A NEW METHOD OF UTILISING STABILITY STUDY RESULTS IN APPLYING OUT-OF-STEP PROTECTION TO ALLOW OBSERVABILITY OF ROTOR ANGLE UNSTABLE CONDITIONS

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Abstract

Power system rotor-angle unstable conditions may cause undesired operation of distance relays, resulting in the unnecessary switching of lines. To prevent the possible undesired operation of distance relays, a protection type known as out-of-step blocking is used. This protection type is complemented by another type of protection, known as out-of-step tripping protection. The tripping protection's main functions are to detect total loss of synchronism and send tripping signals to selected locations in the system to initiate islanding.

In this research the application of out-of-step blocking and tripping protection was investigated. The motivation for the research was provided by system unstable incidents that occurred in Eskom, the electricity utility of South Africa. Detailed out-of-step protection investigations indicated that the out-of-step blocking and tripping protection applied according to a method which is based on an existing approach failed to detect the unstable conditions. In summary, the detailed investigations showed that the existing approach of applying out-of-step blocking and tripping protection is not adequate as it does not allow the necessary observability[1] and correct detection of rotor-angle unstable conditions.

The existing approach seems to involve the following according to literature:

1. the approach is based on the behaviour of the electrical quantities (voltage, current, rotor angle, etc.) of an equivalent two machine power system to determine suitable locations for out-of-step blocking and tripping relays;
2. equivalent impedances representing system impedance are used to calculate the forward and reverse reach settings for the out-of-step protection relays; and

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[1] The use of the term observability are in the context of local "observation" i.e. the trajectory of an impedance locus as 'seen' by an impedance type relay. It does not refer to "observability and controllability" of power system states.

3. a maximum swing frequency, determined from stability studies, is used to calculate the relay timer settings.

The existing approach was tested and investigated by means of a case study in which out-of-step protection was applied to an actual power system. In summary the results indicate that too many assumptions are made in the existing approach and that there is a need to either improve the existing approach or to identify and develop a new approach for applying out-of-step protection. Therefore, from limitations and shortcomings identified in the investigation of the existing approach, a new approach, based on the study of the impedance locus at all locations, was developed. In summary the new approach entails:

1. mathematical modelling of the power system (the actual power system); and
2. studying the impedance locus behaviour at all relay locations to determine locations and settings for out-of-step protection relays.

The new approach was tested and investigated by means of a case study in which out-of-step protection was applied to an actual power system. An investigation of the case study results indicated a significant improvement in the performance of the out-of-step protection during unstable conditions.

As additional support for the new approach, a real case application of out-of-step tripping protection to the Eskom system was presented in Chapter 5. This real case is an Eskom investigation (led by the author) which took place in 1996 and 1997. Eskom investigated the use of out-of-step tripping protection and in 1997 out-of-step tripping protection was applied to the Eskom transmission system, using the new approach and methods of calculating reach and timer settings developed in the research.

It should be noted that both the existing approach and the new approach are techniques for linking relay settings to the results of power system stability studies. A technique could never include the full range of events which may occur in a power system that could lead to system instability. The main reason for this is that a power system model, and not the actual power system, is studied. It is therefore always possible that the experts performing the stability investigations may not identify an incident that could lead to instability on the actual power system. A margin of insecurity will therefore always exist i.e. for that percentage of system unstable cases which may not have been covered during the stability study investigation and therefore not covered in the selection of stability studies used, nonoperation of the protection could still occur. It is therefore important to include as many stability studies as possible in the stability investigation.

In addition to the above, the use of too many stability studies may prove to be unnecessarily time consuming as some studies may be similar with regards to system conditions and contingencies. For this reason, a technique aims to use results from a selection of stability studies which represent a wide variety of incidents that could occur.

It should further be noted that in stability study investigations done for the purpose of applying out-of-step protection, the studies could be more severe (e.g. n-2 or even n-3 contingencies) than the studies used for power system planning purposes. The reason for this is that these severe studies will provide protection settings for which the protection will be effective even beyond the planning criteria.

The range of stability studies in the stability investigation and the choice of the selection of stability studies to represent a wide variety of incidents, were not covered in this thesis as this forms part of the specialised stability investigation. The use of individual stability study results for the purpose of applying out-of-step protection was the subject of the thesis (refer to section 1.1 in Chapter 1, Scope of Research).

A specific technique of linking the individual stability study results with the relay settings could either improve or weaken the reliability of the protection to perform correctly during an unstable incident. The research has indicated that the technique used in the existing approach weakens the reliability of the protection to perform correctly during an unstable incident while the technique used in the new approach improves the reliability of the protection to perform correctly during an unstable incident.

In summary the conclusions drawn from the research are the following:

1. the assumptions made in the existing approach over-simplifies the procedure of applying out-of-step protection;

2. there is a need to either improve the existing approach or identify a new and better approach for applying out-of-step protection;

3. applying out-of-step protection according to the new approach, shows an improvement of protection performance during unstable conditions;

4. even though the new approach was only tested on the Eskom system, the new approach could be acceptable for any complex power system characterised by stability related constraints i.e. long transmission lines connecting generator power stations and supplying power over long distances to load demand areas; and

5. the new approach increases the reliability of out-of-step protection and thus increases confidence in the correct performance and application thereof.

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Abbreviations and Terminology used in this thesis

Abbreviations

1. SS	=	Substation
2. PS	=	Power station
3. SVC	=	Static var compensator
4. ROW	=	Relay operating window

Terminology

1. Out-of-step protection	Out-of-step blocking and tripping protection.
2. Out-of-step blocking protection	Protection used to block undesirable operation of distance relays during rotor-angle unstable conditions.
3. Out-of-step tripping protection	Protection used to detect rotor-angle unstable conditions and initiate tripping at selected locations for the purpose of islanding.
4. Islanding	System separation between stable and unstable generators within a power system during unstable conditions.
5. Power swings	Power oscillations within a power system initiated by disturbances within that system.
6. Out-of-step condition	Loss of synchronism; also system instability.
7. Power system rotor angle unstable conditions	Power swings or out-of-step conditions within a power system, initiated by the response of generator rotor angles.

8. Apparent impedance	Impedance 'calculated' by protection relays measuring voltages and currents from voltage and current transformers respectively, the impedance 'seen' by an impedance type relay.
9. Operating zone	An area defined by a protection characteristic, plotted on an R/X diagram, which initiates protection action when apparent impedance enters the zone.
10. Zone timer	The timer that is started when apparent impedance enters the particular operating zone.
11. Relay Operating Window (ROW)[1]	An area, defined by boundaries, which is drawn in an impedance plane. This area is used to study the impedance locus behaviour at all locations for the purpose of applying out-of-step protection according to the new approach developed in the research.
12. Observability	The use of the term observability are in the context of local "observation" i.e the trajectory of an impedance locus as 'seen' by an impedance type relay. It does not refer to "observabiltiy and controllability" of power system states.

[1] Developed in research

CONTENTS

CHAPTER 1

INTRODUCTION

Power system rotor-angle unstable conditions may cause undesired operation of distance relays, resulting in the unnecessary switching of lines [1-4, 9]. To prevent the possible undesired operation of distance relays, a protection type known as out-of-step blocking[1] is used. The main purpose of the out-of-step blocking protection is to detect unstable conditions (power swings or total loss of synchronism). Upon detection a blocking signal is sent to the distance relay supervised by the out-of-step blocking relay in order to prevent (block) its operation.

This is complemented by another type of protection, known as out-of-step tripping protection[2]. Its main functions are to detect total loss of synchronism and send tripping signals to selected locations in the system to initiate islanding (opening breakers to separate unstable areas in the system).

In this research the application of out-of-step blocking and tripping protection was investigated. The motivation for the research was provided by a system unstable incident that occurred in Eskom (the electricity utility of South Africa)[3] in November 1990. The loss of 400 kV and 765 kV lines to the Cape system load centre weakened transmission line connections between the large northern generation pool and the weaker generation pool in the south. As a consequence the generation in the south started oscillating in relation to the generation in the north. This caused undesired operation of distance relays, resulting in the switching of lines and a complete blackout of the northern, western and southern

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[1] Other names for this type of protection also exist, e.g. power swing blocking [5-14]. The function is, however, the same.
[2] Other names for this type of protection also exist, e.g. power swing tripping [5-14]. The function is, however, the same.
[3] Appendix A provides a brief description of the Eskom network and Eskom's Cape system.

Cape system load centres for almost two hours (total load of approximately 2400 MW at that time) [36].

Additional motivation for this research came in the form of two subsequent incidents related to system stability in the Eskom power system. In December 1995 a single-phase busbar fault at a 400 kV substation located on the main supply route to the western Cape system load centre was cleared by remote line protection after 0,5 seconds. The result was the loss of a substation and severe weakening of the system, causing system instability and a consequent blackout [35].

The third incident occurred in June 1996 when a single-phase busbar fault at a 400 kV substation located on the main supply route to the Cape system load centres was cleared by the busbar protection, resulting in the loss of 400 kV transmission lines. Approximately 30 minutes later another fault occurred at a 765 kV substation also located on the main supply route. Correct protection operation resulted in the loss of the 765 kV transmission lines. With 400 kV lines already out of service, the main supply to the Cape system load centres was weakened even further, creating a power transfer problem and ultimately a loss of synchronism [37].

Detailed out-of-step protection investigations indicated that the out-of-step blocking and tripping protection applied according to a method which is based on an existing approach[4] failed to detect the unstable conditions. The investigations indicated problems with regard to the following [38,39]:

- Locations of out-of-step tripping protection;
- Out-of-step tripping-relay forward and reverse reach settings;
- Out-of-step blocking and tripping protection timer settings; and
- Characteristic types used for the purposes of out-of-step blocking and tripping protection.

In summary, the detail investigations showed that the existing approach of applying out-of-step blocking and tripping protection is not adequate as it does not allow the necessary observability[5] and correct detection of rotor-angle unstable conditions [38,39].

In the research the existing approach of applying out-of-step protection was investigated. From limitations and shortcomings identified in the investigation, a

[4] The existing approach refers to the general approach of applying impedance type out-of-step blocking and tripping protection. According to [1, 5, 11-14, 20, 23, 24, 40-44, 49] the approach involves the following:

1. the existing approach of applying out-of-step protection is based on the behaviour of the electrical quantities (voltage, current, rotor angle, etc.) of a two machine power system. The reason for this is that a real power system that has generators or generator groups which could become unstable with one another, can be represented by a two machine equivalent model. The assumption is therefore made that when the real power system becomes unstable, the behaviour of the electrical quantities in the real power system will be similar to the behaviour of the electrical quantities in a two machine system;
2. the tripping relay locations are selected based on the location of an electrical centre (also known as the voltage zero), determined from stability studies [13, 14, 23, 40, 41, 47];
3. in many cases out-of-step blocking protection is located at all the locations where distance relays are located [42, 43, 47];
4. a source impedance, or equivalent impedance representing system impedance in front of and behind a location are used to calculate the forward and reverse reach settings respectively for a relay located at that location [13, 40, 44, 47]; and
5. a maximum swing frequency, determined from stability studies, are used to calculate relay timer settings [1, 12-14, 20, 40-43, 47].

[5] The use of the term observability are in the context of local "observation" i.e. the trajectory of an impedance locus as 'seen' by an impedance type relay. It does not refer to "observability and controllability" of power system states.

new approach, based on the studying of the impedance locus at all locations, was developed. In summary the new approach entails:

1. mathematical modelling of the power system (the actual power system); and
2. studying the impedance locus behaviour at all relay locations.

Direct results regarding the behaviour of the electrical quantities of the power system is available when modeling the actual power system. There is therefore no need to make use of a two machine system approach to interpret system stability results.

Studying the impedance locus behaviour at all relay locations eliminates the need to use equivalent impedances and swing frequencies to estimate required reach and timer settings respectively. The reason for this is that the impedance locus behaviour is a direct indication of what distance and out-of-step protection relays will 'see' during system unstable conditions.

It should be noted that both the existing approach and the new approach are techniques for linking relay settings to the results of power system stability studies. A technique could never include the full range of events which may occur in a power system that could lead to system instability. The main reason for this is that a power system model, and not the actual power system, is studied. It is therefore always possible that the experts performing the stability investigations may miss an incident that could lead to instability on the actual power system. A margin of insecurity will therefore always exist i.e. for that percentage of system unstable cases which may not have been covered during the stability study investigation and therefore not covered in the selection of stability studies used, non-operation of the protection could still occur. It is therefore important to include as many stability studies as possible in the stability investigation.

The use of too many stability studies will be unnecessarily time consuming as some studies may be similar with regards to system conditions and contingencies.

For this reason, a technique aims to use results from a selection of stability studies which represent a wide variety of incidents that could occur.

