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Research into Specific Numerical Protection Maloperations

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ABSTRACT

High voltage transmission system availability and system security are key performance criteria for electricity utilities worldwide. System disturbances need to be cleared quickly and accurately in order to minimise the impact of faults and to facilitate speedy system restoration. In this context, the South African utility, Eskom has maintained a process of refreshing protective relaying technology as older equipment becomes obsolete and is no longer capable of meeting the utility's requirements.

The difficulties which a process of equipment renewal presents the organisation with include the risk of incorrectly applying the newer technologies within the complex electrical network. The application of new technology is affected by the complexities of the newer technology with respect to the older, more familiar technologies. Some of the difficulties can be addressed with revised commissioning procedures or the use of modern test equipment. Enhanced relay algorithms and settings calculation methodologies can however not be simplified.

Protective relay maloperations cannot always be completely avoided and when they do occur, these must be investigated and addressed to prevent future recurrences.

The research covered by this dissertation focuses on a number of protective relay maloperations on transmission lines using impedance protection algorithms. The research undertaken identifies the previously unidentified causes of the maloperations and describes a relay settings solution for improving the accuracy of the protective relays.

The methodology that was followed in the research covers the following aspects:

- Identification and highlighting of some of the protection relay maloperations that occurred during system faults,
- Review of the fundamental principles involved in system fault analysis,

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- Comprehensive study of the theory involved in the calculation of an overhead line conductor self and mutual-inductance, as well as the calculation of the positive, negative and zero sequence impedances of an overhead line,
 - Brief evaluation of the effect of load impedance on relay measurements and the impact on fault clearing operation,
 - Analysis of the theoretical operation of various numerical relays during single-phase-to-earth faults in radial and meshed (complex) network conditions,
 - Mathematical calculations using typical Newton-Raphson methods to study the impact of resistive single-phase-to-earth faults on the voltage and current measurements at the relaying position with the exclusion of the capacitive components between conductors and conductors and earth,
 - Comparison and evaluation of mathematical calculations and system studies using network simulation software which included all steady state network parameters,
 - Review and analysis of actual system faults that had been previously analysed without definitive conclusion. The faults were re-analysed in an attempt to correlate findings with the hypothesis of the research,
 - Comparison of the performance of protective relay impedance characteristics using positive sequence domain versus loop domain analysis techniques.

This study concluded that significant benefits can be achieved by analysing system faults and relay operation using loop quantities in primary impedance values as opposed to positive sequence or apparent impedance quantities in secondary values. The inherent differences between the positive or apparent impedance characteristics of the relays are nullified when considered in the loop impedance domain, provided that the relays reach settings were calculated correctly.

The study also showed that load current cannot be ignored when calculating settings as it has significant impact on the actual impedance measured during fault conditions. It is therefore crucial that when relays from different manufacturers are being used to protect the same circuit that the differences between the relays and the subsequent measurements are clearly understood and compensated for.

Finally relay setting changes have been proposed for implementation based on the findings of this research. The combination of the theory, network simulations and secondary injections performed on the relays all correlate and therefore validate the research. It is left for the utility and or users of these relays to evaluate the results of this research and implement the necessary changes as applicable.

Key Search Words

- Numerical
- Protection
- Maloperation
- Proposed
- Relay Setting Changes
- Theory
- Network
- Reduction

OPSOMMING

Die beskikbaarheid en sekuriteit van die transmissienetwerk is die sleutelprestasiekriteria vir elektrisiteitsvoorsieningsmaatskappye wêreldwyd. Dit is noodsaaklik dat stelsel foute vinnig en korrek van die stelsel verwyder word om die invloed van sodanige foute te minimaliseer en te verseker dat die stelsel so spoedig moontlik herstel kan word. In hierdie verband het die Suid-Afrikaanse elektrisiteitsvoorsieningsmaatskappy, Eskom, 'n aaneenlopende proses van hernuwing van beveiligingsrelêtegnologie reeds 'n geruime tyd in plek ten einde verouderde toerusting, te vervang.

Van die probleme wat deur 'n proses van hernuwing van toerusting aan die maatskappy gestel was, sluit die risiko in wat gepaardgaan met die foutiewe toepassing van nuwe tegnologie in 'n reeds komplekse elektriese netwerk. Die toepassing van die nuwe tegnologie word beïnvloed deur die kompleksiteit daarvan in verhouding met die ouer en meer bekende tegnologieë. Sommige van die probleme word aangepreek deur middel van hersiende inbedryfstellingsprosedures en die gebruik van moderne toetsuitrusting. Dit is egter nie so eenvoudig om gevorderde relêalgoritmes en die uitwerking van gepaardgaande instellings te analiseer nie.

Dit is nie altyd moontlik om die foutiewe werking van beveiligingsrelê's te voorkom nie, maar dit is van uiterste belang dat wanneer dit gebeur, die oorsaak daarvan deeglik nagevors word ten einde herhaling daarvan te voorkom.

Die navorsing wat in hierdie verhandeling bespreek word, is gefokus op 'n aantal foutiewe impedansiebeveiligingsrelêwerkings op oorhoofse transmissielyne. Die navorsing is daarop gemik om die oorsake van foutiewe relêwerking wat voorheen nie volledig geïdentifiseer was nie, aan te spreek en bied relêstellingsoplossings wat daarop gemik is om die akkuraatheid van die beveiligingsrelê's te bevorder.

