

INVESTIGATING THE DYNAMIC PERFORMANCE OF GENERATOR-POLE-SLIP PROTECTION

by

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DECLARATION

“As the candidate’s Supervisor I agree/do not agree to the submission of this dissertation.”

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ABSTRACT

Generators in an interconnected power system normally remain in synchronism with one another. However, severe faults that lead to loss of heavily loaded generators or large load blocks can cause oscillations in the generator rotor angles that are large enough to result in a pole slip in which a generator, or a group of generators, loses synchronism with the rest of the power system. When a generator pole slips and falls out-of-step with the power system, the generator and system voltages sweep past one another at a slip frequency, producing a pulsating current, which can be greater than a three-phase fault at the generator terminals. An out-of-step generator should therefore be isolated from the power system to prevent damage to the generator, generator transformer and the turbine.

This dissertation analyses the dynamic performance of generator-pole-slip protection during various stable and unstable power swing events. For the purpose of this dissertation, the Siemens 7UM622 machine protection relay is used to test the response of generator-pole-slip protection. This is done in two stages, firstly, within the DigSilent PowerFactory software by modelling the Siemens 7UM622 relay and then applying simulated time domain stable and unstable power swing conditions to the relay model to evaluate its response. Secondly, the actual 7UM622 hardware relay is injected with currents and voltages, which are produced during the time domain pole-slip simulations to determine if the relay hardware device operates in accordance with the Siemens relay technical manual.

The power system analysed in the dissertation was heavily interconnected and a generator pole slip was rather unlikely. If an unlikely generator pole slip were to occur when the system is operating in a normal configuration (all power station outgoing feeders in service), the generator-pole-slip protection was able to detect and disconnect the generator after a single pole-slip cycle.

The critical fault clearing time decreases when an outgoing power station feeder is out of service (n-1 contingency) and therefore the probability of a generator pole slip increases. If a generator pole slip occurs when operating the network under a n-1 contingency, the pole-slip system electrical centre is usually located within the transmission network. In practice, the generator-pole-slip protection settings that are implemented at the power station do not reach into the transmission network (zone 2 disabled). Therefore, if a pole slip were to occur under a n-1 contingency, the generator-pole-slip protection would not be able to detect this condition. The zone 2 generator-pole-slip protection should rather reach into the transmission network, but the trip should only be issued after the third or fourth pole-slip cycle to allow the transmission line out-of-step protection sufficient time to separate the network into islands.

The pole-slip function of the Siemens 7UM622 relay model within DigSilent PowerFactory operated in accordance with the Siemens relay technical manual and can be used in future to optimise and test generator-pole-slip protection settings.

In the majority of cases, the Siemens 7UM622 relay hardware device operated in accordance with the Siemens relay technical manual. The only time that the relay operated incorrectly was when the measured impedance trajectory of a three-phase fault lingers on the inside and outside edge of the pole-slip impedance characteristic before exiting the pole-slip impedance characteristic.

The stable and unstable power swing COMTRADE files that were generated for the tests performed in this dissertation can be used in future to test the generator-pole-slip protection at Kendal power station since it is rather difficult to test the pole-slip protection function properly without a COMTRADE file.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	iii
ABSTRACT	iv
TABLE OF CONTENTS	vi
LIST OF FIGURES	x
GLOSSARY OF TERMS	xiii
LIST OF ABBREVIATIONS	xiv
CHAPTER 1: INTRODUCTION	1
1.1 Introduction	1
1.2 Dissertation Objectives	4
1.3 Outline of Dissertation	5
CHAPTER 2: TRANSIENT STABILITY	6
2.1 Transient Stability	6
2.1.1 Transfer impedance under normal network operating conditions	7
2.1.2 Transfer impedance with one line out of service	7
2.1.3 Transfer impedance with a three-phase fault on line 2.....	8
2.1.4 Power transfer capability plot.....	12
2.2 Summary	14
CHAPTER 3: POWER SWING IMPEDANCE	15
3.1 Deriving An Expression For A Power Swing Impedance Locus.....	15
3.2 Understanding Power Swing Impedance Trajectories	18
3.2.1 Generator reactance during a pole slip	18
3.2.2 Swing impedance ($n = 1$)	18
3.2.3 Swing impedance for $0.6 < n < 1.7$	21
3.3 System Electrical Centre Or Voltage Zero	22

3.4	Damaging Effects Of A Pole Slip	27
3.5	Pole Slip Frequency Or Angular Velocity	28
3.6	Causes Of Torsional Vibration In Turbine-Generator Units	29
3.7	Summary	32
CHAPTER 4: POLE SLIP DETECTION METHODS		33
4.1	Generator Backup Impedance	33
4.2	Loss-Of-Field (LOF) Or Under-Excitation Protection	35
4.3	Overcurrent Protection	37
4.4	Pole Slip Protection Function Of The Siemens 7UM62X Relay	39
4.4.1	Measurement principle.....	39
4.4.2	Out-of-step protection logic	39
4.5	SEL Pole Slip Protection (SEL-300G relay)	45
4.5.1	Single blinder scheme	45
4.5.2	Double blinder scheme	48
4.5.3	Double blinder scheme shortcomings	51
4.6	Alstom Pole Slip Protection (Micom P34X relay)	53
4.6.1	Functional description.....	54
4.7	ABB Pole Slip Protection (REG670 relay).....	56
4.8	Conclusion	58
CHAPTER 5: RELAY MODELLING		59
5.1	Siemens 7UM62X Relay Model In Digsilent PowerFactory	59
5.1.1	Measurement block	63
5.1.2	Starting block	63
5.1.3	$I_1 >$ and $I_2 <$ release block	64
5.1.4	Polarizing block	64
5.1.5	OOS Characteristic 1 and 2 block	66
5.1.6	Out-of-step characteristic 1 and 2 block.....	66
5.2	Kendal Generator Pole Slip Protection Settings Calculation	68
5.2.1	Primary plant data.....	68
5.2.2	Primary and secondary impedances	70

5.2.3	Pole slip impedance characteristic settings	72
5.2.4	Measurement release	76
5.2.5	Number of power swing crossings (pole-slip cycles)	76
5.3	Conclusion	76
CHAPTER 6: DIGSILENT POLE SLIP SIMULATION		77
6.1	Reduced Network Equivalent.....	79
6.2	Pole Slip Scenario 1: Three-Phase Faults With All 400 kV Kendal Outgoing Feeders In Service	82
6.2.1	Critical fault clearing time	83
6.2.2	Measured impedance	85
6.2.3	Pulsating current	89
6.2.4	Pulsating electrical torque and power	90
6.2.5	Pole slip impedance trajectory for equally loaded generators.....	92
6.2.6	Pole slip impedance trajectory for unequally loaded generators.....	94
6.3	Pole-Slip Scenario 2: Three-Phase Fault With The 400 kV Kendal-Duvha Line Out Of Service	98
6.3.1	Critical fault clearing time	98
6.3.2	Pole slip impedance trajectory.....	100
6.3.3	Pulsating generator current and electrical power	102
6.3.4	Power plant disconnect protection.....	104
6.4	Pole-Slip Scenario 3: Three-Phase Fault With All Lines In Service And Generator Underexcited.....	106
6.4.1	Critical fault clearing time	107
6.4.2	Pole slip impedance trajectory and slip (underexcited)	109
6.4.3	Pulsating generator current and electric power	113
6.5	Generator Circuit Breaker Voltage During A Pole Slip	117
6.5.1	Generator circuit breaker voltage when $\delta = 120$ degrees	117
6.5.2	Generator circuit breaker voltage when $\delta = 180$ degrees	120
6.6	Conclusion	124

CHAPTER 7: POLE SLIP COMTRADE PLAYBACK	126
7.1 COMTRADE File Overview	127
7.2 Pole Slip Protection Testing Process Using A COMTRADE File.....	128
7.3 COMTRADE Play Back Testing	131
7.3.1 Scenario 1: Pole slip impedance trajectory in top portion of zone 1.....	132
7.3.2 Scenario 2: Pole-slip impedance trajectory in bottom portion of zone 1	134
7.3.3 Scenario 3: Pole slip impedance trajectory in zone 2	136
7.3.4 Scenario 4: Pole slip trip when δ is more than 120 degrees.....	138
7.3.5 Scenario 5: Pole slip incorrect operation	140
7.3.6 Scenario 6: Pole-slip stability test	142
7.4 Conclusion	146
CHAPTER 8: CONCLUSION.....	148
8.1 Conclusion	148
8.2 Future Work	150
REFERENCES	151
APPENDIX A: XRIO file for the pole-slip protection reach settings.	155

LIST OF FIGURES

Figure 2-1 Normal network operation.....	7
Figure 2-2 Network with one line out of service.....	8
Figure 2-3 Three-phase fault at midpoint of line 2	8
Figure 2-4 Transfer Z: Delta-star conversion for the faulted network	9
Figure 2-5 Final transfer impedance for the faulted network.....	11
Figure 2-6 Power transfer capability plot.....	12
Figure 3-1 Equivalent circuit used to derive the swing impedance	15
Figure 3-2 Simple network used to illustrate the measured swing impedance.....	18
Figure 3-3 Swing impedance when $n=1$ ($E_g = E_s$)	20
Figure 3-4 Swing Impedance ($0.6 < n < 1.7$)	21
Figure 3-5 Network – system electrical centre half way between the transfer impedance..	22
Figure 3-6 Phasor diagram – system electrical centre halfway along the transfer impedance.	23
Figure 3-7 System electrical centre located in the transmission network ($X_g + X_T < X_S$)....	24
Figure 3-8 System electrical centre located within the generator ($X_g + X_T > X_S$)	25
Figure 3-9 Typical pole slip frequency (Kendal 729 MW generator: $H = 3$ s).....	29
Figure 3-10 Generator mechanical torque and electrical torque for a close-up three- phase fault on the EHV network (Siemens Power Engineering – Vol II) [10]	31
Figure 4-1 Typical generator backup impedance characteristic	34
Figure 4-2 Typical generator loss-of-field impedance characteristic.....	35
Figure 4-3 Typical generator current pulsation during a pole-slip condition	37
Figure 4-4 Siemens 7UM622 relay manual extract: polygonal out-of-step characteristic indicating typical power swings trajectories [7].	40
Figure 4-5 Siemens 7UM622 relay manual extract: logic diagram of the out-of-step protection [7].	43
Figure 4-6 SEL 300G relay manual extract: single blinder scheme operating characteristic [8].	46
Figure 4-7 SEL 300G relay manual extract: single blinder scheme logic diagram [8]...	48
Figure 4-8 SEL 300G relay manual extract: double blinder scheme characteristic [8].	49
Figure 4-9 SEL 300G relay manual extract: double blinder scheme logic diagram [8].	50
Figure 4-10 Double Blinder Scheme undesirable tripping [8]......	52
Figure 4-11 Alstom Micom P34X technical manual extract: pole-slip- lenticular characteristic [9].	53

Figure 4-12 Alstom Micom P34X technical manual extract: typically applied pole-slip-lenticular characteristic settings [9].....	54
Figure 4-13 ABB REG670 application manual extract: pole-slip protection characteristic [11]. .	56
Figure 4-14 ABB REG670 technical reference manual extract: simplified pole-slip protection logic diagram [11].	57
Figure 5-1 Siemens 7UM62X Digsilent Relay Model.....	62
Figure 5-2 Digsilent relay model for the Siemens 7UM62X Impedance function sub block	67
Figure 5-3 System impedance measured from the 400 kV busbar at Kendal power station.....	69
Figure 5-4 Pole slip impedance characteristic setting parameters [7].	72
Figure 5-5 Pole slip polygon used to derive Z_a	75
Figure 6-1 Part of the South African north eastern network - Kendal, Tutuka and Duvha power stations.....	78
Figure 6-2 Part of the South African north eastern network reduced by using the PowerFactory network reduction tool.....	80
Figure 6-3 Critical fault clearing time for a three-phase fault on the outgoing Kendal feeders to prevent a generator pole slip	84
Figure 6-4 Impedance trajectory for various three-phase faults along the 400 kV Kendal-Minerva line. ($E_g/E_s > 1$).....	88
Figure 6-5 Pulsating current caused by a pole slip	89
Figure 6-6 Generator pulsating electrical torque and power during a pole slip	91
Figure 6-7 Pole-slip impedance trajectory (Kendal generators equally loaded $P = 580$ MW and $Q = 334$ Mvar).....	92
Figure 6-8 Zoomed in pole-slip impedance trajectory (Kendal generators equally loaded $P = 580$ MW and $Q = 334$ Mvar).....	94
Figure 6-9 Pole Slip impedance trajectory (Kendal generators unequally loaded).....	95
Figure 6-10 Zoomed in pole-slip impedance trajectory (Kendal generators unequally loaded)	96
Figure 6-11 Critical fault clearing times for three-phase faults on the outgoing Kendal feeders to prevent a generator pole slip (400 kV Kendal-Duvha line out of service).....	99
Figure 6-12 Pole Slip impedance trajectories with the 400kV Kendal – Duvha line in and out of service	100
Figure 6-13 Generator pulsating electric power and current during a pole slip with the 400 kV Kendal-Duvha line in and out of service.....	103

Figure 6-14 Simplified power plant disconnect logic reproduced from [36].....	106
Figure 6-15 Critical fault clearing time for three-phase faults on the outgoing Kendal feeders to prevent a generator pole slip (All five outgoing 400kV Kendal feeders in service and Kendal generators underexcited)	108
Figure 6-16 Pole-slip impedance trajectory with the Kendal generators underexcited and fault distance varied	110
Figure 6-17 Pole-slip frequency for a three-phase fault on the Kendal-Minerva line with the Kendal generators operating in the underexcited mode.....	111
Figure 6-18 Pole-slip impedance trajectories for a three-phase fault with the generator importing reactive power	112
Figure 6-19 Generator pulsating current during a pole slip (close up three-phase fault with the generator importing 18 Mvar and 118 Mvar).....	114
Figure 6-20 Generator pulsating electric power during a pole slip (close up three-phase fault with the generator importing 18 Mvar and 118 Mvar)	115
Figure 6-21 Pole-slip impedance trajectory for a pole-slip trip issued when $\delta \approx 120^\circ$.	118
Figure 6-22 Voltage magnitude and phase angle when the pole-slip trip is issued when $\delta \approx 120^\circ$	119
Figure 6-23 Pole-slip impedance trajectory for a pole-slip trip issued when $\delta \approx 180^\circ$.	120
Figure 6-24 Voltage magnitude and phase angle when the Kendal 22 kV generator breaker is forced to trip when $\delta \approx 180^\circ$	122
Figure 7-1 Pole slip protection testing process using a COMTRADE file.....	129
Figure 7-2 Pole-slip impedance trajectory - zone 1 (generator transformer).....	132
Figure 7-3 Pole-slip voltages, currents and binary signals - zone 1 (generator transformer).....	133
Figure 7-4 Pole-slip impedance trajectory for a zone 1 trip	134
Figure 7-5 Pole-slip voltages, currents and binary signals - zone 1 (generator).....	135
Figure 7-6 Pole slip impedance trajectory - zone 2 (system)	136
Figure 7-7 Pole-slip voltages, currents and binary signals - zone 2 (system)	137
Figure 7-8 Pole-slip trip when δ is more than 120 degrees	138
Figure 7-9 Pole-slip voltages, currents and binary signals when δ is more than 120 degrees.	139
Figure 7-10 Power-swing impedance trajectory - incorrect relay operation	140
Figure 7-11 Power-swing voltages, currents and binary signals - incorrect relay operation	142
Figure 7-12 Impedance trajectory for a stable power swing – correct relay operation	144
Figure 7-13 Power-swing voltages, currents and binary signals - correct relay operation	145

GLOSSARY OF TERMS

Power Swing: A variation in three-phase power flow which occurs when the generator rotor angles are advancing or retarding relative to each other in response to changes in load magnitude and direction, line switching, loss of generation, faults, and other system disturbances [1].

Pole Slip: A condition whereby a generator, or group of generators, terminal voltage angles (or phases) go past 180 degrees with respect to the rest of the connected power system [1].

Stable Power Swing: A power swing is considered stable if the generators do not slip poles and the system reaches a new state of equilibrium, i.e. an acceptable operating condition [1].

Unstable Power Swing: A power swing that will result in a generator or group of generators experiencing pole slipping for which some corrective action must be taken [1].

Out-of-Step Condition: Same as an unstable power swing [1].

System Electrical Centre of Voltage Zero: It is the point or points in the system where the voltage becomes zero during an unstable swing [1].

LIST OF ABBREVIATIONS

CB – Circuit Breaker

CT – Current Transformer

VT – Voltage Transformer

AVR – Automatic Voltage Regulator

EHV – Extra High Voltage ($U_n \geq 220$ kV)

HV – High Voltage (44 kV < U_n < 220 kV)

Hz – Hertz

LOF – Loss-of-Field

3PF – Three-Phase Fault

COMTRADE – **C**ommon format for **T**ransient **D**ata **E**xchange for power systems (It is a file format for oscilloscope data. It is used by many companies for recording oscilloscopes and computer simulations used in high voltage substation design. The COMTRADE file format has been standardised by the IEEE.)

XML – eXtensible Markup Language

XRIO – eXtended Relay Interface by OMICRON

CHAPTER 1: INTRODUCTION

1.1 Introduction

In most cases, generators within an interconnected network operate at a frequency close to nominal frequency. The South African power system frequency (50 Hz) will typically vary by ± 0.15 Hz. The generators are coupled by their magnetic poles and the coupling force is “elastic”, allowing a certain amount of angular play between the generator rotors during system disturbances. Power system faults, loss of heavily loaded generators and the loss of large load blocks will result in a sudden change in electrical power, whereas the mechanical power input to the connected generators will remain relatively constant (dependent on the turbine response). These disturbances can cause oscillations in the generator rotor angles, which can result in undesirable power flows and an out-of-step condition. An out-of-step condition will occur if the “elastic” coupling is insufficient to hold a generator or a group of generators in synchronism with the rest of the power system during these disturbances. Once synchronism is lost, the generator or generators will operate at slightly different frequencies and the difference is known as the slip frequency.

In an interconnected power system, the rotors of each synchronous machine in the system rotate at the same average electrical speed. The power delivered by the generator to the power system is equal to the mechanical power applied by the prime mover, neglecting losses. During steady-state operation, the generator electrical power output is equal to the mechanical power input. When the system is disturbed due to a fault, the electrical power out of the machine changes. The electrical power out of a machine can change rapidly, but the mechanical power into the machine is relatively slow to change. Because of this difference in speed response, there exists a temporary difference in the balance of power. This power unbalance causes a difference in torque applied to the shaft, which causes it to accelerate or decelerate, depending on the direction of the unbalance. As the rotor changes speed, the relative rotor angle changes.

A close-in transmission fault causes a generator's electrical output power to be significantly reduced. The resultant difference between the electrical power and the mechanical turbine power causes the generator rotor to accelerate with respect to the system, increasing the generator rotor angle. When the fault is cleared, the electrical power is restored to a level corresponding to whatever increased value of generator rotor angle has been reached by the time the fault is cleared. Clearing the fault essentially removes one or more transmission elements from service and at least temporarily weakens the transmission system. After clearing the fault, the electrical power out of the generator becomes greater than the turbine power. This causes the unit to decelerate, reducing the momentum that the rotor gained during the fault. If there is enough retarding torque after the fault clearing to make up for the acceleration during the fault, the generator will be transiently stable on the first swing and will move back toward its operating point. If the retarding torque is insufficient, the power angle will continue to increase until synchronism with the power system is lost. Power-system stability depends on the clearing time for a fault on the transmission system. Shorter fault-clearing time stops the acceleration of the rotor much sooner, assuring that sufficient synchronising torque is available to recover with a large safety margin. Therefore, protection engineers need to ensure that fast acting protection is installed on transmission systems [17].

Recent studies indicate that a critical fault clearing time of 70 ms is required to maintain stability for generating stations around the northern part of South Africa [14]. This will be the case until all the new 765 kV transmission lines have been built and commissioned. Therefore, transmission protection operating times of around 15 ms to 20 ms and breaker opening times of around 40 ms are required to maintain stability. The required critical fault clearing times have become extremely short, which increases the probability of a generator pole slip so it is essential to ensure that the generators are adequately protected in the event of a pole slip.

When a generator is out-of-step with the power system, the generator and system voltage phasors sweep past one another at a slip frequency, producing a pulsating current, which can be greater than a three-phase fault at the

generator terminals. An out-of-step condition should be isolated from the power system to prevent damage to the generator, generator transformer and the turbine. The isolation of any asynchronous portion of the system is also required to allow system restoration.

Large power swings, stable or unstable, can cause unwanted impedance (distance) relay operations at different locations in the power system if the impedance relays have not been set correctly. This could mean that the power swing blocking function has been disabled or, alternatively, it could be enabled but set incorrectly. There are various settings that need to be calculated and entered within the relay for the power swing blocking function to work correctly. Depending on the relay manufacturer, typical power swing blocking settings would consist of: a rate of change of impedance (dZ/dt); two impedance characteristics which are used to define the boundary for the impedance measurement to calculate the rate of change of impedance; a maximum negative sequence current limit (used to specify the degree of asymmetry of the three phase currents); any protection elements that should be blocked by the power swing blocking such as zone 1 or zone 2 impedance also need to be defined.

Incorrectly set impedance relays can respond to the measured impedance during a power swing if this measured impedance enters into the normal zones of protection and the relay then mistakes the measured impedance due to the power swing as being a low impedance due to a short circuit fault. This can aggravate the disturbance, therefore dynamic system simulations should be performed to check the correctness of the calculated out-of-step and power swing blocking settings on impedance relays.

1.2 Dissertation Objectives

This project has four main objectives:

- a) Dynamic simulations will be performed to determine how the pole-slip protection function within the Siemens 7UM622 generator protection relay reacts to large stable and unstable power swings. The power system as well as the generator protection relay that is used for the dynamic simulations are modelled in DigSilent PowerFactory.
- b) Eskom's protection settings philosophy that is used as a guideline to calculate generator-pole-slip protection settings will be analysed to determine if they provide adequate generator protection in the event of a pole slip. The objective of this dissertation is not to develop a new predictive generator-pole-slip protection scheme or algorithm, rather to ensure the correct pole-slip protection relay response after a single generator pole slip has occurred.
- c) The pole-slip protection function within the Siemens 7UM622 generator protection relay will physically be tested by "playing back" COMTRADE files, which are generated during the Digsilent PowerFactory time domain simulations. By "playing back" the COMTRADE files into the relay, the actual relay response can be compared to the Digsilent relay model, which can then be used to validate the Digsilent PowerFactory relay model.
- d) The pole-slip COMTRADE files will also be used in future to test pole-slip protection functions to determine if they operate correctly for stable and unstable (pole slip) power swings since it is rather difficult to test the pole-slip protection function properly without a COMTRADE file.

1.3 Outline of Dissertation

The dissertation consists of eight chapters: Chapter 1 is an introduction; chapters 2 to 4 presents the theory behind generator pole slip occurrences as well as typical generator-pole-slip protection methods used by relay manufacturers; chapters 5 to 7 cover generator pole-slip simulations and relay modelling; chapter 8 discusses the findings and recommendations of the dissertation as a whole.

CHAPTER 1: Provides an introduction to pole-slip / out-of-step protection as well as the objective of the dissertation.

CHAPTER 2: Explains the basics of power system transient stability by using simplified examples.

CHAPTER 3: Derives an expression for a power swing impedance locus. Pole-slip impedance trajectories, pole-slip frequency and various effects are also discussed.

CHAPTER 4: Provides details of the various methods that are used by relay manufacturers for generator pole-slip protection.

CHAPTER 5: Details the DigSilent PowerFactory Siemens 7UM622 generator protection relay model as well as the calculation of the pole-slip protection settings.

CHAPTER 6: Analyses the DigSilent PowerFactory pole-slip simulations and pole-slip relay model response.

CHAPTER 7: Analyses the generator protection relay hardware response by playing back stable and unstable power swing COMTRADE recordings. The relay response is then analysed and compared to the description in the relay technical manual.

CHAPTER 8: Discusses the findings and recommendations for future generator-pole-slip protection settings and relay testing.

CHAPTER 2: TRANSIENT STABILITY

2.1 Transient Stability

A loss of synchronism is a result of some form of system instability. Sudden changes within a network such as a short circuit or line switching can cause a generator to lose transient stability. This type of stability is fundamental to the understanding of pole-slip protection. Three-phase short circuit faults are usually the most severe challenge for transient stability, and the severity of the faults are mainly a function of fault location and the relay tripping time which will be shown later.

The power transfer equation along with a simple network operated under several conditions will be used to explain transient stability.

The equation for the active electrical power transferred out of a synchronous generator terminals is given by [26]:

$$P_e = \frac{E_g E_s}{Z_T} \sin \delta \quad (1.1)$$

Where:

P_e = Electrical power transmitted

E_g = Generator voltage

E_s = Equivalent system voltage

Z_T = Transfer impedance directly between the two voltages

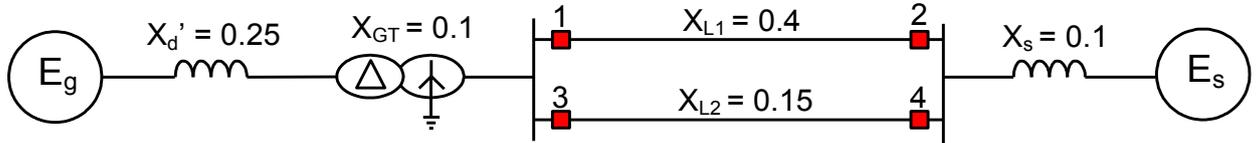
δ = Angle between E_g and E_s

2.1.1 Transfer impedance under normal network operating conditions

Figure 2-1 shows a single-line diagram of a simple single generator connected to an infinite power system via a step-up generator transformer and two parallel lines. This network will be used as an example to explain the basics of transient stability.

The transfer impedance of the unfaulted network state in Figure 2-1 can be calculated as follows:

$$\begin{aligned} Z_T &= X'_d + X_{GT} + \frac{X_{L1} * X_{L2}}{X_{L1} + X_{L2}} + X_S \\ &= 0.25 + 0.1 + \frac{0.4 * 0.15}{0.4 + 0.15} + 0.1 \\ &= 0.559 \text{ p.u.} \end{aligned}$$



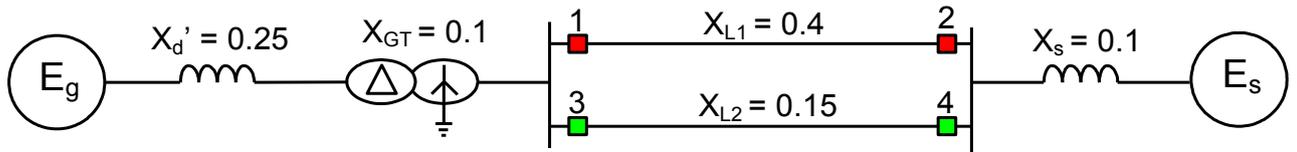
Note: ■ = Circuit breaker closed and ■ = Circuit breaker open

Figure 2-1 Normal network operation

2.1.2 Transfer impedance with one line out of service

The network in Figure 2-2 is similar to the network in Figure 2-1, the difference being that one of the parallel lines are out of service (line 2). The transfer impedance of Figure 2-2 can be calculated as follows:

$$\begin{aligned} Z_T &= X'_d + X_{GT} + X_{L1} + X_S \\ &= 0.25 + 0.1 + 0.4 + 0.1 \\ &= 0.85 \text{ p.u.} \end{aligned}$$

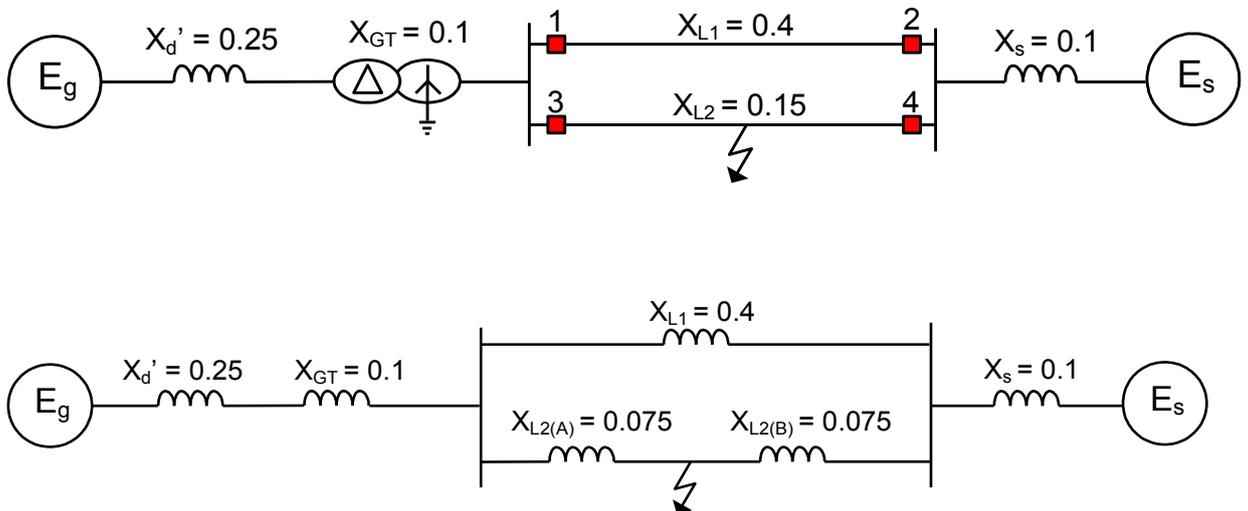


Note: ■ = Circuit breaker closed and ■ = Circuit breaker open

Figure 2-2 Network with one line out of service

2.1.3 Transfer impedance with a three-phase fault on line 2

Figure 2-3 indicates a network with a three-phase fault halfway along line 2. In order for the transfer impedance to be calculated for a three-phase fault halfway along line 2, the network needs to be reduced.



Note: ■ = Circuit breaker closed and ■ = Circuit breaker open

Figure 2-3 Three-phase fault at midpoint of line 2

Firstly, a delta-star conversion needs to be performed to convert the faulted network in Figure 2-3 into the equivalent form shown in Figure 2-4.

$$X_A = \frac{X_{L1} * X_{L2(A)}}{X_{L1} + X_{L2(A)} + X_{L2(B)}}$$

$$= \frac{0.4 * 0.075}{0.4 + 0.075 + 0.075}$$

$$= 0.055 \text{ p.u.}$$

$$X_B = \frac{X_{L1} * X_{L2(B)}}{X_{L1} + X_{L2(A)} + X_{L2(B)}}$$

$$= \frac{0.4 * 0.075}{0.4 + 0.075 + 0.075}$$

$$= 0.055 \text{ p.u.}$$

$$X_C = \frac{X_{L2(A)} * X_{L2(B)}}{X_{L1} + X_{L2(A)} + X_{L2(B)}}$$

$$= \frac{0.075 * 0.075}{0.4 + 0.075 + 0.075}$$

$$= 0.01 \text{ p.u.}$$

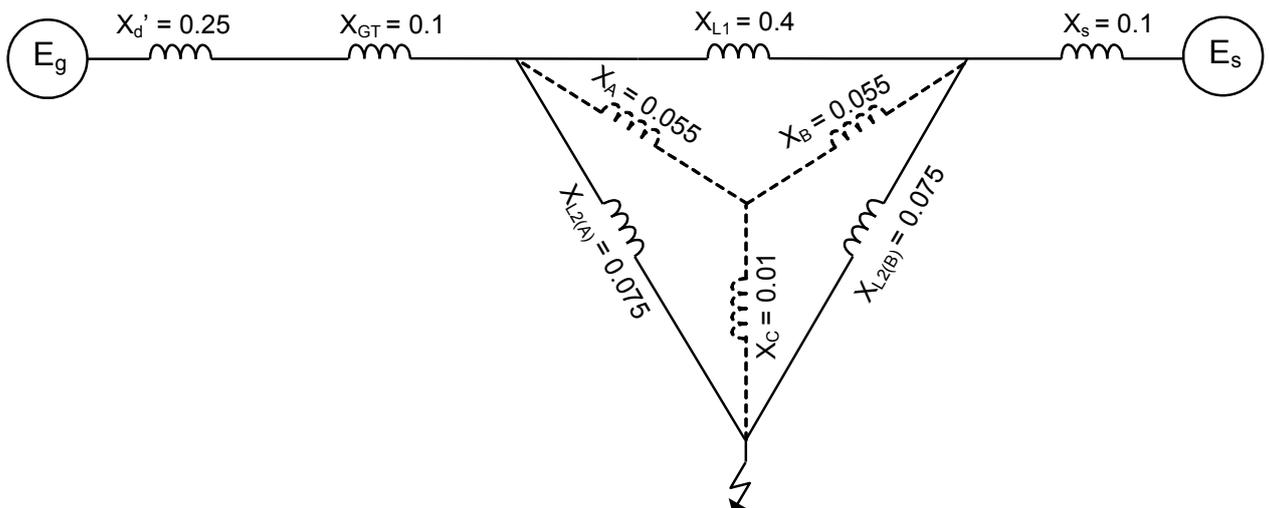


Figure 2-4 Transfer Z: Delta-star conversion for the faulted network

The network can be simplified further and then a final star-delta conversion can be performed to obtain the transfer impedance ($Z_{T(Fault)}$) between E_g and E_s as shown in Figure 2-5. The values of the impedance in each leg of the star connected network in in Figure 2-5 are obtained from Figure 2-4 as follows:

$$\begin{aligned} X_{A1} &= X'_d + X_{GT} + X_A \\ &= 0.25 + 0.1 + 0.055 \\ &= 0.405 \text{ p.u.} \end{aligned}$$

$$\begin{aligned} X_{B1} &= X_S + X_B \\ &= 0.1 + 0.055 \\ &= 0.155 \text{ p.u.} \end{aligned}$$

$$X_{C1} = X_C = 0.01 \text{ p.u.}$$

Star-delta conversion:

$$\begin{aligned} Z_{T(Fault)} = X_{AB} &= X_{A1} + X_{B1} + \frac{X_{A1} * X_{B1}}{X_{C1}} \\ &= 0.405 + 0.155 + \frac{0.405 * 0.155}{0.01} \\ &= 6.834 \text{ p.u.} \end{aligned}$$

$$\begin{aligned} X_{BC} &= X_{B1} + X_{C1} + \frac{X_{B1} * X_{C1}}{X_{A1}} \\ &= 0.155 + 0.01 + \frac{0.155 * 0.01}{0.405} \\ &= 0.169 \text{ p.u.} \end{aligned}$$

$$\begin{aligned}
X_{CA} &= X_{C1} + X_{A1} + \frac{X_{C1} * X_{A1}}{X_{B1}} \\
&= 0.01 + 0.405 + \frac{0.01 * 0.405}{0.155} \\
&= 0.441 \text{ p.u.}
\end{aligned}$$

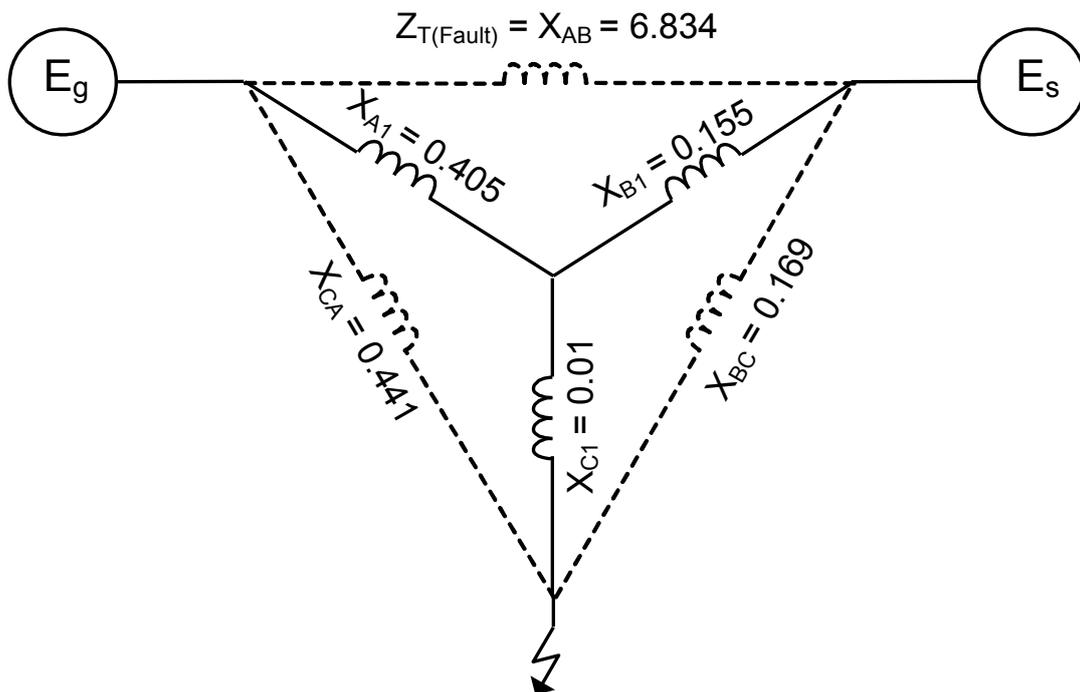


Figure 2-5 Final transfer impedance for the faulted network

From the above analysis it can be seen that the transfer impedance is 0.559 p.u. when both lines are in service, 0.85 p.u. when the faulted line is switched out and 6.834 p.u. when there is a three-phase fault halfway along line 2. This suggests a 1222% increase in transfer impedance between the normal operating network and the unhealthy faulted network. The maximum electrical power transfer (at 90 degrees) under normal conditions is 1.79 p.u. and when there is a three-phase fault half way along line 2 it decreases to 0.15 p.u., which suggests a 92% decrease in the electrical power transfer capability.

2.1.4 Power transfer capability plot

The electrical power transfer curves can be plotted for the three different cases above by using the calculated transfer impedance, the voltage magnitude of E_g and E_s (assume 1 p.u.) and the angle between E_g and E_s , which is varied from 0 degrees to 180 degrees.

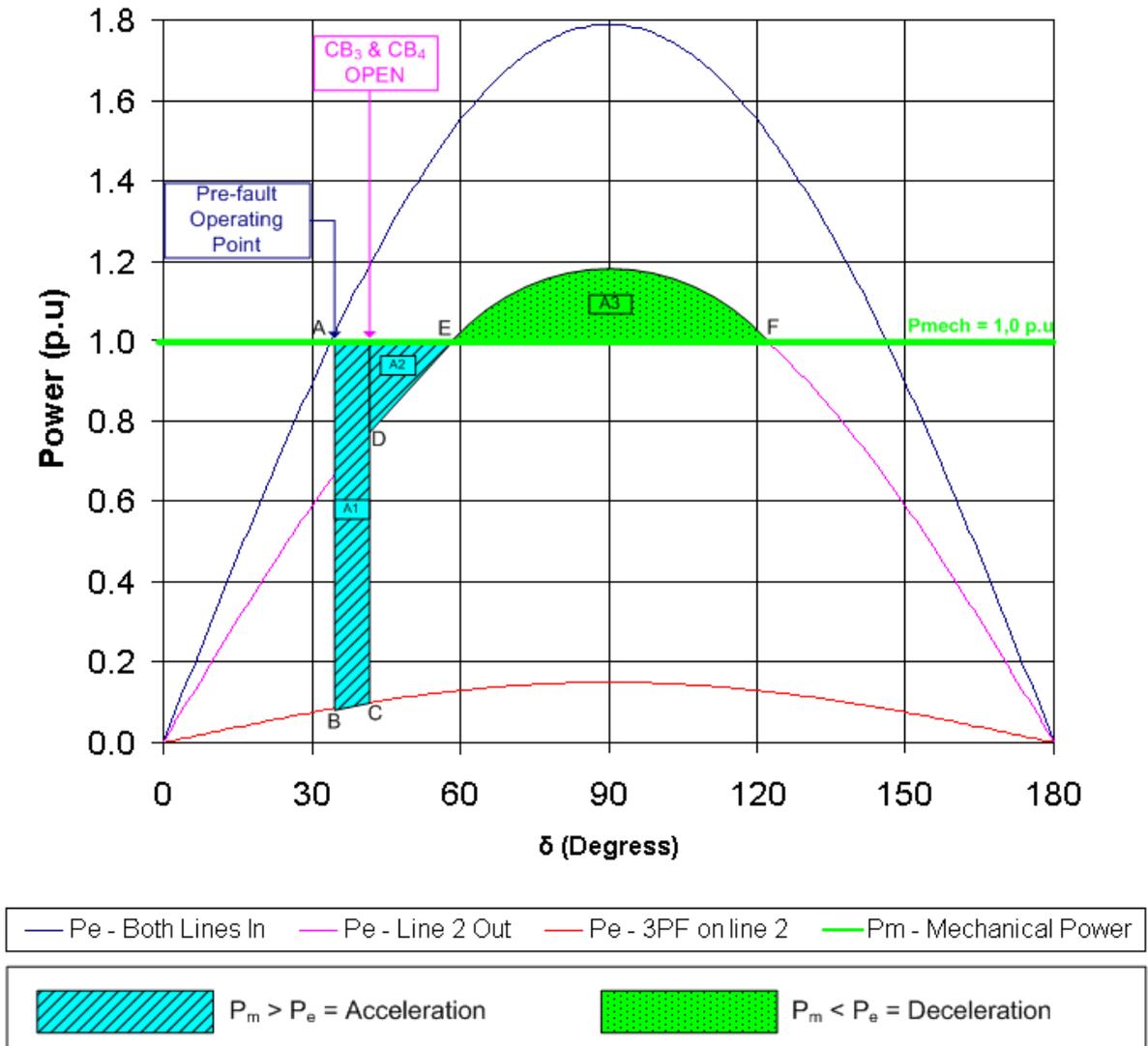


Figure 2-6 Power transfer capability plot

The system is initially operating at point “A” where the electrical power transferred is at 1 p.u. and the angle between the generator and the system voltage is equal to 34 degrees. The mechanical power input is also equal to

1 p.u.; therefore, the electrical power is equal to the mechanical power that means the system is in equilibrium.

A three-phase fault develops halfway along line 2, which immediately reduces the generator's electrical power transfer capability to point "B", which is equal to 0.082 p.u.. The mechanical input power to the turbine is still equal to 1 p.u. at point "B", therefore the mechanical power input is greater than the electrical power transferred, which causes the generator to accelerate along the red power transfer capability curve towards point "C".

At point "C", the protection detects the three-phase fault on line 2 and opens circuit breakers 3 and 4, which disconnects line 2. The electrical power transfer capability immediately jumps to point "D" after line 2 has been disconnected. The electrical power transfer capability is now equal to 0.77 p.u. and the mechanical power input to the turbine remains constant at 1 p.u.; therefore, the mechanical power input is still greater than the electrical power transferred which causes the generator to continue accelerating. The accelerating power will continue to advance the power angle δ towards point "E" (58 degrees) along the magenta power transfer capability curve. The rotor angle advances past point "E" due to the inertia of the generator. When the power angle passes point "E", the mechanical power input to the turbine is less than the electrical power transfer of the generator, which causes the generator to decelerate. The generator will remain stable if there is sufficient decelerating power to prevent the rotor angle from passing point "F". If the rotor angle passes point "F", the electrical power transfer capability of the generator will once again be less than the mechanical power input to the turbine, which would cause the generator to accelerate once again, but this time there would be no means to decelerate the generator, which would cause the generator to pull out of synchronism.

If the system is transiently stable, the rotor angle would oscillate about point “E”, but the oscillations would diminish until point “E” becomes the new steady state operating angle. The system’s stability can be evaluated from the plot in Figure 2-6. The accelerating power is the turquoise area, which is area A1 and A2, and the decelerating power is the green area, which is A3. As long as $A1 + A2 < A3$, the system would remain stable.

2.2 Summary

The power transfer equation (1.1) was used to determine the generator electrical power transfer capability, which was then used to assess the generator transient stability by means of an example. It was shown that operating conditions do affect the transient stability, but transient stability is mainly a function of the fault transfer impedance as well as the relay fault clearing time.

A generator pole slip (loss of synchronism) is as a result of some form of system instability. Transient stability is crucial to the understanding of pole-slip protection. Most pole-slip protection relays utilise an impedance function to detect a pole slip. Typical impedance plots for unstable power swings will be analysed in the following chapter.

CHAPTER 3: POWER SWING IMPEDANCE

3.1 Deriving An Expression For A Power Swing Impedance Locus

The majority of pole-slip and power swing protection relays measure the impedance trajectory of the network to detect a pole slip or power swing. The characteristics of a power swing are similar to the initial stages of a pole slip. An expression for the swing impedance is derived from reference [3] by using the following basic network in Figure 3-1.

