the reactive direction.

A very different picture emerges however when the results are viewed in the loop impedance domain. The 7SA513 relay now measures a greater resistance than the REL531 relay ($R_{RA} \gg R_{RB}$) for faults $> 0 \Omega$, whilst also measuring a greater reactance (the 7SA513 relay underreaches in comparison to the REL513 relay in both resistive and reactive directions). This totally opposite result in the resistive direction is the result of the impact caused by the use of a much different correction factor K_r by the 7SA513 relay for resistive measurements. Evaluation of the resistive reach in the loop domain provides the user with the actual fault resistance that can be detected by the relay within the set resistive reach for a radial application. Actual fault resistance that can be measured by an impedance relay in a meshed network is dependent on remote end in-feed.

Whilst a near perfect relationship between the 7SA513 relay and the REL531 relay exists for bolted faults as viewed in both apparent and loop domains, deviations between the results obtained from the two relays algorithms increased with increasing resistive faults and distance from the measuring position (see Figure 4.22 to Figure 4.27). This phenomenon needs to be fully understood and carefully evaluated when attempting to use relays with different algorithms to provide permissive impedance protection for overhead lines. Should careful consideration not be given to this phenomenon when deciding on settings to be applied to these relays it is possible that proper permissive fault clearance would not be achieved.

Relays measure current and voltage quantities on a per phase basis (V_a, V_b, V_c, I_a, I_b and I_c). The relationships of $V_a/I_a, V_b/I_b$ and V_c/I_c provides the relay with measured loop quantities used to determine the fault impedance in phase-to-earth faults. The positive, negative and zero-sequence quantities used by the relay algorithms to obtain the final operating quantities are calculated from these phase vectors. Each relay manufacturer has it's own unique way in which to represent their relays operating characteristics. In this case, the characteristics for the 7SA513 relay is represented in ohm per phase, whilst that for the REL513 relay is given in ohm per loop. The result of the measurement in the apparent impedance domain for the 7SA513 relay is misleading and can result in resistive reach mismatching between these two relays. The implication is that in order to do a proper comparison of these

relays both relays characteristics have to be presented in the same quantities. For this purpose and to simplify any fault analysis the characteristics should be referred to the loop domain using the relay's respective correction factors. It has been shown in this work that the impedance loop representation provides the user with a simple solution for relay comparison.

The fault investigations referred to in the introduction section and discussed in greater detail in Chapter 5 illustrated that in most cases one common denominator, namely the actual settings implemented on the relays was the cause of maloperation. The reason for this can be attributed to the following aspects;

- i. Validity/accuracy of available overhead line parameters.
- ii. Misinterpretation or misrepresentation of manufacturers information/operating characteristics provided.
- iii. Actual performance of relays within the Eskom system is not fully known or understood.
- iv. The combination of very long, short and series compensated lines complicates setting calculations for distance protection relays.
- v. Different impact of load and remote end in-feed on relays during high resistance faults is not specifically evaluated.

It was found that although the manufacturer of the 7SA513 relay provided specific guarantee limitations, for operation within the Eskom Transmission specified operation time limit of +/-10ms, certain other factors had been overlooked or ignored. One of these had been the harmonic oscillations caused by RLC circuits that require the application of special reactive reach reduction factors. The other was a limitation on the R/X-ratios for the measuring elements. It has been shown in this dissertation that the implementation of correction factor settings using a maximum R/X-ratio of 6 (also indicated by the manufacturer) as determined with loop values resolved incorrect distance protection operations for this relay.

Careful evaluation of the operation of a series capacitor with parallel MOV protection during system faults and the impact thereof on distance protection is necessary in order to determine the best-suited protection settings for different network conditions.

The impact of the dynamically changing RLC values on distance protection measurements during system faults should not be underestimated, since this will lead to maloperation. It is possible that in certain cases where mid-line compensation is used, the zone 1 protection for a specific relay will have to be disabled in order to prevent maloperation.

It has also been shown that the electrical parameters of overhead transmission lines can be determined effectively using common network simulation software tools available. However, to ensure accurate impedances are determined in this way, care should be taken to enter accurate and correct conductor parameters as supplied by the conductor manufacturers. The primary line impedance can also be physically measured with a relatively simple test using the correct primary injection test equipment. Results obtained with primary injection yielded a good correlation to the values calculated using appropriate software.

The non-intrusive secondary injection test methods used in Chapter 6, successfully illustrated relay maloperation and correct operation for different faults under steady state system conditions with the original relay settings. This method of testing relay settings operationally could therefore be utilised prior to implementation. It is also highlighted however, that this method clearly does not cater for dynamic system conditions as was illustrated with the sub-harmonic conditions involved with series capacitor banks utilising MOV bypass protection. Due to the fact that relay algorithms are influenced by the dynamic behaviour of the electrical system during faults it is suggested that transient fault simulation studies should be used in complicated situations to generate comtrade files, which can then be used to test relay operation through secondary injection methods. A more accurate representation of how the relays would respond would be obtained, and the settings could be altered accordingly.

This research has also shown that greater success is achieved with the use of relay characteristics represented in the loop domain and in primary quantities during the analysis of system faults and relay reach comparison. It is therefore suggested that this method of fault analysis and overall setting calculation be implemented and in

order to have one reference of comparison, this should be done using primary impedance values. This work has shown that the correct operation of these impedance relays can be ensured after relay setting calculations using this method. Since overhead line impedances are given as actual values on the high voltage system (primary quantities), this method will always provide for direct comparison between relays and overhead line impedance. It will also facilitate the use of different current transformer ratios at the different line-ends should that be required. It will also eliminate the possibility of misrepresentation of relay reaches as is easily done in secondary impedance quantities.

7.2 Recommendations

This work has highlighted some deficiencies in the current protection relay setting practices. From the conclusions reached in this work the following recommendations can be made;

- i) Relay settings should always be represented in loop impedance quantities to ensure easy analysis and relay co-ordination.
- ii) Steady state non-intrusive test methods can show inadequacies in relay sensitivity, especially between zone and phase selector (starter) elements.
- iii) Transient fault simulations should be done. Comtrade files and secondary injection playback methods with suitable test equipment should be used to verify correct operation for cases where more complex system conditions exist that can result in sub-harmonic oscillations.
- iv) Network simulation tools capable of closely modelling relay algorithms under transient conditions could also be used in the quest to provide the most suitable relay settings.

7.3 Future Work

This work has indicated certain aspects, which fell outside its scope, but which requires further investigation.

- Reasons for differences in the overhead line impedance calculated with the use of algorithms developed by J.R. Carson et. al and algorithms presented by EPRI.
- Reasons for the suspect permeability values used in the default conductor libraries in the PowerFactory database. These libraries are used throughout the entire case file and/or case files used by Eskom and therefore impacts all line parameters in the entire network.
- Impedance measurement for the power swing detection function of the REL531 relay is done on a per phase basis. Impedance loop selections for one out of three or two out of three can be made. This function needs to be carefully analysed, as it is thought that it might have played a role in the maloperation of the relay on the Leander – Grootvlei feeder.