Die metodologie wat gevolg is in hierdie verhandeling, hanteer onder meer die volgende aspekte:

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- Die identifisering van sommige van die foutiewe beveiligingsrelêwerkings wat plaasgevind het tydens stelsel foute,
 - Die hersiening van die fundamentele beginsels met betrekking tot netwerkfoutanalises.
 - 'n Uiteenlopende studie van die teorie rondom die berekening van oorhoofse transmissielyngeleier induktansie en wedersydse induktansie sowel as die bepaling van die positiewe, negatiewe en zero volgorde impedansies.
 - 'n Kort studie om te bepaal wat die uitwerking van die lasimpedansie op relêmeting en die gevolglike relêwerking is, ten einde foute van die stelsel te verwyder.
 - Die analisering van die teoretiese werking van verskeie numeriese relê's tydens eenfasige foute onder radiale en komplekse netwerktoestande.
 - Wiskundige berekeninge met behulp van Matlab-sagteware wat gebruik maak van tipiese Newton-Raphson-metodes, is gebruik om die uitwerking van eenfasige foute op die spanning en stroommetings by die relêverbindingspunt te bepaal. Die kapasitiewe komponente tussen die verskillende fases van die oorhoofse lyn en tussen fases en grond is hier geïgnoreer.
 - 'n Vergelyking van en evaluering van die wiskundige berekeninge en netwerkstudies wat met behulp van netwerksimulasiesagteware uitgevoer is. Alle statiese netwerkparameters is met die simulatiesagteware ingesluit.
 - Hersiening en evaluering van werklike netwerkfoute wat voorheen nie tot konkrete gevolgtrekkings gelei het nie. Die foute is heranaliseer in 'n poging om gevolgtrekkings te maak wat die doelstelling van die hipotese van hierdie navorsing sou ondersteun.
 - Vergelykings word getref tussen die doeltreffende analisering van die positiewe volgordekarakteristieke van die relê's en die soos voorgestel in 'n lusedomein.

Die studie het tot die gevolgtrekking gekom dat daar 'n aansienlike voordeel bestaan wanneer stelselfoute en relêwerking geanaliseer word deur gebruik te maak van primêre impedansielusedomeinwaardes in teenstelling met positiewe volgorde of skyn-impedansies in sekondêre waardes. Die inherente verskille wat tussen die positiewe of skynimpedansiekarakteristieke van die relê's bestaan, verdwyn wanneer

daarna in die lusdomein verwys word. Die enigste vereiste hier is dat die impedansie bereikinstellings van die relê's wat met mekaar vergelyk word, korrek bereken moet wees.

Die studie het ook aangetoon dat lasstroom nie altyd geïgnoreer kan word nie, maar dat dit in ag geneem behoort te word wanneer relêstellings bereken word, aangesien lasstroom 'n aansienlike invloed kan hê op die relêimpedansiemeting tydens stelsel fouttoestande. Dit is daarom belangrik, dat wanneer relê's van verskillende vervaardigers gebruik word om dieselfde oorhoofse stroombaan te beveilig, dat die verskille tussen die relê's, hul meetalgoritmes en eksterne faktore duidelik verstaan word en die nodige kompensasië toegepas word.

Nuwe relêstellings wat gebaseer is op die bevindinge van hierdie navorsing word voorgestel vir implementering. Die kombinasie van die teorie, netwerksimulasies en sekondêre inspuitingstoetse wat op die relê's gedoen is, stem ooreen en kwalifiseer gevolglik hierdie werk. Dit word aan Eskom, die netwerkkoperateur, en ander gebruikers van hierdie relê's oorgelaat om die resultate van hierdie werk te evalueer en te implementeer waar nodig.

Ken HOM in al jou weë, dan sal HY jou paaie gelyk maak
– (Spreuke 13:6)

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TABLE OF CONTENTS

Chapter 1	PROTECTION MALOPERATIONS ON THE ESKOM TRANSMISSION SYSTEM	1
1.1	Introduction	1
1.1.1	Example 1 on 275 kV: Georgedale – Klaarwater line	2
1.1.2	Example 2 on 400 kV: Hydra – Perseus line	2
1.1.3	Example 3 on 400 kV: Athene – Invubu line.....	4
1.1.4	Example 4 on 88 kV (Relay measurement on 275 kV): Etna – Taunus line	5
1.2	Purpose of study	0
1.3	Issues to be addressed	1
1.4	Approach leading to solutions	1
Chapter 2	FAULT IMPEDANCE LOOPS AND OVERHEAD LINE IMPEDANCE CALCULATIONS.....	3
2.1	Introduction	3
2.1.1	Symbols and conventions used	3
2.1.2	Single-phase-to-earth fault loop	4
2.1.3	Phase-to-phase-to-earth fault loop.....	9
2.1.4	Phase-to-phase fault loop	12
2.2	Complex impedance calculations.....	14
2.2.1	Parallel connected sources and branch/equipment impedances.....	14
2.2.2	Equal source voltages	15
2.2.3	Superposition method.....	17
2.2.4	Thevenin’s theory.....	17
2.3	Line impedance calculations from first principles	25
2.3.1	Resistance.....	26
2.3.2	Skin effect.....	33
2.3.2.1	Skin depth	39
2.3.2.2	Current density	40
2.3.3	Proximity effect	40
2.3.3.1	Resistance and inductance relationships	42
2.3.4	Spiralling effect.....	43
2.3.5	Transformer effect	43
2.3.6	Magnetic permeability	44
2.3.7	Inductance of a conductor	46

2.3.7.1	Inductance of a single-phase two-wire line	52
2.3.7.2	Inductance of a multi-phase circuit.....	57
2.3.7.3	Inductance of a single-phase composite conductor line.....	58
2.3.7.4	Inductance of three-phase lines with equilateral spacing	61
2.3.7.5	Geometric mean diameter and radius.....	62
2.3.7.6	Inductance of three-phase lines with unsymmetrical spacing.....	67
2.3.7.7	Overhead conductor impedance matrix	68
2.4	Load impedance and sequence networks.....	83
2.4.1	Balanced delta loads.....	83
2.4.2	Balanced star loads.....	85
2.5	Summary.....	88
Chapter 3 IMPEDANCE PROTECTION RELAY ALGORITHMS.....		90
3.1	Introduction	90
3.2	Relay A (Siemens 7SA513)	90
3.2.1	Earth fault detection	91
3.2.2	Impedance fault detection	93
3.2.3	Directional determination	96
3.2.4	Impact of series compensation	100
3.2.5	Relay tripping characteristics	105
3.2.6	Impact of fault resistance.....	109
3.2.7	Influence of load.....	113
3.2.8	Summary.....	115
3.3	Relay B (ABB REL531)	117
3.3.1	Single-phase-to-earth - zone measuring element.....	117
3.3.2	Single-phase-to-earth phase selection element.....	121
3.3.3	Phase-to-phase zone measuring element.....	123
3.3.4	Phase-to-phase phase selection element	126
3.3.5	Directional determination	130
3.3.6	Impact of series compensation	131
3.3.6.1	Directional control.....	131
3.3.6.2	Voltage reversal.....	133
3.3.6.3	Sub harmonic oscillation.....	134
3.3.6.4	High-speed function.....	139
3.3.7	Impact of fault resistance.....	142
3.3.7.1	Normal distance function	142
3.3.7.2	High-speed function.....	144