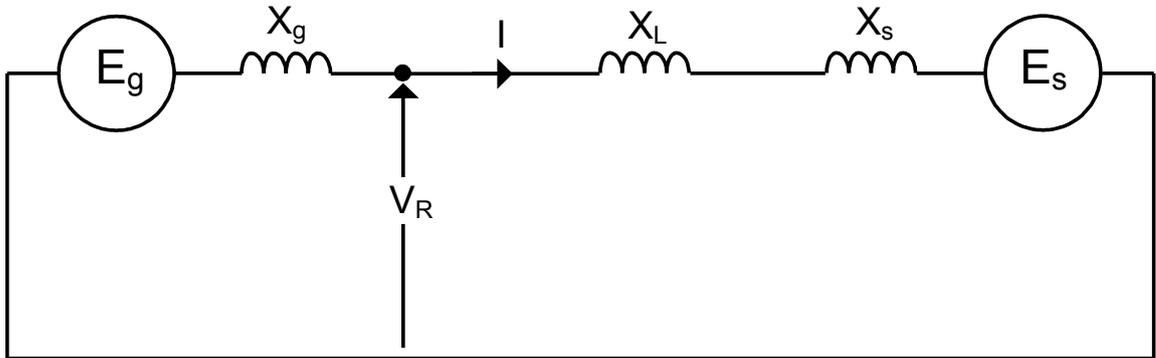


Figure 3-1 Equivalent circuit used to derive the swing impedance

If we let E_s be the reference and let E_g advance in phase ahead of E_s by angle δ , the current measured by the protection relay at the generator terminals:

$$I = \frac{E_g \angle \delta - E_s}{X_g + X_L + X_s} \quad (3.1)$$

The voltage seen by the protection relay at the generator terminals:

$$\begin{aligned} V_R &= E_g \angle \delta - IX_g \\ &= E_g \angle \delta - \frac{E_g \angle \delta - E_s}{X_g + X_L + X_s} X_g \end{aligned} \quad (3.2)$$

The impedance measured by the protection relay at the generator terminal is:

$$\begin{aligned}
 Z_R = \frac{V_R}{I} &= \left(E_g \angle \delta - \frac{E_g \angle \delta - E_s}{X_g + X_L + X_s} X_g \right) \frac{X_g + X_L + X_s}{E_g \angle \delta - E_s} \\
 &= \frac{(X_g + X_L + X_s) E_g \angle \delta}{E_g \angle \delta - E_s} - X_g
 \end{aligned} \tag{3.3}$$

$$\text{Let } E_T = \frac{E_g \angle \delta}{E_g \angle \delta - E_s}$$

$$\text{then } Z_R = (X_g + X_L + X_s) E_T - X_g \tag{3.4}$$

$$\text{Let } n = \frac{E_g}{E_s} \quad \text{and} \quad 1 \angle \delta = \cos \delta + j \sin \delta$$

$$\begin{aligned}
 \text{then } E_T &= \frac{\frac{E_g}{E_s} (\cos \delta + j \sin \delta)}{\frac{E_g}{E_s} (\cos \delta + j \sin \delta) - \frac{E_s}{E_s}} \\
 &= \frac{n(\cos \delta + j \sin \delta)}{n(\cos \delta + j \sin \delta) - 1} \\
 &= \frac{n \cos \delta + j n \sin \delta}{n \cos \delta + j n \sin \delta - 1} * \frac{n \cos \delta - j n \sin \delta - 1}{n \cos \delta - j n \sin \delta - 1} \\
 &= \frac{n^2 - n \cos \delta - j n \sin \delta}{n^2 - 2n \cos \delta + 1} \\
 &= \frac{n(n - \cos \delta - j \sin \delta)}{(n - \cos \delta)^2 + \sin^2 \delta}
 \end{aligned} \tag{3.5}$$

If we substitute (3.5) into (3.4)

$$\text{then } Z_R = (X_g + X_L + X_s) \frac{n(n - \cos\delta - j\sin\delta)}{(n - \cos\delta)^2 + \sin^2\delta} - X_g \quad (3.6)$$

If we consider the case when $E_g = E_s$ ($n = 1$):

$$\begin{aligned} \text{then } Z_{R(n=1)} &= (X_g + X_L + X_s) \frac{(1 - \cos\delta - j\sin\delta)}{(1 - \cos\delta)^2 + \sin^2\delta} - X_g \\ &= (X_g + X_L + X_s) \frac{1 - \cos\delta - j\sin\delta}{2 - 2\cos\delta} - X_g \\ &= \left[\frac{X_g + X_L + X_s}{2} \left(\frac{1 - \cos\delta - j\sin\delta}{1 - \cos\delta} * \frac{1 + \cos\delta}{1 + \cos\delta} \right) \right] - X_g \\ &= \left[\frac{X_g + X_L + X_s}{2} \left(\frac{\sin\delta - j - j\cos\delta}{\sin\delta} \right) \right] - X_g \\ &= \left[\frac{X_g + X_L + X_s}{2} \left(1 - j \left(\frac{1 + \cos\delta}{\sin\delta} \right) \right) \right] - X_g \\ &= \frac{X_g + X_L + X_s}{2} \left(1 - j \cot \left(\frac{\delta}{2} \right) \right) - X_g \quad (3.7) \end{aligned}$$

3.2 Understanding Power Swing Impedance Trajectories

It is important to understand the various typical types of impedance trajectories that can be measured by a pole-slip protection relay in order for one to analyse and interpret a pole-slip event.

3.2.1 Generator reactance during a pole slip

Since the generator reactance plays a role in the determination of the pole slipping impedance locus, it is crucial to use proper reactance values when plotting the impedance loci. At zero slip X_g is equal to the synchronous reactance (X_d), and at 100% slip X_g is equal to the sub-transient reactance (X''_d). The impedance in a typical case has been shown to be equal to the transient reactance X'_d at 50% slip, and to $2X'_d$ with a slip of 0.33% [3], [9]. As most slips are likely to be experienced with the generator running at low asynchronous speed, perhaps 1%, it is sufficient to take the value $X_g = 2X'_d$ when assessing a pole slip [9].

3.2.2 Swing impedance ($n = 1$)

When $E_g = E_s$ ($n=1$) for the simple network in Figure 3-2, the measured swing impedance for the relay located at the generator terminals can be calculated by using equation 3.7

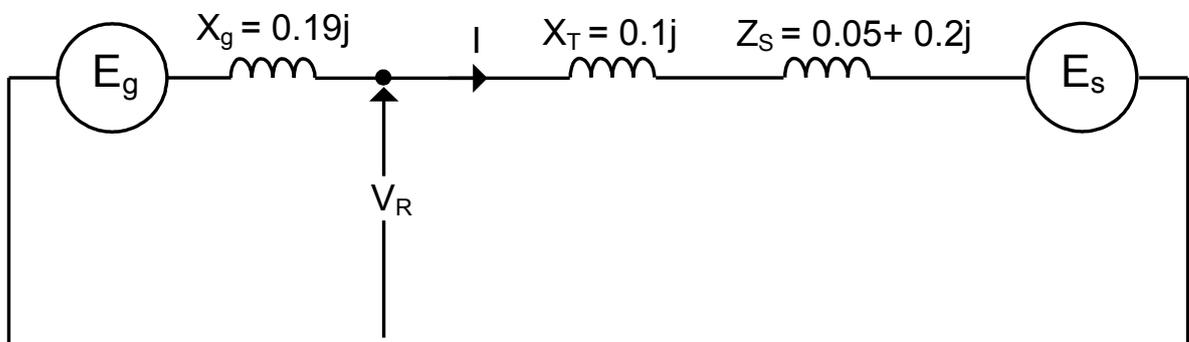


Figure 3-2 Simple network used to illustrate the measured swing impedance

The swing impedance measured by the relay is plotted in Figure 3-3. The measured swing impedance is a straight line moving from right to left since the generator advances ahead of the system. If the system were to advance ahead of the generator, the swing impedance would move from left to right.

When the power angle δ reaches 180 degrees, the generator and the system voltage are 180 degrees out of phase, which means that the generator has pole slipped (which can cause severe damage) and it needs to be separated from the network. If the generator is not separated from the network, it would continue pole slipping, which would cause further severe damage to the generator, generator shaft and turbine. It would not be possible for the generator to regain synchronism without disconnecting the generator after it has slipped a pole.

This dissertation is not intending to develop a new predictive generator-pole-slip protection scheme or algorithm, rather to ensure the correct pole-slip protection relay response after a single generator pole slip has occurred. Therefore, the emphasis of the analysis is on the detection of a pole slip after it has occurred.

The angle δ between the two voltages E_g and E_s is calculated by the impedance relay to determine if a generator has pole slipped. The impedance relay calculates the angle δ by using the measured voltage and current at the generator terminals as well as the predetermined impedances (generator, generator transformer and equivalent system) that are determined by the protection relay engineer.

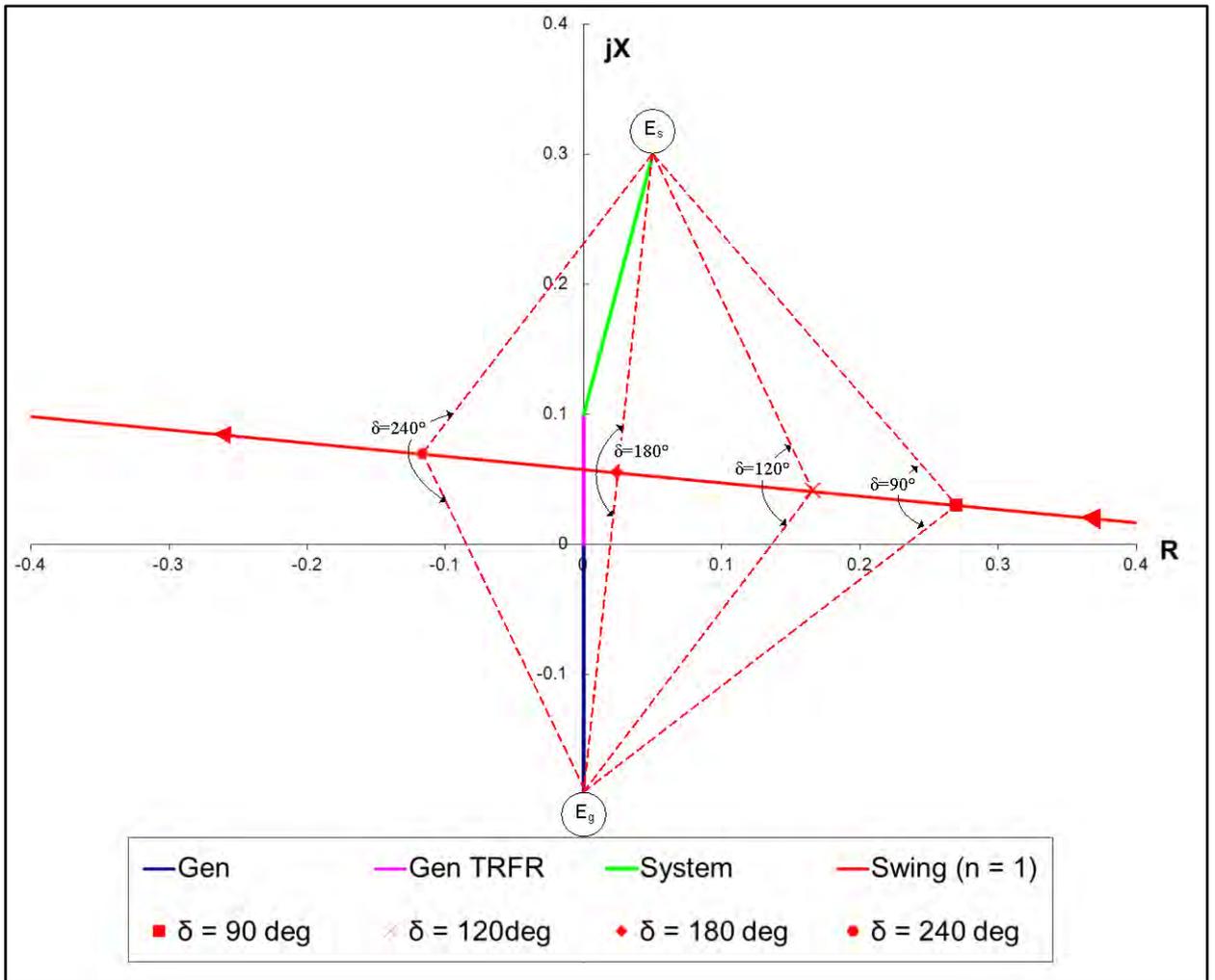


Figure 3-3 Swing impedance when $n=1$ ($E_g = E_s$)

The generator breaker should not be opened when $\delta = 180$ degrees, because this is essentially an out-of-phase switching operation which could exceed the generator breaker rating.

Generator breakers are usually not rated in terms of out-of-phase switching capability. IEEE standard C37.013-1997 [5], governing generator breakers, recommends a rating of 50% for the symmetrical short circuit current rating at a separation angle of 90 degrees and maximum system voltage. Therefore, the pole-slip protection should not trip the generator breaker when $\delta = 180$ degrees, it should delay the trip signal to a point when $90^\circ > \delta > 270^\circ$.

3.2.3 Swing impedance for $0.6 < n < 1.7$

In Figure 3-4, the swing impedances are plotted for different values of n (E_g/E_s). When $E_g = E_s$ ($n=1$), the swing impedance is a straight line. When $E_g > E_s$ ($n>1$), the swing impedance is always above the straight line impedance of $n=1$ and when $E_g < E_s$ ($n<1$), the swing impedance is always below the straight line impedance of $n=1$.

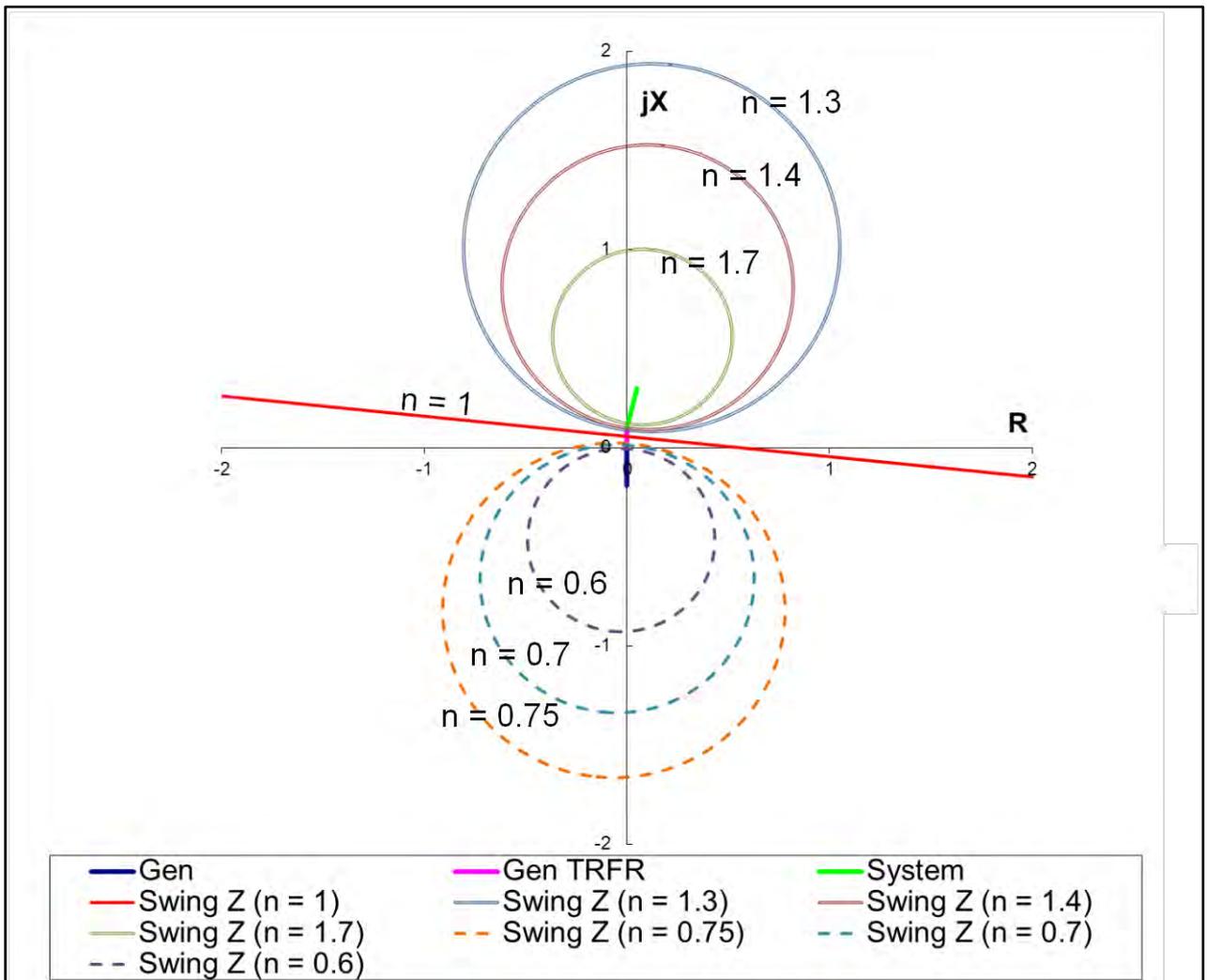


Figure 3-4 Swing Impedance ($0.6 < n < 1.7$)

The various swing impedances in Figure 3-4 are ideal impedance trajectories, which would occur between an ideal system and a generator. In practice, the swing impedance would vary due to the dynamics of the system; e.g. due to the effects of the generator automatic voltage regulator (AVR) and turbine governor.

To test the actual response of a pole-slip protection relay and to determine the measured impedance trajectory of the power swing, the network of interest needs to be modelled in a power system simulation program. The model should include as many of the dynamic controllers as possible to produce an accurate result.

3.3 System Electrical Centre Or Voltage Zero

When the two system voltages are 180 degrees out of phase the voltage between the two systems is at twice the normal voltage and the current flowing between the two systems would be at maximum. Electrically, this condition is equivalent to a three-phase fault applied half way between the two systems. This imaginary fault location is known as the system electrical centre or voltage zero. Since the system electrical centre is like a three-phase fault, the position of the system electrical centre would determine the severity of the damage caused to the generator or generator transformer. If the system electrical centre is in the transmission network it would have less of a damaging effect on the generator or generator transformer and therefore they could possibly withstand several of these pole slips. If the system electrical centre is within the generator or generator transformer, they must be disconnected from the system after a single pole slip to minimise the damage caused to the generator or generator transformer. The system electrical centre is not fixed and is dependent on the network configuration and impedance.

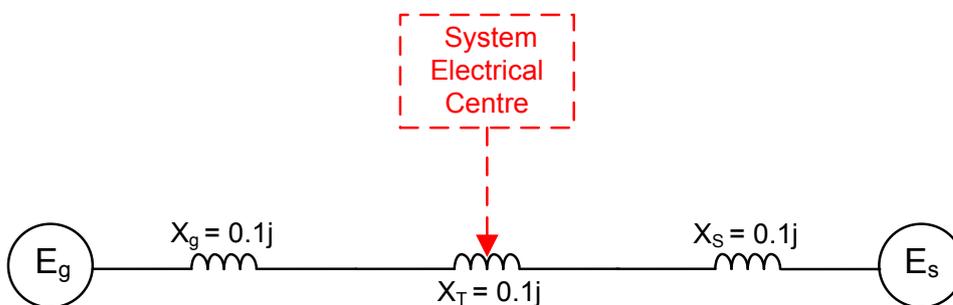


Figure 3-5 Network – system electrical centre half way between the transfer impedance

If we consider the network in Figure 3-5 where $X_g = X_T = X_S$, the electrical centre is exactly half way along the transfer impedance.

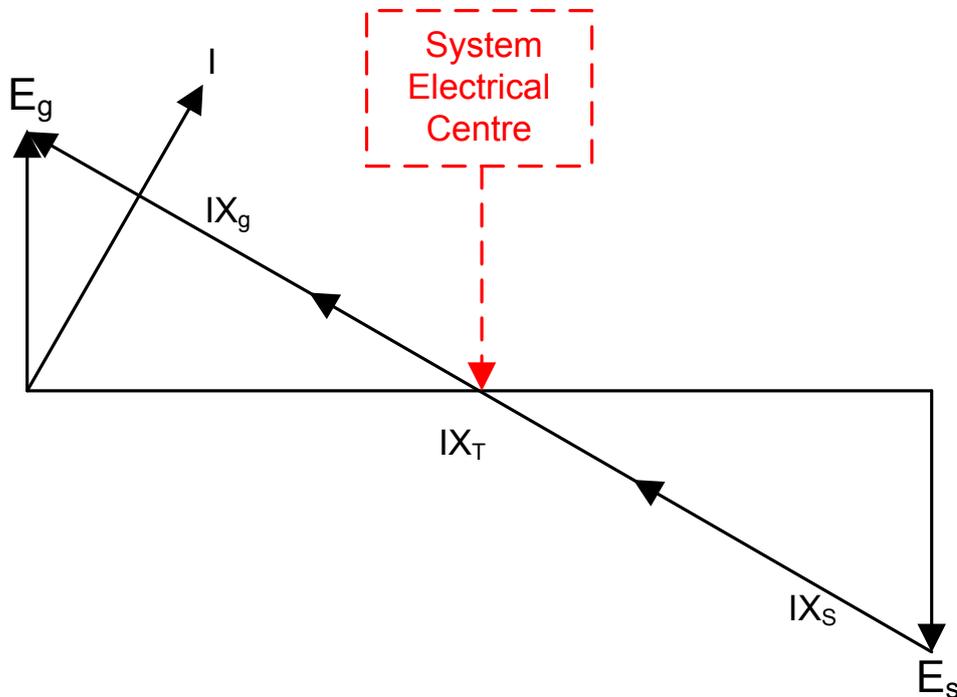


Figure 3-6 Phasor diagram – system electrical centre halfway along the transfer impedance

It is evident from Figure 3-6 that the system electrical centre moves away from the generator as the system impedance increases and the system electrical centre moves closer to the generator as the system impedance decreases. If transmission lines are out of service on the transmission network, the system impedance would increase and the system electrical centre would move into the system away from the generator as shown in Figure 3-7.

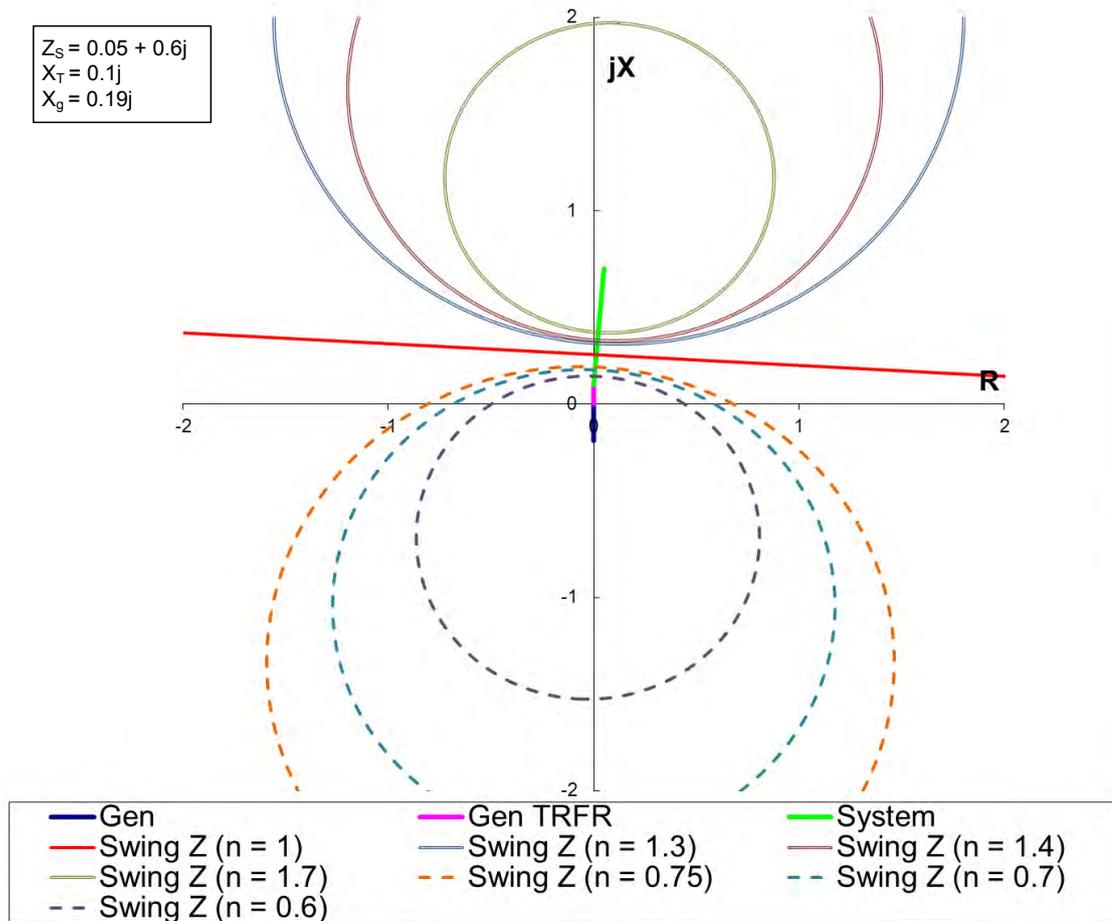


Figure 3-7 System electrical centre located in the transmission network ($X_g + X_T < X_S$)

If a small generator and generator transformer are connected to a very strong system $X_g + X_T > X_S$, it is very possible for the electrical centre to be located within the generator or generator transformer as shown in Figure 3-8. This would typically be the case for small embedded generators connected to a sub-transmission network.

Generator and generator transformer designs have improved over the years, which resulted in the same size generators and generator transformers having a larger MVA capacity, which resulted in higher impedances. On the other hand, system impedances have been decreasing due to EHV networks and large interconnected systems. Therefore, it has become more likely for the system electrical centre to be located within the generator as shown in Figure 3-8.

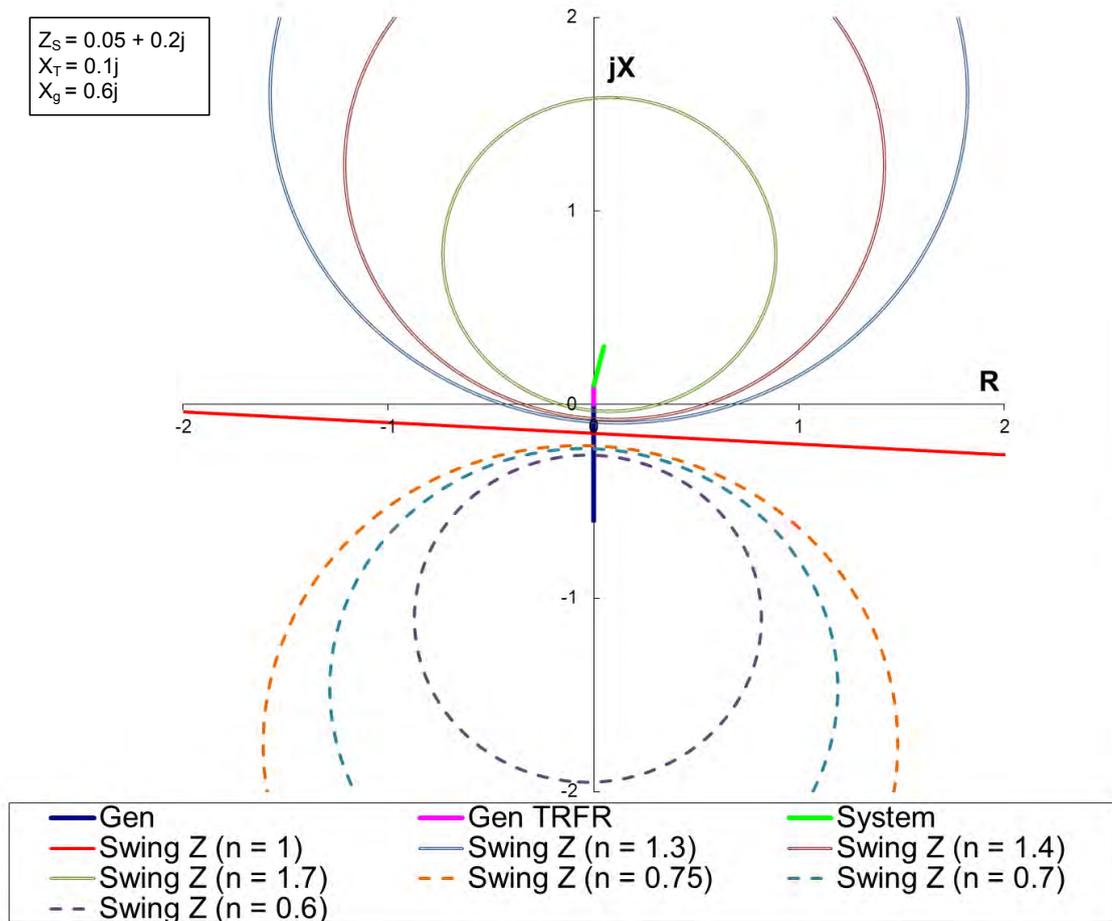


Figure 3-8 System electrical centre located within the generator ($X_g + X_T > X_s$)

In the event of a pole slip, impedance relays on the transmission network would interpret the pole slip as a three-phase fault located at the system electrical centre. Therefore, it is essential for impedance relays on the transmission network to distinguish between a power swing and a three-phase fault to allow the impedance relays to block for power swings and to trip for actual three-phase faults. If the impedance relays on the transmission network were to trip incorrectly for a power swing, the power swing would be aggravated, which may compromise the stability of the network. If the exact location of the system electrical centre is known, strategic out-of-step impedance relays can be installed on either side of the system electrical centre to detect and trip for an out-of-step condition. The out-of-step relay would then send a trip signal to various predetermined locations via communications to separate the network into two islands.

The separation of an out-of-step network should preferably be done at a location where (a) the generation-load balance will permit the parts to continue service temporarily and (b) at a convenient location where the islands can be resynchronised. Usually, these objectives will be in conflict to a varying extent depending on the system operation conditions at the time of the disturbance. As a result, considerable compromise and judgement is required; there are no easy answers [23]. Where a generation-load balance cannot be achieved, some means of shedding non-essential load or generation will have to take place to avoid a complete shutdown of the area. Typically, the location of out-of-step tripping relays determine the location where the system islanding takes place during a loss of synchronism. However, in some systems it may be necessary to separate the network at a location other than the one where out-of-step tripping relays are installed [30].

The current Eskom 400 kV Cape network out-of-step protection separates the South African network into two islands at Droerivier substation, which is near Beaufort West in the Western Cape, and Aries substation, which is near Kakamas in the Northern Cape [18]. The two islands that are formed by the out-of-step tripping are Mpumalanga and Cape, but the Namibian interconnection is connected to the Mpumalanga island as the Cape island has insufficient generating capacity. It is essential to do extensive studies to ensure that the generation and load is correctly distributed between the two islands to ensure that the system remains stable. In practice this is an extremely difficult task to try and balance the generation and load by separating the network at the correct locations. Usually, an under-frequency load shedding scheme is also used to try and stabilise the frequency of the two islands.

3.4 Damaging Effects Of A Pole Slip

As the system electrical centre moves from the system and into the generator, the current magnitude during a pole slip increases and with it thermal and mechanical stress on the generator and the generator transformer. The transient reactance (X_d') is usually used to represent the generator reactance in calculations for pole-slip conditions, but in special cases with low generator transformer and system impedance, the current could exceed the sub-transient fault current at the generator terminals [3], [28]. This is the maximum current the generator is designed to withstand. The absence of DC offset during a pole-slip event does lessen the stress compared to that of a fault case. As the location of the system electrical centre moves toward the neutral end of the generator, current-induced thermal and mechanical stresses approach the design limits. The generator is exposed to these conditions each slip cycle. In addition to these stresses, the rotational speed difference between the rotor and system will induce currents in the rotor similar to those produced by unbalanced stator currents. Prolonged exposure to these currents will cause thermal damage to damper windings, rotor teeth, wedges and the rotor body. Re-stacking of the stator core will be required. Local hot spots may also damage stator windings.

The current pulsation associated with each slip cycle causes severe torque transients in the turbine generator shaft. This stress is at a maximum during the initial period of each torque pulsation. This is the period when shaft damage normally occurs. The fatigue life of the shaft can be used up after a few pole-slip events. If the slip cycle frequency coincides with a natural frequency of one of the shaft sections, shaft fatigue can result. The severe mechanical and electrical transients associated with a pole-slip event necessitate rapid detection and tripping [29], [33].

Prolonged asynchronous operation can also cause diode failures within the excitation system. During each pole slip, these diodes will experience high voltage as they block reverse rotor current. The overvoltage stresses the insulation and can result in breakdown.

On a power system, a loss of synchronism by one or more units will result in cyclic voltage fluctuations as generators slip poles. These voltage dips cause disruptions to customer loads. Induction motors may stall and synchronous motors can lose synchronism. Other processes would be disrupted when the voltage dips cause motor contactors to drop out [3].

3.5 Pole Slip Frequency Or Angular Velocity

The frequency or angular velocity of a pole slip is determined by the accelerating power (as explained in chapter 2), the inertia of the machine and the time to clear the fault. The majority of the generators within Eskom are two-pole steam generator units with an inertia time constant (H) in the range of 2 s - 4 s.

Typically, two-pole steam generator units have an inertia time constant (H) in the range of 2 s – 3 s; four pole steam generators $H \approx 3.5 \text{ s} - 4.5 \text{ s}$; hydro generators have $H \approx 4 \text{ s}$; single shaft gas turbines $H \approx 6 \text{ s} - 8 \text{ s}$; and double shaft gas turbines $H \approx 2 \text{ s}$ [6].

Tandem generators (generator units with a combined high pressure and low pressure turbines connected to a generator) have an average angular slip velocity during the first half cycle of around 250 degrees per second to 400 degrees per second (0.694 – 1.11 slip cycles per second) while for a cross compound unit, the average initial angular slip velocity will be 400 degrees per second to 800 degrees per second (1.11 – 2.22 slip cycles per second). For both types of generators, the average angular slip velocity during the remainder of the slip cycle will fall in the range of 1200 degrees per second to 1600 degrees per second (3.33 – 4.44 slip cycles per second) [6].

The frequency of the first slip cycle is of utmost importance since this is when the relay must be able to detect the pole slip so that the generator can be disconnected from the network to prevent further damage to the generator. The slip frequency should be determined by the means of a transient time domain computer simulation, which would take the above factors into account. The

graph in Figure 3-9 was created by using a computer simulation program (DigSilent PowerFactory) to plot the pole-slip frequency for a generator at Kendal power station with an inertia time constant (H) of 3 s, which is the actual combined turbine-generator inertia time constant and a second scenario with an inertia time constant (H) of 1.5 s. As expected, the graph in Figure 3-9 indicates that the pole-slip frequency increases as the inertia time constant decreases.



Figure 3-9 Typical pole slip frequency (Kendal 729 MW generator: H = 3 s)

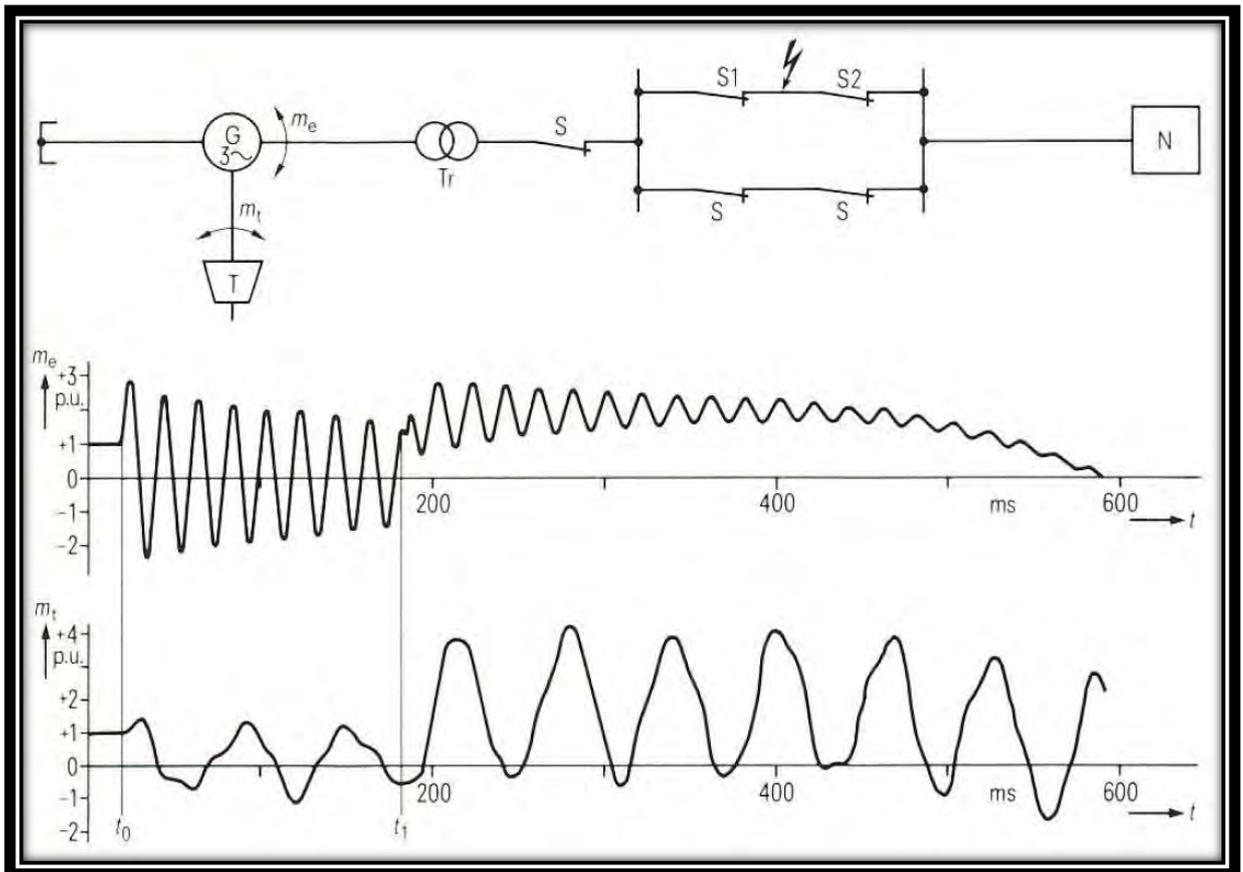
3.6 Causes Of Torsional Vibration In Turbine-Generator Units

Up to a few years ago, terminal short-circuits and out-of-phase synchronising were regarded as being the most severe types of fault leading to torsional vibration in turbine-generator units. Both of these types of faults have been rendered extremely unlikely due to the advancements in technology and design. The generator and generator transformer busbars are phase segregated and are enclosed in a pressurised cylindrical aluminium ducts, which makes it very

difficult for a phase-phase fault to develop. Most power stations have dual synchronisers, which have advanced algorithms to prevent an out-of-phase synchronising event.

A close-up short-circuit on an outgoing power station HV or EHV feeder causes significant stress to the generator windings and the turbine-generator shaft. When the short circuit is cleared by the line protection, the voltage recovers and this causes severe stress. Under these conditions impermissibly high stressing of the coupling and shaft fatigue of the turbine-generator unit can occur depending on the load change and on the fault clearing time.

The fundamental relationships are depicted in Figure 3-10. Torsional vibration is induced in the shaft of a turbine-generator unit by the electrical torque m_e upon occurrence of a three-phase short circuit at time t_0 . The time behaviour of the mechanical torque m_t depends on the torsional natural frequencies below the power frequency of the multi-inertia turbine-generator shaft train and its interconnecting shafts and couplings.



T = Turbine	T_r = Generator Transformer	G = Generator
N = Power System	S = Circuit Breaker	m_e = Electrical torque
m_t = Mechanical torque	t_0 = Inception of 3PF	t_1 = Short-circuit clearance

Figure 3-10 Generator mechanical torque and electrical torque for a close-up three-phase fault on the EHV network (Siemens Power Engineering – Vol II) [10]

At the instant the short-circuit is cleared (time t_1) the largely undamped torsional vibrations can be excited under unfavourable circumstances by unidirectional torque occurring instantaneously as a result of resynchronisation to such an extent that extremely high stresses occur in the couplings and shaft extensions. The magnitude of the stress is largely dependent on the load change of the turbine-generator unit and on the duration of the short circuit.

The resulting maximum mechanical torque, $m_{t \max}$, occurs at varying times depending on the fault clearing time, but by no means immediately subsequent to fault clearance. By increasing the fault clearing time, the possible maximum value of torque also increases, but in some instances the torsional stress is reduced [10].

3.7 Summary

In this chapter, various pole-slip impedance trajectories have been plotted in order to understand how a generator protection relay is used to recognise a pole-slip event. It was shown that the impedance trajectory measured by the relay is a straight line when the generator and system voltage are equal ($E_g = E_s$; $n = 1$). When the generator voltage is greater than the system voltage ($E_g > E_s$; $n > 1$), the impedance trajectory is always above the straight line impedance trajectory associated with the $n = 1$ condition. When the generator voltage is less than the system voltage ($E_g < E_s$; $n < 1$), the impedance trajectory is always below the straight line impedance trajectory associated with the $n = 1$ condition.

The system electrical centre is not fixed and is dependent on the network configuration and impedance. The system electrical centre moves away from the generator as the system impedance increases and the system electrical centre moves closer to the generator as the system impedance decreases. Generator and generator transformer impedances have increased over the years. On the other hand, system impedances have been decreasing. Therefore, it has become more likely for the electrical system centre to be located within the generator. As the system electrical centre moves from the system and into the generator, the current magnitude during a pole slip increases and with it thermal and mechanical stress on the generator and the generator transformer. Therefore, it is critical that the generator-pole-slip protection is able to detect a pole slip which has a system electrical centre located within the generator or generator transformer.

It was also shown that the pole-slip frequency increases as the inertia time constant of the turbine-generator unit decreases.

This chapter has covered the fundamentals of generator-pole-slip protection. The following chapter reviews commercially-available generator protection functions to determine how they operate for a pole slip or power swing.

CHAPTER 4: POLE SLIP DETECTION METHODS

This chapter reviews a number of generic protection functions that are able to detect a pole slip as well as specific pole-slip functions that are used by different relay manufacturers. It is important to understand how the various pole-slip protection functions work to identify their limitations and assess whether they operate correctly for a pole slip or a power swing.

In chapter 6 and chapter 7 dynamic simulations are performed to test whether a Siemens 7UM62X pole-slip protection relay model as well as the hardware device operates correctly. The relay should issue a trip for a real pole slip and it should not issue a trip for a stable power swing. It is therefore also important to have a good understanding of the difference between a correct and incorrect pole-slip protection operation.

4.1 Generator Backup Impedance

Most large generators have backup impedance protection, which is set to have a relatively large reach with a long trip time delay (typical time delay = 1.5 s), which is needed to provide co-ordination between the main and backup protection system. Therefore, the generator backup impedance protection will generally be able to detect a pole slip passing through the impedance characteristic but it will not trip due to the backup impedance time delay.

A typical backup impedance protection characteristic is shown in Figure 4-1. Z_g represents the generator impedance, Z_{GT} the generator transformer impedance and Z_s the system equivalent impedance. The backup impedance protection reach is generally set to 110% of Z_{GT} . Therefore, it provides backup protection to the main protection devices that are protecting the generator, generator transformer and the busbars that are connected to the high voltage side of the generator transformer.

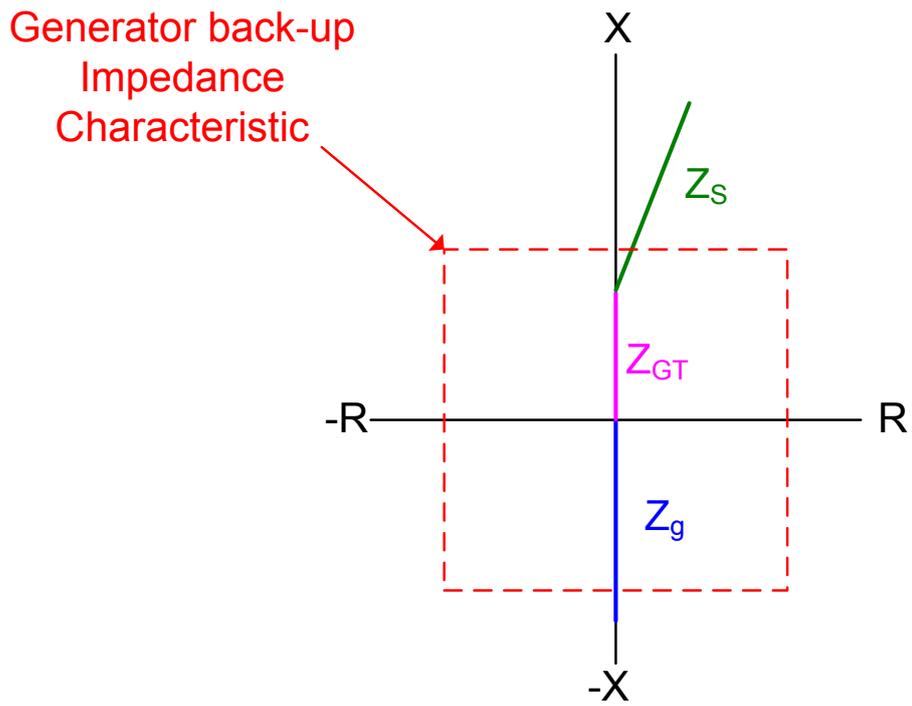


Figure 4-1 Typical generator backup impedance characteristic

4.2 Loss-Of-Field (LOF) Or Under-Excitation Protection

Most loss-of-field protection relays utilise an admittance or impedance characteristic to detect a loss of field. The impedance characteristic is typically an offset mho as indicated in Figure 4-2 and the impedance is measured at the generator terminals. Z_s represents the system equivalent positive sequence impedance, Z_{GT} the generator transformer positive sequence impedance, X'_d the generator direct-axis transient reactance and X_d the generator direct-axis synchronous reactance.

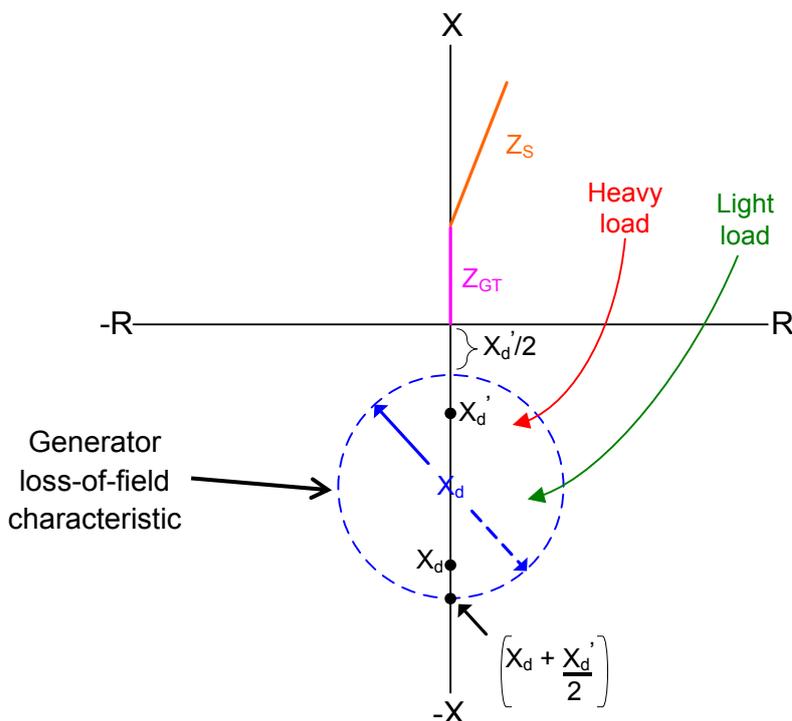


Figure 4-2 Typical generator loss-of-field impedance characteristic

When a generator is initially operating close to full load and a loss of field occurs, the final (steady-state) value of slip frequency will be high, typically in the 2% to 5% range. At this slip, the axis reactances are usually slightly above X'_d and X'_q (transient-direct and quadrature axis reactance). Conversely, for a loss-of-field from light initial load, the slip frequency will be very low, typically in the 0.1% to 0.2% range. At this slip frequency, the axis reactances are slightly less than X_d and X_q (synchronous direct and quadrature axis reactance) [19]. Therefore, the reactance measured by the loss-of-field relay as the generator

slips will vary between X'_d and X'_q if the generator was initially at full load and between X_d and X_q if the initial operation was at light load. Given that X_d is greater than X_q and that X'_d is less than X'_q , the loss-of-field protection must be set to encompass all reactance values between X'_d and X_d if it is to operate for all initial conditions of generator loading [3]. To meet this criteria, it has become standard practice to set the impedance element for this type of scheme with a diameter of X_d and an offset of $\frac{1}{2}X'_d$ as shown in Figure 4-2. The offset of the relay characteristic from the origin also provides selectivity against improper operation during power swings or out-of-step conditions. In an extreme case of zero system impedance, the electrical centre is at the centre of the generator impedance X'_d . Therefore, the loss-of-field relay characteristic is offset by $X'_d/2$ [26].

