

# **Improving High Voltage Power System Performance**

## **Using Arc Suppression Coils**

by

**Robert Thomas Burgess B Com MIEAust CPEng RPEQ**

**A Dissertation**

Submitted in Fulfilment

of the Requirements

*for the degree of*

**Doctor of Philosophy**

at the

**University of Southern Queensland**

**Faculty of Engineering & Surveying**

**2011**

## ABSTRACT

Arc suppression coils provide a low cost method of increasing both the reliability and safety of high voltage transmission and distribution systems. Although the concept is not new, the advent of modern control equipment allows fresh opportunities for them to be used to save lives and to decrease the cost and inconvenience to industry and the community in general that is caused by electricity supply interruptions without incurring large expenditure. Earth fault currents are reduced to almost zero, thus eliminating many short time power supply interruptions and preventing damage to the electricity supply system at the time of the initial fault. Because of the reduction in damage at the time of the fault, many longer duration interruptions are avoided. It is common for live high voltage conductors to be close to the ground and for the fault not to be detected by conventional power system protection equipment. Arc suppression coil systems can detect high impedance earth faults and broken conductors which cannot be detected by conventional protection systems.

There are many system abnormalities which can cause neutral voltages in arc suppression coil systems. The appropriate action to be taken by the protection system depends on the type of system abnormality. The causes of neutral voltages in arc suppression coil systems are analysed and criteria are developed to differentiate between them based on the phase angle and magnitude of the neutral voltage. Fully computerised power system protection systems are now being implemented. These modern protection systems will be able to utilise the criteria developed in this research to take immediate appropriate action based on the neutral voltage caused by the system abnormality.

In existing distribution systems there is a widespread use of two single phase pole mounted auto-transformers connected in open-delta configuration to provide economic in-line three phase voltage regulation. An original method of representing open delta regulators in symmetrical component analyses is developed. It is shown that when open-delta regulators are used in a power system equipped with an arc suppression coil very high voltages can occur. A solution is proposed whereby three single phase pole mounted auto-transformers connected in a closed-delta arrangement are used.

One of the potential problems with these systems is cross country faults caused by the neutral voltage displacement combined with the transient voltages at the time of the initial earth fault. These transient over-voltages are analysed in detail and a method of testing the capability of existing system components to withstand the over-voltages is developed. Simple methods to estimate the transient voltages on overhead power systems are derived. A new method of minimising the transient over-voltages is proposed.

## **CERTIFICATION OF DISSERTATION**

I certify that the ideas, experimental work, results, analyses, software and conclusions reported in this dissertation are entirely my own effort except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any other award except where otherwise acknowledged.

---

Signature of Candidate

---

Date

## **ENDORSEMENT**

---

---

Signatures of Supervisors

---

---

Date

## **ACKNOWLEDGMENTS**

I sincerely acknowledge and thank the following people for their assistance, guidance, support and encouragement throughout the duration of this project.

My supervisor, Dr Tony Ahfock, provided in depth assistance and guidance throughout the project. He always maintained a keen interest in the work and went out of his way to make himself available for consultation whenever I needed it. This work has been discussed in detail with Tony and reviewed by him as the project progressed.

Other academic and technical university staff provided support, technical facilities and most welcome words of encouragement.

Steve Macdonald and Taz Scott of Orion New Zealand Limited showed me one of their existing Earth Fault Neutralizer installations and provided invaluable information on their operating experience.

Ergon Energy staff provided access to the high voltage testing facility and invaluable assistance with the high voltage tests.

My wife, Margaret, endured my seemingly endless time engrossed in the work. She supported and encouraged me. She helped with the proof reading of this dissertation.

# CONTENTS

<b>ABSTRACT</b> .....	<b>ii</b>
<b>CERTIFICATION OF DISSERTATION</b> .....	<b>iii</b>
<b>ACKNOWLEDGMENTS</b> .....	<b>iv</b>
<b>CONTENTS</b> .....	<b>v</b>
<b>LIST OF FIGURES</b> .....	<b>ix</b>
<b>LIST OF TABLES</b> .....	<b>xiii</b>
<b>PUBLICATIONS</b> .....	<b>xiv</b>
<b>Chapter 1 JUSTIFICATION FOR THE PROJECT</b> .....	<b>1</b>
1.1 Principle of operation of arc suppression coils.....	1
1.2 Reasons for using arc suppression coils .....	1
1.3 Current Usage of arc suppression coils .....	2
1.4 Aim of the research .....	3
1.4.1 Analysis of neutral voltages and appropriate responses. ....	3
1.4.2 In-line single phase voltage regulators.....	3
1.4.3 Minimising cross-country faults caused by voltage transients .....	4
1.5 Outline of dissertation .....	6
1.5.1 Analysis of neutral voltages .....	6
1.5.2 In-line single phase voltage regulators.....	6
1.5.3 Minimising cross-country faults caused by voltage transients .....	6
1.6 Summary of research outcomes.....	6
1.6.1 Analysis of neutral voltages .....	6
1.6.2 In-line single phase voltage regulators.....	6
1.6.3 Minimising cross-country faults caused by voltage transients .....	7