3.3.8	Influence of load.....	145
3.3.9	Summary.....	146
Chapter 4	RELAY ALGORITHM COMPARISON USING THEORETICAL NETWORK MODELS.....	148
4.1	Introduction	148
4.2	Radial network	149
4.3	Complex network	170
4.4	Conclusions	183
Chapter 5	RELAY OPERATIONAL ANALYSIS DURING FAULT CONDITIONS .	185
5.1	Sources of maloperation	185
5.2	Athene – Invubu faults analysis	186
5.2.1	Incident.....	186
5.2.2	Investigation and findings	187
5.2.3	Overhead line impedance measurements	191
5.2.3.1	Transmission line equivalent circuit	191
5.2.3.2	Test equipment.....	195
5.2.3.3	Safety precautions.....	197
5.2.3.4	Comparison of measured and calculated impedance.....	198
5.3	Hydra – Perseus fault analysis.....	202
5.3.1	Incident.....	202
5.3.2	Investigation and findings	202
5.4	Georgedale – Klaarwater faults analysis.....	210
5.4.1	Incident.....	210
5.4.2	Investigation and findings	210
5.5	Etna – Taunus faults analysis	215
5.5.1	Incident.....	215
5.5.2	Investigation and findings	216
5.6	Bacchus – Droërivier fault analysis	221
5.6.1	Incident.....	221
5.6.2	Investigation and findings	221
5.7	Leander – Grootvlei fault analysis	226
5.7.1	Incident.....	226
5.7.2	Investigations and findings.....	226
5.8	Relay setting changes.....	232
5.8.1	Athene – Invubu 400 kV line	232
5.8.2	Hydra – Perseus 400 kV line	236

5.8.3	Georgedale – Klaarwater 275 kV line	238
5.8.4	Etna – Taunus 275 kV line	241
5.8.5	Bacchus – Droërivier 400 kV line	243
5.8.6	Leander - Grootvlei 400 kV line	244
5.9	Conclusions	248
Chapter 6 RELAY OPERATION DURING SECONDARY INJECTION TESTING		249
6.1	ABB REL531 Relay (Relay B)	249
6.1.1	Laboratory test results - classic method	249
6.1.1.1	Single-phase-to-earth – measuring elements	250
6.1.1.2	Phase-to-phase measuring elements	250
6.1.2	Impact of healthy phase currents on measurements	251
6.1.2.1	Radial feed with remote breaker open (capacitive charging).....	252
6.1.2.1.1	Phase-to-earth faults at 50% of first line section	252
6.1.2.1.2	Phase-to-earth faults at end of line	255
6.1.2.1.3	Phase-to-phase faults at series capacitor	260
6.1.2.1.4	Phase-to-phase faults at end of line	262
6.1.3	Load current and remote in-feed.....	264
6.1.3.1	Exporting MW and Mvar – remote breaker closed	264
6.1.3.1.1	Phase-to-earth measurement	264
6.1.3.1.2	Phase-to-phase measurement.....	266
6.1.3.2	Importing MW and Mvar – remote breaker closed	269
6.1.3.2.1	Phase-to-earth measurement	269
6.1.3.2.2	Phase-to-phase measurement.....	270
6.1.4	Conclusions.....	272
6.2	SIEMENS 7SA513 Relay (Relay A)	274
6.2.1	Laboratory test results – classic method.....	275
6.2.1.1	Single-phase-to-earth – measuring elements	275
6.2.2	Impact of healthy phase currents on measurements	276
6.2.2.1	Radial feed with remote breaker open (capacitive charging).....	277
6.2.3	Load current and remote in-feed.....	280
6.2.3.1	Exporting MW and Mvar – remote breaker closed	280
6.2.3.1.1	Phase-to-earth measurement	280
6.2.3.2	Importing MW and Mvar – local breaker closed	284
6.2.3.2.1	Phase-to-earth measurement	284

6.2.4	Conclusions.....	287
Chapter 7	CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK.....	288
7.1	Conclusions	288
7.2	Recommendations	293
7.3	Future Work	294
	REFERENCES.....	295
	Appendix A.....	297
	Appendix B.....	298
	Appendix C.....	299
	Appendix D.....	300
	Appendix E	301
	Appendix F	302
	Appendix G.....	303
	Appendix H.....	304
	Appendix I	305
	Appendix J.....	306
	Appendix K.....	307
	Appendix L	308
	Appendix M	309
	Appendix N.....	310
	Appendix O.....	311
	Appendix P	312
	Appendix Q.....	313
	Appendix R.....	314