A loss-of-field (LOF) protection trip is typically time delayed by around 0.5 s to 2 s. A pole-slip impedance trajectory that passes through the generator transformer or the generator terminals will not be detected by the LOF protection due to the offset mho characteristic. If the pole-slip impedance trajectory passes through the generator and it is within the LOF characteristic, the LOF protection would pickup, but it would only trip if the swing remained within the LOF characteristic for more than the LOF time delay setting of around 0.5 s to 2 s. It is clear that the LOF protection would only trip for certain unusual pole-slip conditions and cannot be used exclusively as the main pole-slip protection.

4.3 Overcurrent Protection

A generator-pole-slip condition produces excessively high pulsating balanced currents as shown in the time domain simulation plot in Figure 4-3 for a typical generator-pole-slip condition.

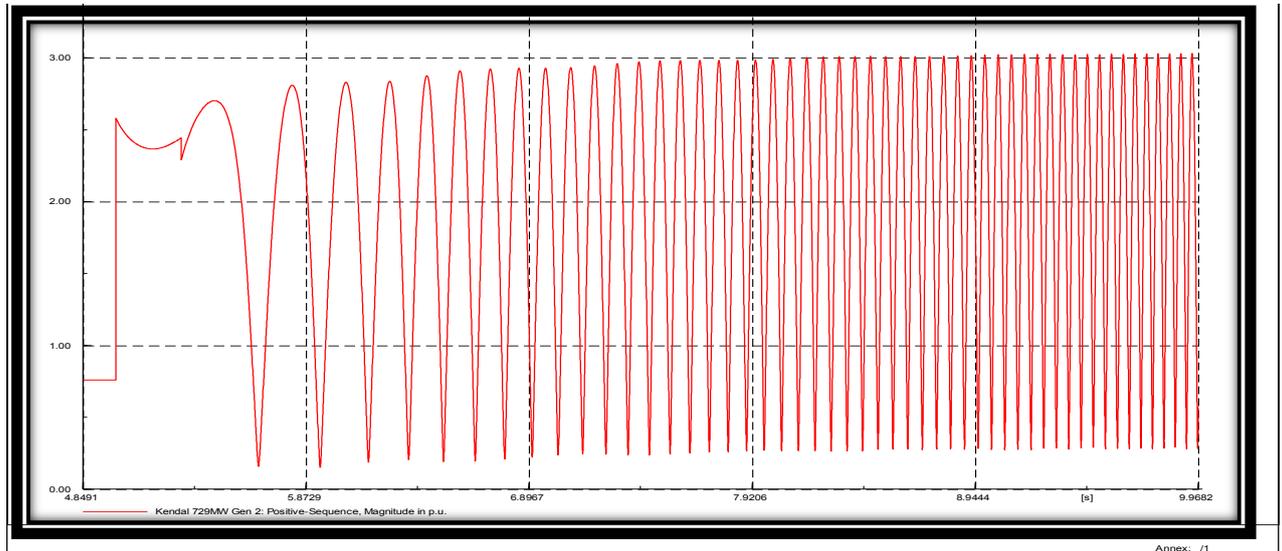


Figure 4-3 Typical generator current pulsation during a pole-slip condition

An overcurrent relay could be used to detect the excessively high current, but the problem is that it is not a sustained current like a typical phase-to-phase or earth fault; instead it is a pulsating current, which is dependent on the slip frequency. The pulsating current duration is reduced each slip cycle and the frequency increases. Therefore, a numerical overcurrent relay with an inverse characteristic would typically pickup and then reset each slip cycle if the reset characteristic was set to instantaneously reset. If an electro-mechanical overcurrent relay was used, it would pick-up and ratchet each slip cycle and eventually it would trip [3]. It is possible to set a numerical relay to have the same type of overcurrent reset characteristic as an electro-mechanical relay to produce the same effect. In South Africa, overcurrent protection is not used on large generators within Eskom, because more sophisticated unit protection is used to detect phase-to-phase faults and impedance protection is used as backup protection for phase faults [24].

According to the IEEE guide on generator protection [25], overcurrent protection is mainly used to provide thermal protection for the generator stator core and windings. For phase-to-phase faults, a simple time-overcurrent relay cannot be properly set to provide adequate backup protection for phase faults. The pickup setting of this type of relay would normally have to be set from 1.5 to 2 times the maximum generator rated full-load current in order to prevent unnecessary tripping of the generator during some emergency overload condition. With this pickup setting and with time delays exceeding 0.5 s, the simple time-overcurrent relay may never operate since the generator fault current may have decayed below relay pickup. After 0.5 s or more, generator fault current will be determined by machine synchronous reactance, and the current magnitude could be well below generator rated full-load current, which would be below the relay setting [25].

Another problem with using an overcurrent relay to disconnect the generator for a pole slip is that you would need the generator to pole slip several times before the generator is disconnected, which is undesirable because each additional generator pole slip will cause severe stress and damage to the generator and turbine. Another concern is that overcurrent protection could issue a trip when $\delta = 180^\circ$, which could destroy the generator breaker as it is generally not rated for 180° out-of-phase switching [22].

4.4 Pope Slip Protection Function Of The Siemens 7UM62X Relay

For the purpose of this dissertation, the Siemens 7UM622 machine protection relay is used to test the response of generator-pole-slip protection. This is done at first within the DigSilent PowerFactory software by modelling the Siemens 7UM622 relay and then applying simulated time domain pole-slip conditions to the relay model to evaluate its response. Secondly the actual 7UM622 relay is injected with actual currents and voltages, which are produced during the time domain pole-slip simulations to validate the software relay model.

4.4.1 Measurement principle

The Siemens out-of-step protection is based on the well-proven traditional impedance measurement and evaluation of the complex impedance phasor trajectory as discussed in chapter 3. The impedance is calculated from the positive sequence fundamental frequency components of the three voltages and three currents. The decision whether or not to separate the generator from the network is made dependent on the locus of the impedance phasor and the location of the electrical centre of the power swing. The measurement characteristic is a power swing polygon as shown in Figure 4-4. The polygon has an inclination angle φ_p , which is adjustable. All four boundaries of the polygon are also adjustable in all directions. The settings engineer has to study and simulate the actual behaviour of the particular generator being protected, and then, based on what is found from studying and simulating the system, set the boundaries and inclination angle of the polygon carefully to meet that system's protection requirements [7].

4.4.2 Out-of-step protection logic

Figure 4-4 is an extract from the Siemens 7UM622 relay manual, which shows the power swing polygon in greater detail. For simplicity purposes the inclination angle φ_p is assumed to be 90° . The setting parameters of impedances Z_a , Z_b , Z_c

and $(Z_d - Z_c)$ determine the power swing polygon. The polygon is symmetrical about its vertical axis. Z_b is measured in reverse direction into the generator, in the forward direction (Z_c) into the generator step-up transformer, and the second stage (Z_d) into the power system.

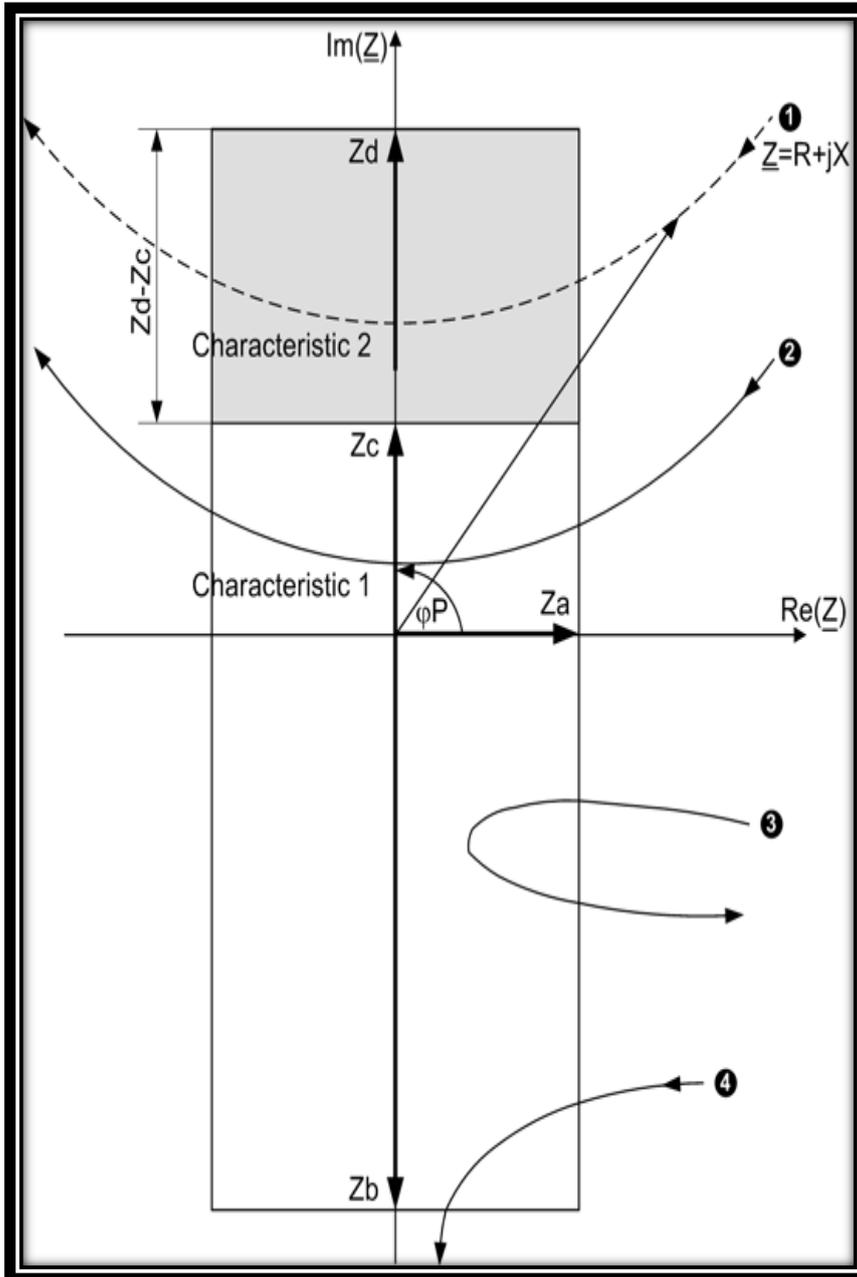


Figure 4-4 Siemens 7UM622 relay manual extract: polygonal out-of-step characteristic indicating typical power swings trajectories [7].

The power swing polygon is divided into two parts. Characteristic 1 (i.e. the non-hatched area) represents the lower section of the rectangle. Characteristic 2 covers the upper hatched area. The settings engineer should configure the relay so that characteristic 1 detects an out-of-step condition with a system electrical centre located within the generator or the generator transformer. As an example, in Figure 4-4 an out-of-step impedance trajectory ② traverses through the top half of characteristic 1, which is the generator transformer. Characteristic 2 is generally configured to detect an out-of-step condition with a system electrical centre located within the system. The out-of-step impedance trajectory ① in Figure 4-4 traverses through characteristic 2, which is typically an out-of-step condition, which has a system electrical centre located within the system.

Power swings are three-phase symmetrical occurrences. The first prerequisite is therefore the symmetry of the measured currents. A condition for power swing detection is that the positive sequence component of the current exceeds an adjustable limit I_1 while the negative sequence current remains below an adjustable value I_2 . Additionally, detection of an out-of-step condition requires that the impedance phasor enters a power swing characteristic at one side, passes through the imaginary axis or characteristic dividing line, and exits the polygon at the opposite side as shown by impedance trajectory ① and ② in Figure 4-4. On the other hand, it is also possible for an impedance phasor to enter and exit the power swing polygon on the same side. In this case, the power swing tends to stabilise as shown by impedance trajectory ③ and ④ in Figure 4-4.

A three-phase fault applied to the system side of the generator transformer would be measured by the out-of-step protection relay as point Z_c on the polygon in Figure 4-4. The three-phase fault impedance measured by the out-of-step protection relay moves almost instantaneously from the pre-fault load impedance (outside the polygon) to Z_c inside the polygon. The relay identifies the measured impedance as a fault and not a power swing, because it moved into the polygon almost instantaneously. In order for the relay to detect a power swing, it requires at least two different impedance measurements within the

polygon. Therefore, the width of the polygon determines the maximum detectable swing frequency. If the width of polygon is set according to the relay manufacturer recommendations, the relay is capable of detecting a maximum power swing frequency of 10 Hz [7]. Figure 3-9 in chapter 3 indicates that the slip frequency for an out-of-step generator at Kendal power station is less than 10 Hz around the 6th slip cycle. Most generators will not have a slip frequency that exceeds 10 Hz before six slip cycles and secondly they would be disconnected from the network before reaching six slip cycles. Therefore, the relay capability of measuring a maximum slip frequency of 10 Hz is usually sufficient, but should always be confirmed by transient stability studies.

When an out-of-step condition is recognised, i.e. when the impedance phasor has passed through a power swing characteristic, a counter n_1 (for characteristic 1) or n_2 (for characteristic 2) is incremented as shown in the out-of-step protection logic diagram in Figure 4-5. A trip command is issued when the number of power swing polygon crossings has reached a selectable number.

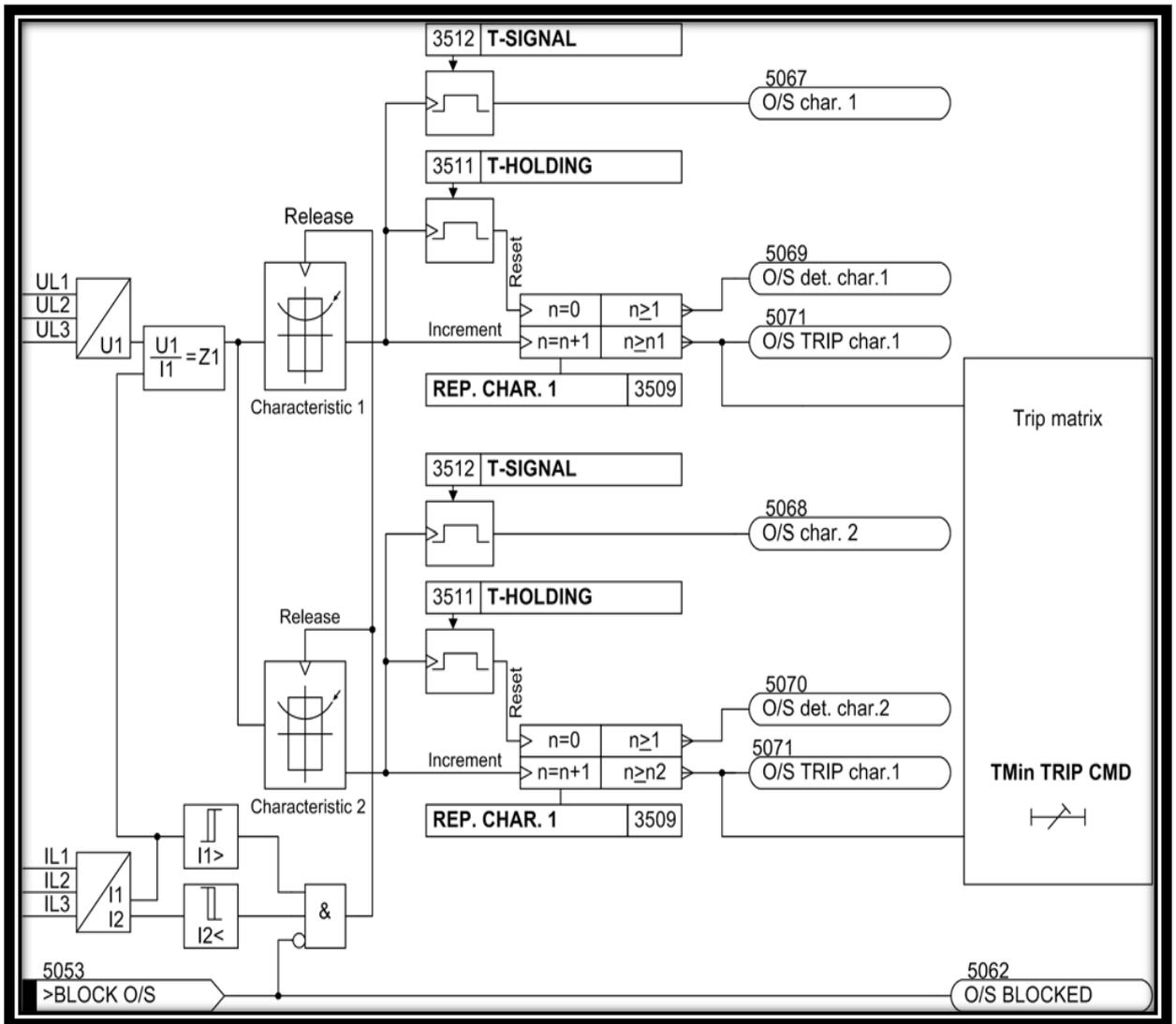


Figure 4-5 Siemens 7UM622 relay manual extract: logic diagram of the out-of-step protection [7].

The number of crossings permitted for an out-of-step impedance trajectory traversing through characteristic 1 is usually set to one since an out-of-step impedance trajectory within the generator or generator transformer cannot be tolerated too long, because the power swing frequency tends to increase causing even greater machine stress. A sustained out-of-step condition can result in high currents that can cause forces in the generator windings and undesirable transient shaft torques. It is possible for the shaft to snap as a result of these high magnitude transient torques [23]. Therefore, if the out-of-step impedance trajectory traverses through characteristic 1, the generator is disconnect immediately after the first slip cycle.

On the other hand, for out-of-step conditions where the electrical centre is out in the transmission system, the detection of the out-of-step condition and isolation of the unstable generator(s) are accomplished by the transmission line out-of-step protection [26]. Therefore, the number of crossings permitted for an out-of-step impedance trajectory traversing through characteristic 2 is usually set to around four slip cycles, which allows the transmission line out-of-step protection to operate before the generator out-of-step protection. Characteristic 2 of the generator out-of-step protection therefore serves as backup protection to the transmission line out-of-step protection. If the transmission line out-of-step protection fails to separate a system that is out-of-step, the generator(s) will be disconnected after around four slip cycles. A generator can generally tolerate a higher number of crossings when the system electrical centre is located within the transmission system [7].

The practice in China is to only trip steam turbo-generators if the out-of-step impedance trajectory passes through the generator impedance characteristic and not to trip if the impedance trajectory passes through the transmission system. However, if the out-of-step impedance trajectory passes through the generator transformer impedance characteristic the practice is to allow the generator to operate for a number of slip cycles to allow resynchronization. Note that their specification states that the generators should be able to sustain 20 oscillation cycles for out-of-step events initiated by close-in line faults, and to be capable of doing this a number of times. In addition, hydro generators are usually not equipped with out-of-step protection, because their experience and tests have shown that hydro units can withstand out-of-step operation [27] .

It is always recommended for the protection engineer to determine the acceptable number of slip cycles by performing dynamic simulations to determine if it is acceptable to subject the generator(s) to more than one slip cycle for an out-of-step condition with a system electrical centre located within the generator transformer or the transmission system.

4.5 SEL Pole Slip Protection (SEL-300G relay)

The SEL 300G [8] relay has two different pole-slip protection functions, the single blinder scheme and the double blinder scheme. The single blinder scheme is a basic scheme with fewer settings compared to the double blinder scheme, which is slightly more complex and provides more security against incorrect tripping for stable swings.

4.5.1 Single blinder scheme

The impedance characteristic of the single blinder scheme is shown in Figure 4-6. The detecting elements of this scheme consist of two blinder elements (78R2 & 78R1) and a mho impedance element (78Z1), which supervises the function. To prevent operation for stable power swings appearing in the generator or generator transformer impedance characteristic, the scheme needs to be supervised by a mho positive sequence impedance element. The scheme is also supervised by an additional positive sequence current element. The blinder elements look in opposite directions, therefore an impedance value at the centre of the mho characteristics would cause both blinder elements to pickup.

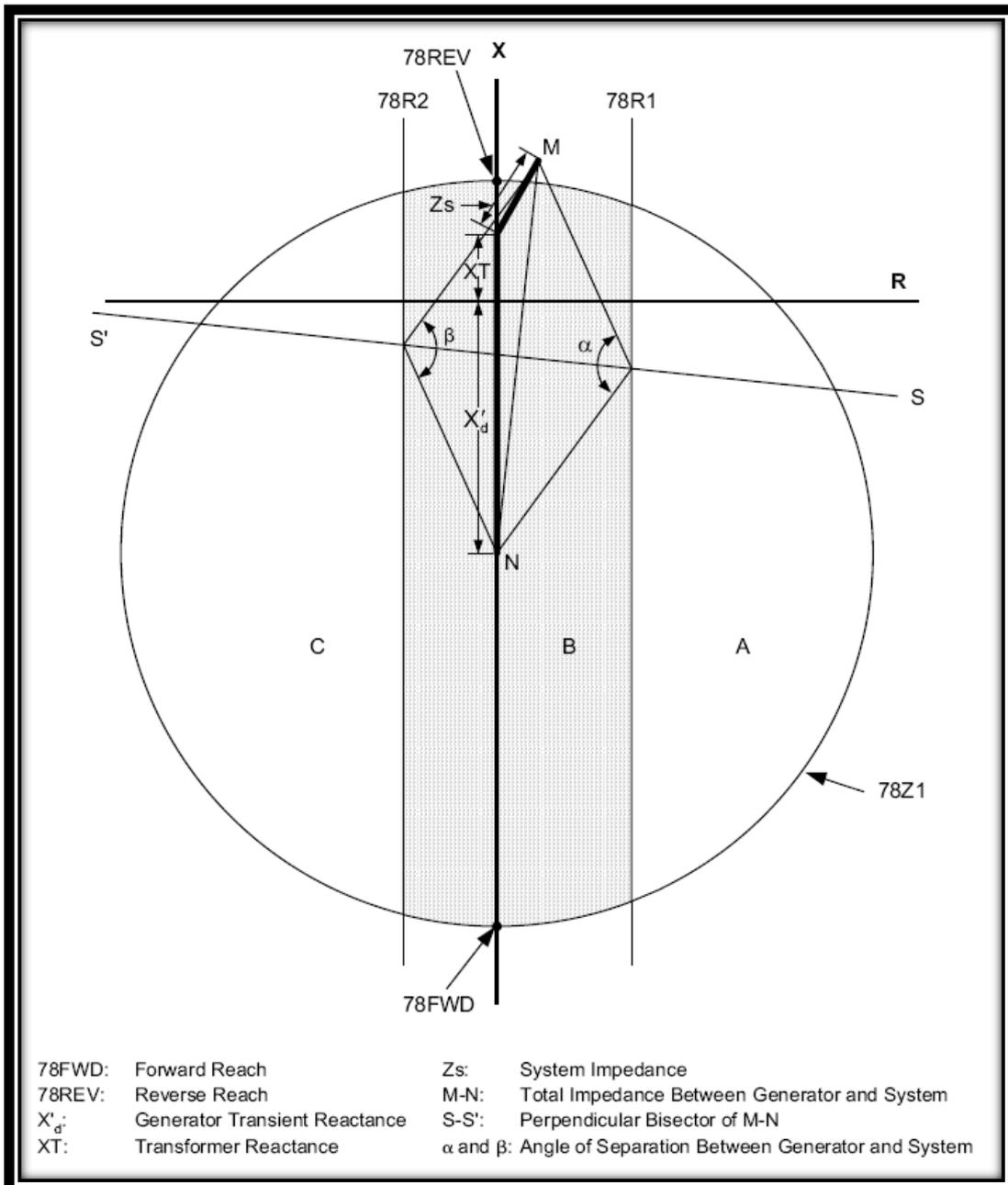


Figure 4-6 SEL 300G relay manual extract: single blinder scheme operating characteristic [8].

This scheme detects an out-of-step condition by tracking the path of positive-sequence impedance trajectories that pass through the protection zone. The logic that is used by the single blinder scheme to detect an out-of-step condition is shown in Figure 4-7. If the relay detects an out-of-step condition, the following relay elements are asserted:

- A swing is detected when the positive-sequence impedance moves from the load region into area A (left blinder 78R2 and mho element 78Z1 assert)
- An out-of-step condition is detected when the impedance trajectory advances further to area B between the two blinders (right blinder 78R1, left blinder 78R2, and mho element 78Z1 assert).
- At the time the impedance trajectory exits the mho circle via area C, the generator has pole slipped and the relay issues a trip after a set time delay.
- The above description is only for trajectories traveling from right to left. Out-of-step trajectories travelling from left to right traverse the protection zone in the reverse sequence (i.e., from area C to B to A). The relay functions in the same way whether trajectories travel from right to left or from left to right.

As shown in Figure 4-7, logic is provided for the single blinder scheme to distinguish between short-circuit faults and out-of-step conditions by tracking the path of the impedance trajectory. During short-circuit faults, the impedance will move from the load region to inside the mho element and between the two blinders almost instantaneously preventing the out-of-step function from picking up [8].

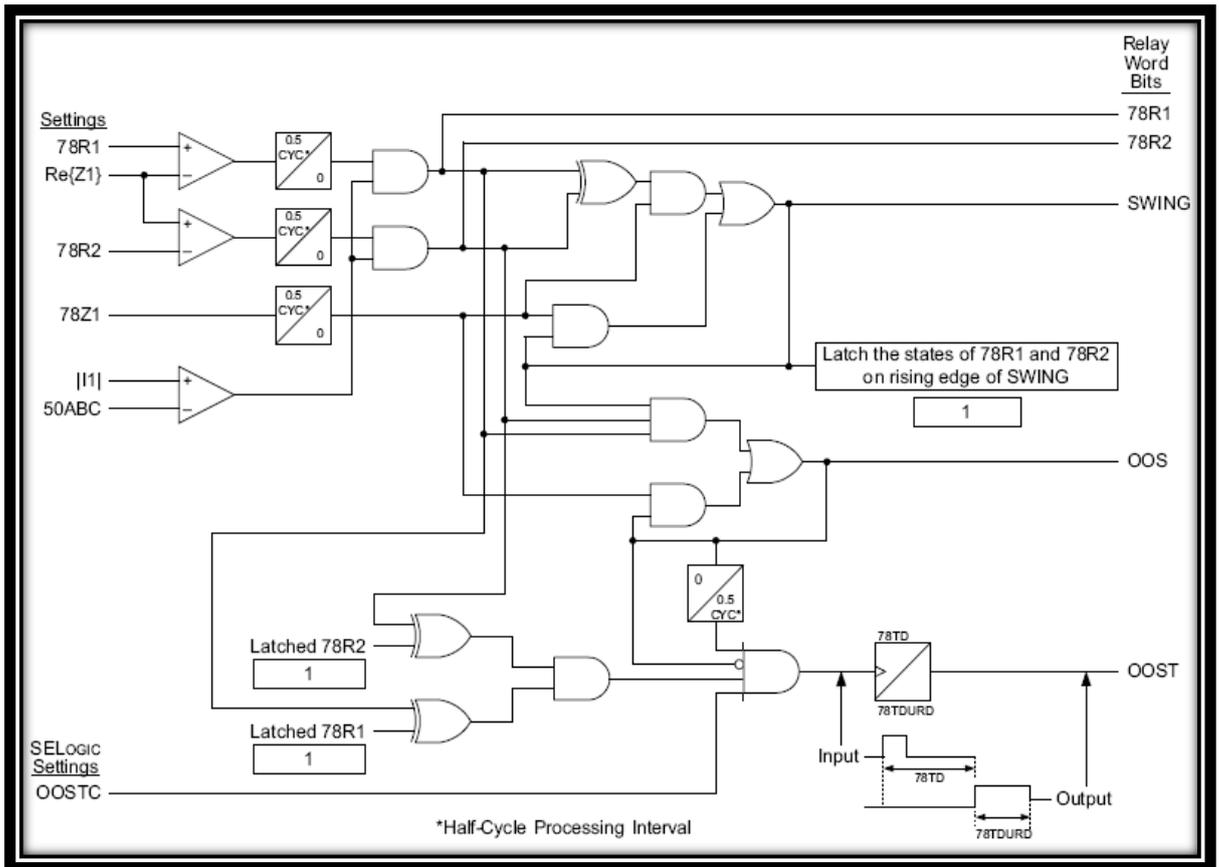


Figure 4-7 SEL 300G relay manual extract: single blinder scheme logic diagram [8].

4.5.2 Double blinder scheme

The double blinder scheme functions in a manner, which is very similar to the single blinder scheme described in section 4.5.1. The impedance characteristic of the double blinder scheme is shown in Figure 4-8. The detecting elements of this scheme consist of two pairs of blinder elements, outer resistance blinder 78R1 and inner resistance blinder 78R2. It also has a mho impedance element

The logic that is used by the double blinder scheme to detect an out-of-step condition is shown in Figure 4-9. If the relay detects an out-of-step condition, the following relay elements are asserted:

- A power swing is detected when the positive-sequence impedance stays between the outer and inner blinders for more than the 78D time delay setting (78R1 asserts, mho element 78Z1 may or may not assert).
- An out-of-step is detected when the impedance trajectory advances further inside the inner blinder (78R1, 78R2, and mho element 78Z1 assert).
- At the time the impedance trajectory exits the mho circle at any point, the relay issues a pole-slip trip after a set time delay.

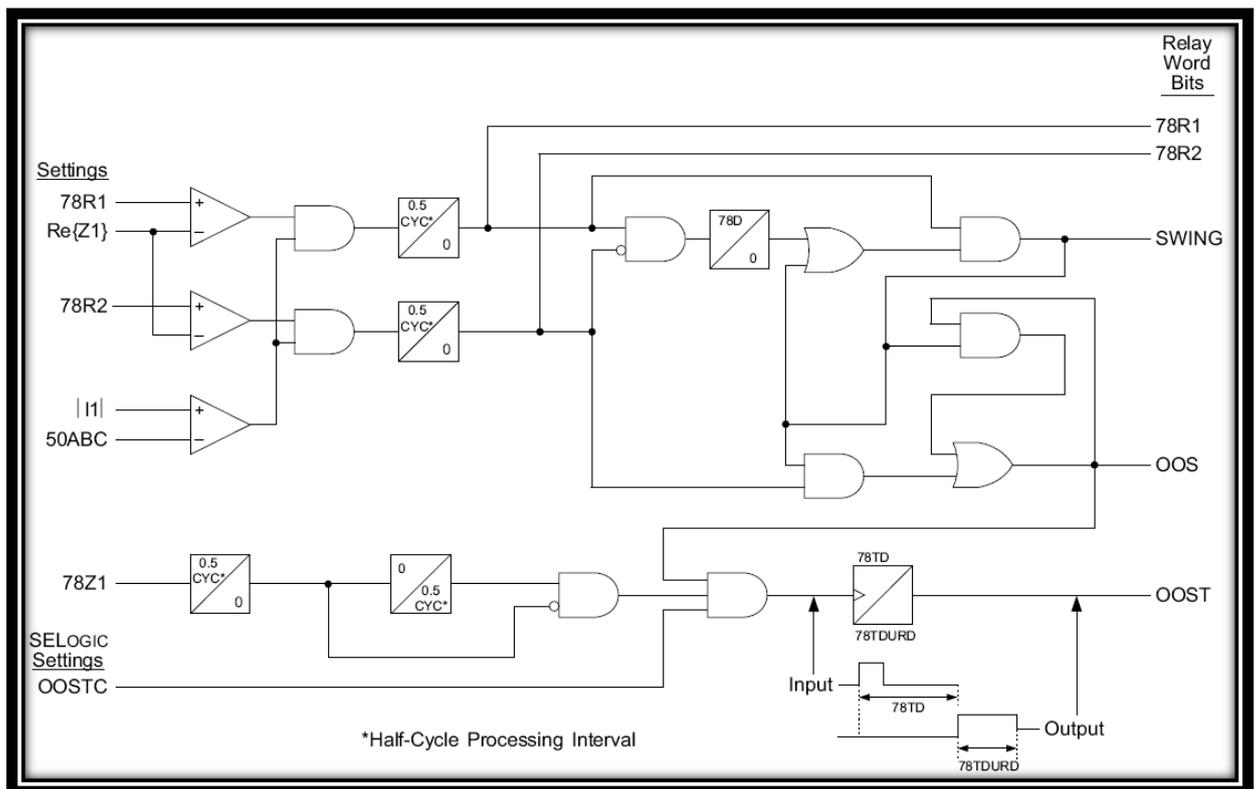


Figure 4-9 SEL 300G relay manual extract: double blinder scheme logic diagram [8].

As shown in Figure 4-9, the double blinder scheme distinguishes between short circuit faults and out-of-step conditions by monitoring the length of time that the

impedance trajectory stays between the two blinders. During short-circuit faults, the impedance either moves inside the inner blinder or goes through the two blinders almost instantaneously so the 78D does not time out. Either case prevents the out-of-step element from picking up [8].

4.5.3 Double blinder scheme shortcomings

The diagram in Figure 4-10 will be used to discuss two shortcomings of the double blinder impedance characteristic. Two possible power swing impedance trajectories (① and ②) are indicated on the impedance plot.

The important difference between the single blinder and double blinder scheme is that with the double blinder scheme, after a swing has been identified by crossing the outer to inner blinder within a set time, a trip will be issued regardless of the direction in which the swing exits the mho characteristic [28]. For the first (①) out-of-step impedance trajectory in Figure 4-10, it is possible for the relay to trip the breaker when $\delta = 180^\circ$, which could destroy the generator breaker as it is generally not rated for 180° out-of-phase switching.

The second (②) impedance trajectory in Figure 4-10 indicates that it is possible for the scheme to operate for a recoverable power swing. The single blinder scheme does not have this problem, because the single blinder scheme would only operate when the impedance trajectory crosses the inner blinder and then exits at the outer blinder, which means that it has crossed the point where $\delta = 180^\circ$ and the generator will not recover [29]. Usually, 78R2 is set to coincide with a point where $\delta = 120^\circ$, which is generally considered as a point where the generator is unlikely to recover from a power swing, although this may still be possible.

4.6 Alstom Pole Slip Protection (Micom P34X relay)

The pole-slip impedance characteristic of the Alstom Micom P34X relay is shown in Figure 4-11. The detecting elements of the relay consist of a lenticular (lens) impedance characteristic and a single straight line blinder that bisects the lens characteristic into two equal parts. The third part of the characteristic is a reactance line that divides the characteristic into two zones namely zone 1 and zone 2. Zone 1 would usually be used to detect a pole-slip impedance trajectory with a system electrical centre located within the generator or generator transformer. Zone 2 would detect a pole-slip impedance trajectory with a system electrical centre located within the transmission system.

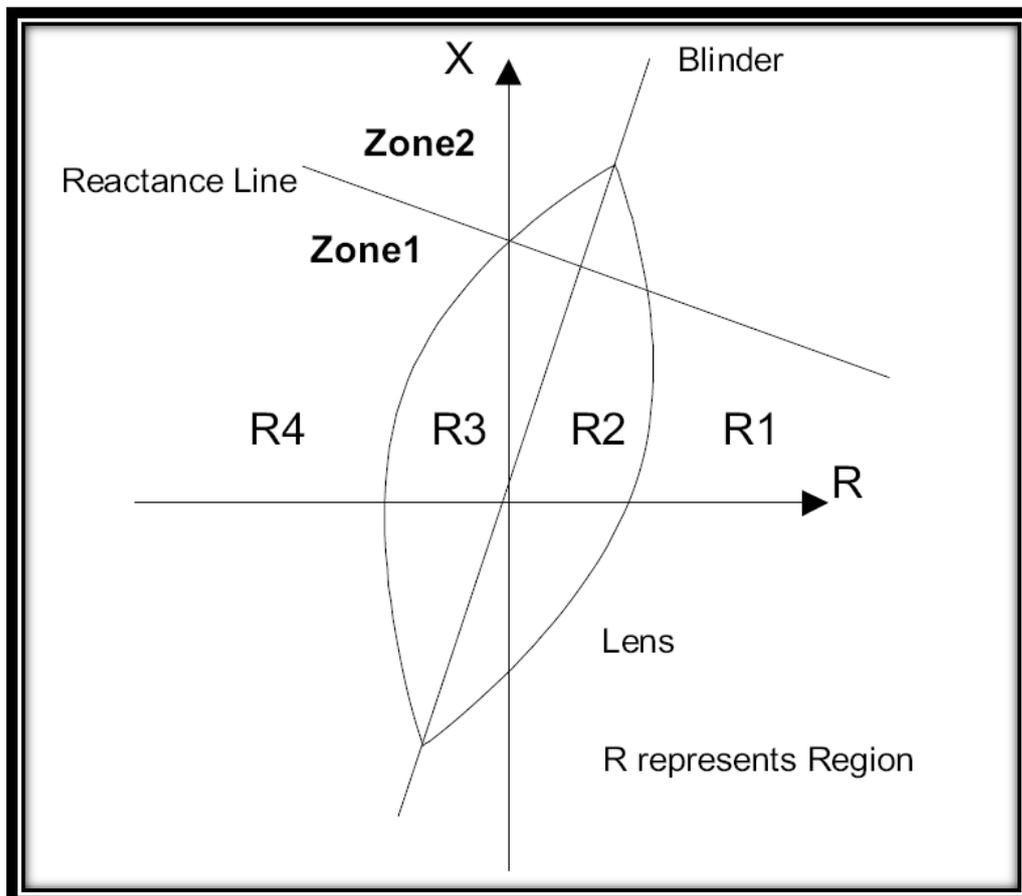


Figure 4-11 Alstom Micom P34X technical manual extract: pole-slip-lenticular characteristic [9].

4.6.1 Functional description

The method used by the relay to detect a pole slip will be described by using Figure 4-12. The measured load impedance is usually in region R1. When a power swing is detected the measured impedance moves from region R1 to R2 and timer T1 is started. If the measured impedance remains within region R2 for longer than the set time of timer T1 and then crosses the blinder and moves to region R3, timer T2 is then started. If the measured impedance now remains within region R3 for longer than the set time of timer T2 and then exits region R3 of the lens characteristic and moves to region R4, a pole-slip condition is flagged and the generator is tripped. It is possible to set the number of allowable pole slips before tripping to more than one pole slip if desired.

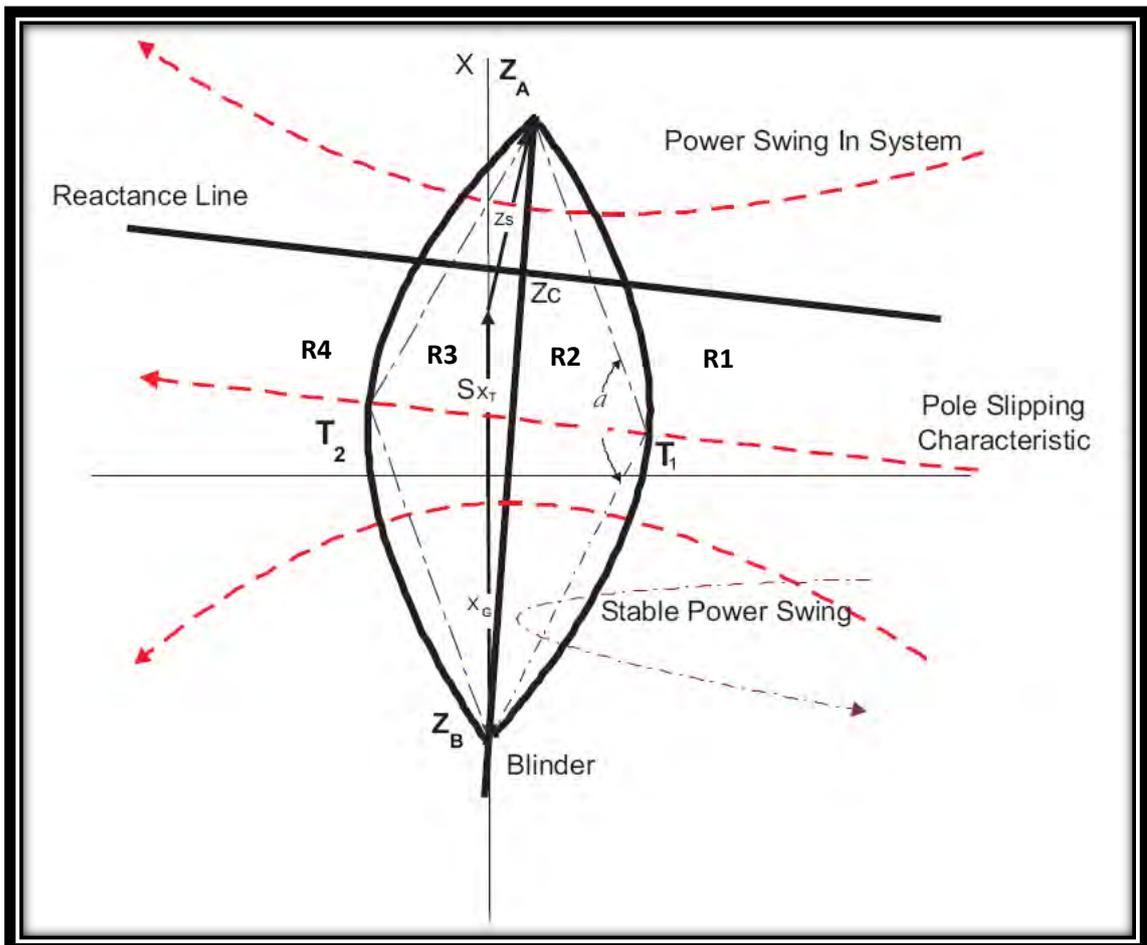


Figure 4-12 Alstom Micom P34X technical manual extract: typically applied pole-slip-lenticular characteristic settings [9].

When a generator is out of step with the system, the impedance locus is expected to traverse from right to left across the lens and the blinder. However, if the generator is running as a motor, as in the pumping mode of a pumped storage generator, the impedance locus is expected to swing from the left to the right. The relay has a pole-slip mode setting to determine whether the protection operates in a “generating” mode or in a “motoring” mode or “both”. For a pumped storage generator, its operation can switch from generating mode to motoring mode and vice versa [9].

4.7 ABB Pole Slip Protection (REG670 relay)

The ABB pole-slip protection function is similar to the other relay manufacturers described previously. The pole-slip impedance characteristic of the ABB REG670 relay is shown in Figure 4-13. It also measures the impedance trajectory to detect a pole-slip condition, but the main difference is that it doesn't have a fixed mho, quadrilateral or lenticular characteristic with blinders. The generator, generator transformer and the system impedances are set within the relay. The relay then uses these settings to calculate the rotor angle relative to the system as well as the location of the measured pole-slip system electrical centre. Zone 1 would be used to detect a pole-slip impedance trajectory with a system electrical centre located within the generator or generator transformer. Zone 2 would detect a pole-slip impedance trajectory with a system electrical centre located within the transmission system.

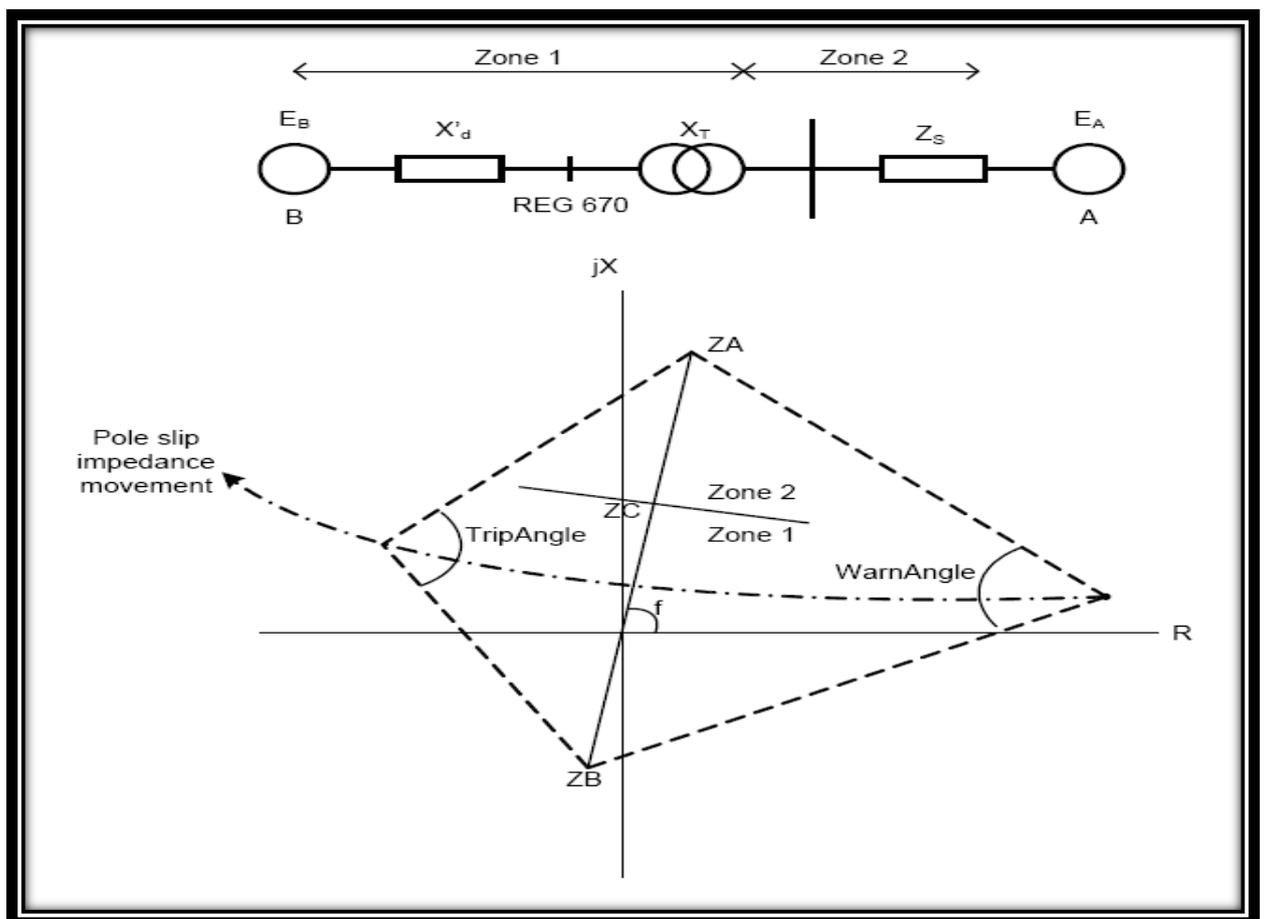


Figure 4-13 ABB REG670 application manual extract: pole-slip protection characteristic [11].