<b>Chapter 2</b>	<b>LITERATURE REVIEW AND SCOPE .....</b>	<b>8</b>
2.1	Usage of arc suppression coils .....	8
2.2	Analysis of neutral voltages .....	9
2.3	In-line single phase voltage regulators .....	10
2.4	Minimising Cross Country Faults .....	10
<b>Chapter 3</b>	<b>METHODOLOGY .....</b>	<b>12</b>
3.1	Analysis of neutral voltages .....	12
3.2	In-line single phase voltage regulators .....	12
3.3	Minimising cross country faults .....	13
<b>Chapter 4</b>	<b>ANALYSIS OF NEUTRAL VOLTAGES .....</b>	<b>14</b>
4.1	An accurately tuned simple system .....	14
4.2	Causes of abnormal neutral voltages .....	19
4.2.1	A line to earth fault. ....	19
4.2.2	Out of balance in the line to earth capacitance. ....	19
4.2.3	An open circuit in one phase line .....	19
4.3	A line to earth fault.....	19
4.4	A disturbance in the line to earth capacitance balance.....	21
4.5	An open circuit .....	24
4.5.1	An open circuit in one phase with no earth fault .....	25
4.5.2	The effect of distributed generation. ....	28
4.5.3	Open circuit with a line to earth fault.....	31
4.6	Appropriate actions to take on detecting an abnormal neutral voltage. ....	35
4.7	Evaluation of fault and appropriate actions.....	37
4.8	Summary .....	39

<b>Chapter 5</b>	<b>IN-LINE VOLTAGE REGULATORS .....</b>	<b>41</b>
5.1	Open-delta regulators .....	41
5.1.1	Modelling of open-delta regulators using symmetrical components ...	44
5.1.2	Analysis of a simple system with open delta regulators .....	48
5.2	Three star connected auto-transformers .....	56
5.2.1	Three star connected single phase auto-transformers with the star point earthed.....	57
5.2.2	Three star connected single phase auto-transformers with the star point unearthed .....	59
5.3	Three delta connected single phase auto-transformers.....	61
5.3.1	Modelling of three delta connected auto-transformers using symmetrical components.....	62
5.3.2	Analysis of a simple system with delta connected auto-transformers .	72
5.4	Static VAR compensation .....	78
5.5	Summary .....	79
5.5.1	Results from modelling of open-delta voltage regulators .....	79
5.5.2	Results from modelling of three star connected auto-transformers. ....	79
5.5.3	Results from modelling of three delta connected auto-transformers. ..	79
5.5.4	Results for static VAR compensation .....	80
5.5.5	Summary of results for in-line voltage regulators .....	80

<b>Chapter 6</b>	<b>MINIMISING CROSS COUNTRY FAULTS.....</b>	<b>82</b>
6.1	A radial line without any branches .....	83
6.1.1	The worst case scenario for the peak voltages .....	84
6.1.2	Estimation of frequency and decay time for a typical 11 kV overhead line type.....	88
6.1.3	Approximate methods for transient voltage estimation .....	91
6.2	Typical zone substation distribution systems .....	93
6.3	Implications for existing systems .....	96
6.4	Testing of system components .....	97
6.5	Proposed method of controlling transient over-voltages.....	98
6.6	Summary .....	101
<b>Chapter 7</b>	<b>CONCLUSIONS AND FURTHER WORK .....</b>	<b>102</b>
7.1	Analysis of neutral voltages .....	102
7.2	In-line single phase voltage regulators .....	102
7.3	Minimising cross country faults .....	103
7.4	Cost benefit analyses .....	103
<b>Chapter 8</b>	<b>REFERENCES .....</b>	<b>105</b>
<b>APPENDIX A1 .....</b>	<b>ANALYSIS OF AN OPEN CIRCUIT COMBINED WITH LINE TO EARTH FAULTS.....</b>	<b>111</b>
A1.1	Unknown quantities and equations .....	111
A1.2	A matlab script to solve the equations .....	113
<b>APPENDIX A2 .....</b>	<b>ZERO SEQUENCE CAPACITANCE OF TRANSFORMERS CONNECTED TO THE LINE.....</b>	<b>115</b>