It should further be noted that in stability study investigations done for the purpose of applying out-of-step protection, the studies could be more severe (e.g. n-2 or even n-3 contingencies) than the studies used for power system planning purposes. The reason for this is that these severe studies will provide protection settings for which the protection will be effective even beyond the planning criteria.

The range of stability studies in the stability investigation and the choice of the selection of stability studies to represent a wide variety of incidents, were not covered in this thesis as this forms part of the specialised stability investigation. The use of individual stability study results for the purpose of applying out-of-step protection was the subject of the thesis (refer to section 1.1 in Chapter 1, Scope of Research).

A specific technique of linking the individual stability study results with the relay settings could either improve or weaken the reliability of the protection to perform correctly during an unstable incident. The research has indicated that the technique used in the existing approach weakens the reliability of the protection to perform correctly during an unstable incident while the technique used in the new approach improves the reliability of the protection to perform correctly during an unstable incident.

1.1 Scope of research

When the application of out-of-step protection becomes a consideration in a utility, the procedure is as follows [9, 11-14, 20, 23, 33, 34, 40, 41]:

1.	System stability analyses through the simulation of a wide verity of incidents in respect of the system where out-of-step protection is to be applied.

2.	*The application of out-of-step blocking and tripping protection.*	3.	An investigation to determine the locations where system separation should take place for the purpose of islanding.	4.	An investigation to establish restoration procedures following islanding.

Blocks 1, 2, 3 and 4 refer to specialised investigations. System stability and restoration were not addressed in this research. Block 2 therefore represents the topic of the research presented in this thesis.

It may be worthwhile to add that for the stability investigation in block 1, an unlimited amount i.e. any amount of stability studies are done to determine all possible system unstable scenarios. The stability studies done in block 1 are then used in the investigations shown in blocks 2, 3 and 4. However, because the number of stability studies could be large, the investigations in blocks 2, 3 and 4 may become unnecessarily time consuming as some of the stability studies may be similar with regards to system conditions and contingencies. It therefore may become im-practical to perform all the possible stability studies identified in block 1 when doing the investigations in blocks 2, 3 and 4. To eliminate the use of too many stability studies, the expert(s) performing the investigation in block 1 could choose a selection or number of stability studies that will be representative of the complete range of stability studies done. The selection or number of stability studies could be different for different investigations and utilities. This number of stability studies chosen by the expert(s) are then used for the investigations in blocks 2, 3 and 4. The choice of stability studies as well the number of stability studies were not addressed in this thesis because, as mentioned above, block 2 represents the topic of this thesis.

1.2 Methodology

To investigate the existing approach, out-of-step protection was applied to an actual power system. To record the performance of the out-of-step protection during unstable conditions, mathematical models, representing the behaviour of the protection, was included in the power system model. A stability study was done to evaluate and investigate the protection performance results.

To test the new approach, out-of-step protection was applied to the same power system according to the new approach. As for investigating the existing approach, the performance of the out-of-step protection during unstable conditions were recorded by including mathematical models, representing the behaviour of the protection, in the power system model. To evaluate and investigate the protection performance results the same stability study referred to in the previous paragraph was done.

The stability study done to provide necessary results for applying out-of-step protection as well as enable the evaluation and investigation of the protection performance, is a stability study which is based on the actual incident that occurred within the Eskom power system in June 1996.

It should be noted that for the purpose of illustration within the thesis, only one stability study was done. The new approach was, however, also used by Eskom when out-of-step tripping protection relays within the Eskom transmission system had to be relocated and set at their new locations (This investigation was done by

Eskom in 1996 and 1997). This real case example of using the new approach uses a number of stability studies, and is presented in Chapter 5.

1.3 Assumptions

1. The exact load composition of the total Eskom load demand is not known. Simulations of the second and third of the aforementioned three incidents did, however, indicate that the behaviour of the load composition in the Cape system is closest to a constant impedance load type behaviour [35, 37]. During the simulations the remaining load in the Eskom system was represented as displaying a combination of constant current and constant impedance behaviour[6]. As the load model does not play a significant role in the research, the load was modelled as follows:

   Cape system load demand:

   $P_{load}+jQ_{load}$ = 100% constant impedance load type behaviour

   Remaining load demand in the Eskom system:

   P_{load} = 100% constant current load type behaviour

   jQ_{load} = 100% constant impedance load type behaviour

1.4 Other factors affecting the basis of the research

1. The protection was applied to an actual power system (for the purposes of the research and reasons given under section 1.4 no 2, the Eskom power system was used). The reason for using an actual power system is that benchmark and equivalent systems are simplified systems and do not represent the actual behaviour of a real system that most protection and power system engineers have to contend with when applying out-of-step protection.

[6] Eskom uses the load model combination indicated in the text when doing dynamic analysis.

2. For the purposes of the research the Eskom power system was used (Appendix A provides a description of the Eskom power system). The reasons for this are the following:
   - The Eskom system is a complex power system and experiences a large variety of operating conditions and disturbances (small and large perturbations, transient and dynamic types of instability). It therefore represents an universal example of a real power system.
   - Eskom requested, motivated, supported and made available all necessary resources to enable this research.
   - Because of logistic limitations, testing of the new approach was limited to the use of the Eskom power system.

3. The mathematical representation of the real power system used for this research was provided by Eskom. Eskom uses the data for system performance investigations on a daily basis. In addition, all three stability incidents referred to in paragraphs 3, 4 and 5 of this chapter, were simulated with this data and simulation results compared well with recorded results [35-37]. It is therefore believed that the power system model used for the purposes of the research is adequately representing the real Eskom system.

4. In the research the complete Eskom power system was modeled. However, due to the size of the Eskom power system, results for a portion of the Eskom power system were presented in Appendix D (results for case study done in Chapter 3) and Appendix F (results for case study done in Chapter 4). The reason for this is that the results for the remaining system are additional information and does not add any value to the thesis contribution.

5. Because out-of-step blocking protection is applied, in practice, to supervise distance relays during power swings and out-of-step conditions, only undesired operation of distance relays was considered in this research.

6. Because out-of-step protection relays are mostly of the impedance type, i.e. operating in the impedance plane, impedance type out-of-step protection was used for the purposes of this research.

7. To investigate and test both the existing approach and the new approach, an impedance type out-of-step protection relay with a concentric circle type characteristic, not necessarily centred at the origin of the impedance plain, was used. (Appendix B explains the operating philosophy). Many characteristic types exist [1, 9, 13, 14, 30, 40, 41, 43] and to investigate and test both the existing approach and the new approach, any one of these characteristic types can be used. The concentric circle characteristic type was chosen because it is representative and uncomplicated.

8. Stability studies and power system modelling in this thesis were done by using the PTI PSS/E (Power System Simulator) software tool. The reason for this is that Eskom uses PSS/E for system analysis and the power system is therefore completely represented by PSS/E mathematical models.

9. PSS/E has a variety of mathematical models for protection that can be included in the same way mathematical models for generators and other power system equipment can be included in the program when doing system studies. The thesis selected to use the 'Double Circle Blocking or Tripping Relay' model by PSS/E as this is a mathematical model representing the concentric circle type relay used for the purposes of the research.

10. For the purposes of this research, one stability study was used. The reasons are:
    - one stability study is sufficient to investigate and identify limitations and shortcomings of the existing approach; and
    - one stability study is sufficient to demonstrate the use of the new approach and the improvement in protection performance.

In addition it is necessary to mention the following:

When applying out-of-step protection to a utility, several stability studies, representing a wide verity of incidents which may lead to system instability on the power system, are done[7]. Each stability study's results are analysed to determine locations and settings suitable for the particular stability study. This is followed by analysing the complete set of results obtained for the individual stability studies. From this analysis, the choice of final locations, settings and an out-of-step protection scheme-design are done to be suitable for all the stability studies done. The purpose of out-of-step protection scheme-design is to allow system islanding if relays at some locations did not detect due to fact that not all unstable scenarios can be covered in the selection of stability studies done[8]. The method of analysing the complete set of results (for the purpose of determining final locations, settings and an out-of-step protection scheme-design), could be different for each utility because protection coordination and application philosophies are different. Methods of analysing the complete set of results for the purpose of determining final locations, settings and a scheme-design were not addressed in this thesis. The thesis addressed the analyses of individual stability study results.

Chapter 5 presents a real case application of out-of-step protection using the new approach. In this real case application the results of a number of stability studies which represent most of the incidents that could cause instability in the Eskom system, are used to link the relay settings with the stability study results. The complete set of results are analysed and final locations and settings as well as a scheme design are chosen according to Eskom's method

[7] Ideally the full range of system contingencies that could lead to system instability should be covered when applying out-of-step protection. However, the use of too many stability studies may prove to be unnecessarily time consuming as some studies may be similar with regards to system conditions and contingencies. For this reason results from a selection of stability studies which represents the wide verity of incidents covered in the stability investigation, are used.

[8] The specialised stability investigation could never include the full range of events which may occur in a power system that could lead to system instability. The main reason for this is that a power system model, and not the actual power system, is studied. It is therefore always possible that the expert(s) performing the stability investigation may miss an incident that could lead to instability on the actual power system. A margin of insecurity will therefore always exist i.e. for that percentage of system unstable cases which may not have been covered during the stability investigation, non-operation of some protection relays could still occur.

of analysing the complete set of results as well as Eskom's protection philosophies.

1.5 Structure of the thesis

Chapter 2 discusses the performance of distance relays during unstable conditions. Out-of-step blocking and tripping protection and the considerations in applying this protection to allow observability of rotor-angle unstable conditions are also discussed.

Chapter 3 presents the existing approach as identified in literature reviews. As an example of out-of-step protection application according to the existing approach, Eskom's methods to determine locations and calculate settings, are presented. In addition Chapter 3 also includes a case study of out-of-step protection applied according to the existing approach. Protection performance results, showing limitations and shortcomings of the existing approach are also presented.

Chapter 4 presents the new approach of applying out-of-step protection which is based on studying the impedance locus behaviour at all locations. A comparison between the existing approach and the new approach is given. A case study of out-of-step protection applied according to the new approach is also included in Chapter 4, together with protection performance results. A discussion on the protection performance results is also presented.

Chapter 5 presents a real case example where out-of-step tripping protection was applied to the Eskom power system, using the new approach.

Chapter 6 provides a summary of the research, a discussion of the findings of the research and the conclusions drawn from the research.

CHAPTER 2

PROTECTION OPERATION AND BLOCKING DURING ROTOR-ANGLE UNSTABLE CONDITIONS

This chapter provides a brief introduction to the undesired operation of distance relays during rotor-angle unstable conditions (power swings and out-of-step conditions). It also discusses out-of-step blocking and tripping protection as well as the three considerations relating to the use and application of out-of-step protection.

2.1 Distance relay performance during rotor-angle unstable conditions

Due to the large fluctuations in a generator's electrical output quantities during rotor-angle unstable conditions, distance relay performance and power system stability are closely related [1-4, 8-10, 12-18, 22, 26, 27, 29].

Power system protection monitors the system's electrical and physical parameters in order to detect abnormal conditions. During rotor-angle unstable conditions, the performance of protection types that monitor voltages and currents is affected by the behaviour of these system parameters [1-4, 9].

Distance relays

Distance relays measure voltages and currents for the purpose of 'calculating' impedance. This is known as apparent impedance and is represented in an impedance plane (R-X plane). If the apparent impedance describing an abnormal condition is within an operating zone, a zone timer (if used) is started. When this timer expires, the line protected by the distance relay is isolated from the system.

A typical distance relay have more than one operating zone: an instantaneous directional zone 1 and one or more time-delayed zones [1, 15]. Figure 2.1 shows the operating characteristics for a single distance relay using zones of protection.