The logic that is used by the ABB REG670 relay to detect an out-of-step condition is shown in Figure 4-14. The relay has a setting to define the number of pole slips that should occur within zone 1 or zone 2 (N1Limit and N2Limit) before a trip is issued as well as a setting to define the trip angle ($\delta \leq \text{tripAngle}$). The relay will only issue a trip when the measured rotor angle is less than the set value (usually 90°), which reduces the stress on the generator breaker and prevents re-striking.

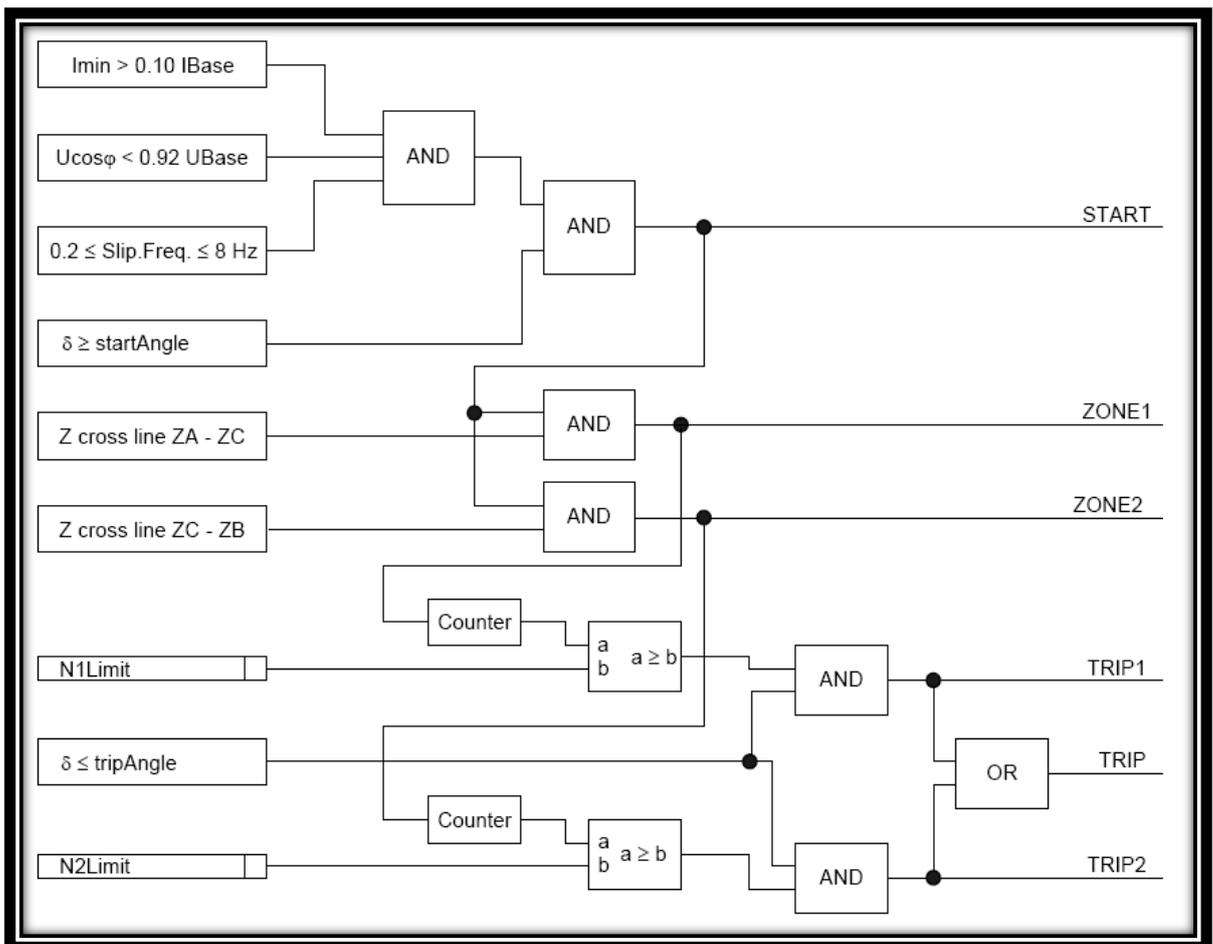


Figure 4-14 ABB REG670 technical reference manual extract: simplified pole-slip protection logic diagram [11].

4.8 Conclusion

A number of generic protection functions such as backup impedance, overcurrent and loss-of-field have been reviewed in this chapter. It was found that these protection functions are able to detect certain out-of-step conditions even though they have not been designed to specifically detect an out-of-step condition. However, the generic protection functions cannot be relied on as the sole means of providing out-of-step protection, therefore a specific out-of-step protection function is needed.

The out-of-step protection functions that were reviewed did not have any predictive or preventive algorithms to prevent a generator pole slip from occurring. The out-of-step protection functions all respond to a generator pole slip by disconnecting the generator after a certain settable number of pole-slip cycles. The generator or turbine may be damaged by the time the out-of-step protection has operated.

Relay manufacturers have developed specific out-of-step protection functions to detect out-of-step conditions. The different specific out-of-step detection methods used by Siemens, SEL, ABB and Alstom have been reviewed. All four manufacturers use an impedance measurement to detect an out-of-step condition, but the out-of-step impedance characteristics as well as the algorithms used are slightly different. This dissertation focuses on the Siemens out-of-step protection function but, since all four manufacturers' out-of-step protection functions are very similar (based on impedance measurement), the method used to test the other relays would be very similar. Therefore, the method that is used in the following chapters to test the Siemens out-of-step protection function could be used to test an out-of-step protection function from another relay manufacturer.

The methods used by the different relays to identify a stable and unstable power swing were analysed to determine if an incorrect relay operation is possible. It is important to understand the difference between a correct and incorrect relay operation, because in chapter 6 and chapter 7 dynamic simulations are performed to test whether a Siemens 7UM62X pole-slip protection relay model as well as the hardware device operates correctly.

CHAPTER 5: RELAY MODELLING

This chapter provides an overview of the Siemens 7UM622 generator protection relay model in DigSilent PowerFactory. The relay model has various protection functions, but for the purpose of this dissertation the main focus area will be the pole-slip protection function. The chapter also shows how the settings required for the pole-slip protection functions of this relay model are calculated for a particular generator whose protection is being studied in the dissertation.

5.1 Siemens 7UM62X Relay Model In Digsilent PowerFactory

The Siemens 7UM62X relay model that was used for the pole-slip protection testing has many other protection functions besides out-of-step protection. The relay model covers the majority of the functions used in generator protection and it is divided into seven sub-relays. These sub-relays and their elements are summarised below using the terminology adopted in the DigSilent PowerFactory manuals.

- Over-current (F50/51)
- Differential (F87)
- Loss-of-field (F40)
- Power (F32)
- Distance elements (F21)
- Voltage (F27/59)
- Frequency (F87)

The overcurrent sub-relay consists of the following elements:

- First stage overcurrent element with a seal in feature ($I >$)
- Second stage overcurrent element with a directional characteristic ($I >>$)
- Simplified thermal image element
- Phase overcurrent with voltage restraint (51V).
- Negative sequence $I^2t = k$ characteristic
- Negative sequence time defined element
- 90% stator earth fault protection ($3I_o >$)
- Sensitive earth fault protection (2 elements: $IE >>$ & $IEE >>$)

The differential sub-relay consists of the following elements:

- Phase differential block with double bias slope
- Ground differential block with single bias slope

The loss-of-field sub-relay consists of the following elements:

- Admittance Characteristic 1 (yChar1)
- Admittance Characteristic 2 (yChar2)
- Admittance Characteristic 3 (yChar3)
- Current starting

The power sub-relay consists of the following elements:

- Reverse power valve open ($P > \text{Reverse T-SV-OPEN}$).
- Reverse power valve closed ($P > \text{Reverse T-SV-CLOSE}$)
- Forward power maximum threshold ($P_f >$)
- Forward power minimum threshold ($P_f <$)

The distance sub-relay consists of the following elements:

- Three polygonal trip elements (Z1, Z1b, Z2)
- Power swing blocking
- Current starting with faulted loop selection
- Two pole-slip characteristics (Out of Step)
- Pole-slip positive sequence current release ($I_{1>}$) and negative sequence current release ($I_{2<}$)

The voltage sub-relay consists of the following elements:

- Two phase-to-ground undervoltage time defined elements
- Two phase-phase overvoltage time defined elements
- Two phase-ground overvoltage time defined elements
- One positive sequence voltage time dependent element
- One volts/hertz time dependent element
- One volts/hertz time defined element

The frequency sub-relay consists of the following elements:

- Four overfrequency / underfrequency elements
- Four df/dt elements

Figure 5-1 indicates the complete Siemens 7UM62X Digsilent relay model. The protection blocks that are shaded in red were not used for the purpose of this dissertation. Only the elements that are used for the pole-slip protection were enabled and tested.

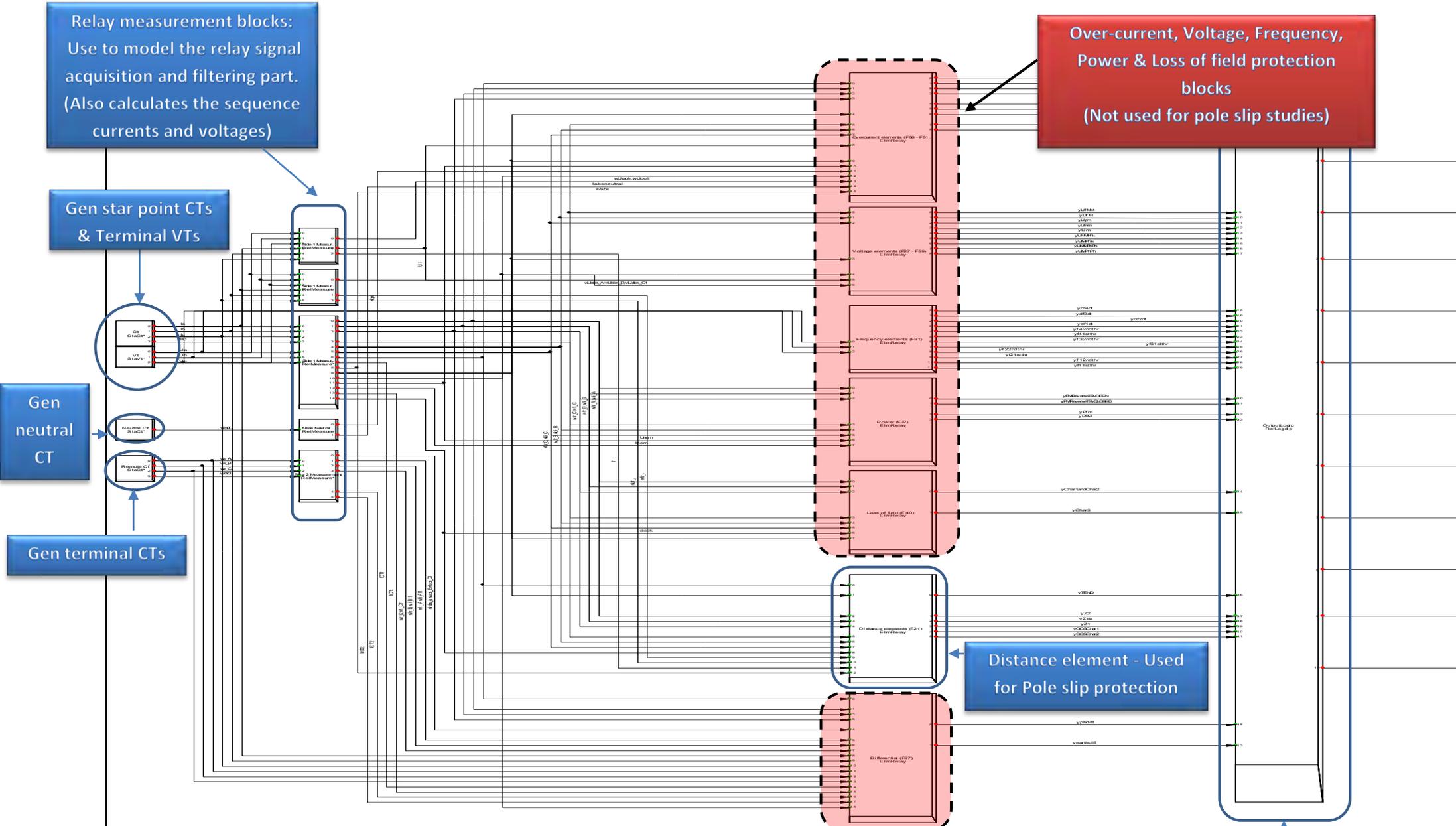


Figure 5-1 Siemens 7UM62X Digsilent Relay Model

Differential Protection Block
(Not used for pole slip studies)

Protection Trip inputs and outputs

The Siemens 7UM622 Digsilent relay in Figure 5-1 is an overall view of the relay protection blocks or functions. The work in this dissertation focuses solely on the pole-slip protection function, which is part of the distance element (F21) relay model subset that is indicated in Figure 5-2. The function blocks that are used for the pole-slip protection distance element are described below.

5.1.1 Measurement block

This function block is used to model the relay signal acquisition and filtering part. It also calculates the sequence currents and voltages, delta current and voltage as well as the phase-phase currents and voltages. The measurement block gets its input signals from the generator current and voltage transformers. The measurement block output signals are then sent to the various protection blocks [12].

5.1.2 Starting block

The starting block implements the fault detection logic used by the Siemens 7SA5XX and 7SA6XX relays. The Siemens 7UM62X technical relay manual does not refer to any starting function and it is not possible to set any of the starting parameters within the actual relay hardware. The Siemens 7UM62X technical relay manual only refers to a positive and negative sequence current release function, which is described in section 5.1.3.

The Digsilent relay model for the Siemens 7UM622 relay has implemented the starting function based on the Siemens 7SA5XX and 7SA6XX relays. There are four different types of fault detection methods available: overcurrent ($I >>$), underimpedance / overcurrent ($Z < / I >$), impedance (Z) and directional underimpedance / overcurrent ($Z \phi < / I >$) detection logic.

The overcurrent ($I >>$) element has been selected as the starting element that enables the out-of-step impedance measurement. If any of the phase currents exceed the phase current setting threshold ($I_{ph >>}$), the out-of-step impedance

measurement will be started. Since the starting block is an additional function block that is not part of the Siemens 7UM622 relay, the $I_{ph}>>$ threshold has been set to a relatively low value of 0.2 p.u. to ensure that the out-of-step impedance measurement is always enabled when the generator is synchronised.

5.1.3 $I_1>$ and $I_2<$ release block

Power swings are three-phase symmetrical occurrences. The first prerequisite is therefore the symmetry of the measured currents. The measurement for the pole-slip impedance is enabled if the positive sequence component of the current exceeds an adjustable limit $I_1>$, while the negative sequence current remains below an adjustable limit $I_2<$. Generally, the setting value $I_1>$ release should be set above the generator stator rated current (I_N) i.e. about 120% of I_N , to avoid pickup during an overload. Depending on network conditions, smaller pickup values are permitted so that the measurement may be released all the time. As pole-slip conditions are symmetrical occurrences, the pickup threshold of the negative sequence component of the current $I_2<$ release should be set to approximately 20% of I_N .

5.1.4 Polarizing block

The polarizing block is an element used by distance protection models and directional overcurrent and earth fault models. The purpose of the polarizing block is to provide the distance protection zones with the “polarized” current and voltage signals, which are used to evaluate the trip rules. The inputs to the polarizing block are current and voltage signals from the measurement block, which have been filtered by the measurement block. The polarizing block also calculates the resistance and reactance, which is an output that is used as an input for the impedance measurement block [12].

Different types of calculated polarizing quantities can be selected within the polarizing block. The polarizing “type” determines, which kinds of polarizing signals must be processed. The polarizing types are:

- Phase-to-phase / phase-to-earth (both the phase-to-phase loop and the phase-to-earth polarizing signals are calculated)
- Phase-to-phase (only the phase-to-phase loop polarizing signals are calculated)
- Phase-to-earth (only the phase-to-earth loop polarizing signals are calculated)
- Earth fault switching (the phase-to-phase or the phase-to-earth polarizing signals are calculated accordingly with the detected fault type)
- Fault type switching (the polarizing signals are calculated only for the loop affected by the fault, it works like a single-phase polarizing block)
- Single phase

The phase-to-phase and phase-to-earth polarizing types were selected as the polarising types for the pole-slip impedance calculation. This means that the relay model will calculate both the phase and the earth fault operating and polarizing quantities (currents and voltages), regardless of the fault type.

The relay model can use any of the following various possible methods to calculate the polarizing signal:

- Self
- Cross (quadrature)
- Cross (quad phase-to-phase)
- Positive sequence
- Self, ground compensated

The cross (quadrature) polarizing method was used, which utilises the phase-to-phase polarizing voltages.

5.1.5 OOS Characteristic 1 and 2 block

The OOS characteristics utilise the polygonal block which implements the typical distance protection polygonal characteristics. Different types of polygonal characteristic can be selected, the Siemens (R,X) polygonal characteristic is used for the pole-slip protection simulations. The secondary impedance (R, X) characteristic for the pole-slip protection is set within this function block.

5.1.6 Out-of-step characteristic 1 and 2 block

The name of this function block is very similar to the name of the function block used in section 5.1.5 (OOS Characteristic 1 & 2 block) so it is very easy to confuse the two. Digsilent should give this function block a more descriptive name to avoid confusion. The out-of-step characteristic block basically counts the number of pole-slip cycles. The permissible number of pole-slip cycles before tripping is set within this function block. The output from this function block issues the generator trip signal as soon as the set permissible number of pole slips has been exceeded.

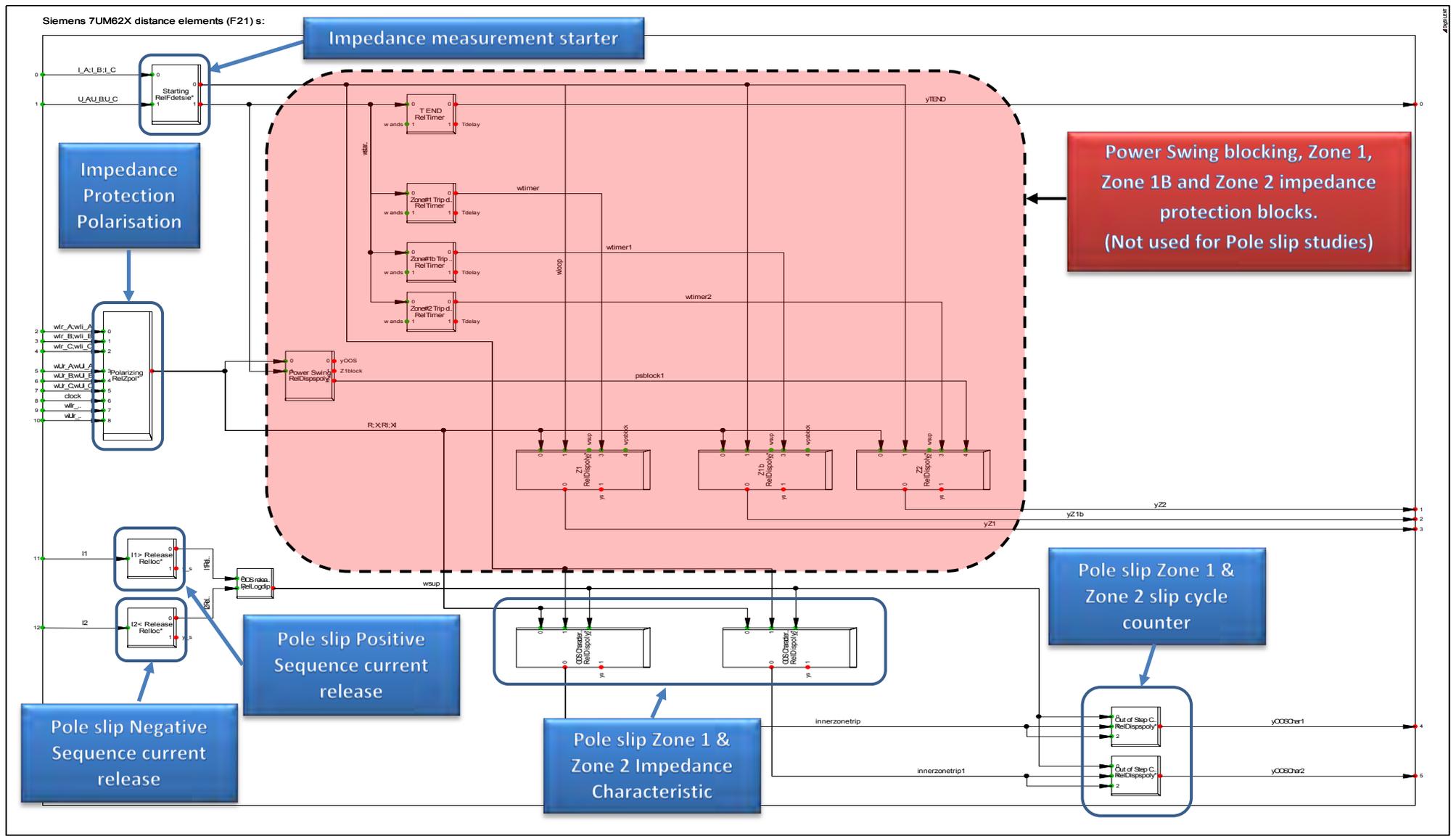


Figure 5-2 Digsilent relay model for the Siemens 7UM62X Impedance function sub block

5.2 Kendal Generator Pole Slip Protection Settings Calculation

The power stations that are modelled within the Eskom interconnected network for the purpose of the pole-slip simulations in this dissertation are Kendal, Tutuka and Duvha. The generator protection relay that is used at Kendal power station (Siemens 7UM622) for pole-slip protection has been modelled in Digsilent and the applied pole-slip settings are calculated below.

5.2.1 Primary plant data

Kendal generator transformer data:

$$S_{GT} = 730 \text{ MVA}$$

$$V_{GT} = 420 \text{ kV}/22 \text{ kV}$$

$$Z_{GT(p.u.)} = 12.6 \%$$

Kendal generator data:

$$S_G = 810 \text{ MVA}$$

$$V_G = 22 \text{ kV}$$

$$X_d = 2.23 \text{ p.u.}$$

$$X'_d = 0.272 \text{ p.u.}$$

$$X''_d = 0.27 \text{ p.u.}$$

$$H = 3 \text{ s.}$$

Note: The generator has a larger rating than the generator transformer. This is not a problem, because the generator usually supplies its own auxiliaries as well as the common plant auxiliaries when it is synchronised to the network. Therefore, when the generator is running at full load, the power sent out through the generator transformer is below the generator transformer rating.

System impedance at Kendal 400 kV busbar:

Figure 5-3 indicates the system impedance measured at the 400 kV busbar at Kendal Power Station with all five of the outgoing Kendal 400 kV feeders in service and all Kendal generators out of service.

$$Z_{System(400\text{ kV})} = 9.047\ \Omega \angle 86.62^\circ$$

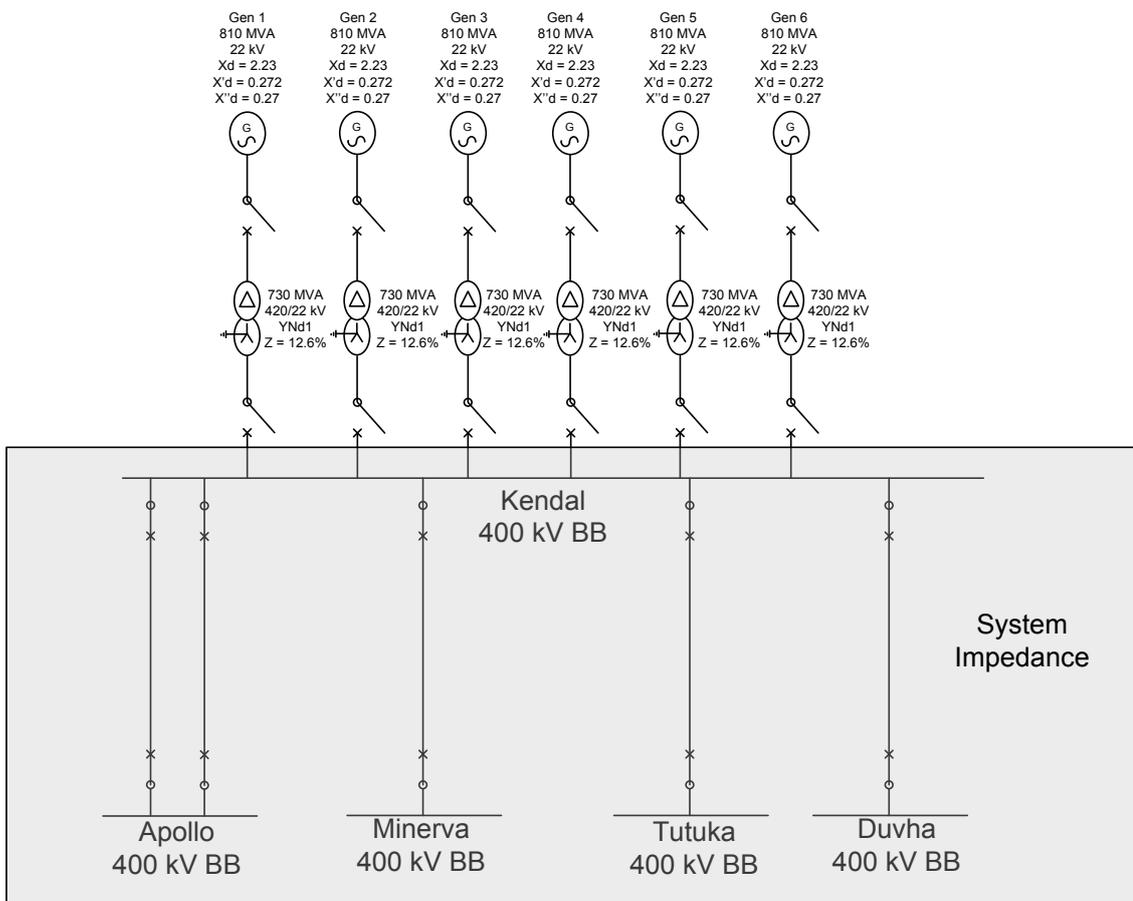


Figure 5-3 System impedance measured from the 400 kV busbar at Kendal power station

The out-of-step impedance relay measurement is measured at the 22kV generator terminals. Therefore, the 400kV system impedance must be referred to the 22kV side of the generator transformer.

$$Z_{System(22kV)} = 9.047 \Omega \angle 86.62^\circ * \left(\frac{22}{420}\right)^2$$

$$= 0.0248 \Omega \angle 86.62^\circ$$

Kendal generator protection current and voltage transformer ratios:

$$CT_{Ratio} = 22000 / 1$$

$$VT_{Ratio} = 22000 / 110$$

$$\frac{CT_{Ratio}}{VT_{Ratio}} = \frac{22000 \times 110}{22000 \times 1} = 110$$

5.2.2 Primary and secondary impedances

Generator transformer primary and secondary impedance calculation:

$$Z_{GT(Prim)} = Z_{GT(p.u)} \times \frac{V_{GT}^2}{S_{GT}}$$

$$= 0.126 \times \frac{22 \text{ kV}^2}{730 \text{ MVA}}$$

$$= 0.0835 \Omega \text{ (Primary)}$$

$$Z_{GT(Sec)} = Z_{GT(prim)} \times \frac{CT_{Ratio}}{VT_{Ratio}}$$

$$= 0.0835 \Omega \times 110$$

$$= 9.19 \Omega \text{ (Secondary)}$$

Generator primary and secondary impedance calculation:

$$\begin{aligned}Z_{G(Prim)} &= X'_d \times \frac{V_G^2}{S_G} \\ &= 0.272 \times \frac{22 \text{ kV}^2}{810 \text{ MVA}} \\ &= 0.162 \Omega \text{ (Primary)}\end{aligned}$$

$$\begin{aligned}Z_{G(Sec)} &= Z_{G(prim)} \times \frac{CT_{Ratio}}{VT_{Ratio}} \\ &= 0.162 \Omega \times 110 \\ &= 17.88 \Omega \text{ (Secondary)}\end{aligned}$$

System secondary impedance calculation:

With all five of the outgoing Kendal 400 kV feeders in service and all Kendal generators out of service:

$$\begin{aligned}Z_{System(Sec)} &= Z_{System(22 \text{ kV})} \times \frac{CT_{Ratio}}{VT_{Ratio}} \\ &= 0.0248 \Omega \times 110 \\ &= 2.73 \Omega \text{ (Secondary)}\end{aligned}$$

5.2.3 Pole slip impedance characteristic settings

Figure 5-4 indicates all the impedances that need to be set to form the quadrilateral characteristic for the pole-slip impedance protection.

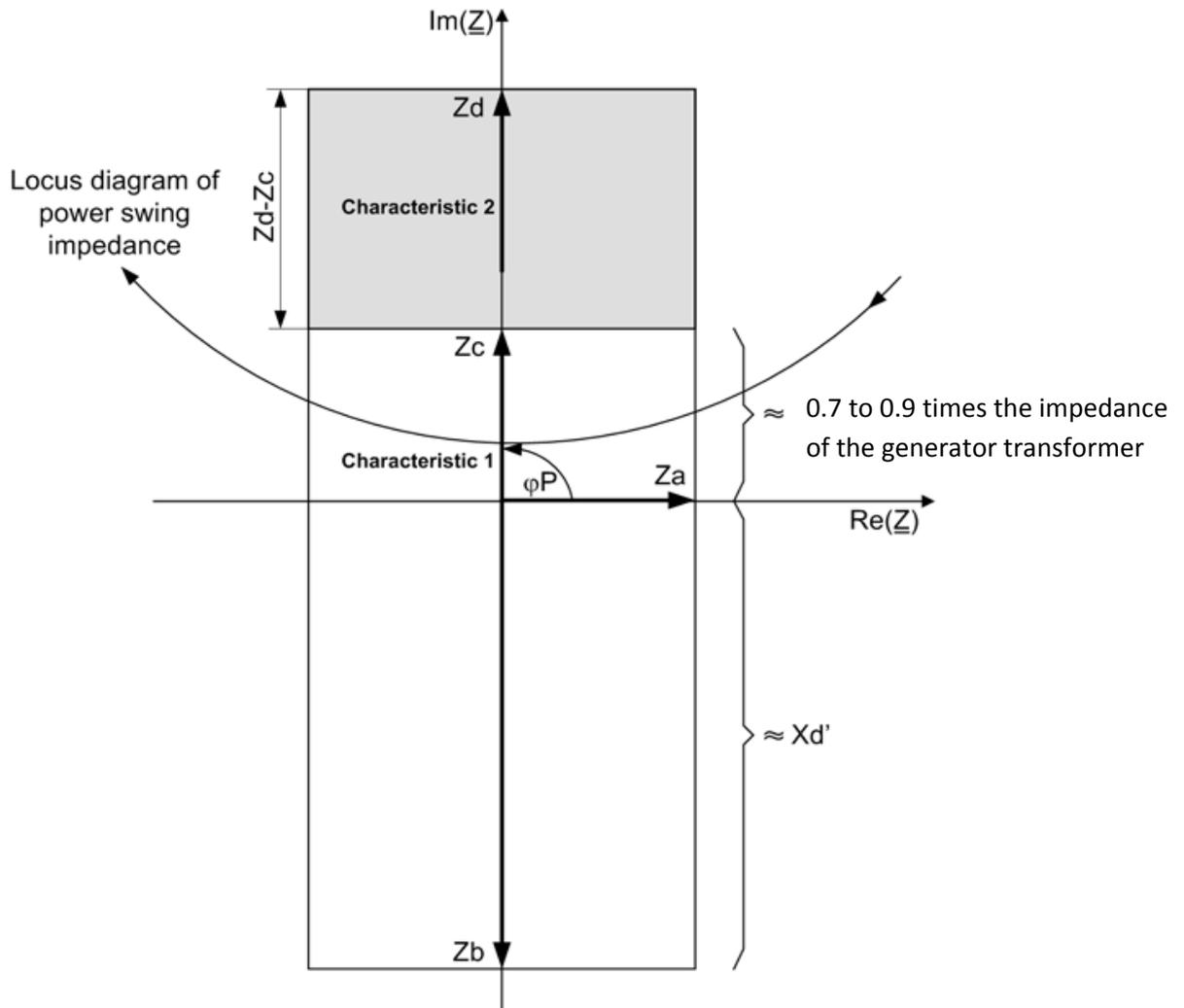


Figure 5-4 Pole slip impedance characteristic setting parameters [7].

$$\begin{aligned}
 Z_b &= Z_{G(sec)} \\
 &= 17.88 \Omega \text{ (Secondary)}
 \end{aligned}$$

The permitted number of pole-slip impedance trajectories traversing through characteristic 1 (zone 1) will be set to one and the permitted number traversing through characteristic 2 (zone 2) will be set to three. Therefore, it is important to ensure that characteristic 1 does not overreach into the network as this could result in a generator out-of-step protection trip being issued before the transmission out-of-step protection. A setting of 0.9 times the impedance of the generator transformer is chosen to ensure that the out-of-step impedance reach for characteristic 1 does not overreach into the network. The 10% margin will account for errors in the transformer impedance, current and voltage transformer errors and relay errors. This will ensure that a pole-slip impedance locus crossing through line Z_c of characteristic 1 in Figure 5-4 is within the generator transformer and not within the network.

$$\begin{aligned}
 Z_c &= Z_{GT(sec)} \times 0.9 \\
 &= 9.19 \Omega \times 0.9 \\
 &= 8.27 \Omega \text{ (Secondary)}
 \end{aligned}$$

Line Z_d is equal to the impedance of the network, plus Z_c (90% of the generator transformer impedance), plus the remaining 10% of the generator transformer impedance. Characteristic 2 is equal to $Z_d - Z_c$ which relates to the system impedance plus 10% of the generator transformer impedance. This will ensure that the 10% of the generator transformer impedance that was excluded from characteristic 1 (to prevent overreaching) is included in characteristic 2. The permitted number of pole-slip impedance trajectories traversing through characteristic 2 is set to three so it is acceptable for characteristic 2 to overreach into the generator transformer.

$$\begin{aligned}
 Z_d &= Z_c + (Z_{GT(sec)} \times 0.1) + Z_{System(sec)} \\
 &= 8.27 + (9.19 \Omega \times 0.1) + 2.73 \Omega \\
 &= 11.92 \Omega \text{ (Secondary)}
 \end{aligned}$$

$$\begin{aligned}Z_d - Z_c &= 11.92 \Omega - 8.27 \Omega \\ &= 3.65 \Omega \text{ (Secondary)}\end{aligned}$$

Note: The “ $Z_d - Z_c$ ” setting is the reach for characteristic 2 (zone 2), which is set to reach into the network for this study. Typically, within Eskom zone 2 is not used and is therefore not set to reach into the network [34] and the reasoning for not reaching into the network is to prevent an “incorrect” pole-slip operation. From an Eskom power station perspective, the transmission line protection is relied upon to separate the system for an out-of-step condition, which has a system electrical centre located within the transmission network. For the purpose of this study, it has been set to reach into the network so that the advantages and disadvantages can be assessed.

$$\begin{aligned}Z_{tot} &= Z_d + Z_b \\ &= 3.65 \Omega + 11.92 \Omega \\ &= 15.57 \Omega \text{ (Secondary)}\end{aligned}$$

The setting Z_a affects the width of the pole-slip polygon and is derived from Figure 5-5. The pole-slip polygon should pickup when the power swing angle (δ) is 120 degrees or greater. Usually a system will not recover when the power swing angle between two systems exceeds 120 degrees.

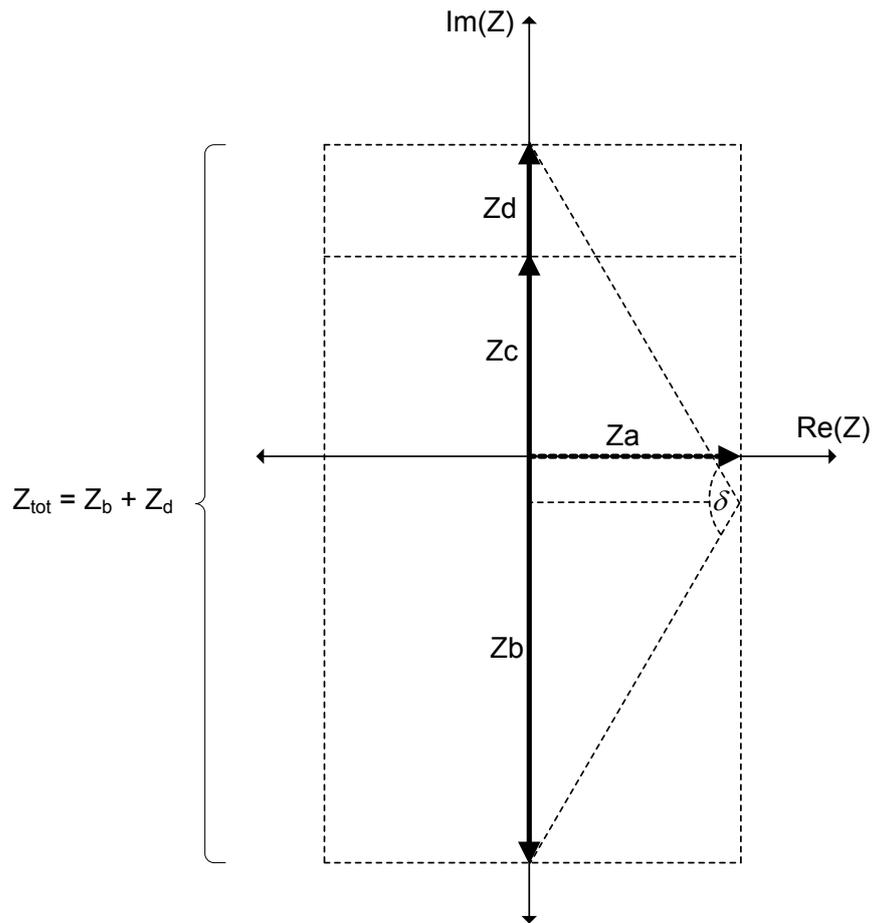


Figure 5-5 Pole slip polygon used to derive Z_a

$$\begin{aligned}
 Z_a &= \frac{Z_{tot} / 2}{\tan(\delta/2)} \quad \text{and } \delta = 120^\circ \\
 &= \frac{Z_{tot} / 2}{\tan(120^\circ/2)} \\
 &= 0.289 \times Z_{tot} \\
 &= 0.289 \times 15.57 \, \Omega \\
 &= 4.5 \, \Omega \text{ (Secondary)}
 \end{aligned}$$

5.2.4 Measurement release

Power swings are three-phase symmetrical occurrences. The first prerequisite is therefore the symmetry of the measured currents. The measurement for the pole-slip impedance is enabled if the positive sequence component of the current exceeds an adjustable limit $I_1 >$ release, while the negative sequence current remains below an adjustable limit $I_2 <$ release.

Generally, the setting value $I_1 >$ release should be set above the generator stator rated current (I_N) i.e. about 120% of I_N , to avoid pickup during an overload. As pole-slip conditions are symmetrical occurrences, the pickup threshold of the negative sequence component of the current $I_2 <$ release should be set to approximately 20% of I_N .

5.2.5 Number of power swing crossings (pole-slip cycles)

The permitted number of pole-slip impedance trajectories traversing through characteristic 1 (zone 1) has been set to one and the permitted number traversing through characteristic 2 (zone 2) has been set to three.

5.3 Conclusion

The Siemens 7UM622 out-of-step generator protection relay model in DigSilent PowerFactory was reviewed. The generator out-of-step protection settings for the Siemens 7UM622 relay used at Kendal power station were calculated. The settings that were calculated in this chapter will be used in chapter 6 and chapter 7 to test the Siemens 7UM622 out-of-step generator protection relay model in Digsilent PowerFactory as well as the actual Siemens 7UM622 out-of-step generator protection relay.

CHAPTER 6: DIGSILENT POLE SLIP SIMULATION

This chapter describes how the Siemens 7UM622 pole-slip protection relay model discussed in chapter 5 responds to various stable and unstable power swing events. A part of the South African power system in the north eastern region shown in Figure 6-1 has been modelled in detail along with the pole-slip protection relays (Siemens 7UM622) that are used to protect the generators at Kendal power station. Kendal power station has six 729 MW generators, Tutuka has six 600 MW generators and Duvha has six 600 MW generators. This part of the network is strongly interconnected and is generally not prone to pole slips due to the strong interconnection as well as the fast fault clearing times on the transmission network.

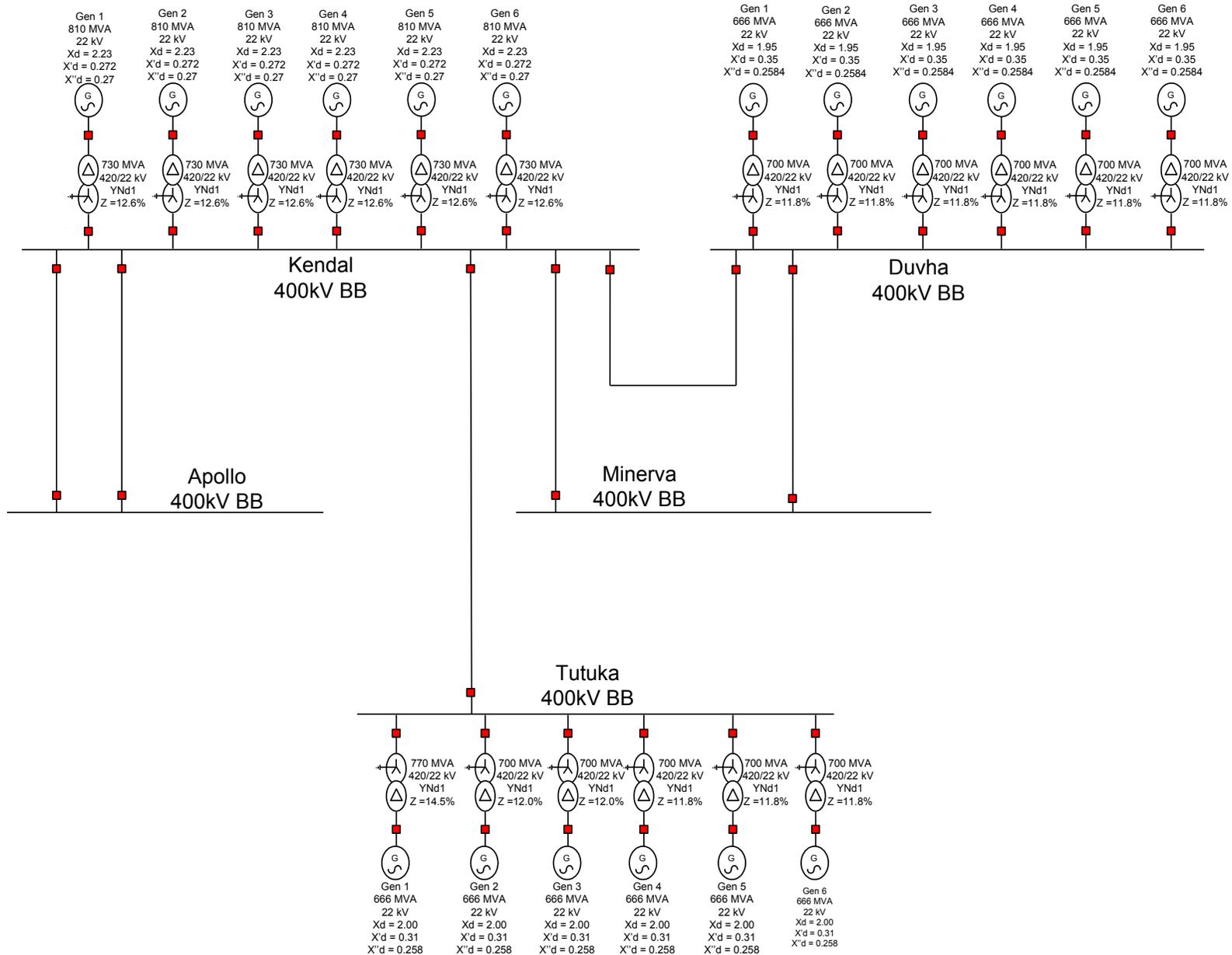


Figure 6-1 Part of the South African north eastern network - Kendal, Tutuka and Duvha power stations

When performing stability and pole-slip studies, a three-phase fault is generally the worst case scenario. Various three-phase faults will be applied along four of the outgoing 400 kV feeders at Kendal power station. The three-phase fault location as well as the fault clearing time will be varied to determine the specific fault conditions that will cause the Kendal generators to pole slip. The response of the pole-slip protection relays installed at Kendal will then be monitored to determine if the relays respond correctly.

6.1 Reduced Network Equivalent

The network shown in Figure 6-2 has been reduced by using the DigSilent PowerFactory network reduction tool. Most modern power system simulation packages have an equivalent network reduction tool [1]. A typical application of network reduction is when a network that is part of or adjacent to a much larger network must be analysed, but cannot be studied independently of the larger network. In such cases, one option is to model both networks in detail for calculation purposes. However, there might be situations when it is not desirable to do studies with the complete model. For example, when the calculation times would increase significantly or when the data of the neighbouring network is confidential and cannot be published. For the purpose of this dissertation, the network was reduced to reduce the simulation time.