List of Figures

Figure 1.1: A-phase-to-earth fault in reverse on adjacent feeder	2
Figure 1.2: Red-to-B-phase fault at the remote busbar	3
Figure 1.3: C-phase-to-earth fault on remote busbar	4
Figure 1.4: Reverse A-phase-to-earth fault on 88 kV network.....	5
Figure 2.1: A-phase-to-earth fault.....	5
Figure 2.2: Phase-to-earth fault theoretical diagram	7
Figure 2.3: B-C Phase-to-earth fault.....	9
Figure 2.4: B-C-Phase fault.....	12
Figure 2.5: Parallel source and admittance branches [5]	15
Figure 2.6: Reduction of equal source voltages [5]	16
Figure 2.7: Graphical superposition illustration [5].....	17
Figure 2.8: Thevenin open-circuit pre-fault voltage illustration	18
Figure 2.9: Load-flow with strong source.....	19
Figure 2.10: Three-phase fault with strong source	20
Figure 2.11: Load-flow with weak (single) source.....	20
Figure 2.12: Three-phase fault with weak source.....	21
Figure 2.13: Topology illustration with single-phase fault on small network	23
Figure 2.14: Influence of conductor stranding on ac/dc-resistance ratio [13]	29
Figure 2.15: Ultimate ac/dc-resistance ratio between traditional and optimal stranding [13]	29
Figure 2.16: Resistance of a conductor as a function of temperature [1]	30
Figure 2.17: Resistance variations based on temperature and current [13]	32
Figure 2.18: Variation in ac-resistance per type of conductor [13].....	33
Figure 2.19: Increase in current density per layer [13]	35
Figure 2.20: Theoretical explanation for uneven current distribution in ACSR conductors [13].....	36
Figure 2.21: Skin effect curves for bolted round bare stranded conductor [8]	38
Figure 2.22: Magnetic field strength of two conductors in parallel.....	45
Figure 2.23: Cross-section of a cylindrical conductor [1]	48

Figure 2.24: Current (I) flowing through a conductor produces a magnetic field (B) around the conductor [3]	50
Figure 2.25: External magnetic flux between points P1 and P2 for a single conductor [1]	51
Figure 2.26: Field due to current in conductor 1 only [1]	53
Figure 2.27: Single-phase circuit inductance calculation with reference to point P [1]	55
Figure 2.28: Multi-phase circuit with current vector sum equal to zero.....	57
Figure 2.29: Single-phase composite conductor circuit [1]	59
Figure 2.30: Three-phase line equilaterally spaced with no earth conductor [1].....	61
Figure 2.31: Cross-section of a stranded conductor [18].....	64
Figure 2.32: Multi-layer stranded type ACSR conductor	65
Figure 2.33: Conductor image inside earth return [11]	69
Figure 2.34: Image conductor resistance linked to frequency (Appendix G)	70
Figure 2.35: Three-phase overhead line with earth returns [9].....	78
Figure 2.36: Three-phase source with Delta load.....	84
Figure 2.37: Star load configurations [9].....	86
Figure 2.38: Positive, negative and zero sequence circuits for balanced load [9]	88
Figure 3.1: Pick-up/reset characteristic for earth current detector [16].....	92
Figure 3.2: Earth fault processing [16].....	92
Figure 3.3: Impedance fault detection characteristics [16]	94
Figure 3.4: Voltage references for directional determination [16].....	97
Figure 3.5: 7SA513 Directional characteristic [16].....	97
Figure 3.6: Simple network diagram [16].....	98
Figure 3.7: Impact of source impedance and load on directionality of a distance relay [16]	99
Figure 3.8: Reverse fault impact on forward characteristic [6].....	99
Figure 3.10: Fault impedance spiralling effect [6].....	103
Figure 3.11: Equivalent series impedance [6].....	105
Figure 3.12: 7SA513 Tripping characteristic [16].....	107
Figure 3.13: Double ended in-feed supply circuit	111
Figure 3.14: Apparent fault resistance dependent on fault location [6].....	112
Figure 3.15: 7SA513 Tripping characteristics with fault resistance [6]	112

Figure 3.16: Influence of load transfer on distance relay measurement [6]	113
Figure 3.17: Approximate reaches with and without load compensation [6].....	114
Figure 3.18: Characteristic for the phase-to-earth measuring loop [20].....	119
Figure 3.19: Phase-to-earth loop operational characteristics for zone and phase elements [20].....	122
Figure 3.20: Operating characteristic of phase-to-phase zone elements [20]	125
Figure 3.21: Phase selection with zone operating characteristic [20].....	129
Figure 3.22: Network with Series Capacitor [20]	134
Figure 3.23: Sub-harmonic reduction curve [20].....	135
Figure 3.24: High-speed operation characteristic [20]	140
Figure 4.1: Simple radial network.....	150
Figure 4.2: Thevenin's super positioning theorem [5].....	151
Figure 4.3: Bacchus - Droërivier reduced network diagram.....	153
Figure 4.4: Apparent measured impedance at different fault locations for relays A and B (Matlab).....	162
Figure 4.5: Apparent measured impedance at different fault locations for relays A and B (PowerFactory)	163
Figure 4.6: Loop measured impedance at different fault locations for relays A and B (Matlab)	164
Figure 4.7: Loop measured impedance at different fault locations for relays A and B (PowerFactory).....	165
Figure 4.8: Relay A, no-load versus load measurement for radial condition	167
Figure 4.9: Relay B, no-load versus load measurement for radial condition	168
Figure 4.10: Apparent measured impedance comparison for relay A and B	169
Figure 4.11: Relays A and B loop impedance measurements for end line faults.....	169
Figure 4.12: Multi-source network with fault at point F	170
Figure 4.13: Multi-source, multi-load sequence network	172
Figure 4.14: PowerFactory load-flow results from multi-source system	172
Figure 4.15: Matlab load-flow results from multi-source system.....	173
Figure 4.16: Apparent measured impedance at different fault locations of relay A under in-feed conditions	174
Figure 4.17: Apparent measured impedance at different fault locations of relay A under in-feed conditions	175