## LIST OF FIGURES

Figure 1.1 Connection diagram of a high voltage open-delta voltage regulator.....	4
Figure 1.2 Typical line voltages before and after a single phase to earth fault on an 11 kV distribution system fitted with an arc suppression coil. ....	5
Figure 4.1 Simple single line power system. ....	14
Figure 4.2 Symmetrical component network for the simple system with a single line to earth fault at the load end. ....	16
Figure 4.3 Fault currents for the simple system with a low impedance single line to earth fault and with various values of arc suppression coil parameters. ....	17
Figure 4.4 Neutral voltages for the simple system with various resistances of single line to earth faults and with various values of arc suppression coil parameters. ....	18
Figure 4.5 Neutral voltage for a simulated single line to earth fault varying from zero to 1 M $\Omega$ , and with faults on each phase line in turn. The reference phase angle is A to N. ....	20
Figure 4.6 Urban Zone substation area 11 kV network. ....	21
Figure 4.7 Symmetrical component network for the simple system with an out of balance line to earth capacitance. ....	22
Figure 4.8 Neutral voltage for a simulated out of balance capacitance varying from plus 10% of $C_L^0$ to minus 10% of $C_L^0$ on each phase line in turn. The reference phase angle is A to N. ....	23
Figure 4.9 Symmetrical component network for the simple system with the line impedances ignored, the arc suppression coil losses represented by a single resistor and out of balance line to earth capacitance. ....	24
Figure 4.10 Neutral voltage for the simple system with the line impedances ignored, the arc suppression coil losses represented by a single resistor and out of balance capacitance varying from zero to infinity. The reference phase angle is A to N. ....	24
Figure 4.11 Sequence network for the simple system as shown in Figure 4.1 with an open circuit in one conductor. ....	25
Figure 4.12 Neutral voltage for a simulated open circuit on each phase line in turn, with the proportion of the network on the load side of the open circuit varying continuously from 0% to 100% and with 100 kW of connected load on the load side. The reference phase angle is A to N. ....	26
Figure 4.13 Sequence network of the simple system with an open circuit in one conductor and with line inductances and all losses ignored. ....	27
Figure 4.14 Delta-star connected transformer with an open circuit in one line. ....	29

Figure 4.15 Sequence network for the simple system with an open circuit in one conductor and with isolated three phase generation on the load side. ....	29
Figure 4.16 Sequence network for the simple system with an open circuit in one conductor, with line inductances and all losses ignored and with isolated three phase generation on the load side.....	30
Figure 4.17 EMTP representation of an open circuit in one phase line and isolated generation.....	31
Figure 4.18 Sequence network for the simple system with an open circuit and simultaneous single line to earth faults at the same location and in the same conductor.....	32
Figure 4.19 Neutral voltage for an open circuit at three locations, and a line to earth fault at the same location on the load side varying from zero to 1 M $\Omega$ , and with faults on each phase line in turn. The reference phase angle is A to N. ....	33
Figure 4.20 Neutral voltage for an open circuit at three locations, and a line to earth fault at the same location on the source side varying from zero to 1 M $\Omega$ , and with faults on each phase line in turn. The reference phase angle is A to N. ....	34
Figure 4.21 Bypassing of arc suppression coil.....	35
Figure 4.22 Possible fault types and appropriate actions deduced from the neutral voltage. ....	38
Figure 4.23 Logic for taking action on the basis of the neutral voltage.....	39
Figure 5.1 Open-delta regulator connections. ....	41
Figure 5.2 Pole mounted open-delta regulator.....	42
Figure 5.3 Voltage phasor diagram for an open-delta regulator. ....	43
Figure 5.4 Symmetrical component representation of an open-delta regulator. ....	48
Figure 5.5 Simple 11 kV System showing zero sequence and earthing components. ....	49
Figure 5.6 Symmetrical component representation of a simple system with an open-delta voltage regulator.....	50
Figure 5.7 Sequence network representation of the simple system with an open-delta regulator referred to the zero sequence side.....	51
Figure 5.8 EMTP Representation of the simple system with an open-delta voltage regulator. ....	52
Figure 5.9 Sequence Network for the simple system with line inductances and all losses ignored. ....	53
Figure 5.10 EMTP Representation of the simple system with an open-delta voltage regulator and a saturable magnetic cored suppression coil.....	54