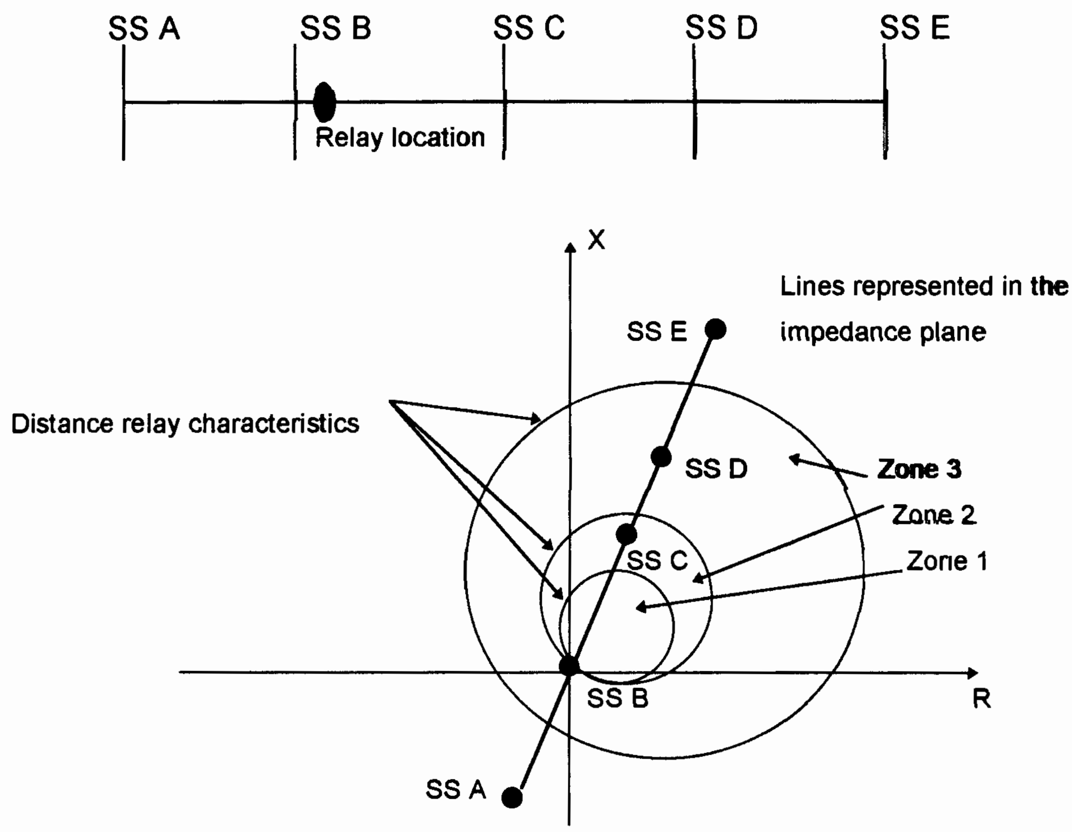

Figure 2.1: Operating characteristics for a distance relay using zones of protection

The electrical voltages and currents in a power system oscillate during power system unstable conditions [5-16]. Due to the voltage and current oscillations, impedance calculated from measured voltages and current quantities will oscillate according to the following equation [43]:

$$Z = \frac{V}{I} \qquad (2.1)$$

The impedance 'seen' by a distance relay during rotor angle unstable conditions will therefore display an oscillatory behaviour, with its magnitude increasing and decreasing. This behaviour of the impedance in the impedance plane results in undesired operation of distance relays when the impedance enters the relay characteristics [1-5, 17] and the zone timers time out. The combination of distance relays in intertripping schemes does not necessarily overcome the potential problem of an impedance relay's response to unstable conditions.

2.2 Out-of-step blocking and tripping protection

Out-of-step blocking protection

From section 2.1 it is clear that protection action is necessary to prevent undesired operation of distance relays during rotor-angle unstable conditions.

To prevent the undesired operation of distance relays during power system unstable conditions, **out-of-step blocking protection** is used. The function of the out-of-step blocking protection is to supervise a distance relay. Upon detection of a power swing or out-of-step condition it sends a blocking signal to the distance relay to prevent undesired operation when the impedance enters the distance relay characteristics.

The method of detecting power system unstable conditions is based on the fact that the change in voltages and currents during rotor-angle unstable conditions is slow compared with the fast change in these electrical parameters during short-circuit conditions. Rotor-angle unstable conditions can therefore be detected by monitoring the rate of change of the impedance 'seen' by the out-of-step blocking relay [1, 4, 9, 12, 13-15, 29, 31, 34, 40-43] (Appendix B explains the operating philosophy for the out-of-step blocking protection used for the purposes of the research).

Out-of-step tripping protection

In addition to solving the problem of undesired operation of distance relays, it is necessary to protect the system in such a way that when it is unstable (out of step), system separation of the unstable generators can take place. The separation of the unstable generator stations is also known as islanding.

To initiate islanding **out-of-step tripping protection** is used. The function of the out-of-step tripping protection is to detect out-of-step conditions; and upon detection it must send tripping signals to selected locations to initiate islanding.

The detection of the rotor angle unstable conditions is as in the case of out-of-step blocking protection.

2.3 The three considerations affecting observability and detection of rotor-angle unstable conditions

Three considerations are equally important in the application of out-of-step blocking and tripping protection to allow observability and detection of rotor-angle unstable conditions. To allow the correct application of these relays, these considerations must be taken into account. They are as follows:

- Location
- Reach settings
- Timer settings

Location

If it is possible for a power system to undergo unstable conditions, undesired operation of distance relays may occur. The choice of out-of-step blocking relay locations is therefore important because it must ensure that all such distance relays are blocked before undesired operation of the relay occurs.

When the system is subjected to out-of-step conditions, detection of those conditions should take place at all times, and as soon as possible. The correct location(s) for out-of-step tripping relay(s) are therefore equally important to ensure successful islanding as soon as the system becomes unstable.

Reach settings

Reach settings determine the size of the out-of-step protection characteristics. If these settings are not correct, the apparent impedance may never enter the operating zones and enable detection. With incorrect reach settings, it is also possible for apparent impedance to enter the relay's operating zones under system healthy conditions and wrongly initiate blocking or tripping. Undesired operation of distance relays may also occur if reach settings for out-of-step protection were not coordinated with the distance relay reach settings at the same location.

Timer settings

The zone timer settings of out-of-step relays are the settings that allow distinction between fault conditions and system unstable conditions. The timer settings are therefore the settings that allow out-of-step blocking and tripping protection to perform their respective functions. With incorrect timer settings, out-of-step blocking and tripping protection will not perform their respective functions.

2.4 Summary and conclusions

This chapter provided a brief introduction to the undesired operation of distance relays during rotor-angle unstable conditions (power swings and out-of-step conditions).

It also discussed out-of-step blocking and tripping protection as well as the three considerations relating to the use and application of out-of-step protection to allow observability of rotor-angle unstable conditions.

From this chapter, the following conclusions can be drawn:

1. Preventative action is necessary to prevent undesired operation of distance relays during rotor-angle unstable conditions.

2. To prevent the undesired operation of distance relays during power system unstable conditions, **out-of-step blocking protection** is used.

3. In addition to solving the problem of undesired operation of distance relays, it is necessary to protect the system in such a way that when it is unstable (out of step), **out-of-step tripping protection** can operate to separate the unstable generator stations.

4. Three considerations are equally important in the application of out-of-step blocking and tripping protection to allow observability of rotor-angle unstable conditions. They are as follows:

    - Location of the out-of-step relays
    - Reach settings of the out-of-step relays
    - Timer settings of the out-of-step relays

CHAPTER 3

EXISTING OUT-OF-STEP PROTECTION APPLICATION APPROACH

3.1 The existing approach

Very little literature on the topic of out-of-step protection and the application thereof to a power system exists. However, from literature that does exist and personal experience it was found that the existing approach of applying out-of-step protection consistently has three considerations to dealt with when using impedance type protection relays. These considerations are:

1. Relay locations;
2. Relay reach settings; and
3. Relay timer settings.

How these considerations are dealt with individually is now briefly presented.

1. Relay locations

Out-of-step blocking

Out-of-step blocking is nearly always used in conjunction with distance protection [42, 43]. For this reason out-of-step blocking protection could be located at every location where distance relays are located. Each utility may however decide whether the blocking protection should be enabled at every location or only certain locations.

Out-of-step tripping

The choice of out-of-step tripping relay locations seem to be approached differently by different utilities. However, one common approach is to use the location of an area known as the electrical centre of the system, as an indication of the most suitable relay location(s). What the electrical centre is and how to find it, as defined and understood according to literature, is explained below.

Reference [23] states that out-of-step tripping relays located closest to the electrical centre tend to operate whereas those located further away from the electrical centre tend to not operate. Out-of-step tripping relays are therefore located within the electrical centre area.

Reference [41] supports the statement made in reference [23] by stating that the location of the electrical centre determines the location of measurement i.e. the location of out-of-step tripping relays.

In both references [40] and [41] as well as in reference [14] it is stated that in cases, if the electrical centre is within the transmission system, some utilities prefer to not make use out-of-step tripping relays, but choose to call upon distance relays (the undesired operation of distance relays) to trip lines in order to separate unstable generators at the location where the electrical centre is located for the specific out-of-step condition. If, however, the electrical centre is within the generator or step-up transformer, an out-of-step tripping relay is located at the generator terminals.

Another approach to determine the location of out-of-step tripping relays is given in references [14] and [13]. The approach entails determining the ideal location for system separation during instability. The location chosen is such that it ensures a generation load balance within the islands formed as well as allows a fast and easy system restoration. Relays are then located at these locations and relied upon to detect an out-of-step condition to trip local breakers.

In general it seems as if the electrical centre location is dominant when deciding on the location of out-of-step tripping relays.

The electrical centre

The electrical centre (also referred to as the voltage zero [20]) of a system is represented by the location where the voltage in the system decreases closest to zero during a power swing or an out-of-step condition [13, 14]. This definition is based on the assumption that a real power system that undergoes power swings and out-of-step conditions can be represented by a two-machine model [13, 14]. This assumption implies that during system unstable conditions there are moments when the angle difference between the phasors representing the voltage behind the subtransient reactance of the generating machines will be 180° [33, 12]. In the two-machine model the 180° separation occurs at a location between the equivalent generating units. The electrical conditions at that stage are very similar to those of a three-phase fault condition (the voltages in all three phases are close to zero) [13, 14, 17, 33].

Another method to determine or find the electrical centre is presented in reference [41]. This method also uses a two machine equivalent model to represent a power system. From the equivalent model the source impedances and line impedances are plotted in an impedance plane to represent the system impedance, The impedance locus as seen by a relay during an unstable condition, as derived from the equivalent model, is also plotted within the impedance plane. The impedance locus is circular because it is derived from a two machine equivalent model [1, 2, 4, 13-15, 34, 40-43]. The position on the system impedance line which coincides with the impedance locus shows the location of the electrical centre within the equivalent model. The location determined is then used to approximate the electrical centre location within the real power system.

2. Relay reach settings

The reach settings of an out-of-step protection relay (blocking or tripping), coordinated with load encroachment, determines the size of the relay characteristic(s). The size of the characteristic defines an operating zone and is important to allow detection of an out-of-step condition as the apparent impedance needs to enter the operating zone [40].

Out-of-step blocking

In the case of blocking protection, reach settings for relay types using circular or blinder type characteristics, are normally chosen to be larger than the outermost distance relay characteristic reaches [1, 13, 14, 18, 33, 49]. The exact amount is chosen according to the relay type used.

Out-of-step tripping

The reach settings, as in the case of identifying locations, can be determined differently by different utilities. In reference [44] one method to determine the forward and reverse reach settings for a relay type using a circular type characteristic is given. (This method is also described under section 3.3.2b which presents the method used by Eskom.) The method entails the use of an equivalent two machine system to represent an actual power system. The impedance between the two generators within the two machine system is determined by calculating equivalent impedances for the actual power system. The forward and reverse reaches for out-of-step tripping relays are then chosen to be such that the sum of the forward and reverse reaches is equal to the equivalent system impedance between the two generators within the two machine system.

In reference [13] a similar approach is used for out-of-step tripping relays using circular type characteristics. The equivalent impedance between the two machines in the two machine system is broken down more to represent equivalent impedances between substations. The impedance line within the impedance plane, which represents the impedance between the two generators in the two machine system, is drawn to superpose the impedance locus obtained from expected rotor angle behaviour. The crossing point between the impedance locus and the impedance line indicate up to what station the forward and reverse reaches be set to.

Reference [40] provides a method to determine reach settings for out-of-step tripping relays using blinder type characteristics. An equivalent two machine system with equivalent impedance between the two generators is also used to represent the actual power system and an impedance locus is derived from expected rotor angle excursions. As the angle difference between the generators increases to the point where it is expected to represent an unstable system, a minimum resistance is recorded within the impedance plane. This minimum resistance value is used as the left and right side reach settings.

In general one can derive from the above that to determine the required reach settings for out-of-step tripping relays, equivalent system impedances are used.

3. Relay timer settings

Impedance type out-of-step protection (blocking and tripping) uses operating zone timers [1, 5, 11-14, 20, 23, 24, 40-43, 49]. Timers are used because the rate of change of the impedance as it enters the operating zones is the indication of whether the condition is a fault or an unstable condition [1, 5, 11-14, 20, 23, 24, 40-43, 49]. As the apparent impedance enters an operating zone, a zone timer is started. If the zone timer times out while the impedance is still within the operating zone, detection will take place. Depending on the type of relay, more than one operating zone can be used and for each operating zone a zone timer exists. References [1, 5, 11-14, 20, 23, 24, 40-44, 49] gives examples of out-of-step protection relays using one or more operating zones.