Figure 4.18: Apparent measured impedance at different fault locations of relay B under in-feed conditions	175
Figure 4.20: Apparent impedance comparison at different fault locations for relay A and B under in-feed conditions.....	176
Figure 4.22: Loop impedance measurement at different fault locations for relay A under in-feed conditions	180
Figure 4.23: Loop impedance measurement for relay A under in-feed conditions...	180
Figure 4.24: Loop impedance measurement for relay B under in-feed conditions...	181
Figure 4.25: Loop impedance measurement for relay B under in-feed conditions...	181
Figure 4.26: Loop impedance comparison for relays A and B under in-feed conditions	182
Figure 4.27: Loop impedance comparison for relays A and B under in-feed conditions	182
Figure 5.1: Voltage traces for Athene – Invubu incident.....	188
Figure 5.2: Current traces for Athene - Invubu incident.....	189
Figure 5.3: Digital traces for Athene - Invubu incident.....	190
Figure 5.4: Athene - Invubu impedance locus at time of fault.....	190
Figure 5.5: Transmission line equivalent circuit [14].....	192
Figure 5.6: Injection test for A-B loop [14]	192
Figure 5.7: Schematic layout of line impedance test equipment [15].....	196
Figure 5.8: CPCU20 unit [15]	196
Figure 5.9: CPC 100 primary injection test set [15]	197
Figure 5.10: Tower 1 near Athene substation [15].....	199
Figure 5.11: Frequency response of resistance and reactance [15].....	200
Figure 5.12: dc-resistance sensitivity analysis [7].....	202
Figure 5.13: Network interconnectivity diagram.....	203
Figure 5.14: Voltage traces for Hydra - Perseus fault.....	205
Figure 5.15: Current traces for Hydra - Perseus fault.....	206
Figure 5.16: Binary signals for Hydra - Perseus fault	207
Figure 5.17: Enlarged voltage traces for Hydra - Perseus fault	207
Figure 5.18: Enlarged current traces for Hydra - Perseus fault	208
Figure 5.19: Hydra - Perseus impedance locus at the time of fault	208
Figure 5.20: Voltage traces for Georgedale - Klaarwater 275 kV feeder	212

Figure 5.21: Current traces for Georgedale - Klaarwater 275 kV feeder	213
Figure 5.22: Binary traces for Georgedale – Klaarwater 275 kV feeder	214
Figure 5.23: A and B-phase current angular comparisson	214
Figure 5.24: Current vector diagrams before and during the A-phase fault.....	214
Figure 5.25: Georgedale - Klaarwater impedance locus at time of fault	215
Figure 5.26: Voltage traces for Etna - Taunus 275 kV feeder	217
Figure 5.27: Current traces for Etna - Taunus 275 kV feeder.....	218
Figure 5.28: Binary traces for Etna - Taunus 275 kV feeder	219
Figure 5.29: Etna - Taunus 275 kV enlarged current traces.....	219
Figure 5.30: Etna - Taunus 275 kV current vector diagram.....	220
Figure 5.31: Etna - Taunus 275 kV fault impedance locus before changes	220
Figure 5.32: Bacchus - Droërivier voltage and current traces.....	222
Figure 5.33: Superimposed fault currents on Bucchus - Droërivier feeder	223
Figure 5.34: Bacchus - Droërivier binary signals.....	223
Figure 5.36: Bacchus - Droërivier phase-to-phase fault loop impedance	225
Figure 5.37: Leander - Grootvlei 400 kV Feeder voltage and current fault traces ...	229
Figure 5.38: Leander - Grootvlei red and neutral currents.....	230
Figure 5.39: Leander – Grootvlei current vectors prior and during the fault	230
Figure 5.40: Leander - Grootvlei binary trip signals.....	230
Figure 5.41: Leander - Grootvlei 400 kV phase-to-earth fault loop impedance	231
Figure 5.42: Leander - Grootvlei 400 kV phase-to-earth fault apparent impedance	231
Figure 5.43: Athene - Invubu impedance locus after setting changes.....	234
Figure 5.44: Athene - Invubu impedance loop relationship (before)	235
Figure 5.45: Athene - Invubu loop impedance relationship (after).....	235
Figure 5.46: Hydra - Perseus impedance plot with time markers before change ...	237
Figure 5.47: Hydra - Perseus impedance plot with time markers after change	238
Figure 5.48: Revised settings with fault impedance locus	240
Figure 5.49: Atna - Taunus 275 kV fault impedance locus after changes	242
Figure 5.50: Etna - Taunus final impedance plot in loop domain.....	242
Figure 5.51: Bacchus - Droërivier impedance plot after phase-to-earth PHS setting correction.....	243
Figure 5.52: Leander - Grootvlei loop impedance, PHS reach corrected	244
Figure 5.53: Leander - Grootvlei Zone and Phase Selector reach comparisson	246

Figure 5.54: Sequence Network for a Phase-to-Earth fault in a radial network247

Figure 5.55: Simplified Sequence Network for Phase-to-Earth fault in radial network
.....247

List of Tables

Table 2.1: Geometric mean radius for bundle conductors [1].....	63
Table 2.2: Example conductor GMR calculation results.	67
Table 2.3: Overhead Line Conductor Positioning Example	76
Table 2.4: Self Impedance Calculation Comparison.....	76
Table 2.5: Sequence Impedance Results (MathCAD versus Matlab).....	82
Table 2.6: Sequence Impedance Results (Matlab versus PowerFactory)	83
Table 4.1: 500 MVA Load-flow comparisons	153
Table 4.2: Results comparison for radial network.....	155
Table 4.3: Results comparison using the Generic impedance equation.....	157
Table 4.4: Apparent reach comparison for relay A	161
Table 4.5: Apparent reach comparison for relay B	162
Table 4.6: Loop impedance measurements for relay A	163
Table 4.7: Loop impedance measurements relay B	164
Table 4.8: Comparison of no-load versus 500 MVA load export for end-of-line fault on generic relays	166
Table 4.9: Comparison of no-load versus 500 MVA load export for end-of-line fault on relay A (7SA513) are tabled below.....	166
Table 4.10: Comparison of no-load versus 500 MVA load export for end-of-line fault on relay B (REL531) are tabled below.....	167
Table 4.11: Remote end in-feed influence on apparent relay A reach.....	173
Table 4.12: Remote end in-feed influence on apparent relay B reach.....	174
Table 4.13: Remote in-feed impact on loop impedance measurement for relay A. .	178
Table 4.14: Remote in-feed impact on loop impedance measurement for relay B ..	178
Table 4.15: Calculated versus measured relay loop reaches for relay A.....	179
Table 4.16: Calculated versus measured relay loop reaches for relay B.....	179
Table 5.1: Impedance comparison for Athene - Invubu line	200
Table 5.2: Corrected impedance values for Athene - Invubu line.....	201
Table 5.3: Impedance comparison for Hydra - Perseus line.....	209
Table 5. 4: Summary of settings for Georgedale - Klaarwater feeder.....	239