Figure 5.11 Magnetizing curve of the earthing inductor.....	55
Figure 5.12 Phase voltages for the simple system with a practical, saturable earthing inductor and a voltage regulator ratio of 1.1. ....	56
Figure 5.13 Two auto-transformers mounted on a single pole .....	56
Figure 5.14 Three auto-transformers mounted on a single pole. ....	57
Figure 5.15 Three star connected auto-transformer with the star point earthed voltage regulator connections. ....	58
Figure 5.16 Zero sequence representation of a three star connected auto-transformers with the star point earthed .....	58
Figure 5.17 Three star connected auto-transformers with the star point unearthed voltage regulator connections. ....	59
Figure 5.18 Zero sequence representation of a three star connected auto-transformers with the star point unearthed. ....	61
Figure 5.19 Three delta connected auto-transformers voltage regulator connections	62
Figure 5.20 Phasor diagram for the normal operation of a three delta connected auto-transformer voltage regulator. ....	63
Figure 5.21. Currents in a three delta connected auto-transformer voltage regulator. ....	64
Figure 5.22. Zero sequence currents in a three delta connected auto-transformer voltage regulator.....	65
Figure 5.23 Phasor diagram for a three delta connected auto-transformer voltage regulator with $P_b$ greater than $P_a$ and $P_c$ . ....	69
Figure 5.24 Positive sequence voltage ratio provided by three delta connected auto-transformers.....	71
Figure 5.25 Positive sequence voltage boost provided by three delta connected auto-transformers as a ratio of the voltage boost of each individual auto-transformer.....	71
Figure 5.26 Three delta connected auto-transformers in a simple 11 kV system showing zero sequence and earthing components. ....	72
Figure 5.27 Zero sequence network of the simple system. ....	73
Figure 5.28 EMTP representation of three single phase delta connected auto-transformers in the simple system.....	75
Figure 5.29 Neutral voltage, for each auto-transformer in turn out of ratio by plus 10 %, and the portion of the network on the load side of the regulator varying continuously from 0 % to 100 %.....	76

Figure 5.30 Possible fault types and appropriate actions deduced from the neutral voltage and in-line voltage regulator alarms. ....	77
Figure 5.31 Logic for taking action on the basis of the neutral voltage and in-line voltage regulator alarms. ....	78
Figure 6.1 Simple 11 kV System showing zero sequence and earthing components. ....	83
Figure 6.2 Symmetrical network representation of the simple system. ....	84
Figure 6.3 Transient voltages for the single line model as shown by EMTP. ....	90
Figure 6.4 Transient voltages on the un-faulted phase lines of the physical model. .	91
Figure 6.5 Time constants for the decay in transient oscillations for typical 11 kV overhead line construction. ....	92
Figure 6.6 Time constants for the decay in transient oscillations for a typical 11 kV overhead line construction in cycles of the transient oscillations. ....	93
Figure 6.7 Urban zone substation distribution system. ....	94
Figure 6.8 Transient voltages on a healthy phase of the urban distribution system. .	94
Figure 6.9 Rural zone substation distribution system. ....	95
Figure 6.10 Transient voltages on a healthy phase of the rural distribution system. .	96
Figure 6.11 Arrangement for testing network system components. ....	97
Figure 6.12 Test voltage applied to power system components. ....	98
Figure 6.13 Thyristor bank to control transient over-voltages. ....	99
Figure 6.14 Transient voltages on a healthy phase of the urban distribution system with thyristor control. ....	100
Figure 6.15 Transient voltages on a healthy phase of the rural distribution system with thyristor control. ....	100
Figure A1.1 Symmetrical component representation of an open circuit with a single line to earth fault on either side of the open point and on the same phase line. ....	111
Figure A2.1 Connections for testing the zero sequence capacitance of a typical transformer .....	115

## LIST OF TABLES

Table 5.1 Summary of in-line voltage regulator connections in terms of criteria for successful arc suppression coil operation .....	81
Table A1.1 Unknown symmetrical component quantities in a system with a single line to earth fault on either side of the open point and on the same phase line.....	112
Table A2.1 Capacitance of HV winding to LV winding and earth for a sample of typical 11 kV to 415 V transformers.....	116

## **PUBLICATIONS**

The following papers are direct outcomes of this research project.

### **Published**

[1] R. Burgess and A. Ahfock, "The use of arc-suppression coils in power systems with open-delta regulators," in *Universities Power Engineering Conference (AUPEC), 2010 20th Australasian*, pp. 1-6.

[2] R. Burgess and A. Ahfock, "Minimising the risk of cross-country faults in systems using arc suppression coils," *Generation, Transmission & Distribution, IET*, vol. 5, pp. 703-711.

[3] R. Burgess and A. Ahfock, "The use of voltage regulators in power systems with arc-suppression coils," in *Universities Power Engineering Conference (AUPEC), 2011 21st Australasian*

### **Under consideration for publication**

[4] R. Burgess and A. Ahfock, "Evaluation of neutral voltages in arc suppression coil systems".