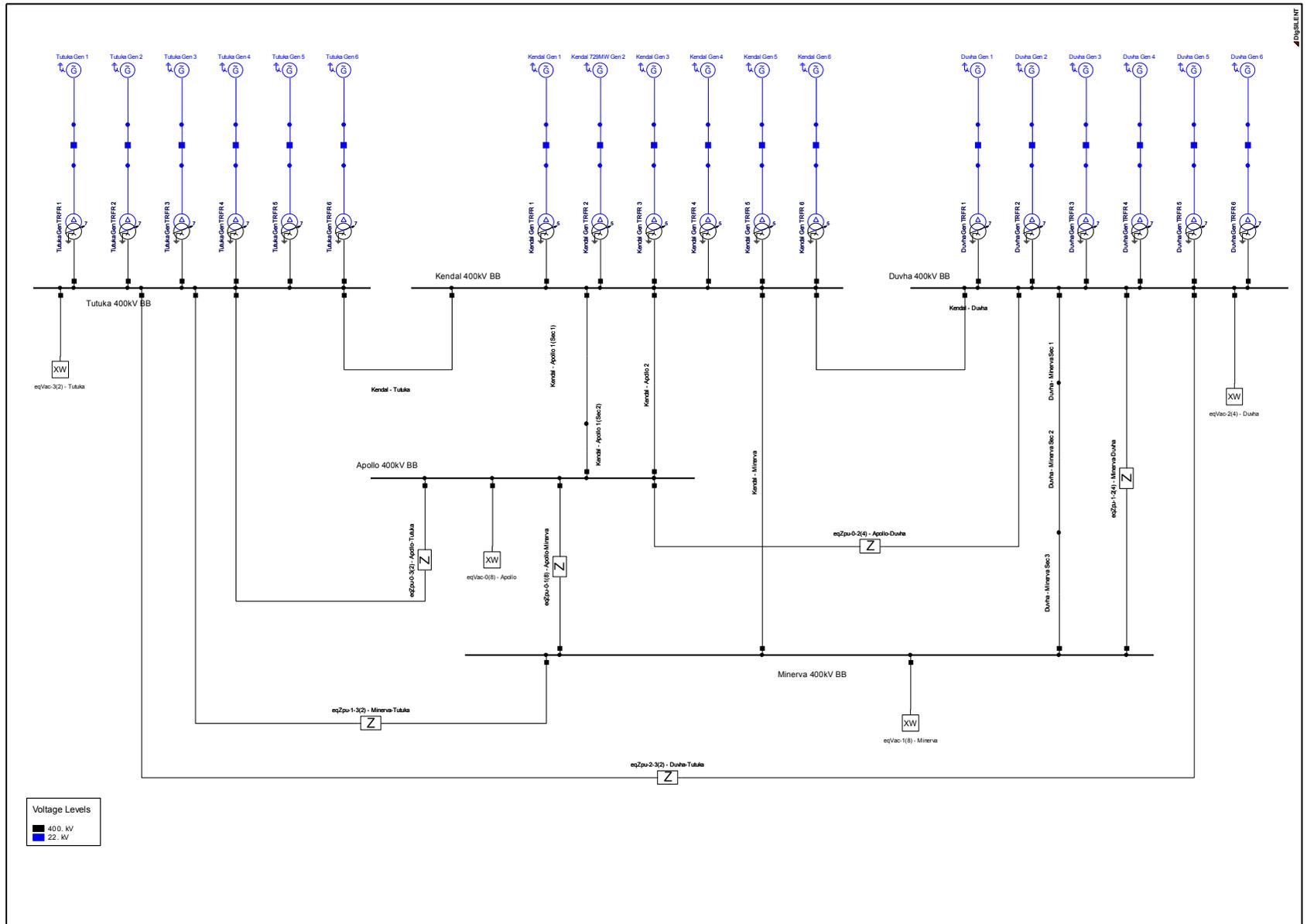


Figure 6-2 Part of the South African north eastern network reduced by using the PowerFactory network reduction tool

It is common practice to provide a simplified representation of the neighbouring network that contains only the interface nodes (connection points). These can then be connected by equivalent impedances and voltage sources, so that the short-circuit and load-flow response within the kept (non-reduced) system is the same as when the detailed model is used [31].

PowerFactory's network reduction algorithm produces an equivalent representation of the reduced part of the network and calculates its parameters. This equivalent representation is valid for both load flow and short-circuit calculations, including asymmetrical faults such as single-phase faults.

Network reduction for load flow analysis is an algorithm based on sensitivity matrices. The basic idea is that the sensitivities of the equivalent grid, measured at the connection points in the kept grid, must be equal to the sensitivities of the grid that has been reduced. This means that for a given (virtual) set of ΔP and ΔQ injections in the branches, from the kept grid to the grid to be reduced, the resulting ΔU and $\Delta \Phi$ (voltage magnitude and voltage phase angle variations) in the boundary nodes must be the same for the equivalent grid as those that would have been obtained for the original grid.

Network reduction for short-circuit analysis is an algorithm based on nodal impedance or nodal admittance matrices. The basic idea is that the impedance matrix of the equivalent grid, measured at the connection points in the kept grid, must be equal to the impedance matrix of the grid to be reduced. This means that for a given (virtual) additional $\Delta \underline{I}$ injection (variation of current phasor) in the boundary branches, from the kept grid to the grid to be reduced, the resulting $\Delta \underline{U}$ (variations of voltage phasor) in the boundary nodes must be the same for the equivalent grid, as those that would have been obtained for the original grid [31].

6.2 Pole Slip Scenario 1: Three-Phase Faults With All 400 kV Kendal Outgoing Feeders In Service

The pre-fault conditions at Kendal power station before the pole-slip simulations were conducted in section 6.2.1 to section 6.2.5 were:

- All six of the 729 MW Kendal generators were in service with $P = 580$ MW and $Q = 334$ Mvar (all six generators loaded equally)
- All five 400 kV feeders (Apollo 1, Apollo 2, Duvha, Tutuka and Minerva) from Kendal were in service

The pre-fault conditions for section 6.2.6 were slightly different:

- All six of the 729 MW Kendal generators were in service. Five generators were equally loaded with $P = 580$ MW and $Q = 336$ Mvar; the sixth generator was loaded differently with $P = 680$ MW and $Q = 351$ Mvar
- All five 400 kV feeders from Kendal were in service

The following tests were carried out in within section 6.2.1 to section 6.2.6 to analyse various pole-slip conditions:

- In four of the 400 kV feeders from Kendal (Apollo 1, Duvha, Tutuka and Minerva), three-phase faults were applied at locations from 5% to 25% along the line length from Kendal. For each fault location on each feeder, the critical fault clearing time was determined. A low critical fault clearing time increases the probability of an out-of-step event; therefore it is important to determine whether the transmission protection is fast enough to prevent an out-of-step condition from occurring.
- In section 6.2.2, three-phase faults with a fixed fault clearing time of 350 ms were applied to the 400 kV Kendal – Minerva feeder at locations from 10% to 25% along the line length from Kendal. For each fault location on the 400 kV Kendal – Minerva feeder, the Siemens

7UM622 measured impedance was plotted and analysed to determine if the relay responds correctly to a stable or unstable power swing as described in section 4.4.

- In section 6.2.3 and section 6.2.4 the pulsating current, electrical torque and electrical power was plotted and analysed for a pole slip caused by an unstable power swing that was caused by a three-phase fault on the 400 kV Kendal – Minerva feeder.
- The measured relay impedance was plotted and analysed for pole-slip impedance trajectories when the generators at Kendal were equally loaded (section 6.2.5) versus unequally loaded (section 6.2.6).

6.2.1 Critical fault clearing time

The critical fault clearing time plots in Figure 6-3 indicate the maximum permissible clearing times for three-phase faults in order to prevent the Kendal generators from pole slipping. The shortest critical fault clearing time of 250 ms is for a three-phase fault located 5% away from Kendal along the 400kV Kendal – Tutuka and the 400 kV Kendal – Minerva lines. As the fault distance from Kendal power station increases, the critical fault clearing time also increases.

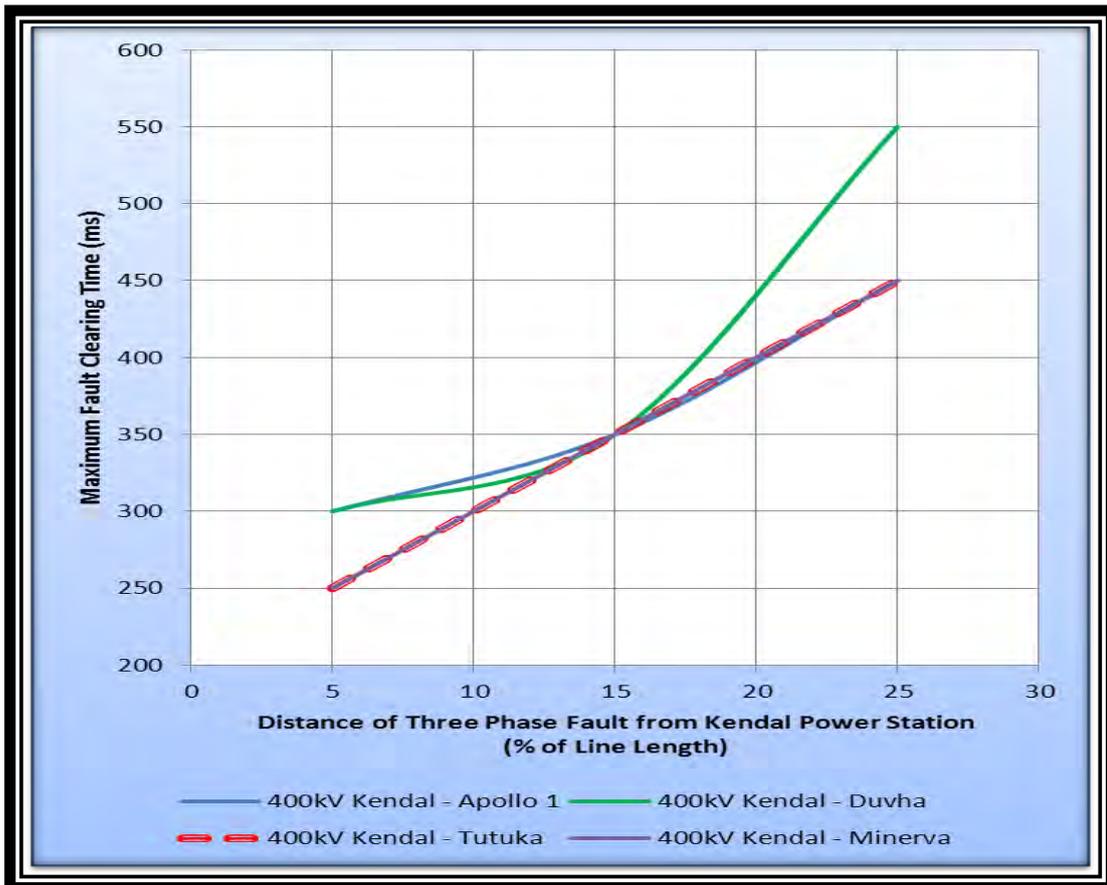


Figure 6-3 Critical fault clearing time for a three-phase fault on the outgoing Kendal feeders to prevent a generator pole slip

Transmission EHV feeders generally have dual main protection systems. Most EHV feeders have communication assisted impedance protection as well as overcurrent protection. The zone 1 impedance reach is set to cover 80% of the line length and the high-set overcurrent protection [35] is generally set to trip for phase faults along 80% of the line.

Therefore, close up faults (5% away from Kendal) are generally cleared in less than 100 ms by the zone 1 impedance protection or the high-set overcurrent protection. The zone 1 impedance protection as well as the high-set overcurrent protection has no intentional time delay. Faults that are 25% away from Kendal would also be cleared by the zone 1 protection as well as the high-set overcurrent protection. Therefore, it is very rare to have a fault clearing time of more than 100 ms for a three-phase fault which is located along the first 80% of the line.

The Kendal generators would pole slip for a close up three-phase fault located 0% to 20% away from Kendal for the following unlikely protection response:

- Zone 1 impedance protection (main 1 and main 2) fails to operate,
- High-set over current protection (main 1 and main 2) fails to operate, and
- Fault is detected and cleared by the zone 2 impedance protection within around 450 ms, which includes the circuit breaker opening time.

The generators would pole slip for the hypothetical scenario above since the fault clearing time is longer than the critical fault clearing time indicated in Figure 6-3. This would result in a multiple unit trip and would have dire consequences for the network. Therefore, it is critical to ensure that the undelayed protection is working correctly at all times.

6.2.2 Measured impedance

The purpose of this section is to determine whether the Siemens 7UM622 pole-slip protection relay model in Digsilent PowerFactory operates correctly for stable and unstable power swings. Power swings were simulated by applying three-phase faults at different locations along the Kendal – Minerva line with a constant fault clearing time. Different severities of power swing can be simulated by varying the fault clearing time or the fault location. For the ease of graphical analysis it was decided to only vary the fault location and keep the fault clearing time constant. The power swing impedance trajectories for the various fault scenarios were plotted in Figure 6-4 to graphically determine if the protection operated correctly.

The impedance plot in Figure 6-4 indicates the impedance measured by the Siemens 7UM622 generator protection relay installed at Kendal power station. The quadrilateral characteristic shown on the impedance diagram is the pole-

slip protection settings for the generators at Kendal power station, which were calculated in chapter 5 under section 5.2.

The secondary impedance trajectory is measured for the various three-phase faults applied along the 400 kV Kendal – Minerva line. The transmission line fault clearing time was fixed to 350 ms and the fault location from Kendal power station was varied from 10% to 25%. The fixed fault clearing time of 350 ms was chosen to produce stable and unstable power swings to analyse how the relay model responds to a stable and unstable power swing.

The impedance trajectories in Figure 6-4 all look very similar. The blue impedance trajectory (three-phase fault 25% away from Kendal along the Kendal-Minerva line) will be explained in more detail. Point ① is the pre-fault load impedance measured by the relay. When a three-phase fault is applied 25% away from Kendal along the Kendal-Minerva line, the measured impedance moves from point ① to point ② instantaneously. Point ② is the fault impedance measured by the relay. The three-phase fault immediately reduces the generator's electrical power transfer capability. The mechanical input power to the turbine is unchanged; therefore the mechanical power input is greater than the electrical power transferred which causes the generator to accelerate and the rotor angle increases. As the rotor angle increases, the impedance measured traverses from point ② to point ③. At point ③, the three-phase fault along the Kendal-Minerva line is isolated by opening the breakers on both sides of the Kendal-Minerva line. The three-phase fault is isolated after 350 ms, therefore it took 350 ms for the impedance trajectory to move from point ② to point ③. When the Kendal-Minerva breakers open, the measured impedance immediately jumps from point ③ to point ④. This is because the electrical power transfer capability has increased because the transfer impedance has decreased. At point ④, the mechanical power input to the turbine is greater than the generator's electrical power transferred, which causes the generator to continue accelerating, which in turn causes an increase in the rotor angle. The measured impedance traverses from point ④ to ⑤ as the rotor angle increases. At point ⑤, the mechanical power input to

the turbine is less than the electrical power transfer of the generator which causes the generator to decelerate which in turn causes the rotor angle to decrease. The measured impedance traverses from point ⑤ to point ⑥ as the rotor angle decreases and moves towards a new steady state rotor angle. The generator remains stable as there is sufficient decelerating power to prevent the rotor angle from increasing past point ⑤.

The green impedance trajectory (three-phase fault 20% away from Kendal) is similar to the blue impedance trajectory (three-phase fault 25% away from Kendal). The difference being, the measured fault impedance is lower since the fault location is closer to Kendal. For the green impedance trajectory, the generator also remained stable as there was sufficient decelerating power to prevent the rotor angle from increasing past 180 degrees.

In the case of the orange and red impedance trajectories (three-phase fault 15% and 10% away from Kendal), there was insufficient decelerating power to prevent the rotor angle from increasing past 180 degrees (pole slip), such that the impedance trajectories accelerated past 180 degrees in each case and the relay model issued a trip when the rotor angle reached approximately 120 degrees. The correlation between the measured impedance and the rotor angle is illustrated in Figure 3-3 in chapter 3.

From the impedance plots in Figure 6-4, a three-phase fault that is located less than or equal to 15% along the 400kV Kendal – Minerva line from Kendal causes the Kendal generators to pole slip. The 7UM622 generator protection relay was set to trip after a single pole slip in zone 1. The relay model detected a pole slip in zone 1 after one slip cycle and correctly disconnected the Kendal generators from the network.

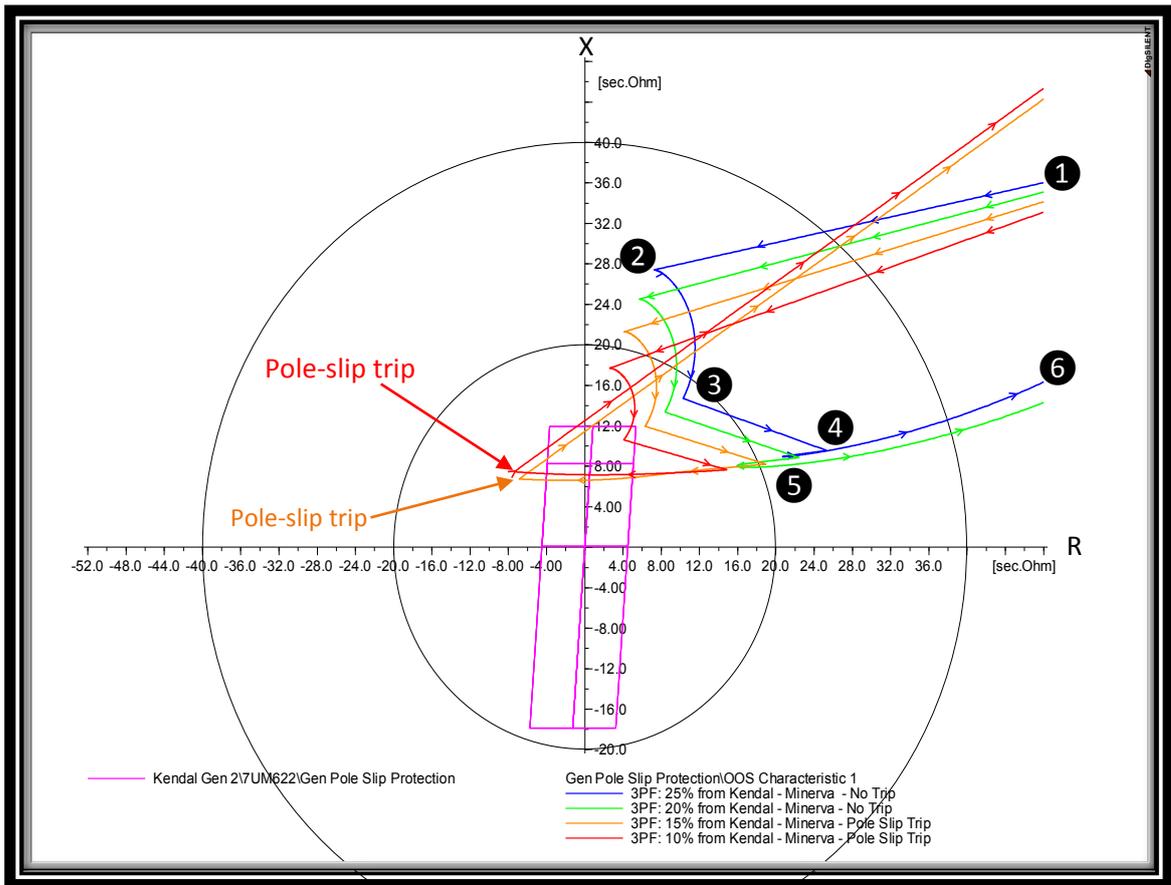


Figure 6-4 Impedance trajectory for various three-phase faults along the 400 kV Kendal-Minerva line. ($E_g/E_s > 1$)

As shown in Figure 6-4, when the fault is less than or equal to 15% along the 400 kV Kendal-Minerva line from Kendal, the system electrical centre for the pole-slip condition passes through the generator transformer, which causes significant stress to the generator transformer as well as the generator.

The system was stable when the three-phase fault was greater than or equal to 20% along the 400kV Kendal - Minerva line away from Kendal. In Figure 6-4, the impedance trajectory measured by the impedance relay for the stable power swing did not enter the pole-slip impedance characteristic and the relay did not issue a trip command which is correct.

6.2.3 Pulsating current

The purpose of this section is to examine the magnitude and severity of the current through the generator during a pole slip when the pole slip is correctly identified by the pole-slip protection and the generator is disconnected. Secondly, if the pole-slip protection does not operate and the generator is left connected to the network. The time current plot in Figure 6-5 indicates the per unit (generator base) current measured at the generator terminals when a three-phase fault is applied 10% away from Kendal along the 400 kV Kendal-Minerva line and the fault is cleared in 350 ms.

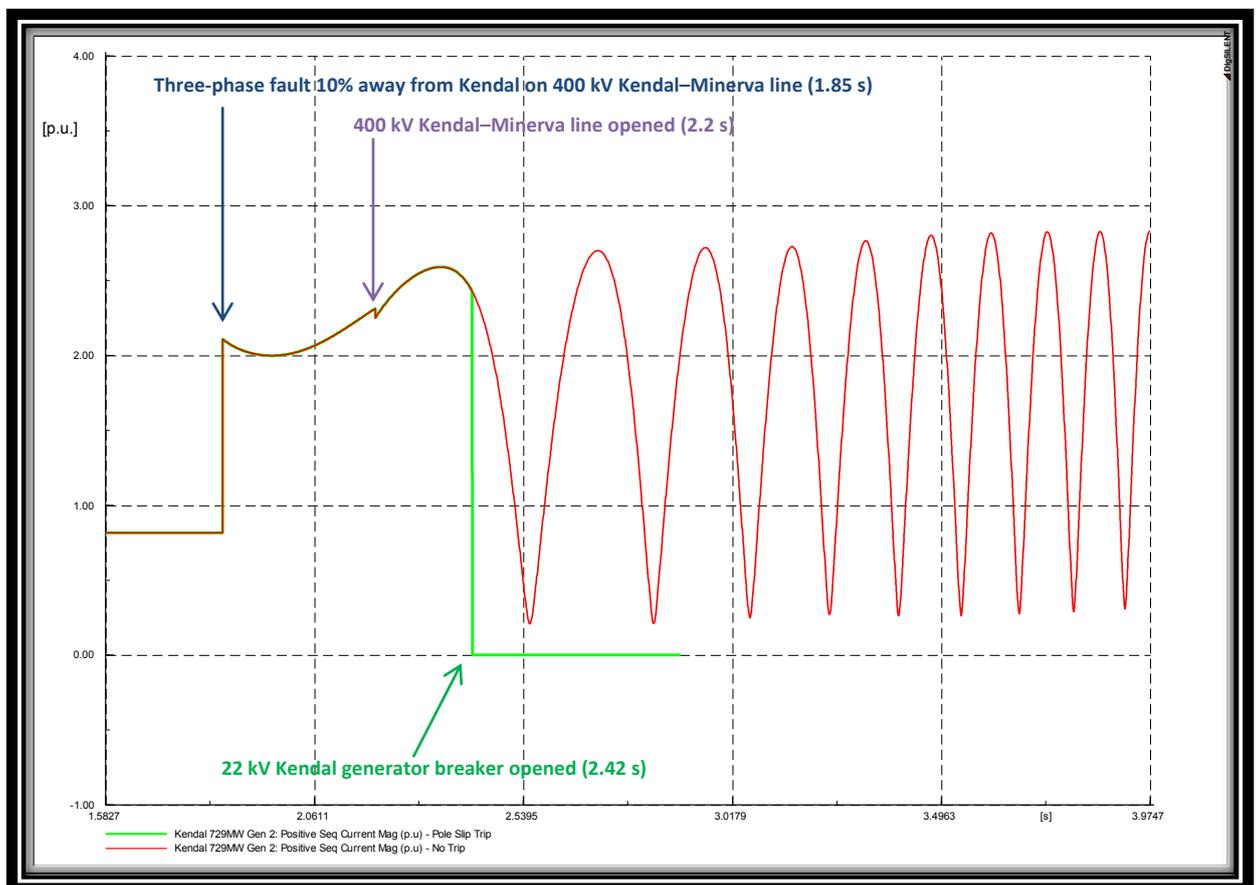


Figure 6-5 Pulsating current caused by a pole slip

In Figure 6-5 the green trace indicates the generator current when the pole slip is correctly detected and the generator is disconnected from the network. The red trace indicates the current that the generator would be subjected to if the pole slip is not detected and the generator remains connected to the network.

The pulsating current peak during the pole slip is higher than the three-phase fault current for a fault on the 400 kV Kendal–Minerva line. Therefore, it is critical to disconnect the generator for a pole slip. It is also clear from Figure 6-5 that the frequency of the pulsating current increases with each slip cycle, which means that the stress and damage caused to the generator and generator transformer increases for each additional slip cycle.

6.2.4 Pulsating electrical torque and power

The purpose of this section is to examine the magnitude and severity of the electrical torque and power measured at the generator terminals during a pole slip when the pole slip is correctly identified by the pole-slip protection and the generator is disconnected; secondly, if the pole-slip protection does not operate and the generator is left connected to the network.

The electric torque and power versus time plots in Figure 6-6 indicate the per unit (generator base) electric torque and power measured at the generator terminals when a three-phase fault is applied 10% away from Kendal along the 400 kV Kendal–Minerva line and the fault is cleared in 350 ms.

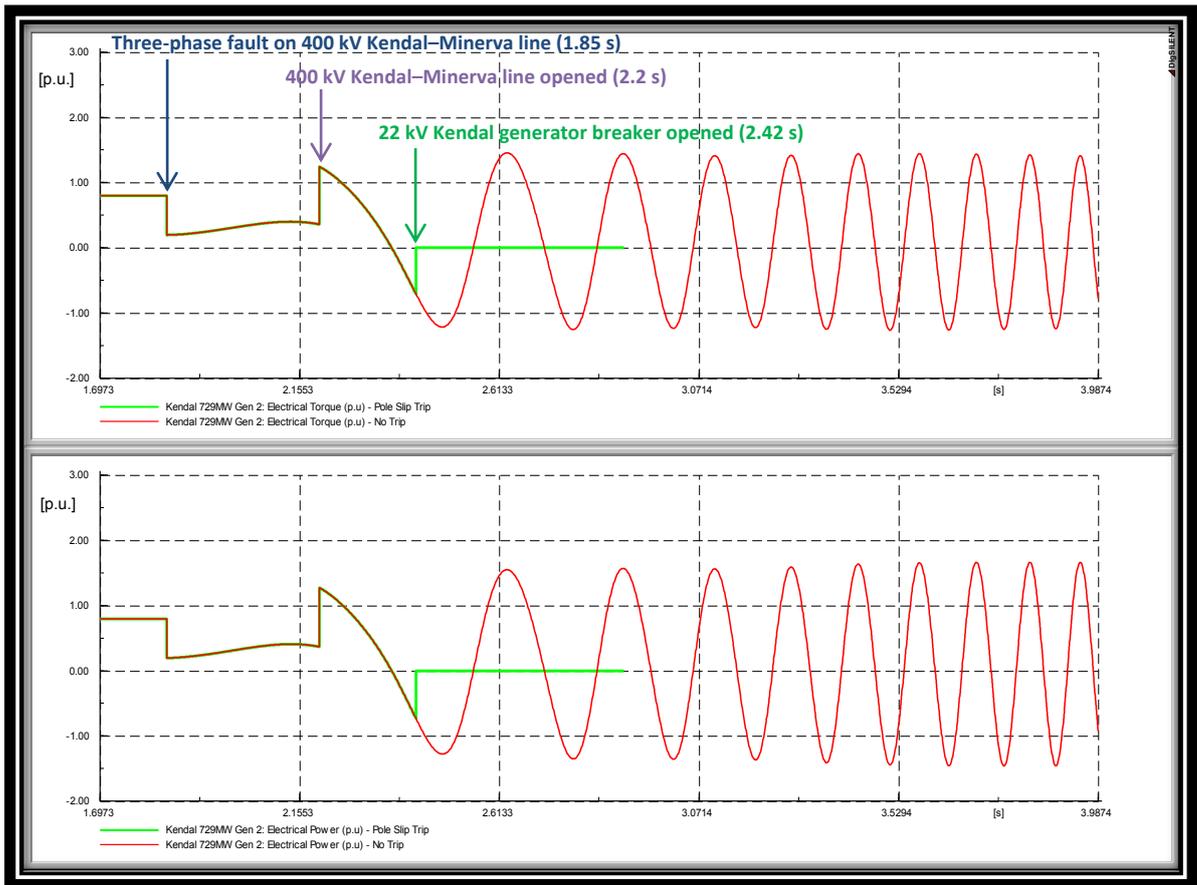


Figure 6-6 Generator pulsating electrical torque and power during a pole slip

It can be seen from Figure 6-6 that if the generator protection does not disconnect the generator from the network during a pole slip (red trace), the generator is subjected to a pulsating electrical torque and power, which alternates between positive and negative. This pulsating torque can cause severe damage to the generator, generator transformer and turbine shaft. Therefore, the generator should be disconnected immediately when the pole-slip system centre is located within the generator or the generator transformer. Similar to the results in section 6.2.3, the frequency of the pulsating electrical torque and power also increases with each slip cycle, which means that the stress and damage caused to the generator, turbine shaft and generator transformer increases for each additional slip cycle.

6.2.5 Pole slip impedance trajectory for equally loaded generators

The purpose of this section is to compare the impedance trajectory obtained from a pole-slip simulation in DigSilent PowerFactory to the classical pole-slip impedance trajectory seen in theoretical texts.

The impedance plot in Figure 6-7 indicates the measured secondary impedance trajectory at the generator terminals when a three-phase fault is applied 10% away from Kendal along the 400 kV Kendal–Minerva line and the fault is cleared in 350 ms. The trip output from the generator pole-slip protection relay model was disabled so that the complete pole-slip impedance trajectory could be measured.

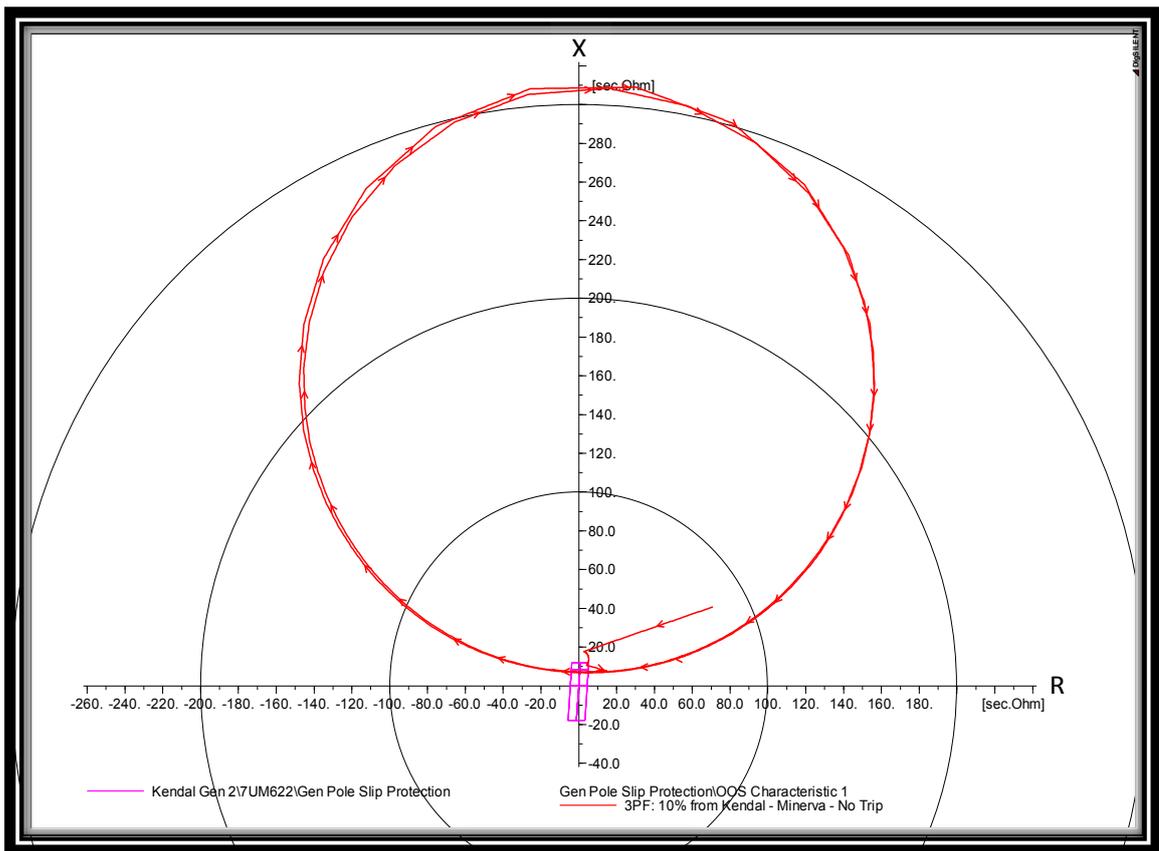


Figure 6-7 Pole-slip impedance trajectory (Kendal generators equally loaded $P = 580$ MW and $Q = 334$ Mvar)

The impedance trajectory in Figure 6-7 is similar to the classical pole-slip trajectory seen in theoretical texts. In practice, the impedance trajectory would not look exactly like this. The reason for the perfect classical impedance trajectory seen in Figure 6-7 is because all six Kendal generators were modelled with exactly the same load ($P = 580$ MW and $Q = 334$ Mvar) and the automatic voltage regulator (AVR) as well as the turbine controller models have been modelled precisely the same for all six units. In practice, the Kendal generators would not be loaded exactly the same and there would be minor differences between the AVRs and governors (both in terms of their controller set-points and their parameters).

The pole-slip impedance plot in Figure 6-8 is the same scenario from Figure 6-7, but the pole-slip impedance characteristic has been enlarged. The first slip cycle enters the impedance characteristic in zone 1 and all subsequent slip cycles remain within zone 1 as expected.

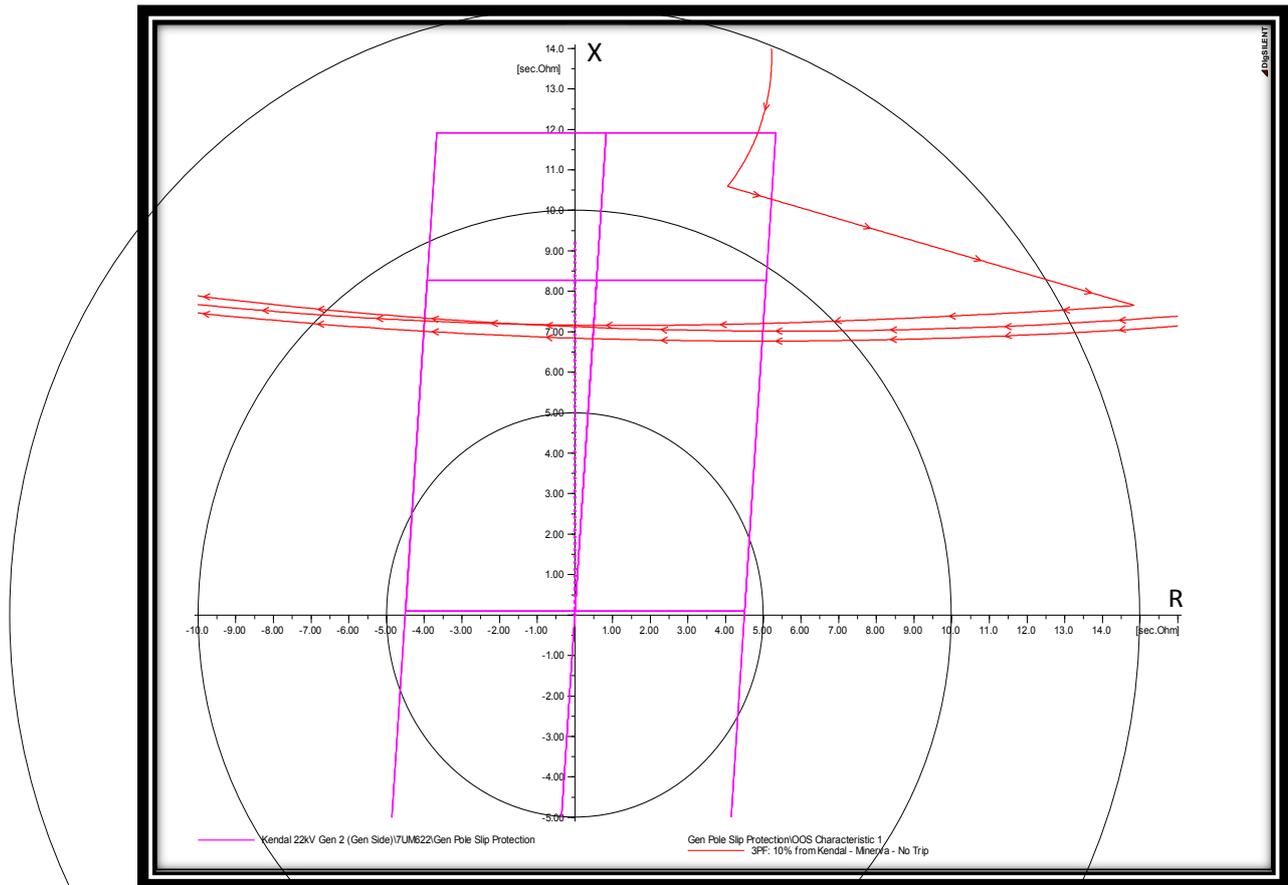


Figure 6-8 Zoomed in pole-slip impedance trajectory (Kendal generators equally loaded $P = 580$ MW and $Q = 334$ Mvar)

6.2.6 Pole slip impedance trajectory for unequally loaded generators

The pole-slip impedance trajectory in Figure 6-9 is for a more realistic operating condition than that shown in the previous case in Figure 6-7 and Figure 6-8. For the pole-slip impedance trajectory plot in Figure 6-9, five of the Kendal generators were loaded equally with $P = 580$ MW and $Q = 336$ Mvar. The sixth generator was loaded with $P = 680$ MW and $Q = 351$ MW. The parameters for the AVR and governor models are exactly the same for all six units, but the AVR and governor set point was different on one of the units, which resulted in a different P and Q loading. The impedance trajectory in this case is no longer a circle with a fixed diameter. The diameter of the impedance trajectory changes significantly with each additional slip cycle, which is due to the unequally loaded generators.

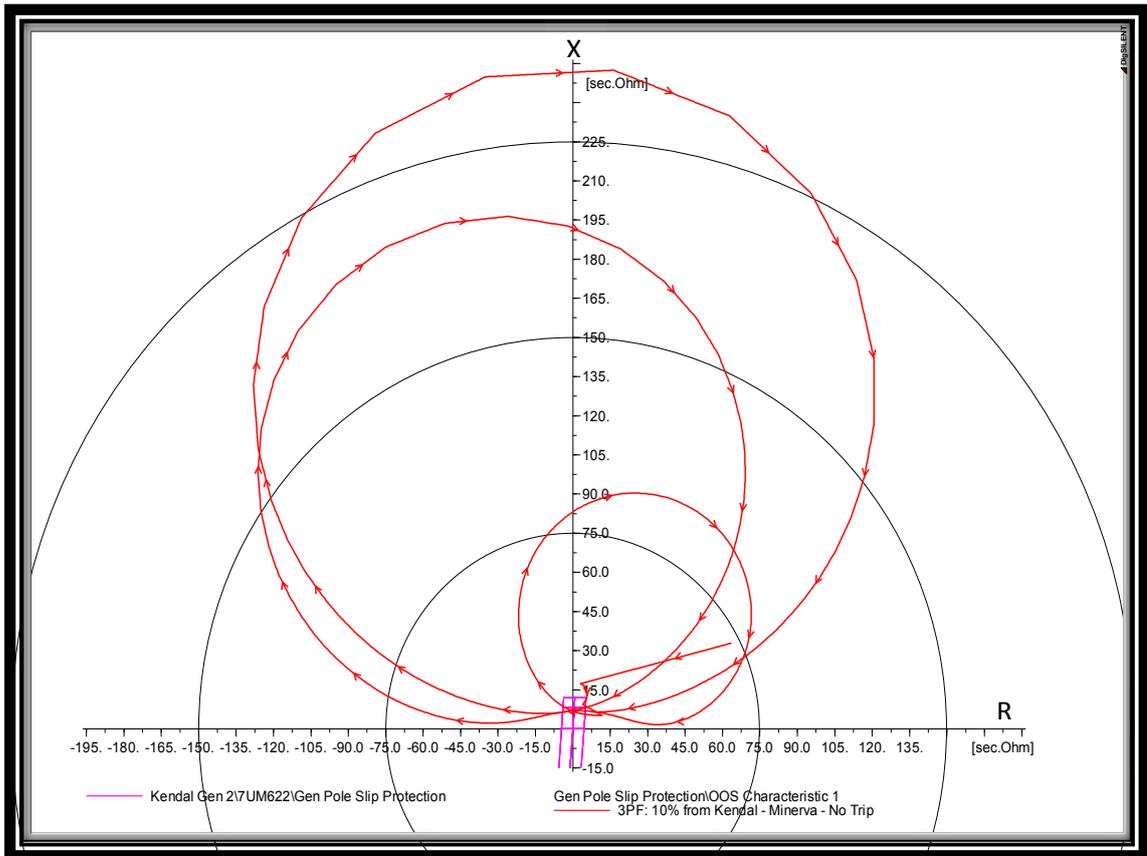


Figure 6-9 Pole Slip impedance trajectory (Kendal generators unequally loaded)

The pole-slip impedance plot in Figure 6-10 is the same scenario from Figure 6-9, but the pole-slip impedance characteristic has been enlarged. The first slip cycle enters the impedance characteristic in zone 1 and it exits the characteristic from zone 2. The second slip cycle enters the characteristic from zone 2 and exits the characteristic from zone 1. The third slip cycle enters and exits the characteristic in zone 1. Therefore, the first and second slip cycles would only be detected as pole slips in zone 2.

Generally, the zone 1 reach would be set to 70% to 90% of the generator transformer and it would trip after a single slip cycle. The zone 2 reach would include the system with or without certain lines in service and it would be set to trip after approximately 4 slip cycles as described earlier in section 4.4.2. Therefore, for the pole-slip impedance trajectory in Figure 6-10, the generator

would only be disconnected after the fourth slip cycle if zone 2 was set to allow a maximum of four slip cycles.

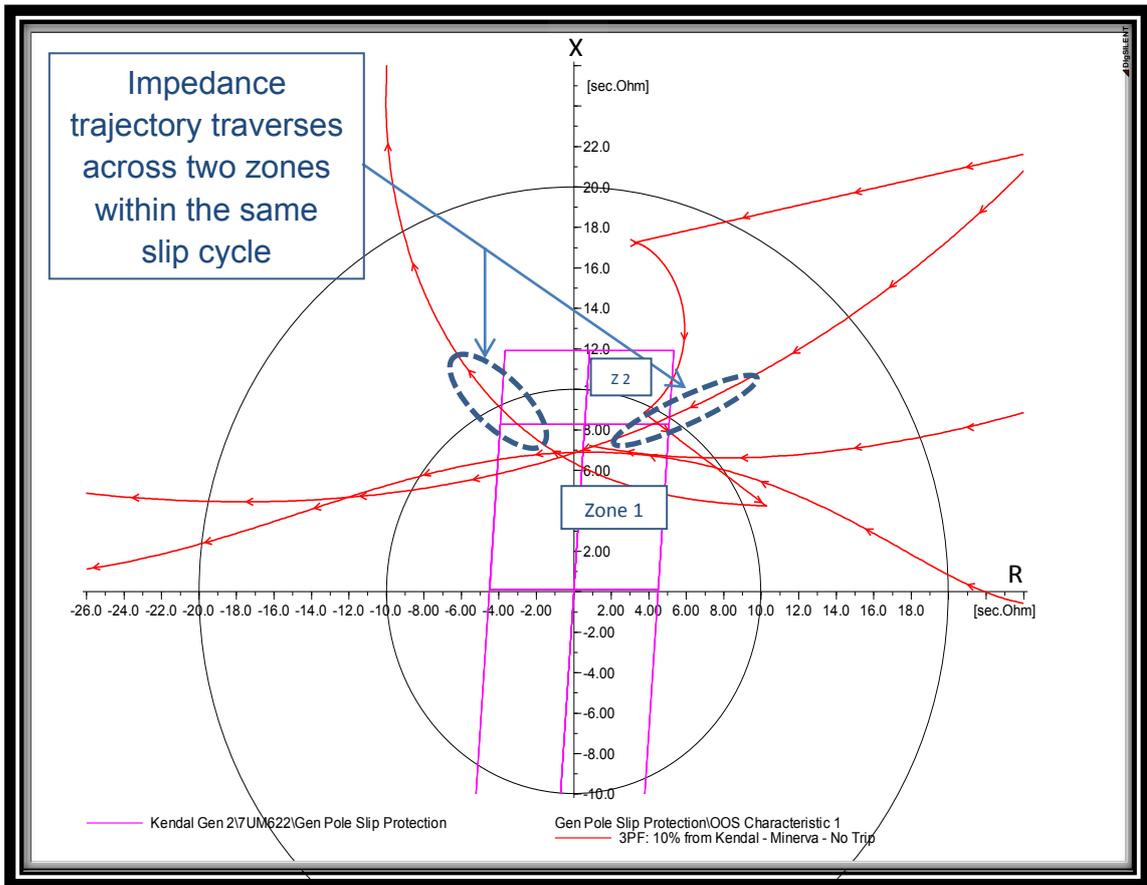


Figure 6-10 Zoomed in pole-slip impedance trajectory (Kendal generators unequally loaded)

For out-of-step conditions, where the system electrical centre is out in the transmission system (zone 2), the detection of the out-of-step condition and isolation of the unstable generator(s) are accomplished by the transmission line out-of-step protection [26]. Therefore, the number of crossings permitted for an out-of-step impedance trajectory traversing through characteristic 2 is usually set to around four slip cycles, which allows the transmission line out-of-step protection to operate before the generator out-of-step protection. Characteristic 2 of the generator out-of-step protection therefore serves as backup protection to the transmission line out-of-step protection. If the transmission line out-of-step protection fails to separate a system that is out-of-step, the generator(s) will be disconnected after around four slip cycles.