List of Definitions

The definitions of system security and reliability can be summarized as follows (listed alphabetically):

Bundle of conductors (conductor bundle) - a group of conductors grouped closely together so as to minimize the effect of corona, as well as to function together as a single conductor within a single or multi-phase circuit.

Displacement voltage – is defined by relay manufacturer A as the total zero sequence voltage ($3V_0$) that develops during single-phase-to-earth system faults.

Geometric Mean Distance (GMD) - the mn^{th} root of the product of all the distances between two sets of bundle conductors respectively having m and n number of conductors within a bundle [1].

Geometric Mean Radius (GMR), also termed Self Geometric Mean Distance - the n^2 root of the product of the distances from every conductor within the bundle of conductors to itself and to every other conductor within the bundle, n being the number of conductors within the bundle [1].

Resistivity - the ratio of an electric field to the current density [3].

System Minutes – (MW energy lost * Number of Minutes)/(MW Peak of previous year – International Load)

System reliability - the probability to remain in the operating state as a function of time, given that the system started in the operating state at time $t = 0$ [10].

System security - the ability of the system to refrain from unnecessary operations [10].

List of symbols

α = angle

α_1 = angle between strands on same layer with centre strand

β = Source voltage angle

δ = depth from conductor surface

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

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

ϕ_L = Phase angle of the short circuit phase current

ϕ_{Loop} = Resistive fault blinder angle for zone measurement of relay B

ϕ_V = Phase angle of the short circuit voltage

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

λ_n = Lay length of conductor layer

φ = number flux linkages of a circuit in weber-turns

φ_a = Total flux for phase A

φ_{1p1} = Flux for conductor 1 due to current in conductor 1

φ_{1p2} = Flux for conductor 1 due to current in conductor 2

φ_1 = Total flux for conductor 1

φ_{int} = Total flux linkages inside a conductor

φ_{ext} = Total external flux of a conductor

φ_{mutual} = Mutual flux of conductor

$\varphi_{n, outer}$ = Outer magnetic flux associated with each layer

$\varphi_{n, inner}$ = Inner magnetic flux associated with each layer

$d\psi$ = Change in flux linkages

$d\varphi$ = Change in flux

$d\varphi/dt$ = rate of change of flux

di/dt = rate of change of current

ϵ_0 = Permittivity of earth

Ω = Ohm

ρ = Resistivity

ρ_a = Resistivity of non-ferrous material

ρ_{al} = Resistivity of aluminium

ρ_e = Earth resistivity

ρ_m = Mass resistivity

ρ_s = Resistivity of steel or ferrous material

ρ_{20} = Conductor resistivity at temperature of 20° C

μ_0 = Relative permeability of air

μ = Absolute permeability of conductor

μ_r = Relative permeability of conductor

ω = angular frequency of current

ω_0 = Fundamental system frequency

γ = Star connection

Δ = Delta connection

$>$ = Greater than sign

$<$ = Smaller than sign

List of variables

A = Conductor cross-sectional area

A = Constant in J.R. Carson's single series expansion

A_s = Cross section area of the steel core

B = Magnetic flux density

C = Degree of series compensation

D = Diameter

d = Diameter of each strand

$D_{aa'} \dots D_{am}$ = Distances between conductor a in composite conductor X and conductor a' through to m in composite conductor Y

$D_{a'a} \dots D_{a'n}$ = Distance between conductor a' in composite conductor Y and conductor a through n in composite conductor X

$d_{a1ij, jj}$ = distance between strands on same layer

D_e Distance between overhead conductor and its image

D_{eq} = Geometric mean distance between conductors of phases a , b and c

D_{ik} = distance between conductor l and image of conductor k

d_{ik} = distance between conductor l and conductor k

D_n = Geometric Mean Radius of of conductor layer n

D_n = Mean diameter (GMR) of layer n

D_{1n} = Distances between conductors $1, 2, 3, \dots, n$

D_p = Mean diameter (GMR) of layer p

D_{1p} = Distance of point P from conductor 1

D_{2p} = Distance of point P from conductor 2

d_{al_Ln} = Product of distances between strands in the n^{th} aluminium layer of conductor, ($n \in 1, 2, \dots, m, m \neq n$)

d_{Ln_m} = Product of distances between strands between different layers in the conductor, ($n \in 1, 2, \dots, m$)

$d_{si, j}$ = distance between strands in same layer

d_s = Skin depth

D_s = Geometric Mean Radius for a solid conductor

D_{ss} = Geometric Mean Radius for a single strand

D_s^b = Geometric Mean Radius for bundle conductor

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

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

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

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

E_a = A-phase source voltage

E_b = B-phase source voltage

E_c = C-phase source voltage

E_{ab} = A-B-phase voltage

E_{bc} = B-C-phase voltage

E_{ca} = C-A-phase voltage

E_r = Resultant parallel source voltage

e = induced voltage

f = Electrical system frequency

F_{sub} = Sub-synchronous frequency

F_{net} = network frequency

H = Magnetic field strength

h_i = average height above earth of conductor i

I_{A1} = First layer current in stranded conductor

I_{A11} = Third layer current in stranded conductor

I_a = A-phase current

I_B = Capacitor bank base current

I_b = B-phase current

I_b = Base current

I_c = C-phase current

I_E = Short circuit earth current (rms)