The timer settings are calculated from maximum swing frequencies which in turn is determined from the rotor angle oscillation results when doing stability studies. Typical swing frequencies obtained this way are in the order of 0,5 Hz to 3 Hz [14, 41, 43]. At times utility recordings have shown swing frequencies of up to 5 Hz [37].

The maximum swing frequency is used to calculate the time it takes the apparent impedance 'seen' by an out-of-step relay, to move from one point to another point on the impedance locus i.e. the rate of change of the impedance that will indicate an out-of-step condition. The swing frequency, therefore, is used to represents the rate of change of the impedance within the impedance plane at any location where out-of-step protection relays are to be located.

References [12, 34, 49] provide a formula with which the rate of change of impedance between two points on an impedance locus can be calculated. The formula is based on the assumption that the impedance loci 'seen' by out-of-step protection relays are circles or circular. This is the case when the impedance locus behaviour is derived from a two machine model which is the approach used in references [12, 34, 49]. The formula is derived in the same manner as shown under section 3.3.2c which presents the method used by Eskom to calculate the timer settings of out-of-step protection relays.

In general the approach of calculating the timer settings for out-of-step protection relays is to determine a maximum swing frequency from stability study results, which, according to the above references, represents the rate of change of the impedance as 'seen' by relays during an unstable condition. It is further assumed that the impedance loci during out-of-step conditions are circles or circular [1, 6, 7, 11-15, 40, 41, 43, 44, 49] which is true when an impedance locus is derived from a two machine system [1, 2, 4, 13-15, 34, 40-43].

3.2 Discussion of the existing approach

The approach of applying out-of-step protection to a power system, as presented under section 3.1, uses many assumptions. With regards to out-of-step blocking protection locations, it is assumed in most cases that all distance protection relays require blocking, irrespective of whether all distance relays will undergo undesired operation or not. In the identification of out-of-step tripping protection locations, an electrical centre area is determined which in itself is derived from an equivalent two machine system.

When determining the reach settings for out-of-step protection relays, the existing approach seems to be making use of an equivalent two machine system, with calculated equivalent impedances to represent the actual power system impedance.

The timer settings are calculated from a rotor angle swing frequency. Firstly it is assumed that this frequency is the same as the rate of change of the impedance 'seen' by any relay within the system. Secondly the approach seems to base its calculation of timer settings on the assumption that the impedance loci 'seen' by relays during unstable conditions are circular.

From the above a number of comments can be made regarding the reliability of the existing approach when wanting to ensure correct application of out-of-step protection:

1. A real system cannot be represented by an equivalent two machine system. Even though it may be sufficient to use when analysing or illustrating other aspects of electrical engineering, it is not suitable when dealing with the application of out-of-step protection. The reason for this is that results obtained from an equivalent two machine system gives results that are not representative of real case scenarios. One example is the general belief that the impedance loci 'seen' by relays during unstable conditions are circles or are circular in appearance.

2. The use of equivalent impedances between nodes of the actual power system, is another aspect of the existing approach that creates questions regarding its reliability. The reason for this is that the use of equivalent impedances ignores the influence of parallel lines, static and dynamic compensation element such as SVC, shunt capacitor and reactor banks and series capacitor banks, and other aspects determining the configuration and dynamic behaviour of a power system.

3. The use of a rotor angle swing frequency to determine the rate of change of the impedance for which an out-of-step protection relay should detect, does not take into account the dynamic behaviour of the system between the generator and the relay location. It is assumed that the frequency of the rotor angle oscillations during instability causes apparent impedance oscillations with the same frequency everywhere within the power system.

4. In addition to the above it appears as if the existing approach assumes that the rate of change of the apparent impedance 'seen' by a relay, is constant. The research found that this is not true. Results indicating these findings can be found in Appendix D, page D-iv and page D-xv. No literature discussing or

mentioning this aspect of the apparent impedance 'seen' by a relay during unstable conditions have been found.

5. The need for blocking protection at all the locations where distance relays are located, creates questions regarding unnecessary expenditure and the increase in risk of incorrect out-of-step blocking protection performance i.e. protection failure or undesired operation. Out-of-step blocking protection, if located at all the locations where distance relays are located, are overcautious as not all locations may require blocking protection. This limitation has been recognised in reference [20] and blocking in these instances are located only where undesired operation of distance relays could occur.

6. The electrical centre could be located at different locations for different unstable conditions. During a single unstable incident it is also possible for an electrical centre to move from one location to another. Locating out-of-step tripping relays within the electrical centre area may, therefore, not detect when called upon. This behaviour of the electrical centre has been recognised in reference [12]. In this reference it is acknowledged that locating out-of-step tripping relays in the electrical centre area will not always ensure correct detection and more detail investigations of the impedance locus in the electrical centre area were studied to obtain optimal locations.

7. The impedance 'seen' at the electrical centre is not always such that the relay will observe the unstable condition. The main reason being that the impedances 'seen' by relays during unstable conditions are not circular or behaving in the manner derived from a two machine model. Due to the dynamic behaviour of a power system, the impedance locus behaves erratically when subjected to unstable conditions. For example, in the existing approach it is said that when the generator is slipping a pole (i.e. instability)

the relay located at the electrical centre will observe an impedance locus in the impedance plane, moving from left to right (or vice versa), crossing the X-axis. The research results, however, indicate that cases may exist where the impedance loci does not behave in this way even though pole slipping is taking place. (As an example refer to the out-of-step tripping protection results in Appendix D, page D-xiv to page D-xviii.)

8. It was found in this research that equivalent impedances used to determine reach settings produce characteristic sizes that are insufficient to allow observability of unstable conditions. Specific results in the research indicated that the use of equivalent impedances produced characteristics that are too small. In these cases the impedance locus never entered the operating characteristic zones to allow detection. As an example refer to the out-of-step blocking protection performance results in Appendix D, page D-vii. Insufficient characteristic reaches determined in this manner have been identified by others [20]. In these cases more accurate analyses were made based on the use of the impedance loci behaviour at the location where the out-of-step protection was to be located.

The research has identified a number of limitations introduced when using the existing approach presented above. These are:

1. During system instability, the electrical quantities of an actual system does not necessarily behave similar to the behaviour of the electrical quantities in a two machine system;

2. The use of equivalent impedances ignores dynamic influences within the real system that affects system impedance, thereby providing inaccurate forward and reverse reach requirements;

3. The assumption that rotor angle swing frequencies represent rate of change of impedance for which out-of-step protection must detect ignores the dynamic influences within the power system which affects the voltage and current measured by the relay at the relay location;

4. The assumption that all distance relays should be equipped with out-of-step blocking protection is overcautious i.e. not all distance relays require blocking; and

5. The use of an electrical centre area to identify locations for out-of-step tripping relays could result in the non-detection of the tripping relays as the location of the electrical centre changes continuously.

In summary it is believed that too many assumptions are made in the existing approach even though this approach may have its advantages. The advantages of the existing approach could be the following:

1. It is straight forward and not time consuming;
2. The application of out-of-step protection is made simple when using this approach;
3. Protection application engineers, not completely familiar with system dynamics, could easily understand the need for out-of-step protection and the principles when applying it to a power system;
4. Powerful tools such as computers and computer software are not needed in order to follow the existing approach; and
5. From points 1 to 4 one could go so far as to say that it is cost effective.

However, the existing approach seems to over simplify the procedure of applying out-of-step protection to a power system. When considering the effect of incorrect performance of this protection (non detection) when a power system becomes unstable should be proof enough that the application of the protection should not be made that simple. In addition one can add the number of incorrect performances of out-of-step protection relays (instability not detected) as further support that the existing approach may not be the best approach. With fast, powerful computers and new advanced computer software available for power system analysis, more detailed analyses are possible which is also less time consuming than in the past.

In conclusion it seems that there is a need to either improve the existing approach or to identify and develop a new approach for applying out-of-step protection.

3.3 Case study: Determining and testing the reliability of the existing approach using Eskom's application methods

To determine and test the reliability of the existing approach the following were done:

1. Out-of-step protection[1] was applied to the Eskom power system according to the existing approach. The methods of determining locations and calculating settings are Eskom's methods which are presented under section 3.3.2. Eskom's methods are based on the existing approach and are sufficient to illustrate the application of out-of-step protection according to the existing approach.
2. The protection performance was recorded by including protection models, representing the behaviour of the protection relays at their locations, in the power system model.

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[1] For the purposes of the research, out-of-step blocking and tripping protection using concentric type characteristics were used. The operating philosophy for the relay types is presented in Appendix B.

3. To evaluate and investigate the protection performance, a stability study was done (stability study presented under section 3.3.1).

Due to the number of calculations involved in the application of the protection, all the calculations and examples are contained in Appendix C.

The stability study done to provide the necessary results for applying out-of-step protection is the stability study presented under section 3.3.1. The same stability study was also done to evaluate and investigate the protection performance results. The stability study is a simulation which is based on an actual incident within Eskom that occurred in June 1996. As mentioned in Chapter 1 under section 1.4, only one stability study was used because it is sufficient to illustrate the application approach and its significant limitations and shortcomings. In addition the stability study represents a severe contingency which caused instability in an actual system and could cause system instability in any power system.

A summary of the protection performance results are presented under section 3.3.3. Appendix D provides details of the protection performance results.

3.3.1. The stability study used in the case study

The stability study is based on the actual incident that occurred within the Eskom system on the 7th June 1996. An Eskom report discussing this event is given in reference [37].

The stability study done involves (refer to Figure 3.1a):

- a three-phase permanent busbar fault at Grootvlei Substation, cleared by busbar protection within 100 ms (breaker operating time);

- a second permanent busbar fault at Alpha Substation, also cleared by busbar protection within 100 ms (breaker operating time);
- the availability of only ±1 100 MW of generation in the Cape system (one Koeberg generator with a capacity of 900 MW and one Palmiet generator with a capacity of 200 MW); whereas the total load demand in the Cape system was ±2 000 MW. For voltage control in the Cape system the first of the two units (each with capacity of 200 MW) at Palmiet is in SCO (synchronous condenser) mode.

The clearance of the first fault, at Grootvlei Substation, involves the switching of all the 400 kV lines out of Grootvlei, leaving only the one 400 kV line from Matla Power Station and the 765 kV supply from Tutuka Power Station to supply the load demand in the Cape system.

The clearance of the second fault, at Alpha Substation, involves the switching of both the 400/765 kV transformers at Alpha, leaving only the one 400 kV line from Matla Power Station to supply the total load demand in the Cape system (approximately 2000 MW) .

The above fault clearance weakens the system severely and, as a consequence, severe power swings, followed by an out-of-step condition, occurs after the clearance of the second fault at Alpha Substation. Figure 3.1a is a representation of Eskom's main supply to the Cape system. The locations of the two faults, as well as the lines that were switched due to correct protection operation, are indicated in Figure 3.1a.

Figures 3.1b and 3.1c show the behaviour of the rotor angle and the electrical power output behaviour respectively, as produced by the faults and their clearance.