Currently, at Kendal power station the zone 2 pole-slip impedance characteristic has been disabled and the zone 1 reach is set to 100% of the generator transformer impedance with a trip setting of one slip cycle. Generally, the reason for disabling zone 2 is to avoid unnecessary tripping of generators for pole slips, which have a system electrical centre that is located within the transmission network. A pole-slip condition with the system centre located within the transmission network is usually detected by the transmission line out-of-step protection, which should then split the network into islands.

The South African transmission network is currently undergoing major expansions so the power system electrical centre is changing as the network changes so it is a rather difficult task to determine the precise location of the system centre within the transmission network so that out-of-step relays can be installed to separate the network into islands during an out-of-step condition. Once the transmission network expansion and strengthening projects have been completed, the transmission out-of-step relay locations and settings will have to be revised and implemented. The transmission out-of-step relay locations and settings will then probably remain the same for a decade or more since massive transmission expansion and strengthening projects are not usually continuously underway.

From a power station perspective, it is not known where or whether out-of-step relays are installed on the transmission network at all points in time. Therefore, from a generator protection point of view, it would be sensible to enable the zone 2 pole-slip impedance characteristic with an impedance reach that looks into the transmission network, but only trips after three to four slip cycles to allow the transmission out-of-step protection sufficient time to first operate. This would ensure that the generators would be adequately protected in the event that the transmission protection failed to operate for a pole slip which has a system electrical centre that is located within the transmission network. Secondly, the extended zone 2 pole-slip impedance characteristic would also cater for measurement and calculation errors in zone 1.

6.3 Pole-Slip Scenario 2: Three-Phase Fault With The 400 kV Kendal-Duvha Line Out Of Service

In the studies to be shown in section 6.3, before three-phase faults were applied to the outgoing 400 kV Kendal feeders, the **400 kV Kendal–Duvha line was taken out of service**, with the remaining four outgoing 400 kV feeders at Kendal left in service (Apollo 1, Apollo 2, Tutuka and Minerva). All six of the Kendal 729 MW generators were in service with $P = 580$ MW and $Q = 334$ Mvar.

6.3.1 Critical fault clearing time

In three of the 400kV feeders from Kendal (Apollo 1, Tutuka and Minerva), three-phase faults were applied at locations from 5% to 25% along the line length from Kendal. For each fault location on each feeder, the critical fault clearing time was determined.

The critical fault clearing time plot in Figure 6-11 indicates the maximum allowable fault clearing times to clear three-phase faults that are located a certain distance away from Kendal on three of its outgoing 400kV feeders. The Kendal generators will pole slip if the fault clearing time exceeds the maximum allowable fault clearing time.

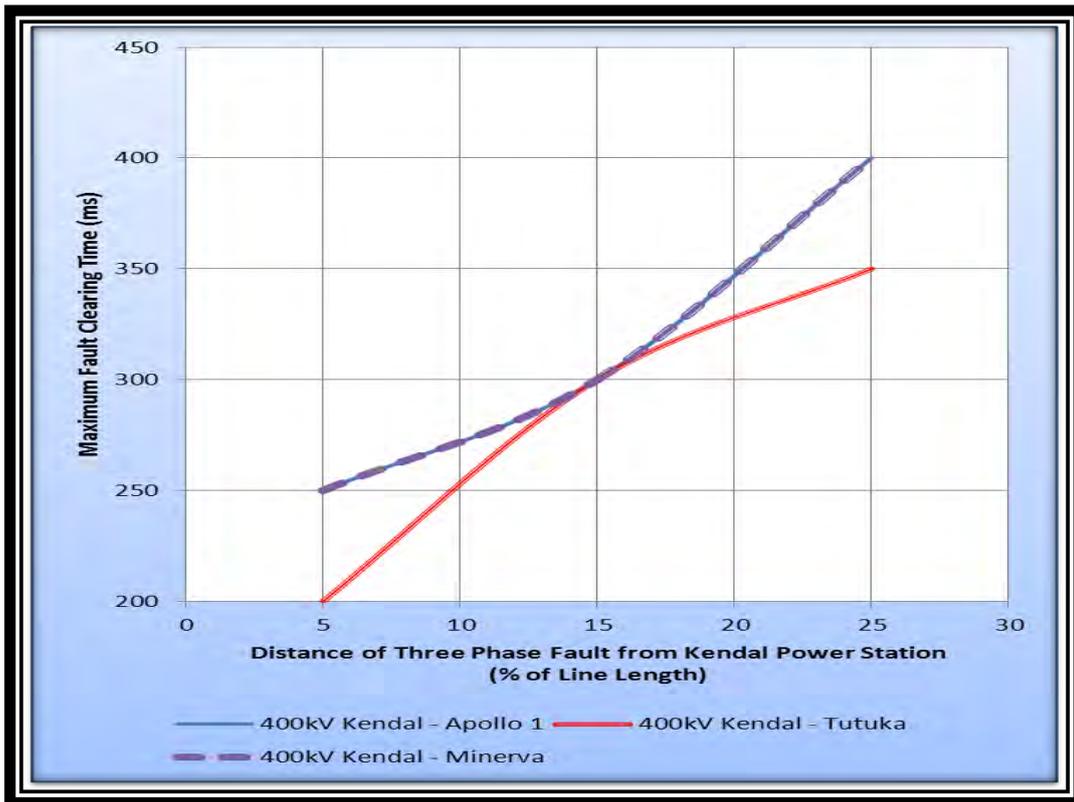


Figure 6-11 Critical fault clearing times for three-phase faults on the outgoing Kendal feeders to prevent a generator pole slip (400 kV Kendal-Duvha line out of service)

As expected, in Figure 6-11 the critical fault clearing time to prevent a generator pole slip is reduced when the 400 kV Kendal–Duvha feeder is out of service. The lowest critical fault clearing time is 200 ms for a three-phase fault on the 400 kV Kendal–Tutuka line.

The reason for removing the 400 kV Kendal–Duvha feeder from service in section 6.3 is because this is the worst case n-1 contingency. i.e. the reduction in critical fault clearing time is the greatest when this particular feeder is taken out of service. It is important to determine the pole-slip impedance trajectory for the case where the 400 kV Kendal–Duvha line is out of service to ensure that the generator-pole-slip protection provides adequate protection under this n-1 contingency since the critical fault clearing times are significantly lower, which increases the probability of a pole-slip occurrence.

6.3.2 Pole slip impedance trajectory

The impedance plot in Figure 6-12 indicates the secondary impedance measured at the generator terminals by the Siemens 7UM622 generator protection relay installed at Kendal power station. The quadrilateral characteristic shown on the impedance diagram is the pole-slip protection setting for the generators at Kendal power station, which were calculated in chapter 5 under section 5.2.

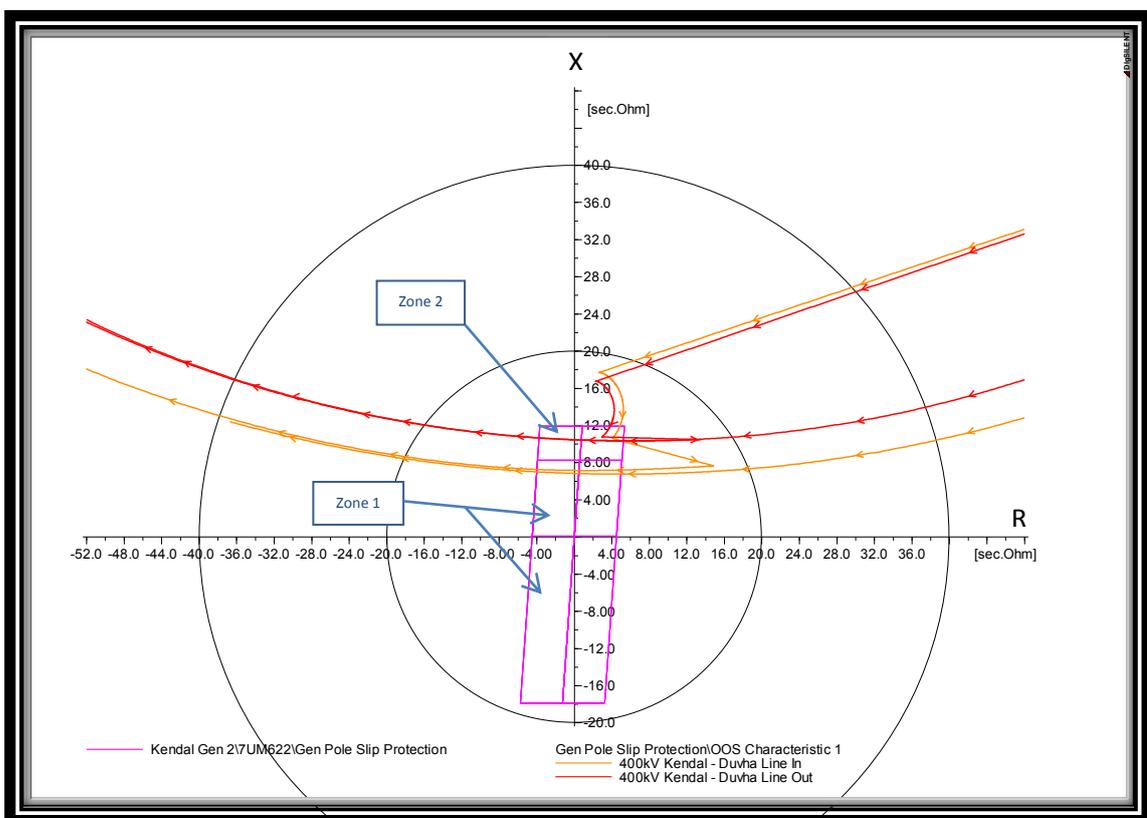


Figure 6-12 Pole Slip impedance trajectories with the 400kV Kendal – Duvha line in and out of service

The first scenario in Figure 6-12 (orange trace) has been taken from the example in section 6.2. All of the 400 kV Kendal outgoing feeders were in service when a three-phase fault was applied 10% away from Kendal along the 400 kV Kendal–Minerva line and the fault was cleared in 350 ms by the transmission line protection. The pole-slip impedance trajectory traverses

across the zone 1 characteristic with the pole-slip system electrical centre located within the generator transformer.

In the second scenario (red trace) in Figure 6-12 , the 400 kV Kendal–Duvha line was out of service when a three-phase fault was applied 10% away from Kendal along the 400 kV Kendal–Minerva line and the fault was cleared in 350 ms by the transmission line protection. Usually the transmission line protection would remove a close-up three-phase fault in less than 100 ms; For the purpose of this study, the transmission line fault clearing time has been exaggerated. When the 400kV Kendal – Duvha line has been removed from service, the system impedance increases and the pole-slip impedance trajectory (red trace) passes through the zone 2 impedance characteristic. Now, the pole-slip system electrical centre is located within the transmission network for this scenario.

If transmission out-of-step protection does not island the network for this pole-slip condition, the Kendal generators would have to be disconnected from the network. As discussed previously, in practice the zone 1 generator pole-slip protection at Kendal power station has actually been set to 100% of the generator transformer impedance and zone 2 has been disabled so it would not be able to detect this pole-slip condition.

The critical fault clearing time is a lot lower when an outgoing 400kV Kendal feeder is out of service, which increases the probability of a Kendal generator pole slip. Therefore, it is essential not to disable the zone 2 pole-slip impedance characteristic so that the generator-pole-slip protection can detect pole-slip conditions, which have a system electrical centre located within the transmission network. The generator protection should not be set to trip immediately (after 1 slip cycle) for a pole slip that has a system electrical centre, which is located in the transmission network, but instead it should only trip after three to four slip cycles to allow the transmission out-of-step protection sufficient time to island the out-of-step network.

6.3.3 Pulsating generator current and electrical power

The current time and power time plots in Figure 6-13 indicate the per unit (generator base) current and electrical power measured at that generator terminals.

For the first scenario in Figure 6-12 (green trace), all the 400 kV Kendal outgoing feeders are in service when a three-phase fault is applied 10% away from Kendal along the 400 kV Kendal–Minerva line and the fault is cleared in 350 ms by the transmission line protection. The magenta trace indicates when the Kendal generators pole slip for this scenario.

In the second scenario (red trace) in Figure 6-12 , the 400 kV Kendal–Duvha line was out of service when a three-phase fault was applied 10% away from Kendal along the 400 kV Kendal–Minerva line and the fault was cleared in 350 ms by the transmission line protection. The blue trace indicates when the Kendal generators pole slip for this scenario.

When the 400 kV Kendal–Duvha line is out of service, the Kendal generators begin to pole slip 60 ms sooner than when the 400 kV Kendal–Duvha line is in service. The impedance plot in Figure 6-12 indicates that the pole-slip system electrical centre is within the transmission network (zone 2) and from Figure 6-13 the maximum pulsating current is 2.443 p.u. and the pulsating power is 1.415 p.u.

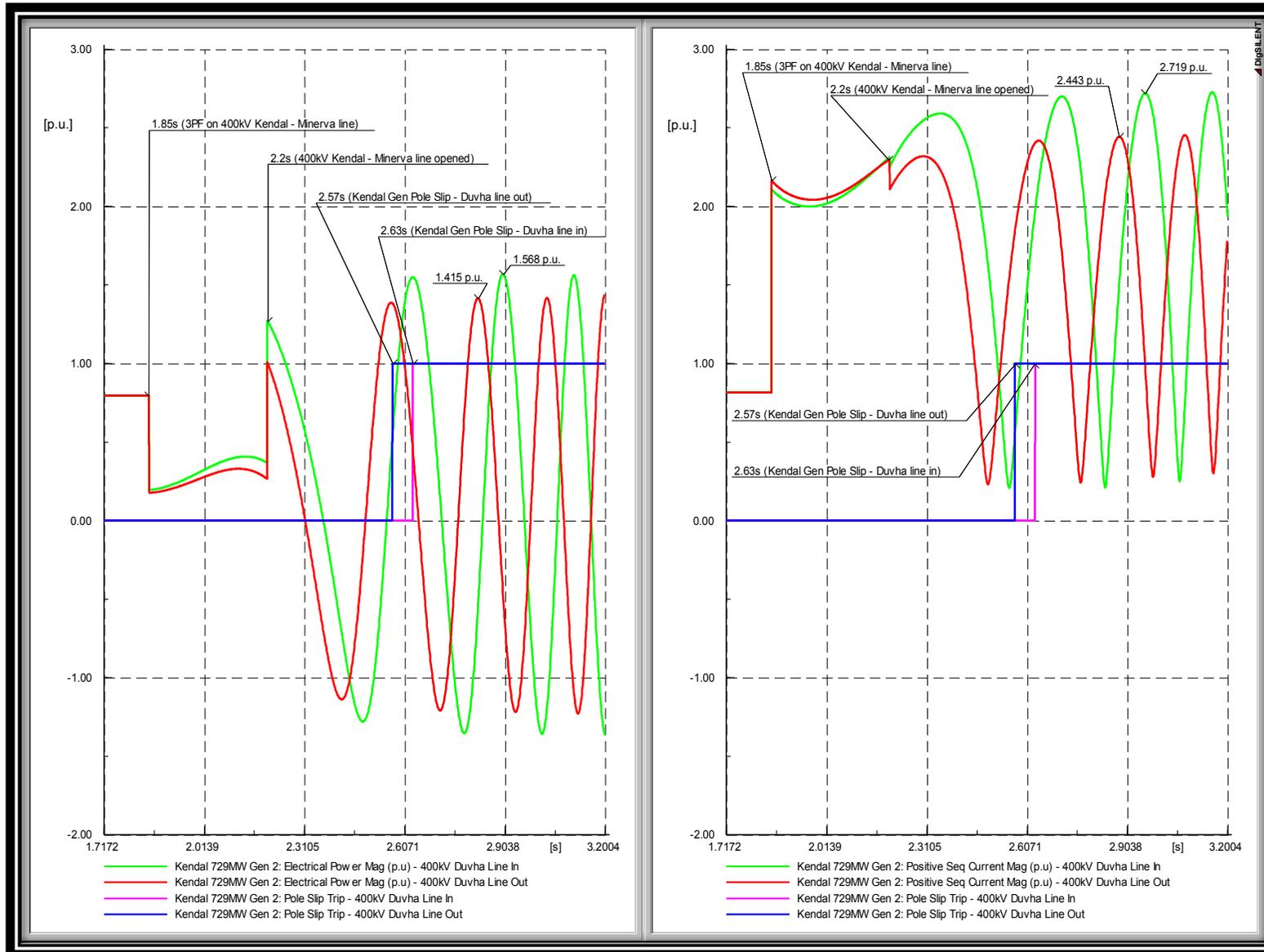


Figure 6-13 Generator pulsating electric power and current during a pole slip with the 400 kV Kendal-Duvha line in and out of service

In Figure 6-13, when the system electrical centre is located within the transmission network (red trace), the pole slip pulsating current and power measured at the generator terminals are not as high as when the system electrical centre lies within the generator transformer (green trace), but it is still extremely high and will cause significant damage to the generator if the generator is not disconnected. The pole slip pulsating current peak is higher than the three-phase fault current, but it is not sustained at that level like a typical fault. The pulsating power alternates to and from the generator, which causes significant stress and damage to the generator and the turbine shaft. The probability of a pole-slip occurrence where the system electrical centre is located within the network is a lot higher due to the reduced critical fault clearing time. Therefore, it is crucial to be able to detect and disconnect a generator (after three to four slip cycles) when the pole-slip system electrical centre is located within the transmission network.

6.3.4 Power plant disconnect protection

In an extensive research program carried out by Kraftwerk Union AG, the effects of all conceivable power system faults and switching operations were investigated with respect to couplings, to material fatigue of the individual shafts and to the stator windings of the generator. It was found that as a rule, even in the case of three-phase faults the torsional stress has no effect on operation when the fault is cleared within 150 ms. Stressing of the stator winding is also low in such cases [10].

Fault clearance is the primary task of the network protection; it acts, therefore, as a primary means of avoiding high stressing of turbine-generator units. Fault clearing times of less than 150 ms are achieved by modern network protection relays in conjunction with high-speed circuit breakers. Reliable fault clearance is only possible where quick acting protection is well matched and of redundant design. This requirement is generally met by the Eskom transmission system protection and fault clearing times of more than 150 ms would generally only be encountered if the protection system cleared a fault in the second step of the

network protection (i.e. if the main protection fails to remove a fault due to a faulty breaker, the breaker fail protection would typically operate in around 150 ms or alternatively the fault would be cleared by the remote backup protection, which has a time delay of around 400 ms (zone 2)).

In such cases, the only effective measure, which is also advantageous from the standpoint of availability, for the avoidance of high torsional stressing is to disconnect the generator and thus the turbine-generator unit from the power system. Immediate resynchronising can then follow. A special protection function called power plant disconnect (PPD) [10] can be used to protect against these conditions and the logic used by the PPD protection scheme is shown in Figure 6-14. Another advantage of this protection is that it can disconnect a generator before it pole slips, which will prevent significant stress and damage.

Kendal power station is the only Eskom power station that makes use of PPD protection. The PPD protection has operated once since the Kendal generators were commissioned in 1993. The PPD operation was due to a Kendal 400 kV busbar short-circuit fault that was not cleared by the bus-zone protection. The PPD logic in Figure 6-14 indicates that a sudden drop of active power occurring due to a short circuit is detected by the PPD protection. This drop is defined as a negative change in active power, $-\Delta P$, within a 60 ms period. If the pre-set negative active power step is exceeded, a delay timer of 200 ms is started, within which time the power system protection should clear the fault. If under-voltage and overcurrent conditions are still present after the 200 ms time delay, this means that the fault could not be cleared by the network protection and the PPD protection would disconnect the unit from the network.

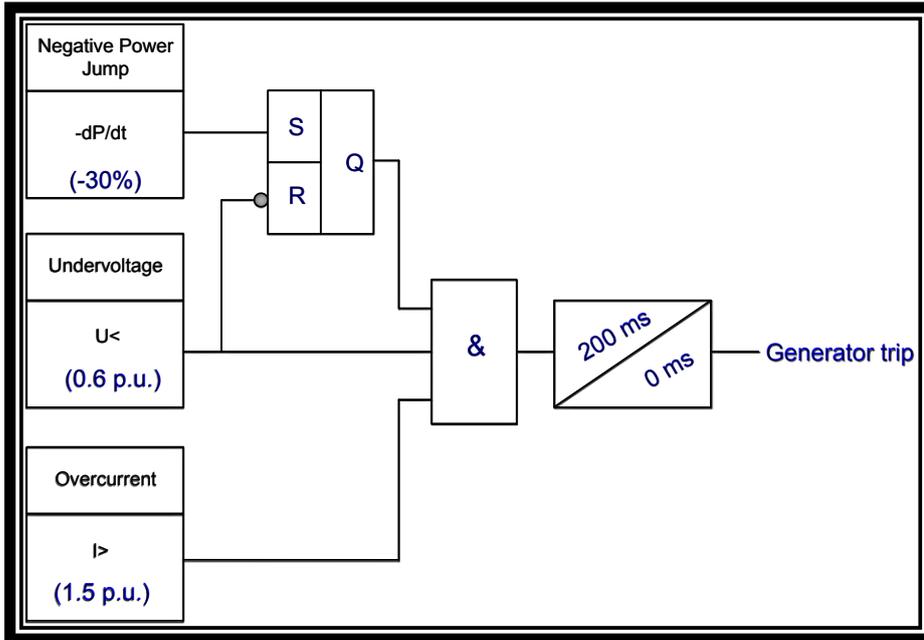


Figure 6-14 Simplified power plant disconnect logic reproduced from [36]

The PPD protection protects the turbine-generator unit against excessive torsional fatigue of the shaft and against undue stressing of the couplings and of the windings. In the case of power system faults of longer duration it prevents asynchronous (out-of-step) operation of the unit and thereby avoids the negative effects on the power system and on the power station auxiliary system. Therefore, PPD protection and pole-slip protection should definitely both be used to provide optimal generator protection in the event of prolonged system fault clearing times.

6.4 Pole-Slip Scenario 3: Three-Phase Fault With All Lines In Service And Generator Underexcited

The purpose of this section is to analyse various generator pole-slip events that could occur when the Kendal generators are operating in the underexcited mode.

The critical fault clearing time is compared to the previous sections to determine if it has increased or decreased. A decrease in critical fault clearing time would obviously indicate that running the generator in the underexcited mode would increase the risk of a generator pole slip and vice versa. Several different pole-slip impedance trajectories are analysed to determine if the pole-slip impedance

trajectories in the underexcited mode correspond to the theory discussed in chapter 3. Secondly, it is important to determine whether the generator pole-slip protection will be able to correctly identify and trip for a pole-slip event when the generator is operating in the underexcited mode. The pulsating current for a pole slip occurring when the generator is importing reactive power (underexcited) is compared to the previous section where the generator was exporting reactive power. The pole-slip frequency measured by the relay during the pole-slip simulations is also monitored to determine if it is within the relay's measuring range.

In the studies to follow in section 6.4.1 to section 6.4.3, before three-phase faults were applied to the outgoing 400kV Kendal feeders, all five of the 400kV feeders from Kendal (Apollo 1, Apollo 2, Duvha, Tutuka and Minerva) were in service, and all six of the Kendal 729MW generators were in service, with the generator active power set points at 580MW. However the **reactive power set point was varied in each of the following subsections**; the actual value of reactive power setpoint used is therefore mentioned explicitly in each of the following subsections.

6.4.1 Critical fault clearing time

In four of the 400 kV feeders from Kendal (Apollo 1, Tutuka, Duvha and Minerva), three-phase faults were applied at locations from 5% to 25% along the line length from Kendal. For each fault location on each feeder, the critical fault clearing time was determined. All six of the Kendal 729 MW generators were in service with $P = 580$ MW and $Q = 18$ Mvar (running in the underexcited mode).

The critical fault clearing time plot in Figure 6-15 indicates the maximum allowable fault clearing times to clear three-phase faults that are located a certain distance away from Kendal along four of its outgoing 400 kV feeders. The Kendal generators will pole slip if the fault clearing time exceeds the maximum allowable fault clearing time.

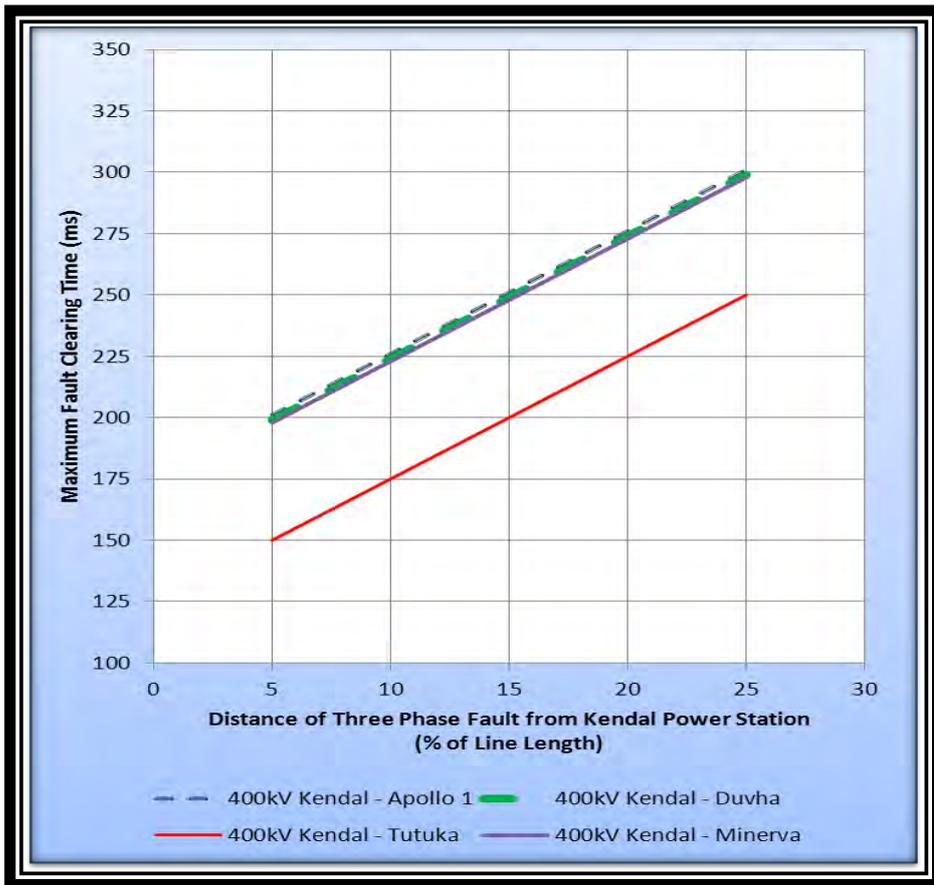


Figure 6-15 Critical fault clearing time for three-phase faults on the outgoing Kendal feeders to prevent a generator pole slip (All five outgoing 400kV Kendal feeders in service and Kendal generators underexcited)

Figure 6-15 indicates that the critical fault clearing time to prevent a generator pole slip is drastically reduced when the Kendal generators are operating in the underexcited mode. The lowest critical fault clearing time is 150 ms for a three-phase fault 5% away from Kendal on the 400 kV Kendal–Tutuka line. In section 6.2.1 discussed previously, the lowest critical fault clearing time was 250 ms for a three-phase fault 5% away from Kendal on the 400 kV Kendal–Tutuka line. Therefore, when operating the Kendal generators in the underexcited mode, the risk of a generator pole slip is increased.

When the Kendal generators are exporting 580 MW and importing 18 Mvar, they are operating relatively close to their power capability limit. This means that any small disturbance can cause stability problems and therefore it would be sensible to avoid operating the Kendal generators in this region. Due to the

reduced critical fault clearing time, the probability of a generator pole-slip occurrence is higher when the Kendal generators are operating in the underexcited mode. The Kendal generators are occasionally run in the underexcited mode late at night (when the system load is low) to reduce the 400 kV busbar voltage by absorbing reactive power from the network. Therefore, since it is a normal condition to run the generators in the underexcited mode, it is fairly possible to have a pole-slip occurrence during this operating condition.

6.4.2 Pole slip impedance trajectory and slip (underexcited)

The impedance plot in Figure 6-16 indicates the pole-slip impedance trajectory for the case where the Kendal generators were exporting 580 MW and importing 40 Mvar (underexcited) when a three-phase fault was applied to the 400 kV Kendal–Minerva line, which was cleared in 300 ms. The fault distance is varied from 10% to 30% away from Kendal along the 400 kV Kendal–Minerva line.

In Figure 6-16, the pole-slip impedance trajectories for all three cases are quite similar. They are all circles with a centre located in the 3rd and 4th quadrant as expected for the underexcited case and the pole-slip system electrical centre is located within the generator transformer.

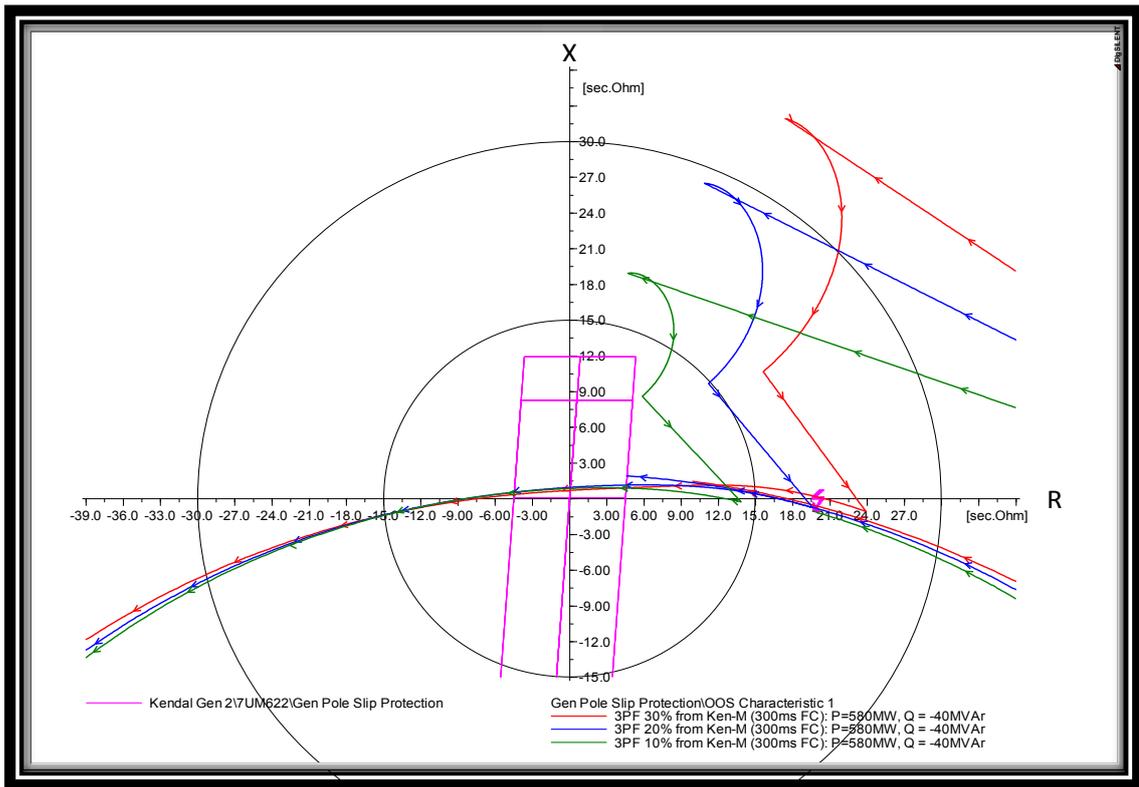


Figure 6-16 Pole-slip impedance trajectory with the Kendal generators underexcited and fault distance varied

The plot in Figure 6-17 indicates the Kendal generator pole-slip frequency for each additional pole-slip cycle. The slip frequency is shown for the three cases where the fault distance was varied from 10% to 30% away from Kendal along the 400 kV Kendal–Minerva line (fault clearing time of 300 ms). Figure 6-17 shows that the closer the three-phase fault is to Kendal, the higher the pole-slip frequency. The worst case slip frequency was at the 6th slip cycle, which is just over 8 Hz for the case where the three-phase fault is 10% away from Kendal. The Siemens 7UM622 generator protection relay is able to detect a maximum slip frequency of 10Hz, so this should not be a problem for the relay.

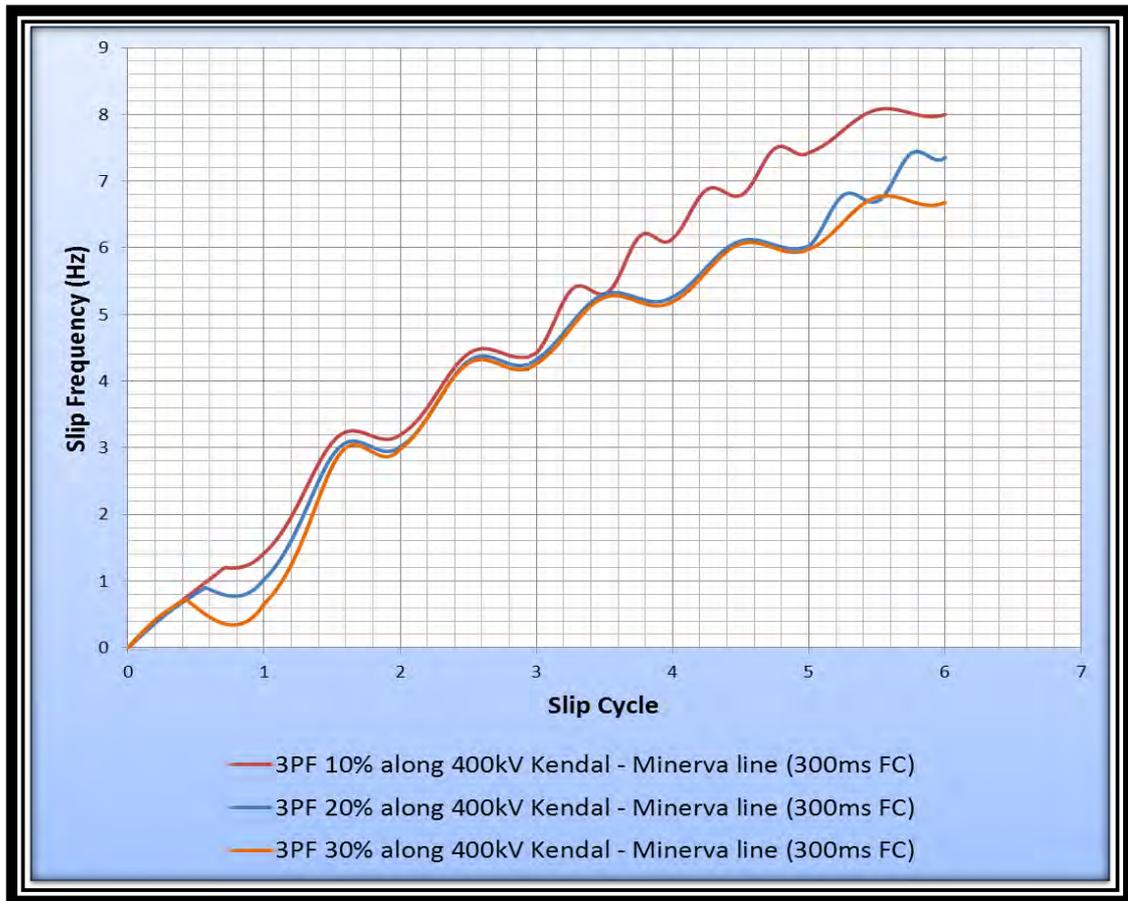


Figure 6-17 Pole-slip frequency for a three-phase fault on the Kendal-Minerva line with the Kendal generators operating in the underexcited mode

The following test was performed to determine how the pole-slip impedance trajectory would be affected by **varying the amount of reactive power absorbed** by the generator. The pole-slip impedance trajectories in Figure 6-18 were triggered by applying a three-phase fault 10% away from Kendal on the 400 kV Kendal–Minerva line and the fault clearing time was set to 250 ms. Before the three-phase fault was applied, all six Kendal generators were exporting 580 MW and importing **18 Mvar to 118 Mvar (underexcited)**.

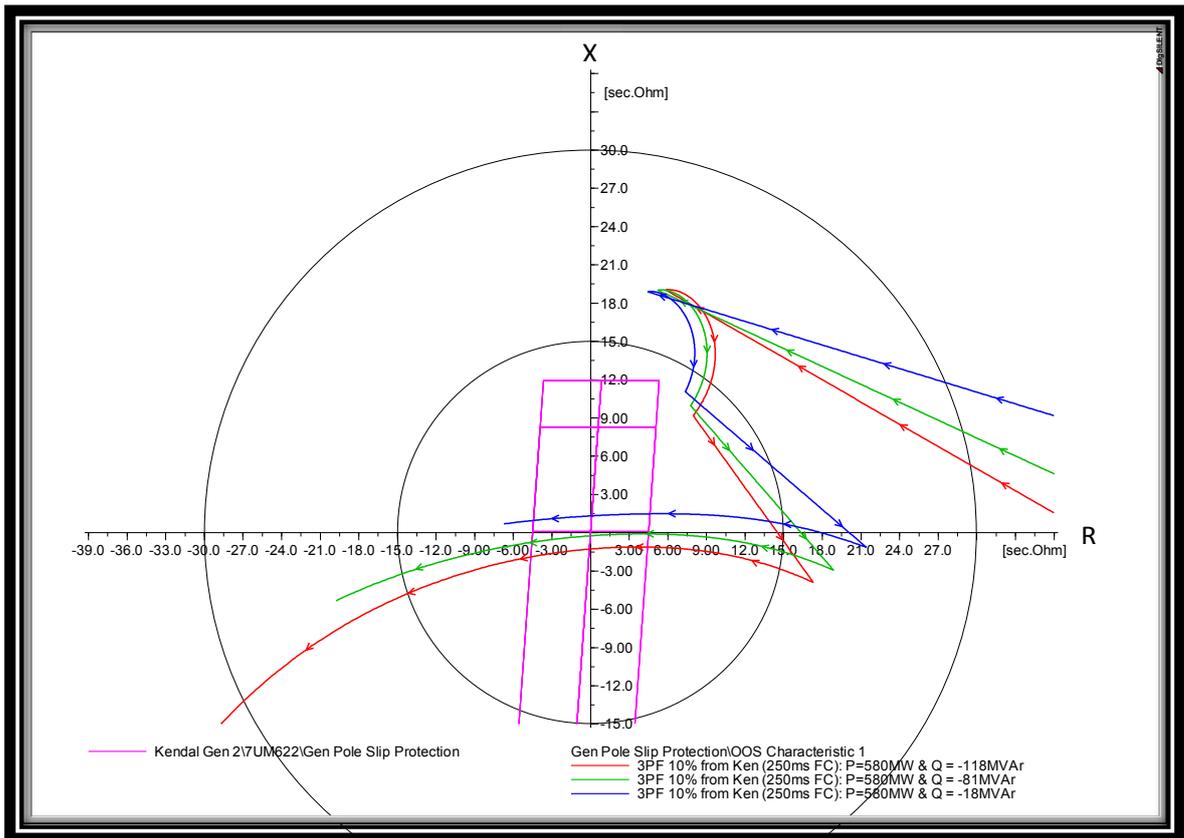


Figure 6-18 Pole-slip impedance trajectories for a three-phase fault with the generator importing reactive power

Figure 6-18 indicates that the system electrical centre for the pole slip passes through the generator transformer when importing 18 Mvar and passes through the generator when importing reactive power of 81 Mvar or more. The pole-slip system electrical centre moves closer to the generator as the generator imports more reactive power.

The loss-of-field (LOF) protection is usually an offset mho characteristic in the 3rd and 4th quadrants as discussed in section 4.2 earlier. Therefore, for this case in Figure 6-18, where the imported reactive power is more than 81 Mvar, the pole-slip impedance trajectory would be detected by the LOF protection as the impedance trajectory passes through the LOF characteristic. The LOF protection would not trip when the pole-slip impedance trajectory passes through the LOF characteristic, because the LOF protection generally has a time delay of around 0.5 s to 2 s, but the pole-slip impedance trajectory takes

less than 100 ms (depends on the slip frequency) to traverse across the LOF characteristic. Therefore, we cannot rely on the LOF protection to disconnect the generator for pole-slip impedance trajectories that traverse across the generator impedance (pole slip which has a system electrical centre located within the generator).

6.4.3 Pulsating generator current and electric power

The purpose of this section is to analyse the pulsating current and electric power during a generator pole slip when the **generator is operating in the underexcited mode**. The results from this section (generator importing reactive power) will also be compared to the results from section 6.3.3 (generator exporting reactive power) to determine which generator operating condition produces the highest magnitude of pole-slip pulsating current and power.

The pole-slip current and power plots in Figure 6-19 and Figure 6-20 respectively were triggered by a three-phase fault 10% away from Kendal on the 400 kV Kendal–Minerva line and the fault clearing time was set to 250 ms. Before the three-phase fault was applied, all six Kendal generators were exporting 580 MW and importing 18 Mvar in scenario one (red trace) and in the second scenario all six Kendal generators were exporting 580 MW and importing 118 Mvar (green trace). The magenta and blue traces are binary outputs that indicate the exact time of the first pole-slip cycle for the Kendal generators when importing 118 Mvar and 18 Mvar respectively.

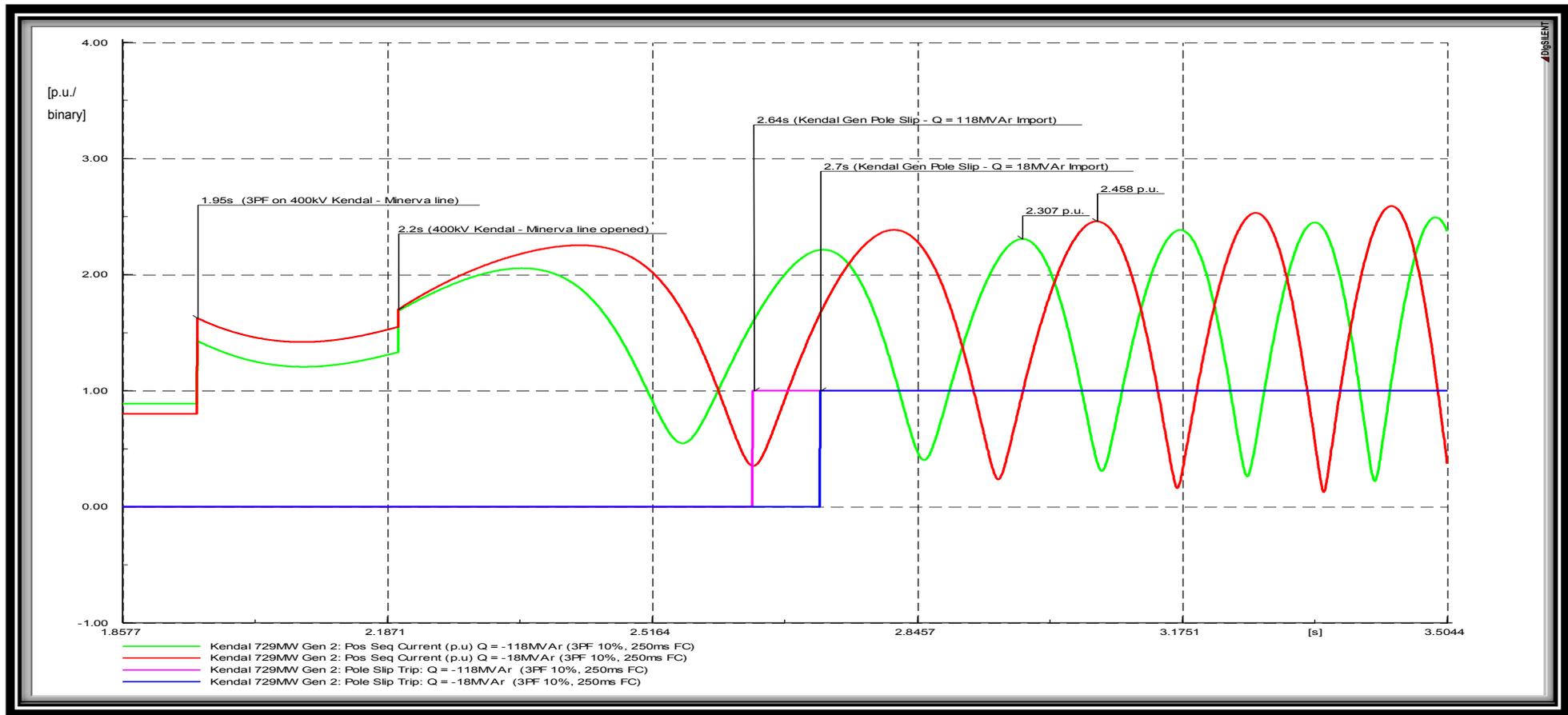


Figure 6-19 Generator pulsating current during a pole slip (close up three-phase fault with the generator importing 18 Mvar and 118 Mvar)

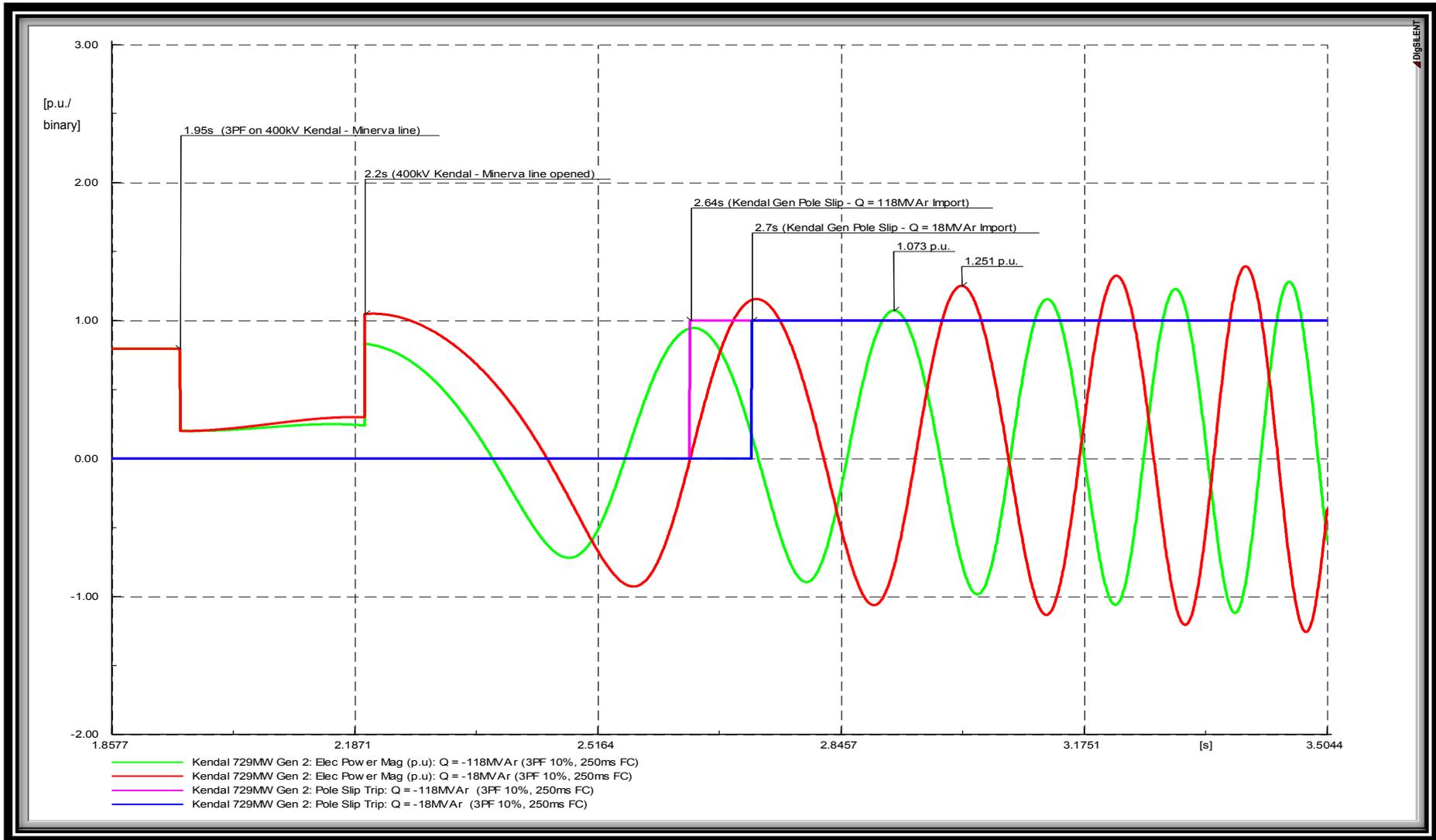


Figure 6-20 Generator pulsating electric power during a pole slip (close up three-phase fault with the generator importing 18 Mvar and 118 Mvar)

The Kendal generators will pole slip sooner when they are operating in the underexcited mode (importing reactive power) than when exporting reactive power as discussed in section 6.4.1.