$I_{E>}$ = Earth current detection threshold value for relay A

I_F = Fault current

I_L = Short circuit phase current (rms)

$I_{L(app)}$ = Load current due to applied voltage

$I_{L(pu)}$ = Load current in per unit

I_{Lu} = Normalised line current

I_N = Rated capacitor bank current, A rms

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

I_s = Current in the steel core
 I_{TH} = Capacitor threshold rating, A rms
 $I_1 \dots I_n$ = Current in the different layers
 I_{L1} = Faulted phase current
 i_{L1} = Phase current for phase L_1
 i_{L2} = Phase current for phase L_2
 i_{L3} = Phase current for phase L_3
 I_N = Earth return current
 I_0 = Zero sequence current
 I_1 = Positive sequence current
 I_2 = Negative sequence current
 J = Current density at depth δ from the conductor surface
 J_s = current density at the conductor surface
 K = enlarging factor due to remote in-feed
 K_{bc} = Capacitor bank constant
 K_F = Impedance enhancement factor
 K_{gf1} = Grading factor used with series capacitors
 km = Kilometer
 K_p = Capacitor bank constant
 k_n = Conductor length factor
 K_L = Generic earth compensation factor
 K_N = Earth loop compensation factor for relay B
 K_R = Resistance earth loop correction factor for relay A
 K_{trans} = transient factor used with series capacitors
 K_X = Reactance earth loop correction factor for relay A
 K_0 = Generic relay earth fault compensation factor
 k_1 = Coefficient of current concentration (specific to conductor type)
 k_2 = Coefficient of current concentration (specific to conductor type)
 L = Inductance of conductor
 L_a = Inductance per phase
 L_{arc} = length of the fault arc in meters
 L_{av} = Average inductance per conductor
 L' = conductor inductance to neutral inclusive of skin effect

L'' = total conductor inductance to neutral inclusive of skin and proximity effect
 L_e = external conductor inductance to neutral assuming uniform current distribution
 L_i = internal conductor inductance assuming uniform current distribution
 L_i' = internal conductor inductance inclusive of skin effect
 L_{int} = Internal inductance of a conductor
 L_{ext} = External inductance of a conductor
 L_N = line earth return inductance for high-speed zone of relay B
 L_{tot} = Total self-inductance of a conductor
 L_1 = Self-inductance of conductor 1
 L_2 = Self-inductance of conductor 2
 m = Mass
 n = Number of layers in a stranded conductor
 n_{al} = number of aluminium strands in conductor
 n_i = Number of strands in layer i
 n_j = number of strands in layer j
 n_s = Number of strands in conductor
 P, Q = correction terms for earth return
 p = per unit value of distance to fault on overhead line
 \bar{p} = complex depth
 ρ = Percentage protection relay reduction reach required due to series compensation
 R = Resistance
 R' = effective ac-resistance inclusive of skin effect
 R_{ap} = Apparent resistance measured for protective zone
 R'' = Total effective ac-resistance inclusive of skin and proximity effect
 $RA1$ = Fault detector resistive reach limit 1 for relay A
 $RA2$ = Fault detector resistive reach limit 2 for relay A
 R_{ac} = ac-resistance
 r_d = Frequency dependent resistance
 R_{dc} = dc-resistance
 R_E, R_C = Equivalent series capacitor resistance
 R_E p.u. = per unit series capacitor resistance
 R_E/R_L = Resistance ratio
 $(R_E/R_L)_{SET}$ = Resistance ratio settings applied to relay A

$R'_{i\text{-internal}}$ = ac-resistance of conductor i in ohm per unit length
 R_F = Fault resistance
 $RFPE$ = Fault resistance setting for phase-to-earth element of relay B
 R_{Lm-Ln} = Phase-to-phase fault loop resistance measurement
 R_m = Measured fault loop resistance for relay B
 R_{phs} = Phase Selector resistance measured
 R_0 = Resistance of material at base temperature
 $R0PE$ = Zero sequence resistance setting for phase-to-earth element of relay B
 $R0PE_{ZM}$ = Zone (M) Zero sequence resistance setting for phase-to-earth element of of relay B
 $R1PE$ = Positive sequence resistance setting for phase-to-earth element of relay B
 $R1PE_{ZM}$ = Zone (M) Positive sequence resistance setting for phase-to-earth element of relay B
 $R1PP$ = Positive sequence resistance setting for phase-to-phase element
 $R1PP_{PHS}$ = Resistive phase-to-phase setting for phase selector element
 $RFPE$ = Phase-to-earth fault loop resistance setting for relay B
 $RFPE_{ZM}$ = Zone (M) Phase-to-earth fault loop resistance setting for relay B
 $RFPE_{PHS}$ = Zone (M) Phase selector fault loop resistance setting for relay B
 $RFPP$ = Fault resistance setting for phase-to-phase element
 $RFPP_{PHS}$ = Fault resistance setting for phase selector element
 R_{FN} = the loop resistance for high-speed zone of relay B
 R_{Ph-E} = Phase-to-earth resistance fault loop measurement
 R_t = dc-resistance at temperature t
 r = radial distance of point P , radius of conductor
 r_a = dc-resistance from manufacturers conductor tables
 r_a' = Geometric Mean Radius of conductor a
 r_d = Frequency dependent resistance of the image conductor
 r_i = radius of conductor i ,
 r_s = Conductor strand radius
 r_1 = Radius of conductor 1
 r_2 = Radius of conductor 2
 S = Maximum apparent load MVA
 S_b = MVA base