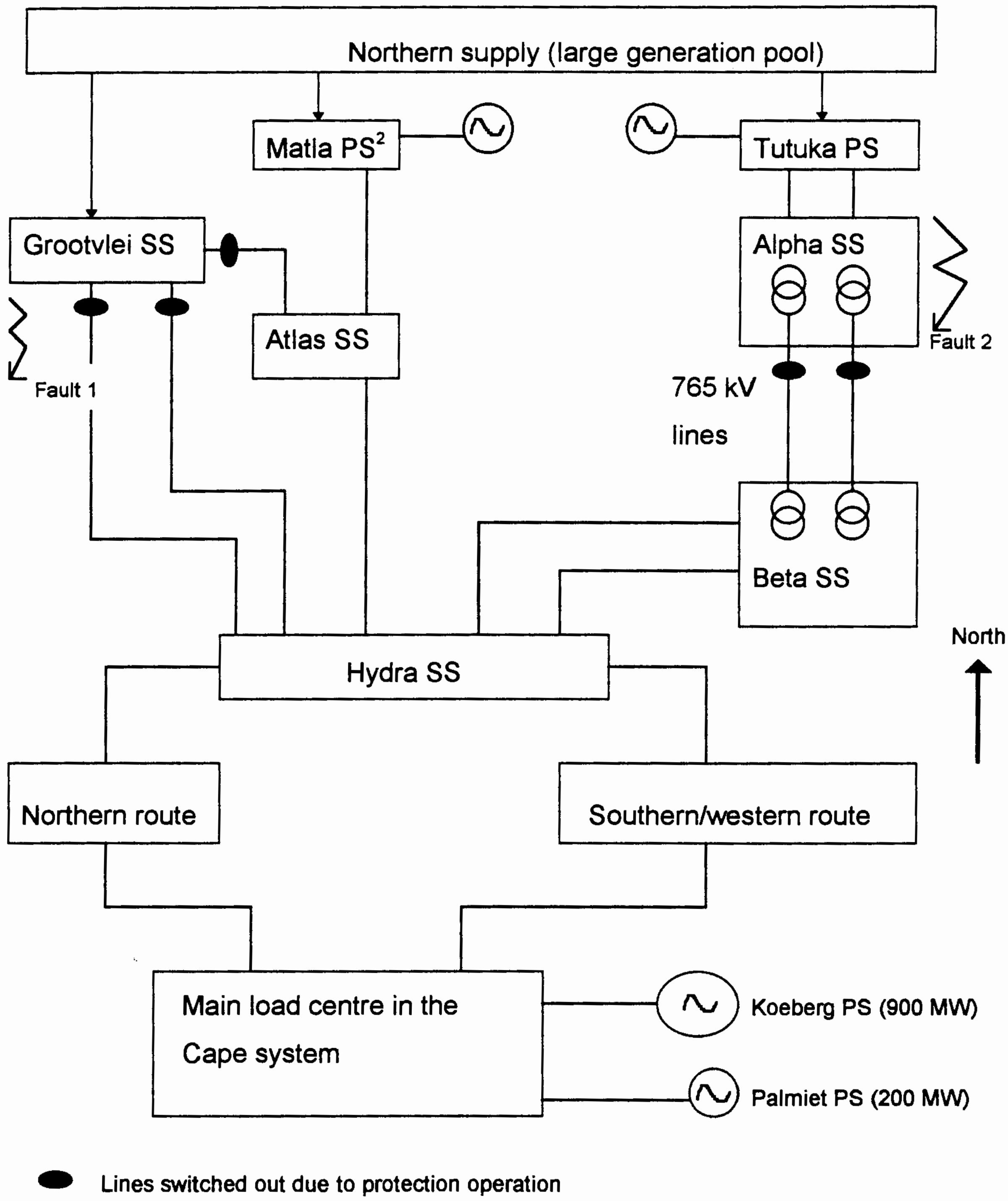

Figure 3.1a: A simplified representation of the Eskom transmission system with large generation in the north and smaller generation in the south.

[2] Matla Power Station is the swing bus in this study.

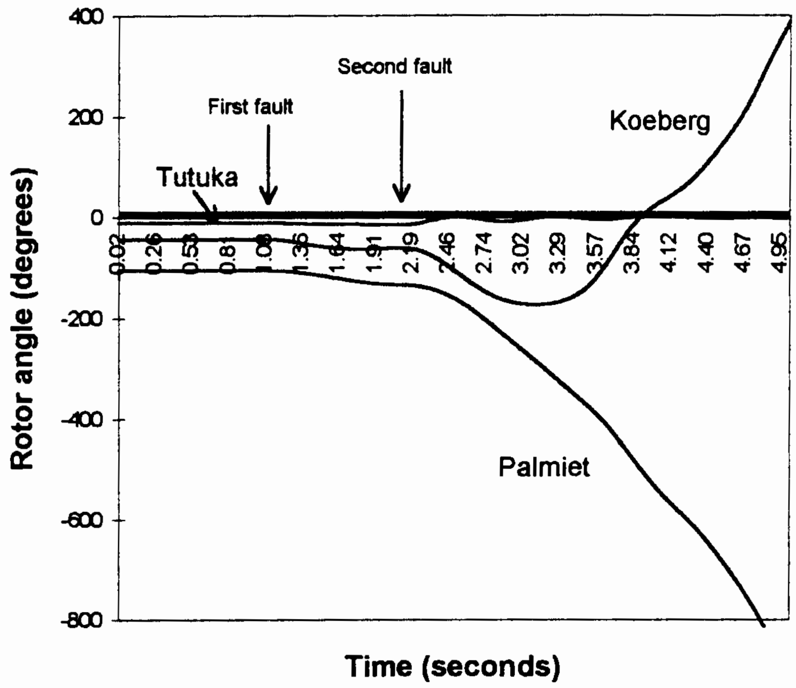

Figure 3.1b: Rotor-angle response

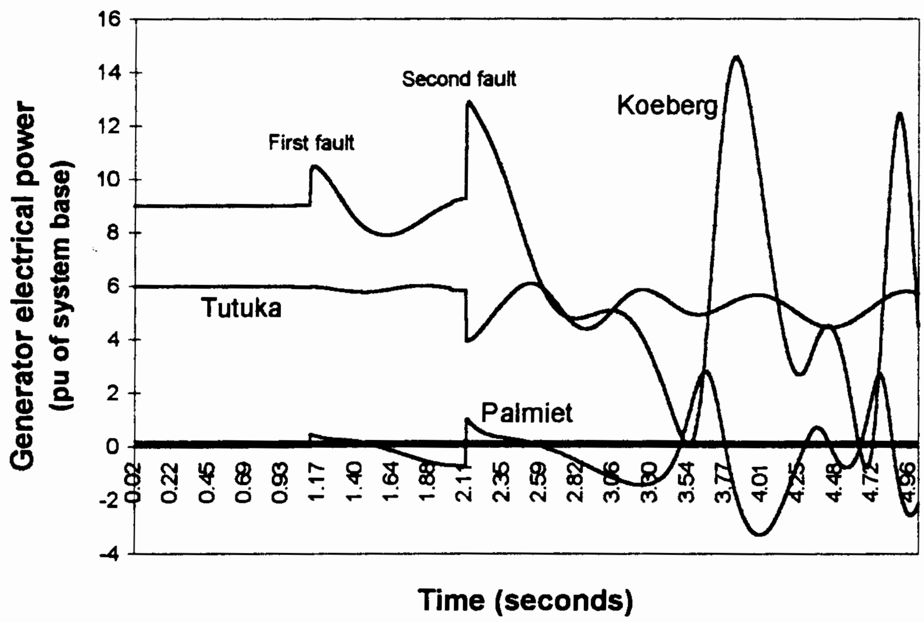

Figure 3.1c: Electrical power output response (power oscillation of Palmiet's first unit is shown - i.e. unit in SCO)

The graphs in Figure 3.1 show that oscillations start in the system due to the weakening of the transmission system between the northern generation pool and the Cape system after the first fault is cleared. An out-of-step condition results from further weakening of the system after the second fault is cleared.

Figure 3.1 also shows that the power stations most affected by the two disturbances are Palmiet and Koeberg. The generators at these stations loses synchronism with the generators in the northern generation pool (Matla Power Station is the swing bus for this study).

The generators at Tutuka Power Station, being located electrically close to the northern generation pool, undergo small oscillations but do not lose synchronism.

3.3.2. Eskom's out-of-step protection application methods [38, 39]

a). Identifying relay locations

Out-of-step blocking protection

The method assumes that undesired operation of all the distance relays in the transmission system (220 kV, 275 kV, 400 kV and 765 kV transmission lines) will occur during power swings and out-of-step conditions. For this reason all distance relays are equipped with out-of-step blocking protection.

Out-of-step tripping protection

The method locates out-of-step tripping protection in the area identified as the electrical centre of the system. The location of the electrical centre is identified by monitoring the voltage at different substations in the system when doing stability studies. The substation voltage magnitudes that comes closest to zero indicates the location known as the electrical centre. More than one substation could be identified to represent the electrical centre location. The amount of out-of-step tripping relays installed in the electrical centre location are determined by the amount of lines connected to the substation(s).

To illustrate how the electrical centre is identified, and therefore the choice of location for the out-of-step tripping relay or relays, the following example is presented:

> Figure 3.2a shows voltage magnitude behaviour obtained in a stability study carried out on the real power system shown in Figure 3.2b. A two-machine representation of the real system is shown in Figure 3.2c. From the voltage magnitude behaviour results it can be seen that the voltage magnitude increases and decreases at the respective locations. At Substation F the voltage magnitude came closest to zero. Therefore the out-of-step tripping relay will be located at Substation F, on both lines leaving that station, as Substation F represents the electrical centre.
>
> For further clarity, if the voltage magnitude results indicated that the voltage magnitude at Substation E came just as close to zero as the voltage magnitude at Substation F, another two out-of-step tripping relays would have been installed at Substation E, on both lines leaving the station.

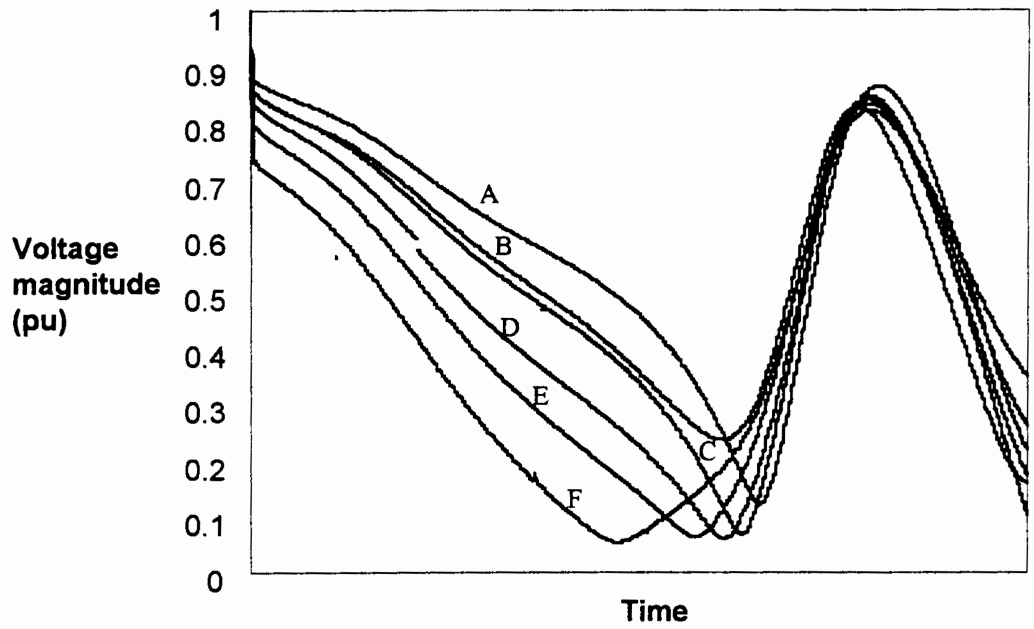

Figure 3.2a: Voltage magnitude behaviour results

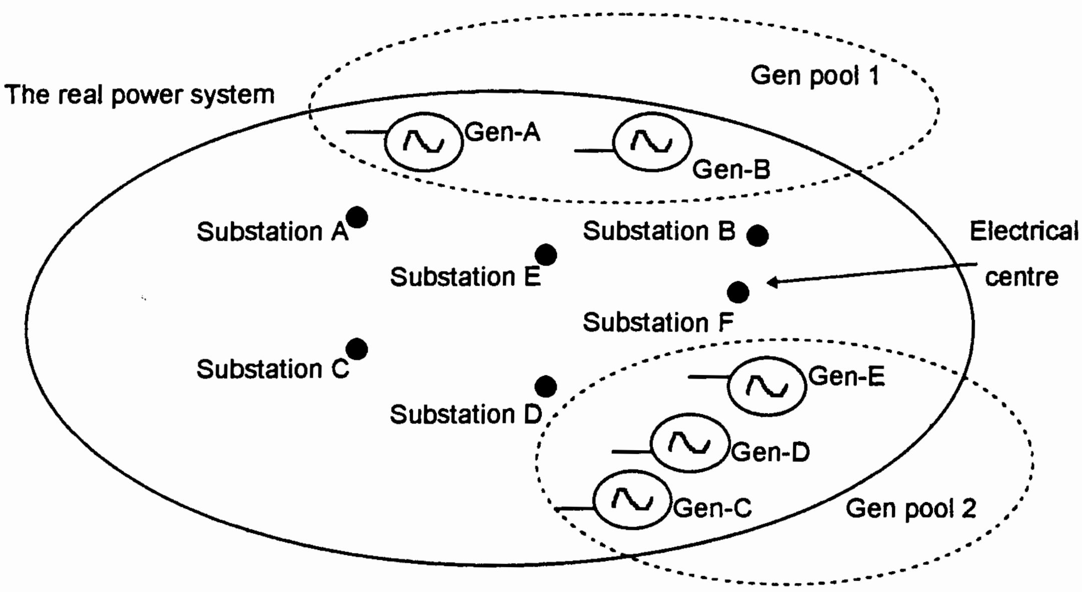

Figure 3.2b: The real power system

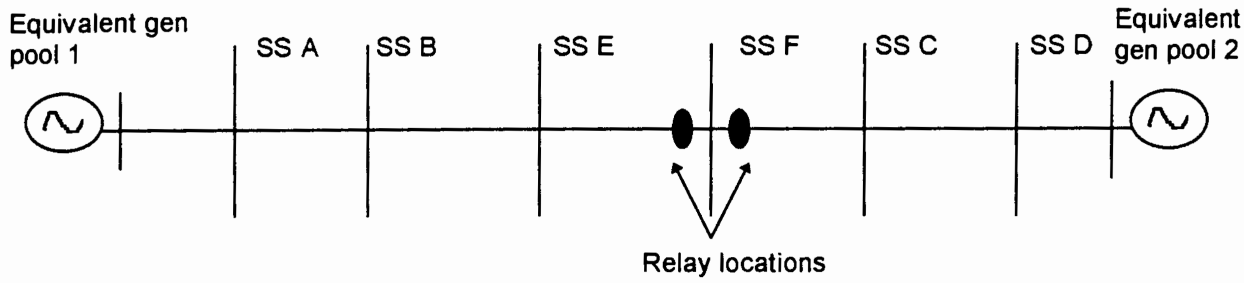

Figure 3.2c: The two-machine representation of the real system

b). Calculating the relay reach settings

The method calculates the forward reach and reverse reach for out-of-step protection relays (blocking and tripping) from the following (Figure 3.3 shows the quantities)[3]:

1. the impedance of the line on which the relay is located (Rl + jXl);
2. the line angle calculated from the line impedance (φ_l);
3. the Thevenin equivalent system impedance[4] in front of the next remote substation[5] ($Z_{Thevenin}$ - in front), calculated at system maximum demand; and
4. the Thevenin equivalent system impedance behind the local substation ($Z_{Thevenin}$ - behind), calculated at system maximum demand.