From Figure 6-19 and Figure 6-20, when operating at 580 MW and importing 18 Mvar (red trace), the pole-slip peak pulsating current is 2.458 p.u. (Figure 6-19) and the power is 1.251 p.u. (Figure 6-20). It was shown in section 6.3.3 that when the generator is operating at 580 MW and exporting 334 Mvar, the pole-slip peak pulsating current is 2.719 p.u. and the power is 1.568 p.u..

The probability of a generator-pole-slip occurrence is higher when operating in the underexcited mode, because the critical fault clearing time is lower. The severity of a pole slip in the underexcited mode is slightly less, but will still cause severe stress and damage to the generator and generator transformer, since the magnitude of the pole slip pulsating current is greater than the current magnitude of a close up three-phase fault.

Figure 6-19 and Figure 6-20 show that the Kendal generators will pole slip sooner as the imported reactive power increases. For the case where all six Kendal generators were importing 118 Mvar, the generators pole slip 60 ms sooner than the when they were importing 18 Mvar but the magnitude of the pole slip pulsating current and power is less for the case where the generators are importing 118 Mvar than when importing 18 Mvar.

6.5 Generator Circuit Breaker Voltage During A Pole Slip

The simulations in this section were performed to determine if the generator breaker is overstressed in terms of overvoltage when the generator is disconnected from the network by the protection due to a generator-pole-slip condition.

In section 6.5.1 and section 6.5.2, a three-phase fault was applied 10% away from Kendal along the 400 kV Kendal–Minerva feeder. The three-phase fault was then cleared in 300 ms by disconnecting the 400 kV Kendal–Minerva line, which caused the Kendal generators to pole slip. The pre-fault conditions were: all five of the 400 kV feeders (Apollo 1, Apollo 2, Duvha, Tutuka and Minerva) from Kendal in service; all six of the Kendal 729 MW generators in service; the generator active power set point was at 580 MW and the reactive power set point was 334 Mvar (exporting).

6.5.1 Generator circuit breaker voltage when $\delta = 120$ degrees

For the above set of conditions, the generator protection relay then issued a trip signal to the Kendal 22 kV generator breaker after a single slip cycle when the trip angle (δ) was approximately 120 degrees. The results for this particular trip angle of 120 degrees are shown on the pole-slip impedance plot in Figure 6-21.

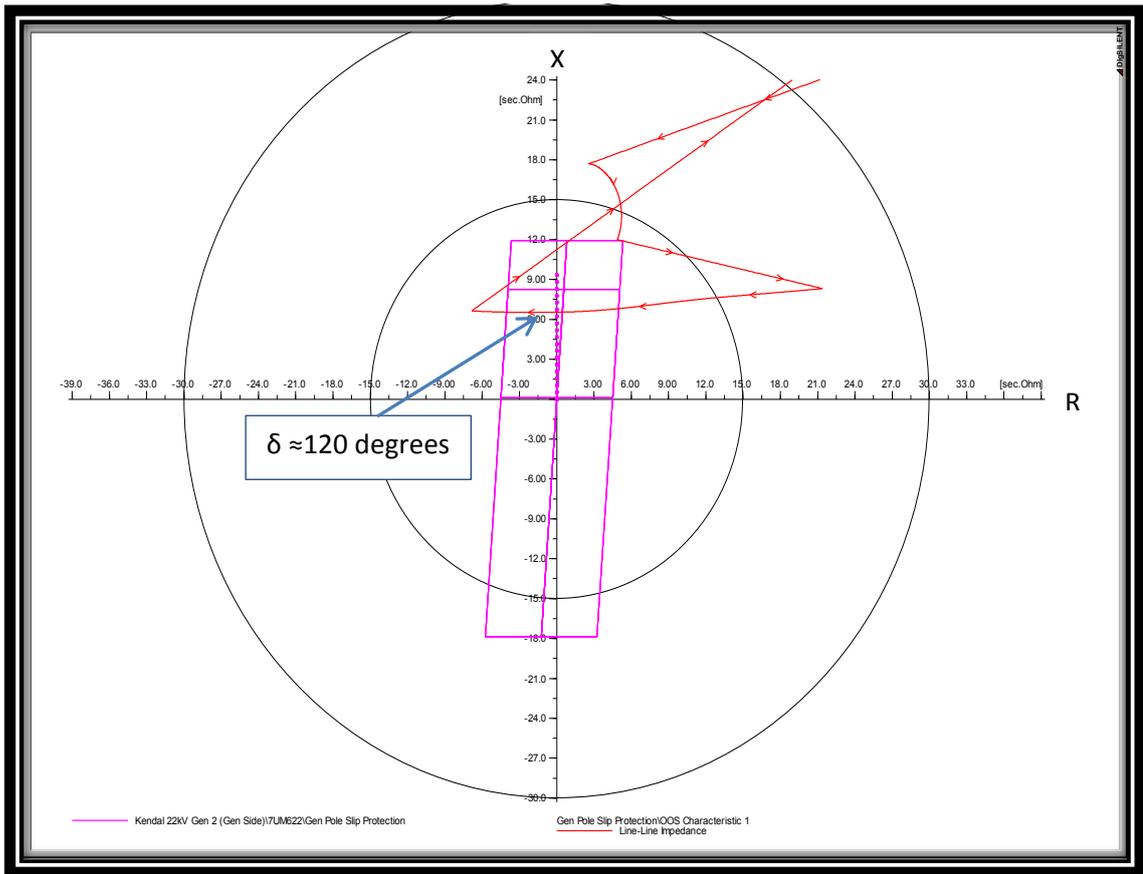


Figure 6-21 Pole-slip impedance trajectory for a pole-slip trip issued when $\delta \approx 120^\circ$

The voltage magnitude and voltage angle across the generator breaker as well as the pole-slip trip output from the relay are shown in Figure 6-22. It can be seen from Figure 6-22 that the pole-slip protection issued a trip at $t = 2.611$ s when δ was equal to 126.64 degrees. The relay has been set to issue a trip when $\delta = 120$ degrees to limit the voltage across the generator breaker to prevent re-striking. The voltage phase angle difference across the generator breaker at the point of tripping ($t = 2.612$ s) is equal to 107 degrees and the voltage difference is equal to 13.67 kV (line to ground). The nominal line to ground voltage is 12.7 kV, therefore the voltage difference across the breaker is only 1.08 x nominal voltage, which would definitely not overstress the generator breaker and a re-striking event is unlikely.

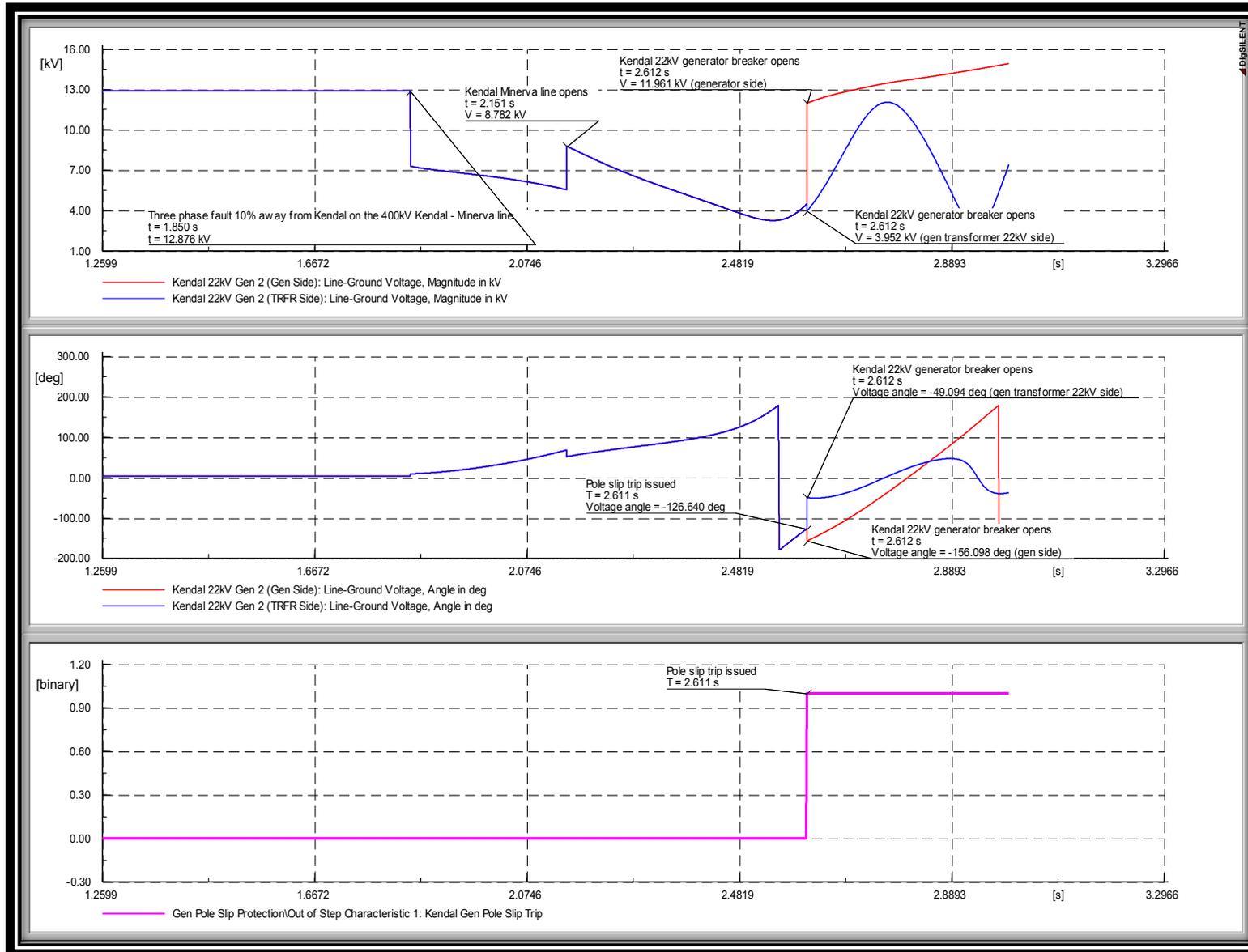


Figure 6-22 Voltage magnitude and phase angle when the pole-slip trip is issued when $\delta \approx 120^\circ$

6.5.2 Generator circuit breaker voltage when $\delta = 180$ degrees

The purpose of the pole-slip trip event simulated in this subsection was to determine if the generator breaker is overstressed when the generator breaker is tripped at a point where $\delta \approx 180$ degrees. The system events that caused the pole slip are stated under section 6.5 and the impedance plot for this pole-slip event is shown in Figure 6-23. For this simulation, the relay pole-slip protection trip was disabled, instead the Kendal 22kV generator breaker was forced open after a single slip cycle at a point on the impedance plot in Figure 6-23 where $\delta \approx 180$ degrees.

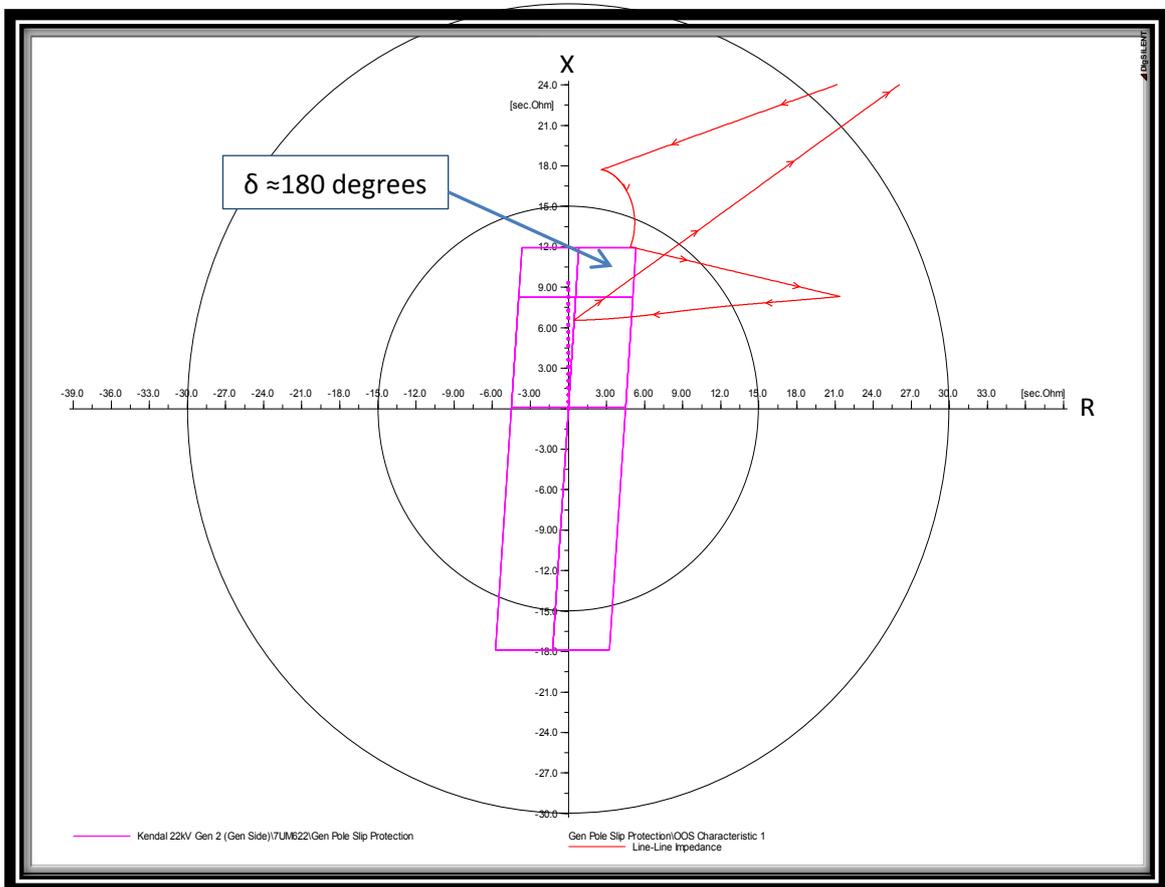


Figure 6-23 Pole-slip impedance trajectory for a pole-slip trip issued when $\delta \approx 180^\circ$

The voltage magnitude and angle across the generator breaker as well as the Kendal 400 kV busbar positive sequence per unit voltage are shown in Figure

6-24. The relay pole-slip protection trip output was disabled, instead the Kendal 22 kV generator breaker was forced open at $t = 2.538$ s, where the value of angle δ on the impedance plot in Figure 6-23 is around 180 degrees. This is meant to be the worst case scenario since the voltages across the breaker are 180 degrees out-of-phase at this point in time. Theoretically, we could expect a voltage of 2 x nominal across the generator breaker when tripping the breaker when $\delta = 180$ degrees. The measured voltage phase angle difference across the generator breaker at the point of opening the generator breaker ($t = 2.538$ s) is equal to 176 degrees and the voltage difference is equal to 14.65 kV (line to ground). The nominal line to ground voltage is 12.7 kV, therefore the voltage difference across the breaker is only 1.15 x nominal voltage, which would definitely not overstress the generator breaker and a re-striking event is unlikely. The reason for such a low voltage difference across the generator breaker despite the voltages across the generator breaker being 176 degrees out-of-phase is due to the low system voltage, which was caused by the three-phase fault. The Kendal 400 kV busbar positive sequence voltage is only 0.193 p.u. (purple trace) at the point where the generator breaker was opened ($t = 2.538$ s).

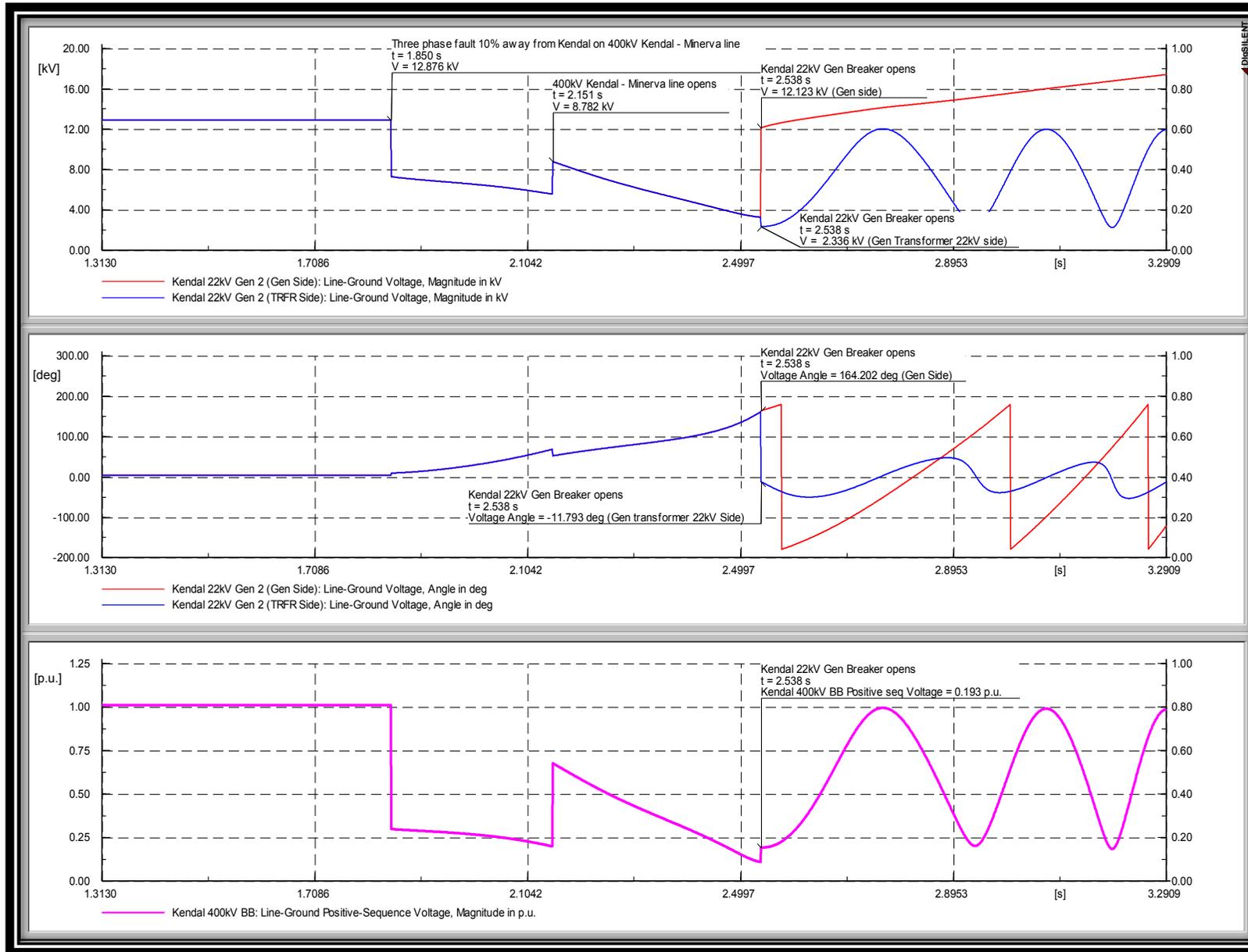


Figure 6-24 Voltage magnitude and phase angle when the Kendal 22 kV generator breaker is forced to trip when $\delta \approx 180^\circ$

Therefore, the pole-slip protection could be set to trip as soon as the pole-slip impedance trajectory has traversed the point where $\delta = 180$ degrees as long as the 400 kV busbar voltage is significantly depressed when a trip is issued to the breaker. If the 400 kV voltage is more than 0.8 p.u. when δ is equal to 180 degrees, the trip should rather be delayed until δ is less than 120 degrees to prevent unnecessary overvoltages across the generator breaker, which could cause re-striking.

A delayed fault clearing time for a fault, which is close to the power station is generally the main cause of a generator-pole-slip condition. The close-up fault in-turn causes a significant reduction in the system voltages so a pole slip caused by a close-up fault would generally not overstress the generator breaker in terms of over voltage when disconnecting the generator from the system due to the depressed system voltage at the point of tripping.

6.6 Conclusion

A number of generator-pole-slip time-domain simulations were performed and analysed in this chapter. The Kendal network that was analysed is heavily interconnected and therefore it is unlikely for a Kendal generator to pole slip. The lowest critical fault clearing time for an n-1 contingency was around 200 ms. The transmission protection installed on transmission networks will generally clear most faults in less than 100 ms. Nevertheless, it was shown that if a Kendal generator pole slip were to occur, the pole-slip pulsating current is higher than the current of a close-up three-phase fault, so it is critical to be able to detect a pole slip and disconnect the generator.

The lowest critical fault clearing time was obtained when one of the outgoing feeders at Kendal was out-of-service. By removing a line, the equivalent impedance of the transmission network is increased and a pole-slip event under this condition resulted in a pole slip with a system electrical centre located within the transmission network. The current generator-pole-slip protection settings that have been applied at Kendal power station do not reach into the transmission network, therefore the generators at Kendal rely solely on the transmission line out-of-step protection to separate the network for an out-of-step condition, which has a system electrical centre located within the transmission network. This type of out-of-step condition is not as severe as when the out-of-step characteristic has a system electrical centre located within the generator or generator transformer, but it may still cause significant damage to the generator, generator transformer and the turbine shaft. Therefore, it is recommended that the generator-pole-slip protection should be able to detect an out-of-step condition, which has a system electrical centre located within the transmission network, but it should only trip the generator after three to four pole-slip cycles to allow the transmission line out-of-step protection sufficient time to separate the out-of-step network.

The Siemens 7UM622 relay model within DigSilent PowerFactory operated in accordance with the Siemens relay technical manual. The relay model tripped correctly for various pole-slip impedance trajectories that were located in zone 1 and zone 2 of the pole-slip impedance characteristic. The pole-slip counter was able to count the number of pole-slip crossings and it issued a correct trip after the set number of pole-slip crossings. Various stable power swings were also simulated; the relay model was able to identify them as stable power swings and therefore never issued an incorrect trip.

In chapter 7, the Siemens 7UM622 relay hardware device will be tested by “playing back” COMTRADE recordings that are generated by DigSilent PowerFactory when performing time domain simulations. The way in which the actual hardware relay responds to various stable and unstable power swing events will be a final check to ensure that the relay operates in accordance with the Siemens relay technical manual.

CHAPTER 7: POLE SLIP COMTRADE PLAYBACK

In chapter 6 a portion of the Eskom power system around Kendal power station as well as the Siemens 7UM622 pole-slip protection relay used at Kendal power station was modelled within DigSilent PowerFactory software. Various close-up three-phase faults were then applied to the 400 kV Kendal outgoing feeders, which triggered stable and unstable power swings. The response of the pole-slip protection relay model during large stable and unstable (pole slip) power swings were then analysed. The relay response was checked to ensure that it operated according to the description in the relay technical manual.

The Digsilent PowerFactory relay software models are built according to the relay technical manual, which describes the mathematical and logical algorithms of the protection device. Therefore it is necessary to determine if the software model is equivalent to the hardware device.

According to a paper from Riga Technical University [15], the difference in the measurement and calculation precision of the model and its real counterparts are usually tolerable, but there exists the probability of rare software errors as well as other irregularities, which exist only in the real device that can affect the device's proper operation. The main objective of this chapter is to determine if any such irregularities exist in the Siemens 7UM622 generator-pole-slip protection relay.

In this chapter, the Siemens 7UM622 relay hardware device is tested by physically testing the pole-slip protection function of the Siemens 7UM622 generator protection relay by playing back COMTRADE files that are generated by DigSilent PowerFactory when performing time domain simulations. By playing back COMTRADE files into the relay, the actual relay response can be compared to the description in the relay technical manual. This chapter will not analyse and explain the characteristics of the impedance trajectories under different operating conditions as was done in chapter 6. Instead, the focus is solely on how the pole-slip impedance function responds to the most onerous

power swing impedance trajectories to determine if the relay operates in accordance with the relay technical manual.

7.1 COMTRADE File Overview

A COMTRADE file contains transient waveform and event data collected from power systems or power system models. The COMTRADE file standard (IEEE C37.111-1999) [16] defines a common format for the data files and exchange medium needed for the interchange of various types of fault, test, and simulation data.

The rapid evolution and implementation of digital devices for fault and transient data recording and testing in the electric utility industry have generated the need for a standard format for the exchange of data. This data is being used in various devices to enhance and automate the analysis, testing, evaluation, and simulation of power systems and related protection schemes during fault and disturbance conditions. Since each source of data may use a different proprietary format, a common data format is necessary to facilitate the exchange of such data between applications. This will facilitate the use of proprietary data in diverse applications and allow users of one proprietary system to use digital data from other systems [16].

Each COMTRADE record has a set of up to four files associated with it. Each of the four files carries a different class of information. The four files are:

- Header (XXX.HDR)
- Configuration (.CFG)
- Data (.DAT)
- Information (.INF)

The header file is an optional ASCII text file, typically created through the use of a word processor program. The data is intended to be printed and read by the user. The header file can include any information in any order desired. Header files were not created for the COMTRADE files used in this dissertation.

The configuration file (.CFG) is an ASCII text file intended to be read by a computer program and, therefore, must be saved in a specific format. The configuration file contains information needed by a computer program in order to properly interpret the data (.DAT) file. This information includes items such as sample rates, number of channels, line frequency and channel information.

The data file (.DAT) contains the value for each input channel for each sample in the record. Conversion factors specified in the configuration file determine how to convert the data values to engineering units. The data file also contains a sequence number and time stamp for each set of samples. In addition to data representing analog inputs, inputs that represent on/off signals (digital inputs) are also recorded. The state of a digital input is represented by a number "1" or "0" in the data file.

The information file (.INF) is an optional file containing extra information that, in addition to the information required for minimum application of the data set, file originators may wish to make available to users. The format provides for public information that any user can read and use, and private information that may be accessible only to users of a particular class or manufacturer. Information files were not created for the COMTRADE files used in this dissertation.

7.2 Pole Slip Protection Testing Process Using A COMTRADE File

The process that was followed to test the Siemens 7UM622 generator protection relay pole-slip function by using a COMTRADE file is shown in Figure 7-1.

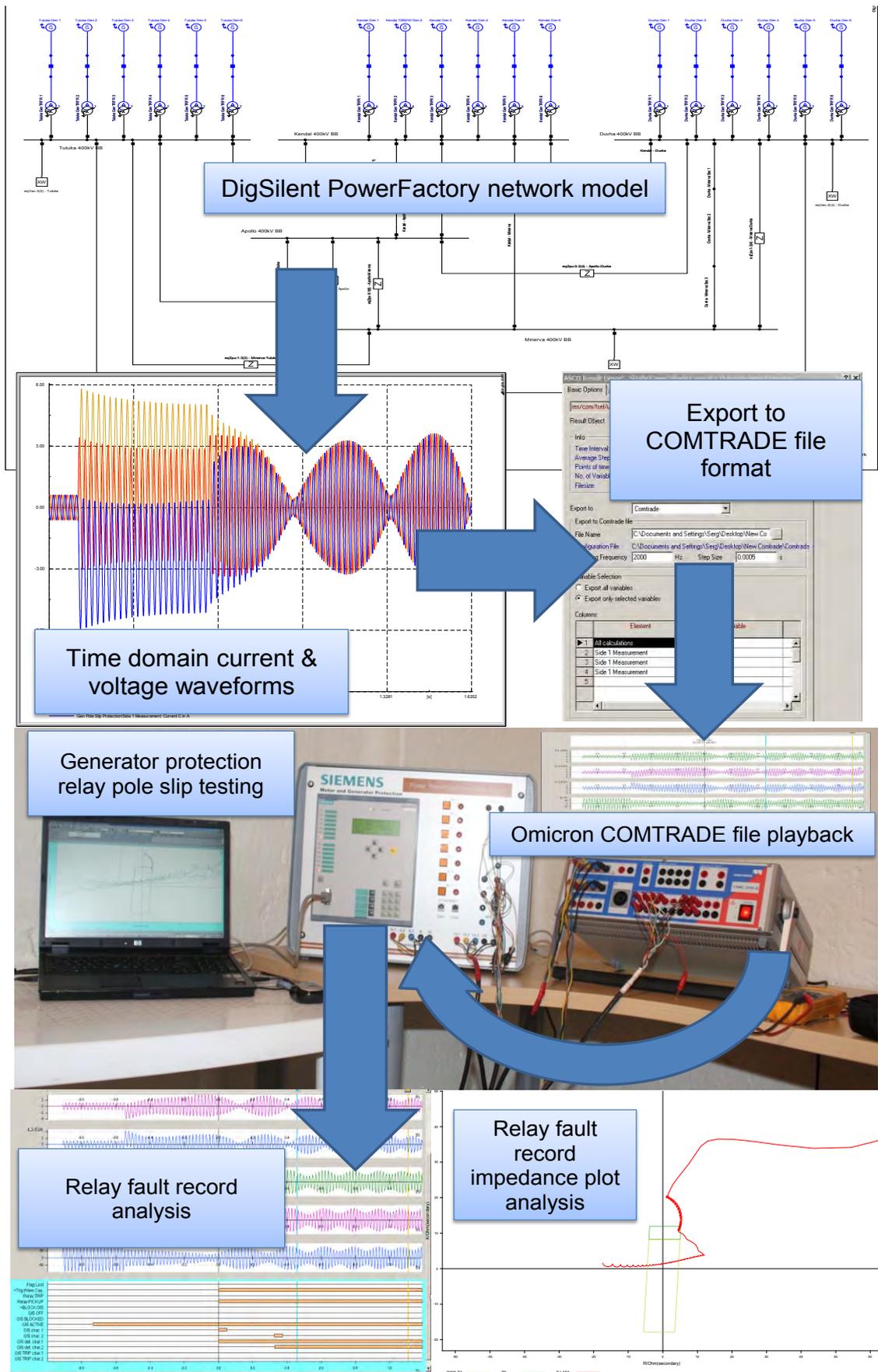


Figure 7-1 Pole slip protection testing process using a COMTRADE file

Digsilent PowerFactory was used to perform dynamic time domain simulations. The three-phase currents and voltages obtained from the time domain simulations were then converted to COMTRADE files, which are then used to test the actual relay device. The COMTRADE files can then be used with any modern relay test equipment, which allows the various analog signals to be played back. For the purpose of this dissertation, the Omicron CMC256 relay test system was used to play back the simulated three-phase current and voltage signals.

The Siemens 7UM622 relay has a built in disturbance recorder that records the relay's analog input and digital output signals whenever a disturbance record is triggered. The relay disturbance recorder was set to start recording as soon as a COMTRADE file was played to the relay. The disturbance records were then analysed by using TransView fault analysis software [37].

The TransView fault analysis software displays all the measured current, voltage and binary signals. TransView also calculates various parameters such as the measured impedance trajectory and the sequence component currents (I_0 , I_1 & I_2) and voltages (V_0 , V_1 & V_2).

When analysing the impedance trajectory of a pole-slip operation, the pole-slip protection impedance reach settings (zone 1 and zone 2) should also be displayed on the impedance plot. The pole-slip impedance trajectory along with the relay binary signals can then be analysed to determine if a trip was issued correctly or incorrectly by the pole-slip protection function.

The relay's COMTRADE disturbance record does not contain the pole-slip protection impedance characteristic. Therefore, the pole-slip protection impedance characteristic was defined by creating an eXtended Relay Interface by OMICRON file (XRIO) [32], which was then imported into the TransView fault analysis software. The XRIO concept was introduced by OMICRON out of a need for a uniform data format for the parameters of protection relays produced by different manufacturers. XRIO is based on the eXtensible Markup Language (XML) and gives direct access to single parameters and their values. XML is a

markup language that was designed to carry data and not display data. XML tags are not pre-defined, instead the tags must be user defined and should be self-descriptive. XRIO provides a common structure for the functionally similar relays from diverse manufacturers to be tested with similar test procedures. Additionally, XRIO permits relay characteristics to be imported into relay testing software as well as fault analysis software such as SIGRA and TransView [32]. An XRIO file was created for the studies in this dissertation to visualise the pole-slip impedance characteristic when analysing the fault recordings within TransView and is shown in *APPENDIX A: XRIO file for the pole-slip protection reach settings*.

7.3 COMTRADE Play Back Testing

This section focuses on how the pole-slip impedance function responds to the most onerous power swing impedance trajectories to determine if the relay operates in accordance with the relay technical manual.

Within DigSilent PowerFactory, various three-phase faults were applied to the outgoing 400 kV feeders at Kendal and the fault clearing time was varied to produce the desired power swing impedance trajectory. The time domain current and voltage waveforms for the power swing events were then exported from DigSilent PowerFactory to a COMTRADE file. The COMTRADE file was then played back to the hardware relay device by using an Omicron CMC256 secondary injection set and the relay was configured to start recording as soon as the COMTRADE file started playing. The relay disturbance recorder recorded the current and voltage waveforms as well as internal relay binary signals, which were analysed to determine if the relay operated correctly.

The pole-slip settings that were applied to the relay were calculated in section 5.2 unless stated otherwise under the specific subsection.

7.3.1 Scenario 1: Pole slip impedance trajectory in top portion of zone 1

The purpose of this subsection is to determine whether the pole-slip protection issues a trip after the first slip cycle when a pole-slip impedance trajectory traverses through the top half of the zone 1 impedance characteristic (generator transformer).

The impedance plot in Figure 7-2 indicates the impedance trajectory measured by the pole-slip protection relay at Kendal. The measured three-phase fault impedance was initially just outside the impedance characteristic of zone 2 and as soon as the fault was cleared, the power swing impedance trajectory traversed through the inside of zone 2 and then exited the zone 2 characteristic. The unstable power swing impedance trajectory then changed directions and came straight back through the top half of the zone 1 impedance characteristic (generator transformer).

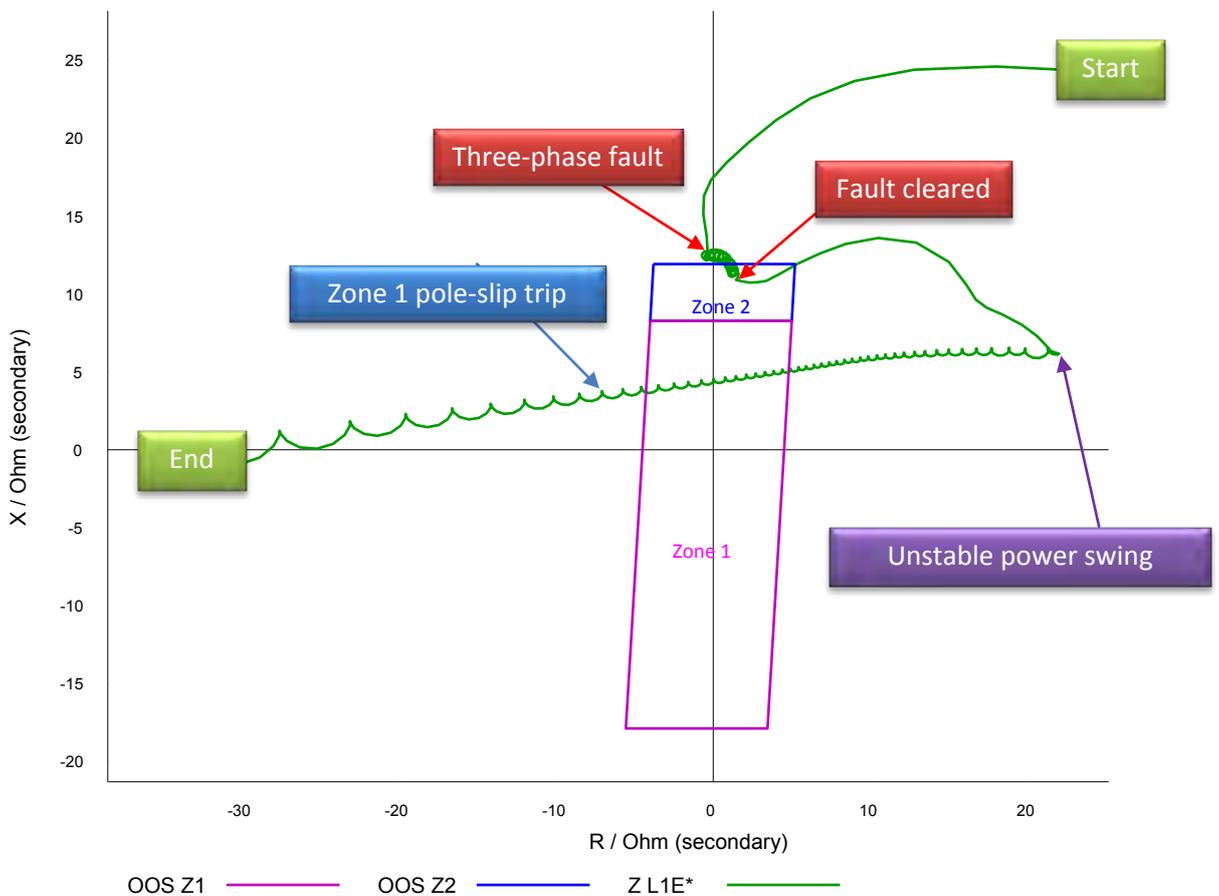


Figure 7-2 Pole-slip impedance trajectory - zone 1 (generator transformer)

Figure 7-3 indicates the voltages and currents measured by the relay as well as the relay internal binary signals for the pole-slip impedance trajectory in Figure 7-2. The binary signals indicate that the relay responded correctly when the power swing impedance trajectory briefly entered and exited the zone 2 characteristic since it did not count this a zone 2 pole slip. The relay tripped correctly by only issuing a trip when the pole-slip impedance trajectory exited the zone 1 characteristic (after the first pole-slip cycle).

Unlike conventional impedance protection, the relay pole-slip protection pickup signal is not activated when the measured impedance is within the zone 1 or zone 2 pole-slip impedance characteristic. The relay pole-slip pickup signal is only activated when: the impedance trajectory enters the pole-slip impedance characteristic at one side, passes through the imaginary axis or characteristic dividing line, and exits the characteristic at the opposite side. Therefore, the relay pickup signal was not activated when the power swing impedance trajectory briefly entered and exited the zone 2 characteristic. The relay pickup signal was issued at the same time as the zone 1 trip signal as this was when all the required pickup conditions were met.

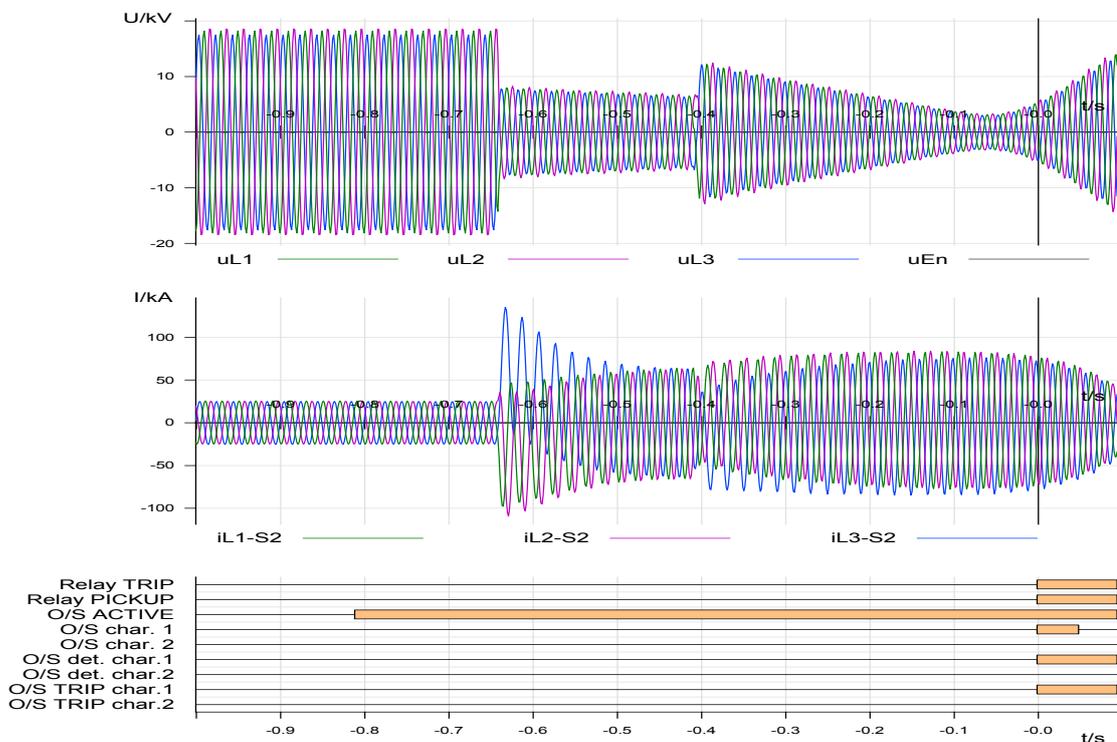


Figure 7-3 Pole-slip voltages, currents and binary signals - zone 1 (generator transformer)

7.3.2 Scenario 2: Pole-slip impedance trajectory in bottom portion of zone 1

The purpose of this subsection is to determine whether the pole-slip protection issues a trip after the first slip cycle when a pole-slip impedance trajectory traverses through the bottom half of the zone 1 impedance characteristic (generator).

The impedance plot in Figure 7-4 indicates the impedance trajectory measured by the pole-slip protection relay at Kendal. The measured three-phase fault impedance was initially just outside the impedance characteristic of zone 2, entered it during the fault, and as soon as the fault was cleared, the power swing impedance trajectory traversed through the inside of zone 2 and then exited the zone 2 characteristic via the zone 1 characteristic. The unstable power swing impedance trajectory then hovered around the outside of the zone 1 and zone 2 impedance characteristic before changing directions and coming back straight through the bottom half of the zone 1 impedance characteristic (generator).

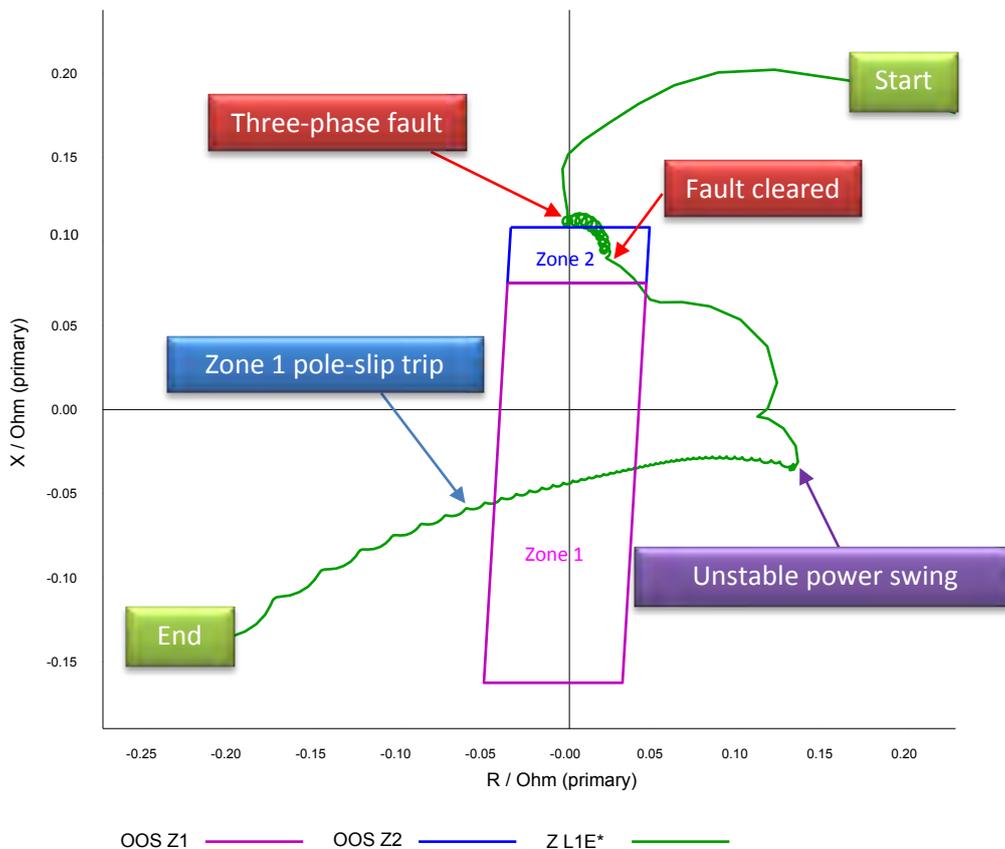


Figure 7-4 Pole-slip impedance trajectory for a zone 1 trip
(Note: Characteristic in primary ohms)

Figure 7-5 indicates the voltages and currents measured by the relay as well as the relay internal binary signals for the pole-slip impedance trajectory in Figure 7-4. The binary signals indicate that the relay responded correctly when the power swing impedance trajectory briefly entered and exited the zone 2 characteristic since it did not count this a zone 2 pole slip. The relay tripped correctly by only issuing a trip when the pole-slip impedance trajectory exited the zone 1 characteristic (after the first pole-slip cycle).