T = Constant for the specific conductor material
 T_{20} = Constant for the specific conductor material at temperature of 20° C
 t = Temperature
 U_{i1}, U_{i2}, U_{i3} = Induced voltages per layer in stranded conductor
 U_E – Zero sequence voltage ($3V_0$)
 V_a = A-phase voltage
 V_b = B-phase voltage
 V_c = C-phase voltage
 V_{aF} = A-phase voltage at point of fault
 V_{app} = Applied load voltage
 V_{a1} = Positive sequence voltage for phase A
 V_b = Base voltage
 V_{L1} = Faulted phase voltage
 V_{L1-E} = Phase-to-earth voltage for phase L_1
 V_{L2-E} = Phase-to-earth voltage for phase L_2
 V_{L3-E} = Phase-to-earth voltage for phase L_3
 $V_{L(pu)}$ = Load voltage in per unit of applied voltage
 V_{mov} = voltage across the MOV
 V_{Ph-E} = Short circuit phase voltage (rms)
 V_{PF} = Pre-fault voltage
 V_0 = Zero sequence voltage
 V_1 = Positive sequence voltage
 V_2 = Negative sequence voltage
 x = factor in per unit of line length
 X = the set positive sequence reactance for high-speed zone of relay B
 X_C = Series capacitor capacitive reactance
 X_F = Fault reactance
 $X'_{i\text{-internal}}$ = internal reactance of conductor i
 x_{ik} = horizontal distance between conductors i and k
 X_{CE}, X_C = Equivalent series capacitor reactance
 X_{CE} p.u. = per unit series capacitor reactance
 X_E/X_L = Inductance ratio
 $(X_E/X_L)_{SET}$ X_L = Inductive reactance ratio settings applied to relay A

X_{Lm-Ln} = Phase-to-phase fault loop reactance measurement

X_m = Measured fault loop reactance for relay B

X_N = Rated value of the capacitive reactance, A rms

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

X_{NH} = the set earth return reactance for high-speed zone of relay B

$X_{n,outer}$ = Outer mutual inductive reactance

$X_{n,inner}$ = Inner mutual inductive reactance

X_{nn} = Complex self-inductive reactance of the nn-th layer

X_{PH-E} = Phase-to-earth reactance fault loop measurement for relay A

X_{phs} = Phase Selector reactance measured

X_{pq} = Complex mutual inductive reactance of the nn-th layer

$X+A$ = Forward reactive reach limit for relay A

$X-A$ = Reverse reactive reach limit for relay A

$X0PE$ = Zero sequence phase-to-earth element reactive reach setting parameter for relay B

$X0PE_{PHS}$ = Zero sequence phase selector element reactive reach setting parameter for relay B

$X0PE_{ZM}$ = Zone (M) Zero sequence phase-to-earth element reactive reach setting parameter for relay B

$X1PE$ = Positive sequence phase-to-earth element reactive reach setting parameter for relay B

$X1PE_{PHS}$ = Positive sequence phase selector element reactive reach setting parameter for relay B

$X1PE_{ZM}$ = Zone (M) Positive sequence phase-to-earth element reactive reach setting parameter for relay B

$X1PP$ = Positive sequence reactance setting for phase-to-phase element relay B

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

X_1 = Overhead line inductive reactance

X_0 = Zero sequence reactance of overhead line

X_1 = Positive sequence reactance of overhead line

X_2 = Negative sequence reactance of overhead line

Y_0 = Zero sequence admittance

Y_1 = Positive sequence admittance
 Y_2 = Negative sequence admittance
 Y_r = Resultant parallel network admittance
 Z_a = A-phase overhead line impedance
 Z_{ABC-N} = Three-phase impedance loop
 Z_{ap} = Apparent impedance
 Z_{A-N} = A-phase-to-earth impedance loop measurement
 Z_{B-N} = B-phase-to-earth impedance loop measurement
 Z_{C-N} = C-phase-to-earth impedance loop measurement
 Z_b = B-phase overhead line impedance
 Z_c = C-phase overhead line impedance
 Z_E = Earth impedance in parallel with earth wire
 Z_{Eii} = Earth contribution term in conductor impedance calculation
 Z_{ii} = Self impedance of conductor
 Z_{ik} = mutual impedance of conductor
 Z_g = Fault impedance to earth in phase-to-phase-to-earth faults
 Z_{Gii} = Geometric term in conductor impedance calculation
 Z_{gen} = Impedance calculated with generic equation
 Z_F = Fault impedance
 Z_L = Loop impedance
 $Z_L AB$ = Positive sequence impedance for circuit AB
 $Z_L BC$ = Positive sequence impedance for circuit BC
 Z_{loop} = Loop impedance
 $Z_{LOADMIN}$ = Minimum load impedance
 Z_{L1-N} = Phase-to-earth loop fault impedance for phase L_1 (*A-phase*)
 Z_{L2-N} = Phase-to-earth loop fault impedance for phase L_2 (*B-phase*)
 Z_{L3-N} = Phase-to-earth loop fault impedance for phase L_3 (*C-phase*)
 Z_n = Neutral-to-earth impedance
 Z_N = Earth-return impedance
 Z_{phs} = Phase Selector impedance measured
 Z_{relA} = Impedance calculated with the equation for relay A
 Z_{relB} = Impedance calculated with the equation for relay B
 Z_{s1} = Source 1 impedance

Z_{s2} = Source 2 impedance

Z_{TA} = Transformer A impedance

Z_{TB} = Transformer B impedance

Z_0 = Zero sequence impedance

Z_1 = Positive sequence impedance

Z_2 = Negative sequence impedance

ΔI = changes in phase current between samples, relay B

$\Delta R'$, $\Delta X'$ = J.R. Carson's correction terms for earth return effects

Δt = change in time

Z_Y = Star connected load impedance

Z_{Δ} = Delta connected load impedance

List of abbreviations

AAC = Stranded aluminium conductor

AAAC = All aluminium conductors

ACSR = Aluminium conductor steel reinforced

GMR = Geometric Mean Radius

GMD = Geometric Mean Distance

MOV = Metal Oxide Varistor

MOVS = Metal Oxide Varistors

ms = milliseconds

MVA = Mega volt ampere

Mvar = Mega volt ampere reactive

MW = Mega Watt

kV = Kilovolt

s = Seconds