---

[3] It should be noted that some of the distance relays used by Eskom have out-of-step blocking protection functions that have fixed forward and reverse reaches. These are preset to be equal to the distance relay forward and reverse reaches. The above method does not apply to these relay types.

[4] Thevenin equivalent system impedance: In the calculation of this impedance it is assumed that a network which contains more than one generator can be represented by a single voltage source and series impedance [28]. The application of a short circuit to the terminals of the equivalent circuit will produce a current flow in the circuit. The voltage and current values at the terminals enable the calculation of a Thevenin equivalent impedance.

[5] The Thevenin equivalent system impedance at a substation is calculated on the assumption that the real system as seen between two points (the substation node and the system earth node) can be represented by one voltage source and a series impedance (Thevenin's theorem [28]). Applying a short circuit between the substation node and system earth produces a voltage and current between the nodes. The impedance calculated from this voltage and current represents the Thevenin equivalent system impedance at the substation. This calculation is normally done using a fault analysis software program.

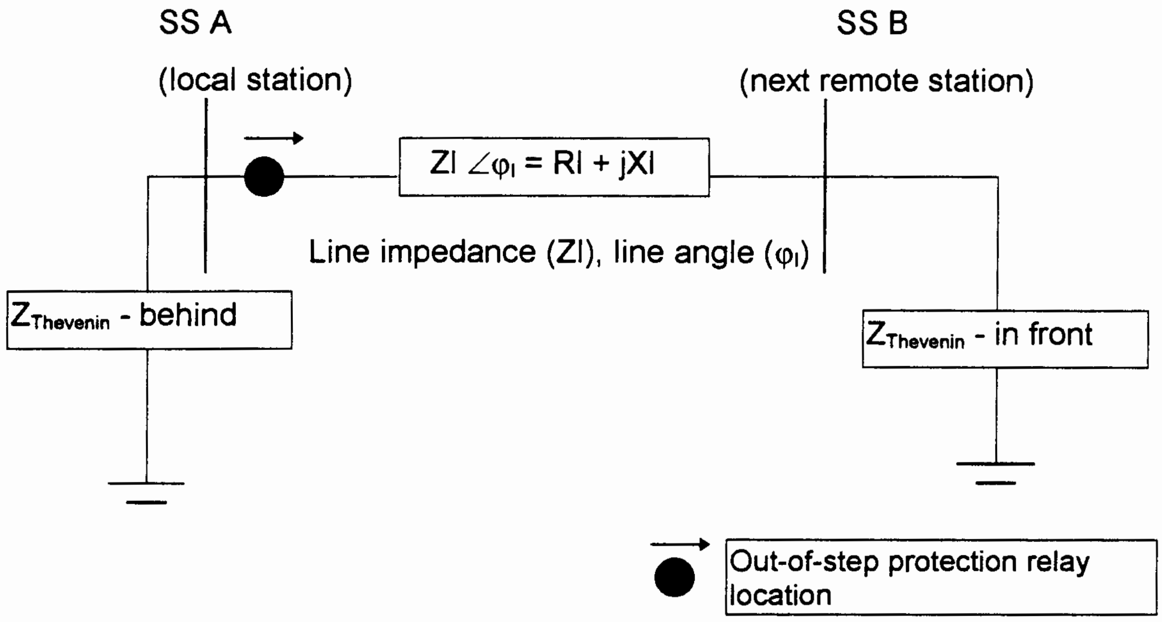

Figure 3.3: Forward and reverse reach calculation

From the above, the forward and reverse reaches are calculated as follows:

$$Zf = |Zf| \angle \varphi_l \text{------------------------------------} (3.1)$$

$$Zr = |Zr| \angle 180 + \varphi_l \text{------------------------------------} (3.2)$$

where

Zf	=	forward reach
$\lvert Zf \rvert$	=	impedance forward reach
		ABS[(line impedance)+(Thevenin impedance in front of next remote substation)]
	=	$\lvert (Rl+jXl) + (Z_{Thevenin}$ - in front$) \rvert$ ---------------------------------(3.3)
Zr	=	reverse reach
$\lvert Zr \rvert$	=	impedance reverse reach
		ABS(Thevenin impedance behind local substation)

$$= \left|(Z_{Thevenin} - behind)\right| \text{--(3.4)}$$

φ_l = line angle

$$= \tan^{-1}\frac{Xl}{Rl} \text{--(3.5)}$$

$Rl+jXl$ = line impedance

c). Calculating the relay timer settings

The relay timer setting for a specific operating zone is taken as the difference between the time when the apparent impedance 'seen' by a relay enters the relay operating zone and that time when the apparent impedance exits the operating zone to enter another operating zone (for example points A and B respectively in Figure 3.4).

The timer setting is calculated from the following:

1. the maximum rate of change of the impedance that is expected during that time when the apparent impedance is within the operating zone; and
2. the change in the angular separation of the unstable generators at that time when the apparent impedance is within the operating zone.

1. <u>The maximum rate of change of the impedance.</u>

The rate of change of the impedance represents the time it takes for the apparent impedance 'seen' by a relay to move from one point to another on the impedance locus. The rate of change of the impedance is therefore used to calculate the time that the impedance spends within an operating zone.

The method used by Eskom is based on the existing approach in that it assumes that the rate the change of the impedance is equal to the rate of change of the angle separation (angle oscillations) between unstable generators. To ensure detection for the fastest angular oscillation that could occur, the maximum frequency of angular oscillation (swing frequency) is used. The swing frequency represents the time it takes for the unstable generators to experience an angle separation of 360° (pole slip).

To determine the maximum swing frequency, the electrical power output of the unstable generators are monitored when doing a stability study. From the electrical power oscillations the maximum frequency of oscillation is calculated and used as the maximum swing frequency.

2. <u>The change in the angular separation of the unstable generators.</u>

It is assumed that the impedance loci 'seen' by impedance type relays, during unstable conditions, are circular and completes a 360° circular trajectory when generator pole slipping is taking place (360° angular separation between unstable generators). Those points where the impedance locus 'seen' by a relay crosses the operating zones defined by the relay's characteristics will therefore indicate the angle separation of the generators at that time. A change in angle separation during that time when the apparent impedance was within the operating zone ($\Delta\theta$ in Figure 3.4) can therefore be calculated.

As mentioned the swing frequency represents the time it takes for the unstable generators to experience an angle separation of 360° (pole slip). With the change in angle separation $\Delta\theta$ known, the time it takes for the unstable generators to experience this angle separation, can be calculated from the following equation:

$$T_{setting} = \frac{\Delta\theta}{360 * fs} \text{ seconds} \quad (3.6)$$

where

$T_{setting}$ = timer setting for the operating zone (seconds)

$\Delta\theta$ = change in angle separation during that time when the apparent impedance is within the operating zone (in degrees)

= θ_B - θ_A in Figure 3.4

fs = maximum swing frequency (Hz)

To illustrate how timer settings are calculated, the following example is presented:

Figure 3.4 shows a relay with a concentric circle out-of-step protection characteristic. For this example the forward reach and the reverse reach for the inner zone are equal and the characteristics are therefore centred at the origin.

According to Eskom's method, a circular impedance locus will be 'seen' at this location. A circular impedance locus is therefore also shown in Figure 3.4.

The system impedance line shown in Figure 3.4 is representing the system impedance between generator pool 1 and generator pool 2 in the real system shown in Figure 3.2b. The angle separation during instability will therefore take place between these generator pools.

1. The maximum rate of change of the impedance.

For the purposes of the example, the maximum swing frequency of the real system shown in Figure 3.2b is fs.

2. <u>The change in the angular separation of the unstable generators.</u>

The timer setting for the operating zone known as the outer zone is calculated by considering the movement of the impedance between two points (A and B in Figure 3.4) on its circular trajectory. The two points are defined by the out-of-step protection's outer and inner characteristics as shown in Figure 3.4.

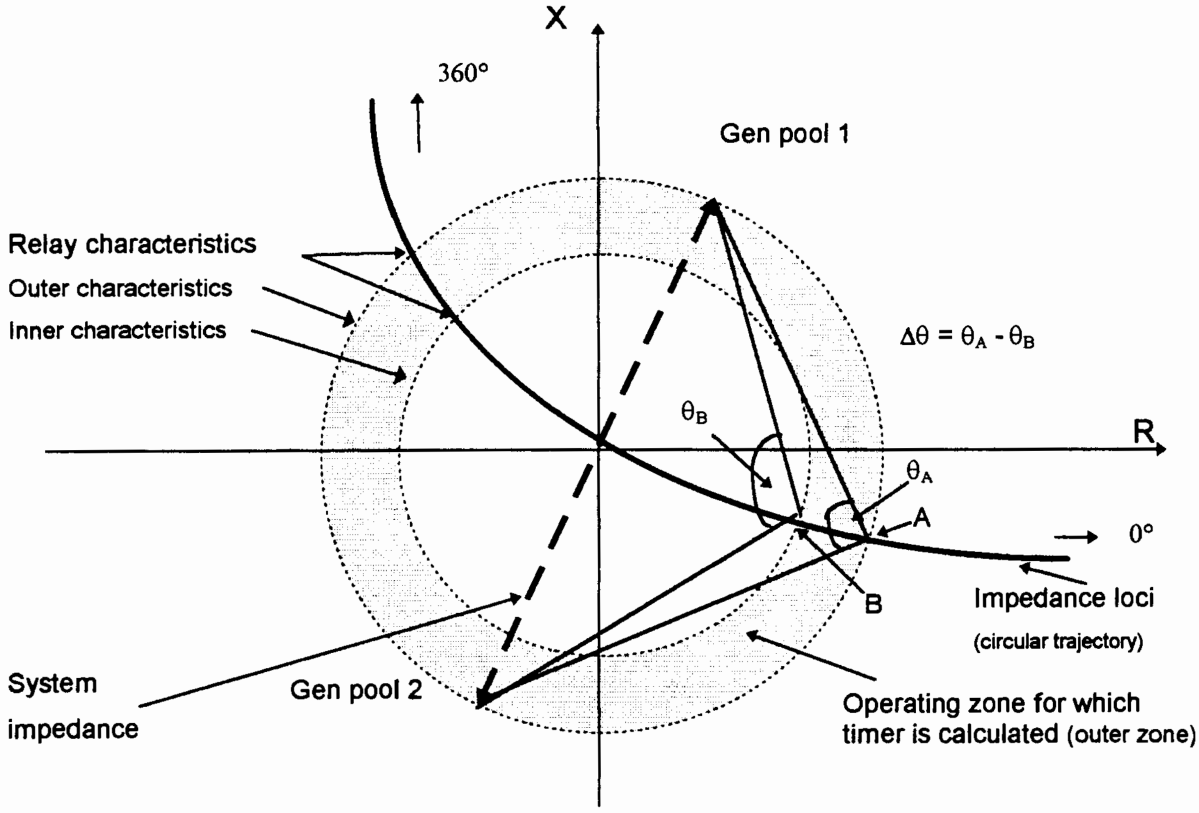

Figure 3.4: Calculation of relay timer settings

At point A the angular separation θ_A between generator pools 1 and 2 is 90° because the outer characteristic is a circle and centred at the origin.