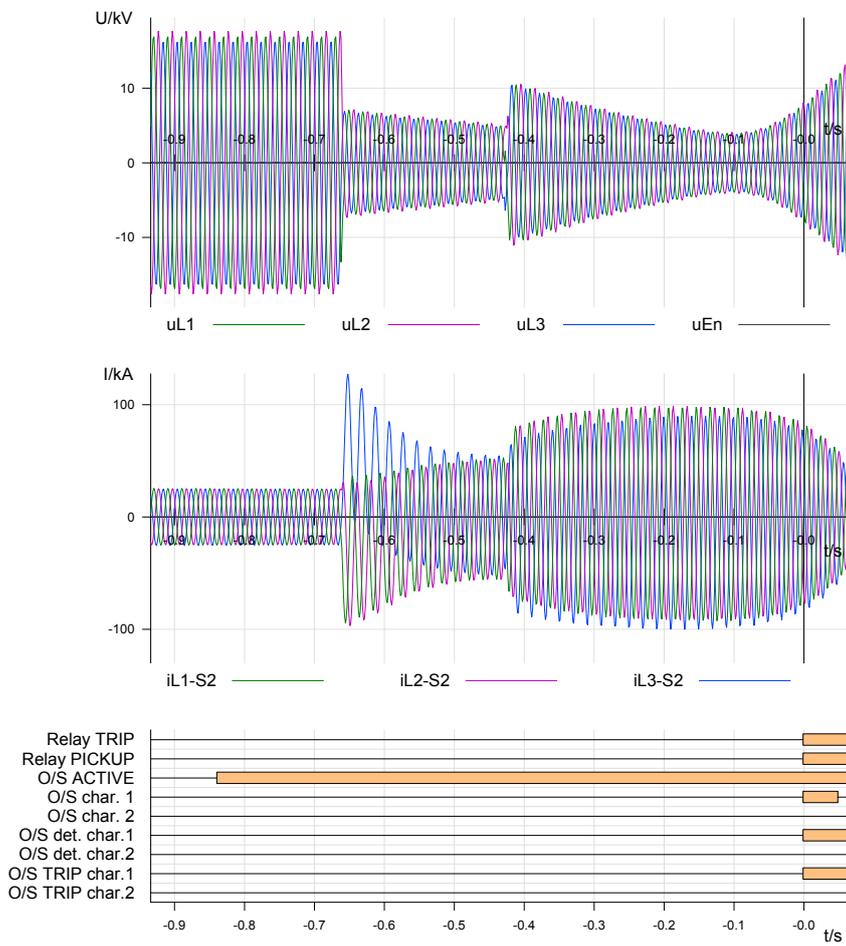


Figure 7-5 Pole-slip voltages, currents and binary signals - zone 1 (generator)

7.3.3 Scenario 3: Pole slip impedance trajectory in zone 2

The purpose of this subsection is to determine whether the pole-slip protection issues a trip after the third slip cycle when a pole-slip impedance trajectory traverses through the zone 2 impedance characteristic (system).

The impedance plot in Figure 7-6 indicates the impedance trajectory measured by the pole-slip protection relay at Kendal. The measured three-phase fault impedance was initially outside the impedance characteristic of zone 2 and as soon as the fault was cleared, the power swing impedance trajectory traversed marginally through the inside edge of the zone 2 characteristic before exiting. The unstable power swing impedance trajectory then changed directions and came straight back through the zone 2 impedance characteristic (system). The impedance trajectory continued to pass through the zone 2 impedance characteristic for three complete slip cycles.

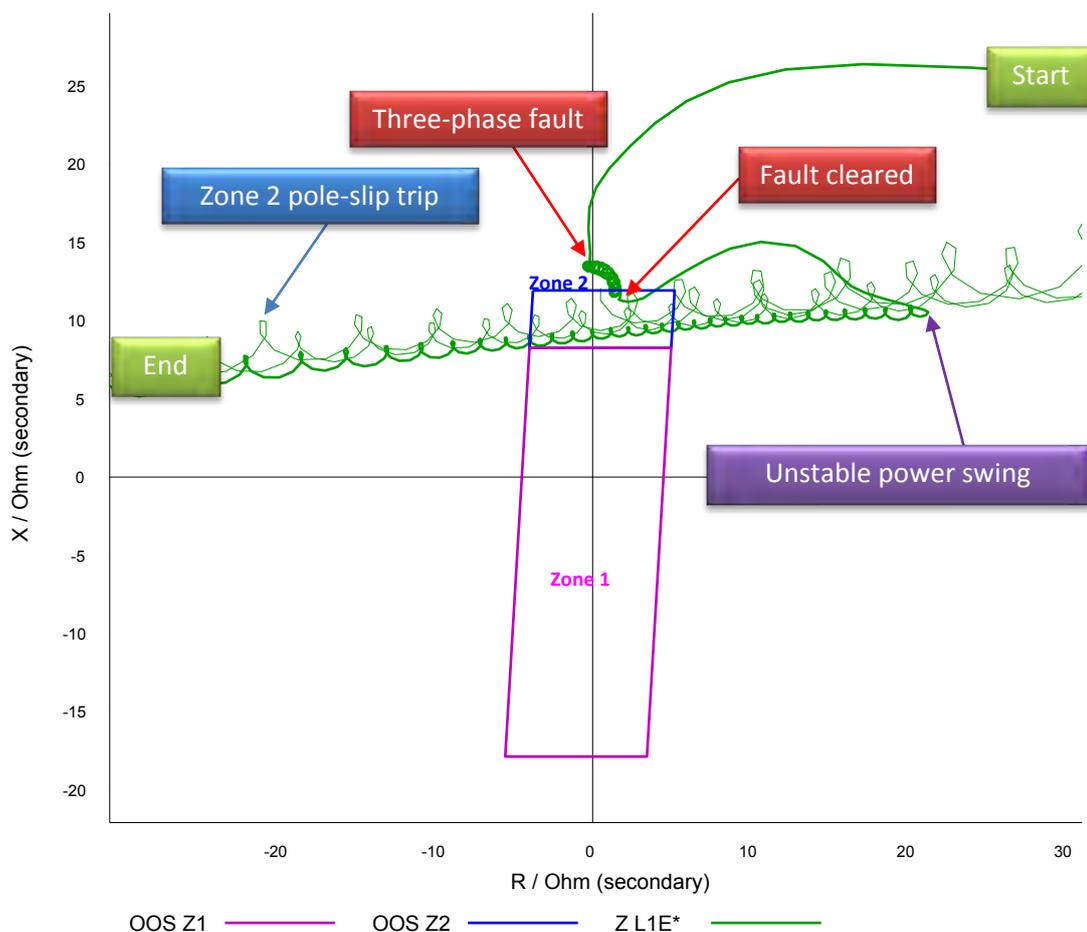


Figure 7-6 Pole slip impedance trajectory - zone 2 (system)

Figure 7-7 indicates the voltages and currents measured by the relay as well as the relay internal binary signals for the pole-slip impedance trajectory in Figure 7-6. The binary signals indicate that the relay responded correctly as it detected all three pole-slip cycles passing through the characteristic of zone 2 and issued a trip after the third pole-slip cycle.

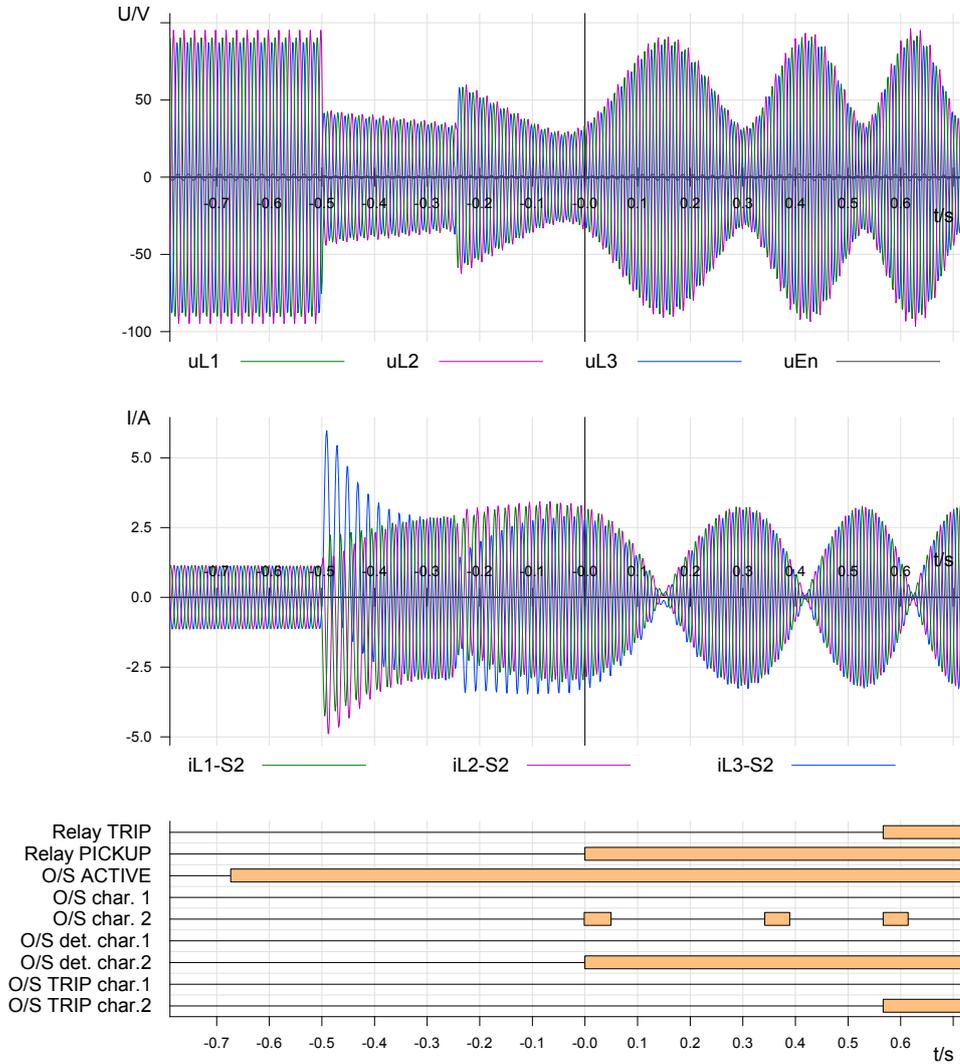


Figure 7-7 Pole-slip voltages, currents and binary signals - zone 2 (system)

7.3.4 Scenario 4: Pole slip trip when δ is more than 120 degrees

The purpose of this subsection is to determine whether the pole-slip protection can issue a trip when δ is more than 120 degrees.

The impedance plot in Figure 7-8 indicates the impedance trajectory measured by the pole-slip protection relay at Kendal. The measured three-phase fault impedance was initially outside the impedance characteristic of zone 2 and when the fault was cleared, the impedance trajectory moved into the top half of the zone 1 impedance characteristic. The impedance trajectory of the unstable power swing then traversed out of the zone 1 impedance characteristic and shortly after exiting the zone 1 impedance characteristic, the impedance trajectory changed direction and headed back into the zone 1 impedance characteristic and exited through the top of the zone 1 impedance characteristic.

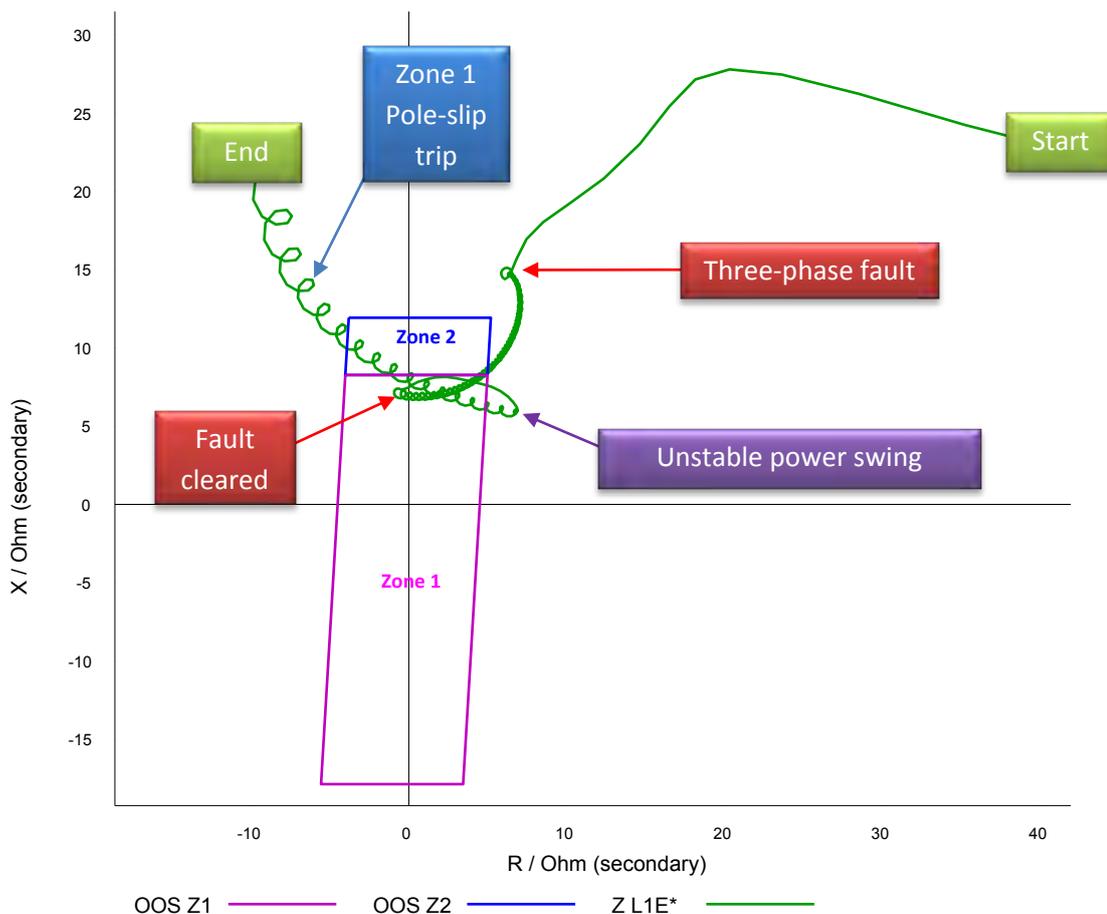


Figure 7-8 Pole-slip trip when δ is more than 120 degrees

Figure 7-9 indicates the voltages and currents measured by the relay as well as the relay internal binary signals for the pole-slip impedance trajectory in Figure 7-8. The binary signals indicate that the relay issued a zone 1 trip command even though the pole-slip impedance trajectory exited the zone 1 characteristic through the top of the zone 1 characteristic. This means that the relay can issue a trip when δ is more than 120 degrees. It was shown earlier in section 6.5 that it is acceptable to trip the Kendal generator breaker for a pole slip even when δ is more than 120 degrees, but this may not be the case at other sites. Therefore, protection engineers should be aware of this relay nuance and should always confirm if it is acceptable to trip the breaker when δ is more than 120 degrees.

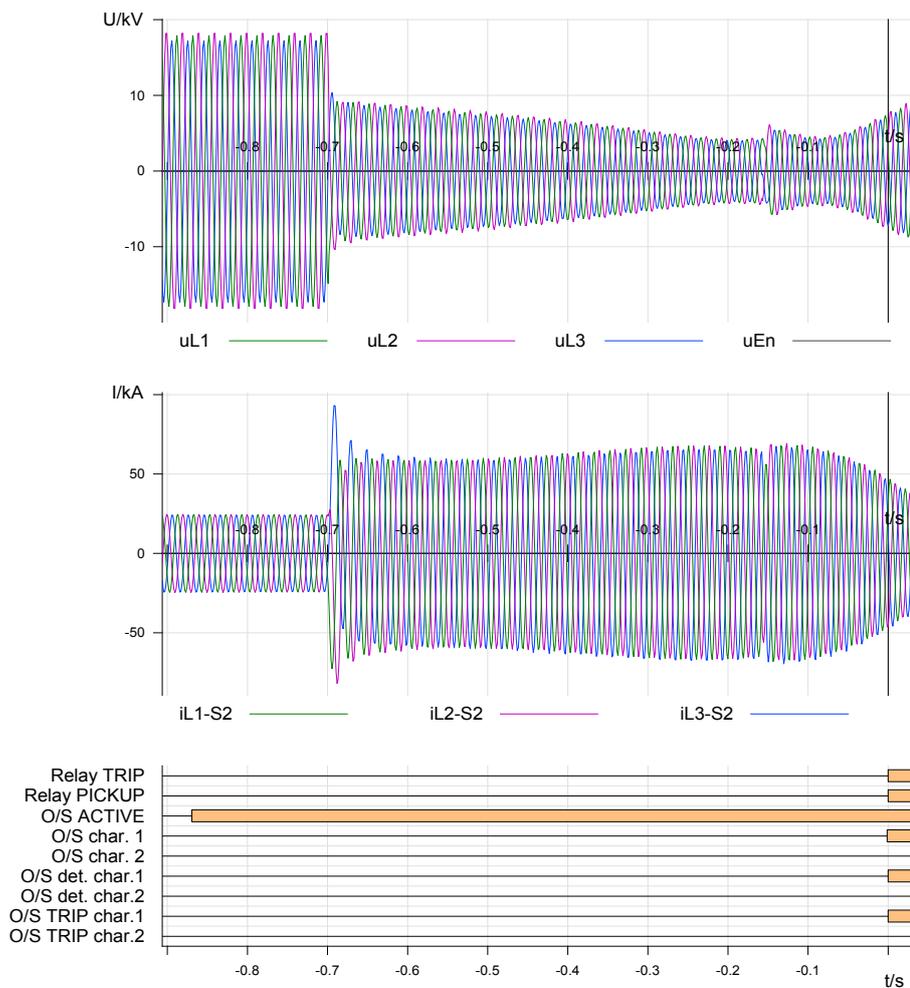


Figure 7-9 Pole-slip voltages, currents and binary signals when δ is more than 120 degrees

7.3.5 Scenario 5: Pole slip incorrect operation

The purpose of this subsection is to determine whether it is possible for the pole-slip protection relay to incorrectly operate for a three-phase fault impedance which is measured within the pole-slip impedance characteristic.

The impedance plot in Figure 7-10 indicates the impedance trajectory measured by the pole-slip protection relay at Kendal. The measured three-phase fault impedance was lingering along the inside and outside edge of the zone 2 impedance characteristic. When the fault was cleared, the impedance trajectory traversed out of the zone 2 characteristic and remained out of the pole-slip characteristic. This was a stable power swing event so the impedance trajectory never traversed back into the pole-slip impedance characteristic after it exited the zone 2 characteristic.

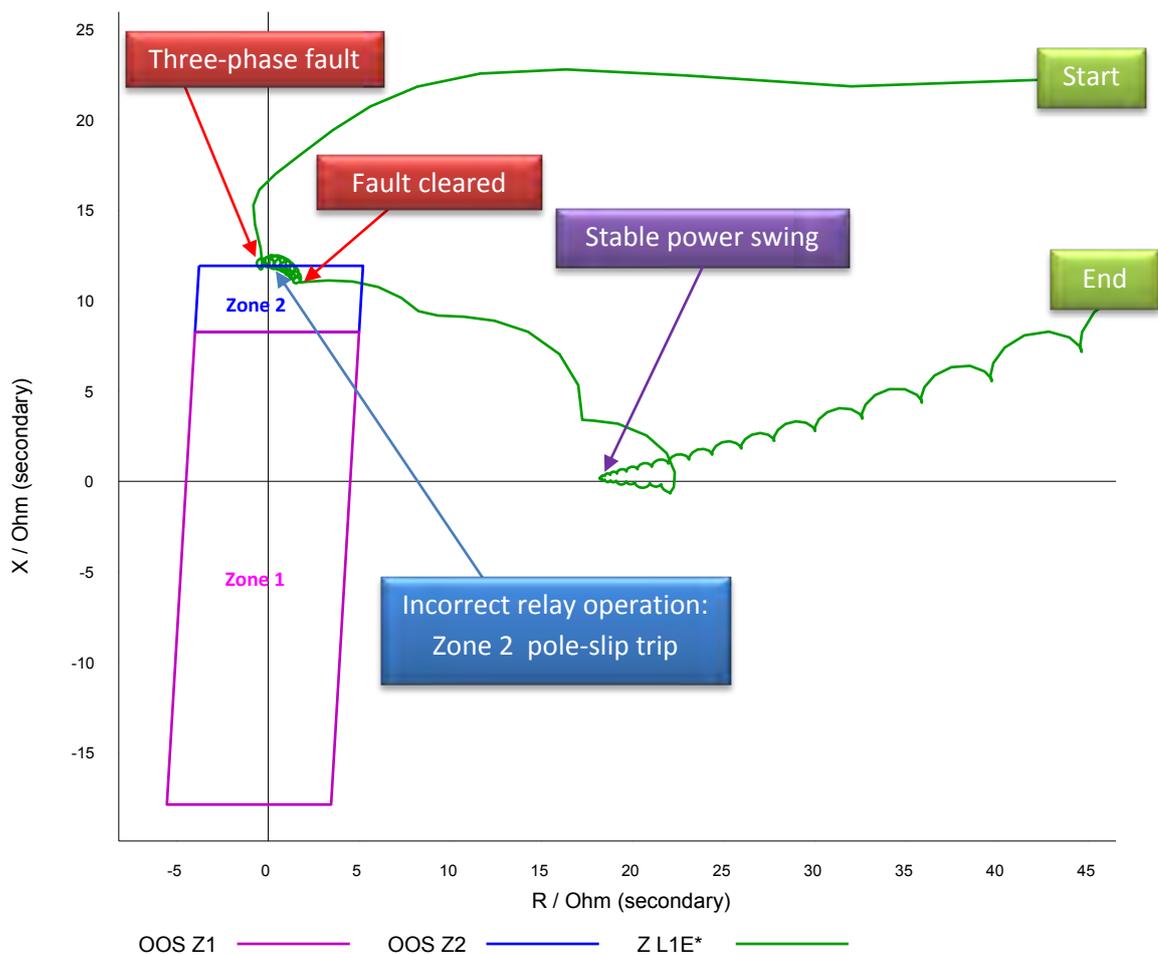


Figure 7-10 Power-swing impedance trajectory - incorrect relay operation

The relay pole-slip counter should only be incremented when: the impedance trajectory enters the pole-slip impedance characteristic at one side, passes through the imaginary axis or characteristic dividing line, and exits the characteristic at the opposite side [7]. The zone 2 pole-slip counter should not have incremented for the impedance trajectory in Figure 7-10, because the impedance trajectory entered the impedance characteristic from the top and not the side.

Figure 7-11 indicates the voltages and currents measured by the relay as well as the relay internal binary signals for the power swing impedance trajectory in Figure 7-10. The binary signals indicate that the zone 2 pole-slip counter was incorrectly incremented for a three-phase fault impedance trajectory. The relay's zone 2 pole-slip element was set to trip after 3 slip cycles for a zone 2 pole slip. The pole-slip trip was not issued by the relay because the pole-slip counter was only incremented once. If the relay was set to trip after a single slip cycle in zone 2, the generator could be tripped incorrectly for a three-phase fault, which is located within the transmission system.

If a similar three-phase fault were to occur on the inside border of the zone 1 impedance characteristic, the relay could issue an incorrect trip since the zone 1 characteristic has been set to trip after a single slip cycle.

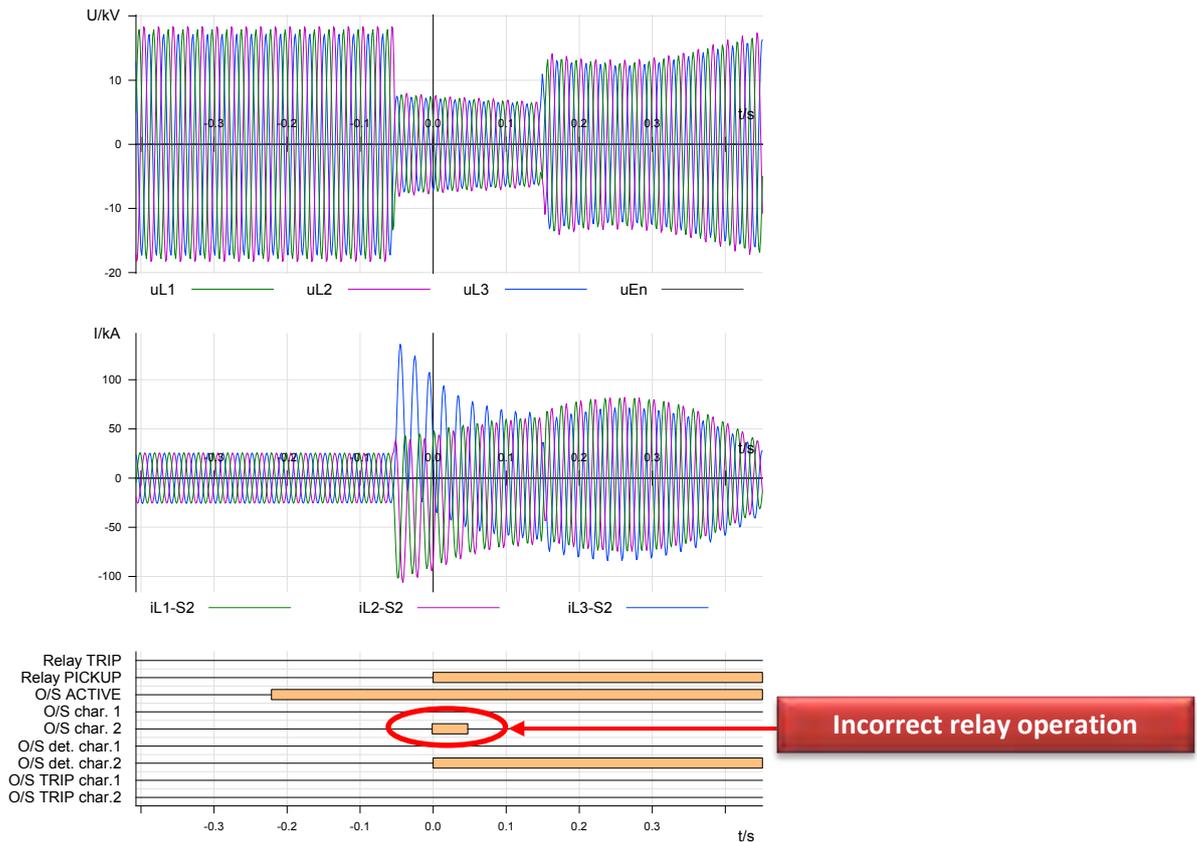


Figure 7-11 Power-swing voltages, currents and binary signals - incorrect relay operation

7.3.6 Scenario 6: Pole-slip stability test

The purpose of this subsection is to determine whether the pole-slip protection relay issues an incorrect trip when the impedance trajectory of a stable power swing enters and exits the pole-slip impedance characteristic from the same side.

In order for this test to be performed, one of the pole-slip impedance characteristic settings calculated in section 5.2 was changed. In section 5.2, the width of the polygon was calculated to ensure that the pole-slip polygon would only pickup when the power swing angle (δ) is 120 degrees or greater. Usually a system will not recover when the power swing angle between two systems exceeds 120 degrees. For the particular system chosen for study, it was not possible to simulate a stable power swing that exhibited a generator rotor angle δ that exceeded 120 degrees and in practice it would be unlikely for a system to

recover once δ has exceeded 120 degrees. Therefore, the width of the polygon (resistance Z_a of the polygon) in the relay's setting was changed from the originally-calculated value of 4.5 ohm to a larger value of 12 ohm for the purpose of this particular test.

By increasing the width of the pole-slip impedance polygon as just described, it is possible to determine how the pole-slip relay responds to a stable power swing impedance trajectory that enters and exits the pole-slip impedance polygon from the same side. If the width of the pole-slip impedance polygon is calculated correctly, it is unlikely for a stable power swing to enter and exit the pole-slip impedance polygon on the same side. In practice, a protection engineer may incorrectly calculate the width of the pole-slip impedance polygon; therefore it is important to understand if the relay would issue an incorrect trip for a stable power swing impedance trajectory when the width of the polygon is too big.

The impedance plot in Figure 7-12 indicates the impedance trajectory measured by the pole-slip protection relay at Kendal. The measured three-phase fault impedance was inside the zone 2 impedance characteristic. When the fault was cleared, the impedance trajectory traversed out of the zone 2 characteristic and into the zone 1 characteristic and then exited the zone 1 characteristic. Shortly after exiting the zone 1 characteristic, the impedance trajectory changed direction and came back into the zone 1 characteristic. Since this was a stable power swing, the impedance trajectory changed direction once again and exited the zone 1 characteristic from the same side that it entered and remained outside of the pole-slip impedance characteristic.

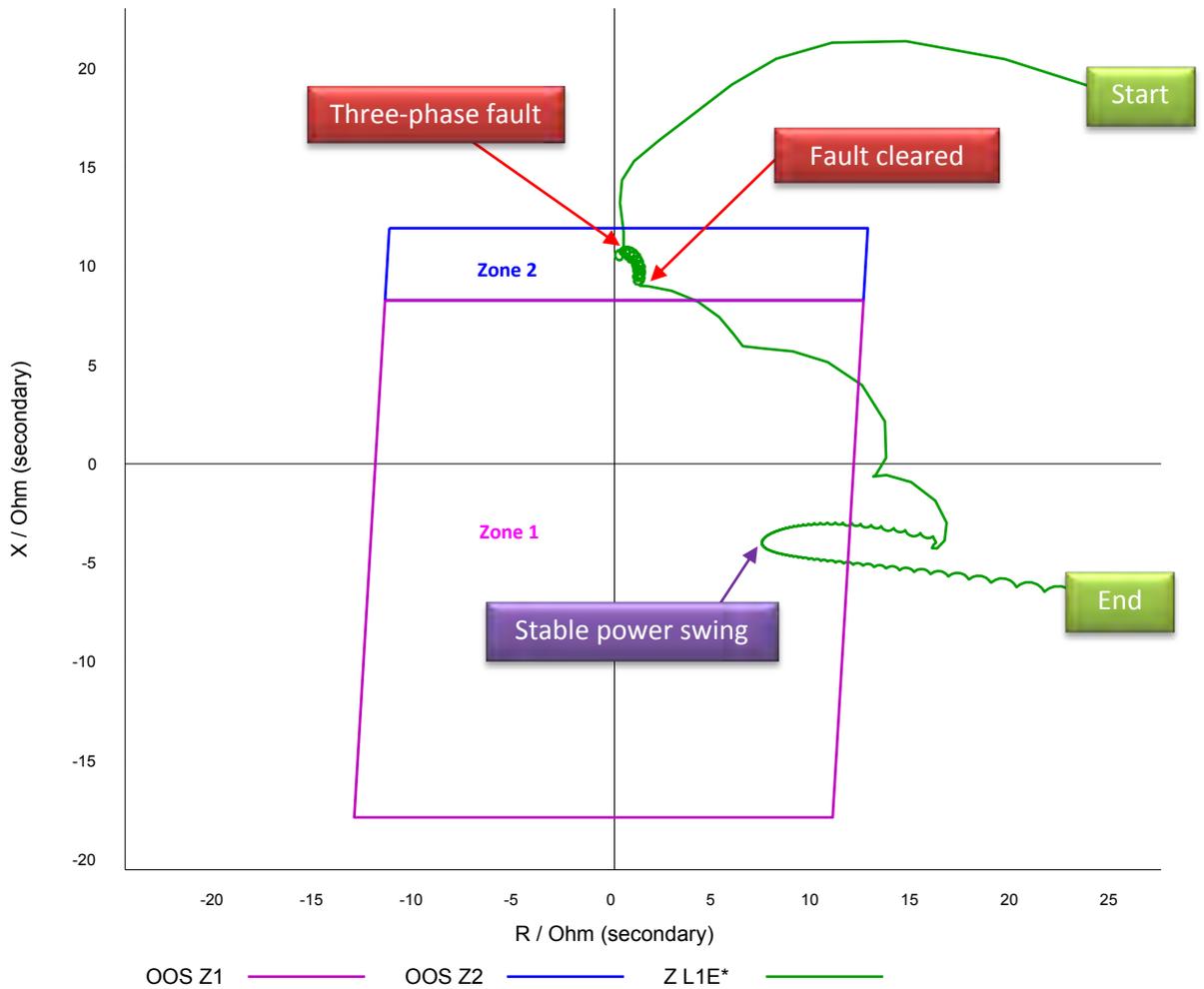


Figure 7-12 Impedance trajectory for a stable power swing – correct relay operation

Figure 7-13 indicates the voltages and currents measured by the relay as well as the relay internal binary signals for the power swing impedance trajectory in Figure 7-12. The binary signals indicate that the relay responded correctly since the zone 1 and zone 2 pole-slip impedance elements never operated when the measured three-phase fault impedance was within the zone 2 characteristic, and secondly when the stable power swing impedance trajectory traversed in and out of the zone 1 characteristic.

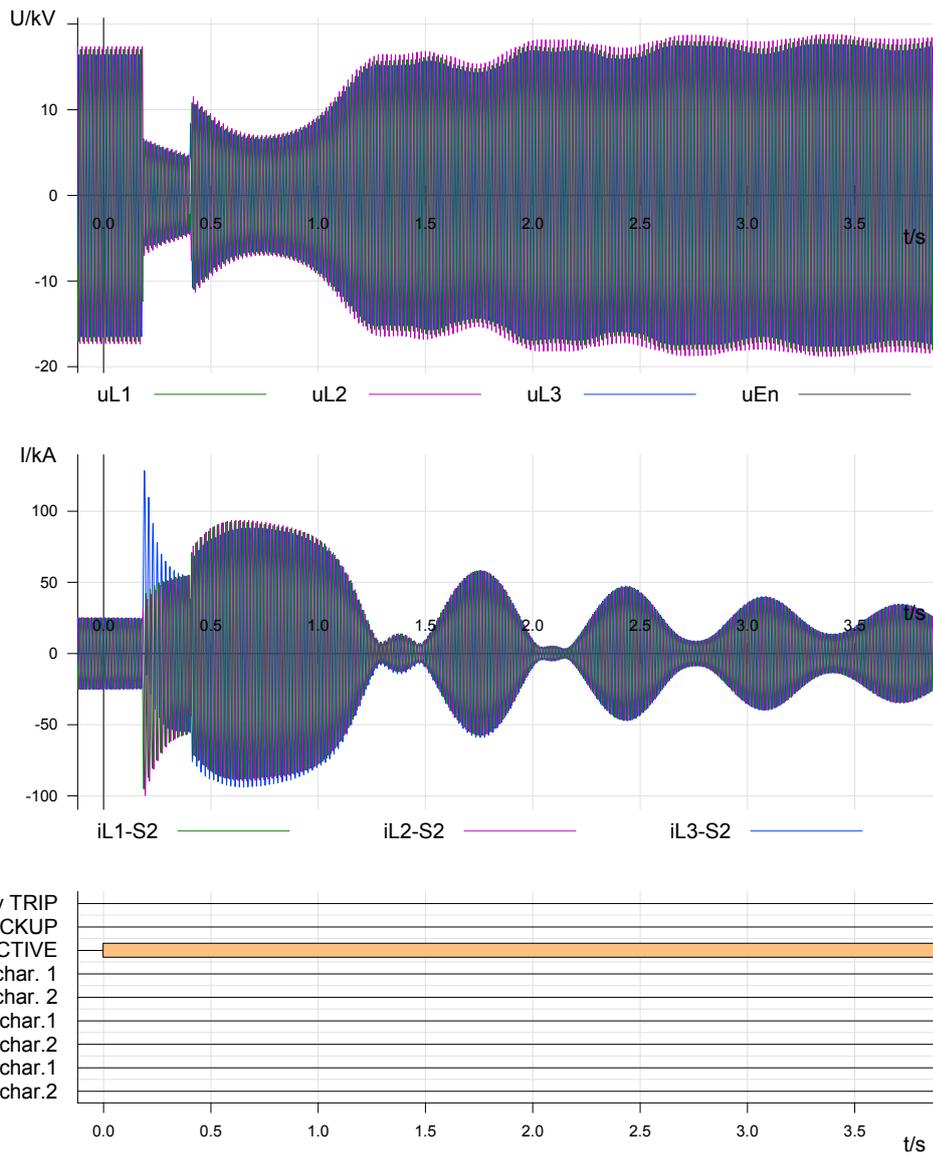


Figure 7-13 Power-swing voltages, currents and binary signals - correct relay operation

7.4 Conclusion

In the majority of cases, the Siemens 7UM622 relay hardware device operates in accordance with the Siemens relay technical manual. A number of stable and unstable power swing COMTRADE recordings were played back to the pole-slip protection relay. The pole-slip protection relay was always able to detect an unstable power swing, which traversed through the zone 1 and zone 2 pole-slip impedance characteristic. The zone 1 and zone 2 pole-slip counters were correctly incremented whenever an unstable power swing impedance trajectory traversed through the pole-slip impedance characteristic and the relay issued a trip after the correct number of set pole-slip cycles.

Usually a system will not recover when the power swing angle between two systems exceeds 120 degrees. Therefore, it is unlikely for a stable power swing to enter and exit the pole-slip impedance characteristic from the same side since the width of the impedance characteristic is usually set to coincide with a point where the power angle is 120 degrees. Nevertheless, the pole-slip protection relay responded correctly to a stable power swing impedance trajectory that enters and exits the impedance characteristic from the same side.

It is possible for the pole-slip protection relay to issue a trip for a pole slip when the power angle (δ) is more than 120 degrees if the impedance trajectory exits the pole-slip impedance characteristic through the top or bottom. If the pole-slip impedance trajectory exits the pole-slip impedance characteristic through the left or right side of the impedance characteristic, the trip will always be issued when δ is less than 120 degrees. It was shown earlier in 6.5 that it is acceptable to trip the Kendal generator breaker for a pole slip even when δ is more than 120 degrees, but this may not be the case at other sites. Therefore, protection engineers should be aware of this relay nuance and should always confirm if it is acceptable to trip the breaker when δ is more than 120 degrees.

The only time that the relay operated incorrectly was when the measured impedance trajectory of a three-phase fault lingers along the inside and outside

edge of the pole-slip impedance characteristic before exiting the pole-slip impedance characteristic. The relay was set to trip after three slip cycles for a zone 2 pole-slip crossing; therefore a pole-slip trip wasn't issued by the relay when the measured three-phase fault impedance lingers along the inside and outside top edge of the zone 2 impedance characteristic, but the zone 2 pole-slip counter was incorrectly incremented. If the relay was set to trip after a single slip cycle in zone 2, the generator could be tripped incorrectly for a three-phase fault, which is located within the transmission system. If a similar three-phase fault were to occur on the inside border of the zone 1 pole-slip impedance characteristic, the relay could issue an incorrect trip since the zone 1 characteristic is set to trip after a single slip cycle.

CHAPTER 8: CONCLUSION

8.1 Conclusion

The power system analysed in this dissertation was heavily interconnected and the worst case critical fault clearing time for a close-up three-phase fault just outside Kendal power station was relatively long (150ms), which implied that the probability of a generator pole slip was rather unlikely. The protection schemes installed on the transmission network are extremely reliable, because they have dual main systems and the protection will generally clear most faults in less than 100ms.

If an unlikely generator pole slip were to occur when the system is operating in a normal configuration (all power station outgoing feeders in service), the pole-slip system electrical centre is usually located within the generator or the generator transformer because the system equivalent impedance is a lot less than the combined impedance of the generator and generator transformer. The generator pole-slip protection is able to detect and disconnect the generator after a single pole-slip cycle when the system electrical centre is located within the generator or generator transformer.

The critical fault clearing time decreases when one of the outgoing feeders at Kendal power station is out of service (n-1 contingency) and therefore the probability of a generator pole slip increases.

If a generator pole slip occurs when operating the network under an n-1 contingency, the pole-slip system electrical centre is usually located within the transmission network. The generator-pole-slip protection settings that are currently implemented at Kendal power station do not reach into the transmission network. Therefore, if a pole slip were to occur under an n-1 contingency, the generator-pole-slip protection would not be able to detect this condition. The generator-pole-slip protection should rather reach into the transmission network, but the trip should only be issued after the third or fourth

pole-slip cycle to allow the transmission line out-of-step protection sufficient time to separate the network into islands. Therefore, the generator-pole-slip protection would serve as backup protection to the transmission line out-of-step protection.

The generators would be subjected to less stress and potential damage if the generator-pole-slip protection were to issue a trip after the first pole-slip cycle for an out-of-step condition, which has a system electrical centre located in the transmission network, but this would probably result in a system blackout since most of the generation would be lost.

The pole-slip function of the Siemens 7UM622 relay model within DigSilent PowerFactory operated in accordance with the Siemens relay technical manual. The relay model tripped correctly for various pole-slip impedance trajectories that were located in zone 1 and zone 2 of the pole-slip impedance characteristic. The pole-slip counter was able to count the number of pole-slip crossings and it issued a correct trip after the set number of pole-slip crossings. Various stable power swings were simulated, the relay model was able to identify them as stable power swings and therefore never issued an incorrect trip. The pole-slip function of the Siemens 7UM622 relay model can be used in future to optimise and test generator-pole-slip protection settings.

In the majority of cases, the Siemens 7UM622 relay hardware device operated in accordance with the Siemens relay technical manual. A number of stable and unstable power swing COMTRADE recordings were played back to the pole-slip protection relay. The pole-slip protection relay was always able to detect an unstable power swing, which traversed through the zone 1 and zone 2 pole-slip impedance characteristic. The zone 1 and zone 2 pole-slip counters were correctly incremented whenever an unstable power swing impedance trajectory traversed through the pole-slip impedance characteristic and the relay issued a trip after the correct number of set pole-slip cycles. The only time that the relay operated incorrectly was, when the measured impedance trajectory of a three-phase fault lingers on the inside and outside edge of the pole-slip impedance characteristic before exiting the pole-slip impedance characteristic.

The stable and unstable power swing COMTRADE files that were generated for the tests performed in this dissertation can be used in future to test the generator-pole-slip protection at Kendal power station. The COMTRADE files can be played back to the pole-slip protection relays to determine if they operate correctly for stable and unstable power swings since it is rather difficult to test the pole-slip protection function properly without a COMTRADE file.

8.2 Future Work

The South African Integrated Resource Plan 2010 – 2030 [38] indicates that 10.31 GW of additional generating capacity should be added to the South African power system in the form of co-generation (1.64 GW), open cycle gas turbines (6.77GW), and closed cycle gas turbines (1.9 GW). Typically, the generators used for these applications would be relatively small and would be coupled to the sub-transmission network (less than 132 kV). The protection schemes installed on the sub-transmission network in South Africa consist of a single main system so they are not as reliable as the transmission protection schemes. Many of the sub-transmission feeder protection schemes do not make use of communication assisted tripping, which results in slower feeder protection tripping times. Generally, the fault clearing time for a sub-transmission network is slower than the fault clearing time of a transmission network. Therefore, when a generator is coupled to the sub-transmission network, the probability of a generator pole slip is relatively high. If the pole-slip system electrical centre is located within the sub-transmission network, the sub-transmission line protection would not be able to separate the system, because no out-of-step protection is installed on the sub-transmission network. Therefore, the generator-pole-slip protection must be able to detect and isolate the generator for this condition. Sub-transmission protection engineers will be faced with significant challenges when new embedded generation is connected to the South African sub-transmission network. Time domain simulations should be performed to ensure that the sub-transmission network as well as the embedded generators are adequately protected against an out-of-step condition.

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APPENDIX A: XRIO file for the pole-slip protection reach settings.

BEGIN TESTOBJECT

BEGIN DISTANCE

ACTIVE YES

LINEANGLE 86.62

PTCONN LINE

CTSTARPOINT LINE

ARCRES NO

IMPPRIM NO

IMPCORR NO

TTOLPLUS 0.01

TTOLMINUS 0.01

TTOLREL 1

ZTOLREL 5

ZTOLABS 0.05

KL 1, 0

KM 0, 0

LINELENGTH 1

BEGIN ZONE

INDEX 1

TYPE TRIPPING

FAULTLOOP LL

LABEL "OOS Z1"

TRIPTIME 0.03

ACTIVE YES

ZTOLABS 0.482900999455381

BEGIN SHAPE

LINE 0, 8.27, 0, RIGHT

LINE 4.5, 0, -93.38, RIGHT

LINE 0, -17.88, 0, RIGHT

LINE -4.5, 0, 86.62, RIGHT

AUTOCLOSE YES

INVERT NO

END SHAPE

END ZONE

BEGIN ZONE

INDEX 2

TYPE TRIPPING

FAULTLOOP LL

LABEL "OOS Z2"

TRIPTIME 0.03

ACTIVE YES

ZTOLABS 0.71559206256078611

BEGIN SHAPE

LINE 0, 11.92, 0, RIGHT

LINE 4.5, 0, -93.38, RIGHT

LINE 0, 8.27, 0, RIGHT

LINE -4.5, 0, 86.62, RIGHT

AUTOCLOSE YES

INVERT NO

END SHAPE

END ZONE

END DISTANCE

END TESTOBJECT