At point B the angular separation between generator pools 1 and 2 is calculated according to the following equation:

$$\theta_B = 2 \times (\tan^{-1} \frac{outer \cdot char \cdot radius}{inner \cdot char \cdot radius})$$

With the swing frequency and the change in angle separation ($\Delta\theta = \theta_B - \theta_A$) known, the timer setting can be calculated according to equation (3.6).

3.3.3 Verification and protection performance results

As mentioned before, the protection performance was recorded during a stability study by including mathematical models for the protection in the power system model. In Appendix C the choice of locations and the calculations of settings were done according to Eskom's method. The protection was mathematically modelled, using the models presented in Appendix B, at the selected locations with the calculated settings. The choice of locations and the calculated settings were taken from the results in Appendix C.

According to the stability study results shown in Figure 3.1, the system underwent power oscillations before it became unstable. For this reason, it was expected that the impedance 'seen' by both the out-of-step blocking and the out-of-step tripping relays at their respective locations in the system would pass through the relay characteristics a number of times.

The performance of the out-of-step blocking and tripping protection was evaluated by determining the percentage of correct detection for the total number of locations where correct detection was expected to take place. The percentage was calculated as follows:

$$\%\ \text{Detection} = \frac{\text{number of locations where correct detection took place}}{\text{number of locations where protection is located}} \times 100\%$$

<u>Out-of-step blocking protection</u>

The purpose of the out-of-step blocking protection is to detect when the impedance enters the characteristic zones and stays there long enough to allow the zone timers to expire. This will enable distance relay blocking every time there is a possibility that undesirable operation of distance relays could occur.

In the stability study done, the impedance passed through the out-of-step blocking protection characteristics more than once. Table 3.1 provides a summary of the out-of-step blocking protection evaluation results and the reasons why nondetection took place at some locations. The percentage of detection is 41,67% as shown in Table 3.1. Note that only the results for the portion of the Eskom system shown in Figure C1, in Appendix C was evaluated. Appendix D provides details of the protection performance results.

Table 3.1: Out-of-step blocking protection evaluation results

Out-of-step blocking relay locations	36
Out-of-step blocking relay detections	15
% detection	41,67%
Reasons for nondetection which resulted in the undesired operation of distance relays	1. At some locations the **zone timer setting for the out-of-step blocking relay was not sufficient.** The timer did not expire while the impedance was passing through the outer zone to enter the inner zone. The reason for this is that the rate of change of the impedance is not constant and that in those cases where nondetection occurred, the rate of change of the impedance, when entering the outer zone, was more than the maximum swing frequency f_s used for the calculation of the timer setting. 2. At some locations the **out-of-step blocking characteristics were not large enough to allow detection** as the impedance entered the out-of-step blocking's outer zone, remained inside the outer zone long enough to allow the timer to expire, but never entered the inner zone to enable detection. 3. At some locations the **distance relay's largest characteristic encroached the out-of-step blocking relay characteristics.** As a result undesired operation of the distance relay occurred because as the impedance entered the blocking relay's characteristics it also entered the distance relay's characteristics.
Reasons for nondetection which did not result in the undesired operation of distance relays	1. At some locations the **impedance never entered the out-of-step blocking relay's characteristics**. Undesired operation at these locations did, however, not take place. Eventhough the non detection of the out-of-step blocking relay did not result in undesired operation of the distance relay, it does raise the concem that an out-of-step blocking relay has been placed at a location where it is not needed, It therefore reflects an unnecessary expenditure as well as an unnecessary increase in risk of protection relay failure.

Out-of-step tripping protection

The purpose of the out-of-step tripping protection is to **not** detect power swing conditions but detect system out-of-step conditions. This will enable the out-of-step tripping protection to send a tripping signal to selected locations to initiate islanding.

Table 3.2 provides a summary of the out-of-step tripping protection evaluation results and the reasons why nondetection took place at some locations. The percentage of detection is 33,33 % as shown in Table 3.2. Note that as for the out-of-step blocking protection evaluation, only the results for the portion of the Eskom system shown in Figure C1, in Appendix C was evaluated. Appendix D provides a detailed presentation of the protection performance results.

Table 3.2: Out-of-step tripping protection evaluation results

Out-of-step tripping relay locations	3
Out-of-step tripping relay detections	1
% detection	33,33%
Reasons for nondetection	1. At one location a **zone timer setting was not sufficient.** The timer did not expire while the impedance passed through the outer and inner zones. The reason for this is that the rate of change of impedance was more than the swing frequency used for calculating the timer setting. 2. At another location **the impedance locus behaviour did not allow detection** i.e. the out-of-step condition was not observable to the out-of-step tripping relay. The reason for this is that the impedance locus did not enter the relay's characteristics in the manner for which locations and settings were determined. As a result the relay did not detect.

3.4 Discussion of verification and protection performance results for the case study presented under section 3.3

For both out-of-step blocking protection and out-of-step tripping protection three main reasons for nondetection were found:

1. timer settings are insufficient;
2. relay characteristic sizes i.e. the reach, are insufficient; and
3. the unstable condition is not observable by the relay.

1. Timer settings are insufficient

When calculating the timer settings two assumptions are made:

- the impedance loci ‘seen’ by impedance type relays are circular during unstable conditions; and
- the swing frequency measured at the generator terminals is the same as the rate of change of the impedance ‘seen’ at an impedance relay location.

Analyses of the results (refer to Appendix D) showed that the above assumptions are not correct.

The impedance loci are not circular because system dynamic behaviour (generator excitation control, system reactive compensation, load demand, etc.) continuously influence the behaviour of the voltage and current measured at a relay location.

The swing frequency measured at the generator terminals is not representative of the rate of change of the impedance 'seen' at a relay location. As mentioned above, the dynamic behaviour of the system continuously influences the behaviour of the voltages and currents within the system. The rate of change is therefore not necessarily the same as the swing frequency. In addition it was also found that the rate of change of the impedance is not constant but increases (accelerates) and decreases (decelerates) continuously.

From the above findings the manner of calculating timer settings using the existing approach could result in insufficient timer settings as found in the cases listed in Tables 3.1 and 3.2.

2. Relay characteristic sizes i.e. the reach, are insufficient.

Within the existing approach, calculation of the reach settings is based on system equivalent impedances. In Eskom's method Thevenin impedances are calculated from which the relay reach settings are determined.

It was found in the research that the use of equivalent impedances may produce insufficient reach settings. The relay characteristics could be too small and the apparent impedance may not enter to within an inner zone to enable detection.

When equivalencing system impedances, the effect of parallel lines, shunt and series compensation and the dynamic control of system impedance (using for example FACTS devices) are not considered. These system components all serve to decrease system impedance and increase power flow. Using equivalent impedances may therefore produce smaller impedance quantities than is the case for the real system. Consequently this may lead to smaller reach settings for out-of-step protection relays.

In addition the existing approach does not seem to consider the need to co-ordinate the out-of-step blocking protection reach settings with the distance relay reach settings. As a consequence, large distance relay characteristics could encroach the out-of-step blocking relay's characteristics. This could lead to the undesired operation of the distance relay although the apparent impedance enters the out-of-step blocking relay's characteristics.

From the above findings the manner of calculating reach settings using the existing approach could result in insufficient reach settings as found in practice during the study.

3. <u>The unstable condition is not observable by the relay.</u>

According to the existing approach, out-of-step blocking relays tend to be located where distance relays are located. The Eskom method locates blocking relays at all the locations where distance relays are located.

The research indicated that not all distance relays within a power system are located within an area where system instability may cause undesired operation. The unstable condition is therefore not necessarily observable at all the locations. Applying out-of-step blocking protection at those locations where the unstable condition is not observed, causes over-expenditure and an increased risk of protection failure. It should, however, be noted that one study alone is not enough indication of whether out-of-step blocking protection is needed or not at a particular location. The use of one study in the above case is purely for illustrative purposes. (refer to section 1.4, no 10 of Chapter 1).

According to the existing approach, out-of-step tripping relays tend to be located in an area identified as the electrical centre. This is also the case when using the Eskom method.

The research results, however, indicated that the electrical centre location is not necessarily the correct location for an out-of-step tripping relay to observe an unstable condition. Due to the dynamic behaviour of the system, the behaviour of the impedance locus at the electrical centre is not as assumed when using the existing approach. The impedance locus is not circular and it does not necessarily move from left to right (or vice versa) during pole slipping conditions. In addition it also does not necessarily approach the origin in the impedance plane during system instability. As a result an out-of-step tripping relay located at the electrical centre of a power system may not detect during unstable conditions.

From the above findings the manner in which locations for out-of-step blocking and tripping relays are chosen when using the existing approach, could result in out-of-step protection relays not observing unstable conditions when required. Ultimately the relays may not detect, as illustrated in the research.

In conclusion, the statement made under section 3.2 is repeated:

> It seems that there is a need to either improve the existing approach or identify a new and better approach to apply out-of-step protection.

3.5 Summary and conclusions

In this chapter the existing approach of applying out-of-step protection was presented. In summary the approach seems to entail the following according to literature:

1. The existing approach of applying out-of-step protection is based on the behaviour of the electrical quantities (voltage, current, rotor angle, etc.) of a two machine power system. The reason for this is that a real power system that has generators or generator groups which could become unstable with one another, can be represented by a two machine equivalent model. The assumption can therefore be made that when the real power system becomes unstable, the behaviour of the electrical quantities in the real power system may be similar to the behaviour of the electrical quantities in a two machine system.
2. The tripping relay locations are selected based on the location of an electrical centre (also known as the voltage zero), determined from stability studies.
3. In many cases out-of-step blocking protection is located at all the locations where distance relays are located.
4. A source impedance, or equivalent impedance representing system impedance in front of and behind a location are used to calculate the forward and reverse reach settings respectively for a relay located at that location.
5. A maximum swing frequency, determined from stability studies, is used to calculate relay timer settings.

The existing approach, using Eskom's methods was illustrated, tested and investigated by means of a case study in which out-of-step protection was applied to an actual power system. An investigation of the case study results indicated the following regarding the existing approach:

1. During system instability, the electrical quantities of an actual power system does not necessarily behave similar to the behaviour of the electrical quantities of a two machine system;

2. The assumption that all distance relays should be equipped with out-of-step blocking protection may be over-cautious because many such blocking relays may be redundant in many stability events;

3. The use of an electrical centre area to identify locations for out-of-step tripping relays is not reliable to ensure observability of unstable conditions;

4. The use of equivalent impedances to calculate reach settings ignores dynamic influences within the real system that affects system impedance; and

5. The use of swing frequencies ignores the dynamic influences within the power system which affects the voltage and current measured by the relay at the relay location.

The conclusions drawn from this chapter are the following:

1. assumptions made in the existing approach seems to be the following:

    - voltage zeros (electrical centre locations) seems to be used to determine tripping relay locations;
    - blocking relays seems to be located at all distance relay locations;
    - equivalent impedances seems to be used to determine reach settings; and
    - swing frequency seems to be used to determine timer settings.

These assumptions could lead to incorrect performance of out-of-step protection;

2. the four assumptions made in the existing approach over-simplifies the procedure of applying out-of-step protection; and

3. there is a need to either improve the existing approach or identify a new and better approach. An example of improving the existing approach could be anything which eliminates some or all of its limitations identified in Chapter 3. References [12] and [20] presents cases where improvements on the existing approach were studied. Examples of new and better approach could be either the use of the new approach presented in this thesis or the use of the phasor angle measurement technique presented in references [24, 46, 47, 48].

CHAPTER 4

PROPOSED OUT-OF-STEP PROTECTION APPLICATION APPROACH INVOLVING A STUDY OF THE IMPEDANCE LOCUS BEHAVIOUR AT ALL LOCATIONS

4.1 Other approaches identified and used in the application of out-of-step protection

As mentioned in Chapter 3 under section 3.2, the limitations introduced when using the existing approach, have been noticed and addressed by others. The need to either improve the existing approach or identify a new approach has therefore been recognised. Reference [20] has recognised that blocking protection for distance relays does not have to be enabled at all locations. In reference [12] the electrical centre location was used as an indication for where relays should be located, but more detailed investigation involving the studying of the impedance locus behaviour within the area where the electrical centre is located, was done to obtain the optimal locations for out-of-step tripping protection. In reference [20] the impedance locus behaviour was studied to determine the required reach settings for out-of-step tripping protection.

A completely different approach was developed in references [24, 46, 47, 48]. This approach entails the measurement of phasor angle differences between distant points in a power system. Using this method, if applied correctly, system instability can be predicted by monitoring the angle difference between distant points (for example generation pools. The use of the phasor angle measurement technique is still very much in the research phase all over the world and although the system has been implemented and tested in certain utilities, correct operation during actual incidents has not yet been recorded. Research done on the phasor angle measurement technique does however indicate that the method could be reliable and in the future may even replace impedance type out-of-step protection relays.

In the research leading to this thesis, a new approach when applying impedance type relays was developed. The new approach involves a study of the impedance locus behaviour to determine locations and settings. The new approach is now presented under section 4.2.

4.2 A new approach involving a study of the impedance locus behaviour at each relay location

The new approach entails the following:

1. The modelling of the power system (the actual power system); and

2. Studying the apparent impedance at all the locations within the power system to determine locations and settings.

The new approach addresses the limitations and shortcomings of the existing approach in the following way (Table 4.1 provides a comparison between the existing approach and the new approach):

1. Direct results regarding the behaviour of the electrical quantities of the power system is available when modelling the actual power system. There is therefore no need to make use of a two machine system approach to interpret system stability results.
2. Studying the impedance locus behaviour at all locations is an indication of what an impedance type relay will 'see' during system unstable conditions. Location and setting decisions made by the protection engineer are therefore based directly on what the relay will 'see'.

Table 4.1: Comparison between the existing approach and the new approach

	Existing approach	**New approach**
Location	Tend to equip all distance relays with out-of-step blocking protection. Out-of-step tripping protection is located in the area identified as the electrical centre of the system.	Impedance loci at all the locations in the system are studied to determine the locations for both out-of-step blocking and out-of-step tripping protection. The method involves the use of an ROW[1].
Reach settings	The reach settings are calculated from equivalent impedances which represent actual system impedance in an equivalent two machine system.	Reach settings are calculated by studying the impedance loci at the chosen locations. The method involves the use of an ROW.
Timer settings	The timer settings are calculated from the rate of change of the impedance in the impedance plane. The rate of change of the impedance is assumed to be constant and equal to the frequency of oscillation of the generator rotor angle oscillations.	The timer settings are calculated by studying the impedance loci and determining the time for which the impedance remains in an operating zone.

<u>What is new in this approach?</u>

What is new in this approach is the attention that is given to the impedance locus 'seen' by a relay at its location. The impedance locus is studied using methods developed in the research. These methods were developed to identify correct locations for out-of-step blocking and tripping relays and to calculate correct settings which would ensure correct detection.

The methods developed to determine locations and calculate reach settings uses an impedance characteristic which defines an area within the impedance plane. This characteristic was named by the research as a relay operating window (ROW). The way in which the impedance enters and exits the ROW is used to determine locations and calculate reach settings. Even though any characteristic shape can be used to define a ROW, the research used a rectangular shape characteristic because it is easy to define the boundaries and suitable for illustrative purposes.

[1] Relay Operating Window. Definition can be found under the Abbreviations and Terminology section of this thesis.

Figure 4.1 illustrates the method of using an ROW. The top and bottom boundaries of the ROW are represented by X_a and X_b respectively. R_l and R_r represent the left and right ROW boundaries respectively. These values are selected based on the relay type used and the load encroachment limitations. More is said about the choice of these parameters when the methods to identify locations and calculate reach settings are presented.

The impedance values when the impedance locus enters and exits the ROW are $R_{enter\text{-}actual}+jX_{enter\text{-}actual}$ and $R_{exit\text{-}actual}+jX_{exit\text{-}actual}$. respectively. The closest distance between the impedance locus and the origin of the impedance plane is $|R_d+jX_d|$.

R_d and X_d are used when determining whether a location requires out-of-step blocking protection. When these values indicate that the apparent impedance is within the ROW, it becomes likely that the apparent impedance may enter the distance relay characteristics and cause undesired operation .

$R_{enter\text{-}actual}$, $X_{enter\text{-}actual}$, $R_{exit\text{-}actual}$, $X_{exit\text{-}actual}$, R_d and X_d are all used when determining whether a location is suitable for out-of-step tripping protection. The reason for this is that these parameters define the way in which the apparent impedance will enter and exit the out-of-step tripping relay characteristics at a given location. If these parameters present an impedance locus that will allow detection at the given location, the location should be suitable for an out-of-step tripping relay.

$R_{enter\text{-}actual}$, $X_{enter\text{-}actual}$, $R_{exit\text{-}actual}$, and $X_{exit\text{-}actual}$ are used to calculate the reach settings. The entry and exit points into and out of the ROW indicates what the size of the largest out-of-step relay characteristic should be to ensure that the impedance locus will enter the relay characteristics.

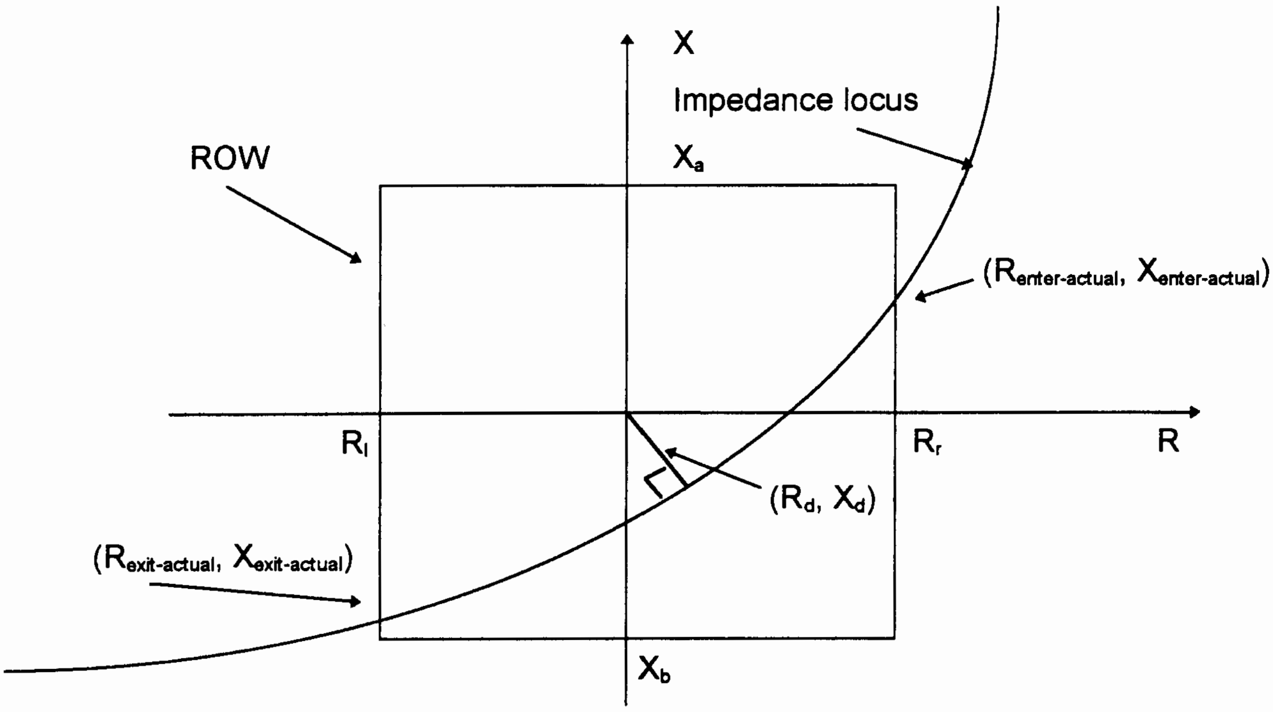

Figure 4.1: The use of the ROW to evaluate observability of power swings and out-of-step conditions

The method developed to calculate the timer settings involves the studying of the impedance locus as it enters the various operating zones of the out-of-step protection relay. A mathematical model representing the relay characteristics is included in the power system model and times when the impedance locus enters and exits the respective operating zones are recorded. From these recorded times, the duration that the impedance stays within an operating zone is calculated. These duration times are evaluated to determine the required zone timer settings.

4.3 The new methods of studying the impedance locus behaviour to determine locations and settings

Chapter 2, section 2.3, discussed the three considerations affecting the application of out-of-step protection to allow observability of rotor-angle unstable conditions. These are:

1. Relay locations
2. Relay reach settings; and
3. Relay timer settings.

4.3.1 Relay locations

4.3.1a Out-of-step blocking protection

To determine whether a chosen location requires out-of-step blocking protection, an ROW is chosen to define an area within the impedance plane with the following boundaries (refer to Figure 4.1):

Xa = forward reach of the largest distance relay characteristic at that location;

Xb = reverse reach of the largest distance relay characteristic at that location;

Rr = maximum resistive value on the R-axis defined by the largest distance relay characteristic at the location;

Rl = minimum resistive value on the R-axis defined by the largest distance relay characteristic at the location;

The need for out-of-step blocking protection is established by determining the following (refer to Figure 4.1):

R_d The corresponding R value of the perpendicular distance between the impedance locus and the origin of the R-X plane

X_d The corresponding X value of the perpendicular distance between the impedance locus and the origin of the R-X plane

R_d and X_d are determined by capturing (monitoring) the R and X values of the impedance locus as it crosses the ROW boundaries. This can be done within a powers system simulation tool (PSS/E in the case of the research) when doing a stability study. A mathematical model representing the boundaries of the ROW can be included in the power system model. R_d and X_d are captured only for those times when detection for the purpose of blocking should take place i.e. during those times when the power system is oscillating as well as those times when the power system becomes unstable[2].

The criterion in identifying locations for out-of-step blocking protection is:

- If $R_l < R_d < R_r$ and $X_b < X_d < X_a$ then the apparent impedance is inside the ROW boundaries and out-of-step blocking protection is needed.

4.3.1b Out-of-step tripping protection

To determine whether a location is suitable for out-of-step tripping protection, an ROW is chosen to define an area within the impedance plane with the following boundaries (refer to Figure 4.1):

Xa = the maximum forward reach specified by the relay manufacturer which will be within the design limit of the relay type to be used;

Xb = the maximum reverse reach specified by the relay manufacturer which will be within the design limit of the relay type to be used;

Rl = Rr

= the maximum allowable resistive reach which will avoid load encroachment.

The suitability of a chosen location is evaluated by calculating the following for that time frame within the stability study when the system is becoming unstable (refer to Figure 4.1):

$$|Z_d| = \sqrt{(R_d^2 + X_d^2)} \text{------------} (4.1)$$

$$\%R_{enter} = \frac{R_{enter\text{-}actual}}{R_r\{R_l\}} \times 100 \text{------------} (4.2)$$

[2] An alternative approach could be the use of a spreadsheet program which contains the impedance locus data captured from the stability study results and a range of data representing the ROW boundaries. A comparison of data to determine when the locus crosses the ROW boundaries can then be performed through the use of spreadsheet functions.

$$\%R_{exit} = \frac{R_{exit\text{-}actual}}{R_r \{R_l\}} \times 100 \text{------------------------------------} (4.3)$$

where

$\lvert Z_d \rvert$	=	The perpendicular distance between the impedance locus and the origin of the R-X plane
$R_{enter\text{-}actual}$	=	The corresponding R value of the impedance locus when entering the ROW
$\%R_{enter}$	=	The %R when the impedance enters the ROW on the right-hand *{left-hand}* side of the X-axis, expressed as a percentage of R_r $\{R_l\}$
$X_{enter\text{-}actual}$	=	The corresponding X value of the impedance locus when entering the ROW
$R_{exit\text{-}actual}$	=	The corresponding R value of the impedance locus when exiting the ROW
$\%R_{exit}$	=	The %R when the impedance exits the ROW on the right-hand *{left-hand}* side of the X-axis, expressed as a percentage of R_r $\{R_l\}$
$X_{exit\text{-}actual}$	=	The corresponding X value of the impedance locus when exiting the ROW

As in the case of determining R_d and X_d explained under section (4.3.1a), $R_{enter\text{-}actual}$, $X_{enter\text{-}actual}$, $R_{exit\text{-}actual}$ and $X_{exit\text{-}actual}$ are determined by capturing (monitoring) the R and X values of the impedance locus as it crosses the ROW boundaries. As already mentioned, this can be done within a power system simulation tool when doing a stability study. A mathematical model representing the boundaries of the ROW can be included in the power system model. For the purpose of out-of-step tripping protection the R_d, X_d, $R_{enter\text{-}actual}$, $X_{enter\text{-}actual}$, $R_{exit\text{-}actual}$ and $X_{exit\text{-}actual}$ are captured only for those times when detection for the purpose of tripping should take place i.e. during those times when the power system becomes unstable.

The criterion in determining the suitability of a chosen location is:

- $R_l < R_{enter\text{-}actual} < R_r$ and $X_b < X_{enter\text{-}actual} < X_a$ to indicate that the impedance is inside the boundaries defined by an out-of-step tripping ROW; and
- $|Z_d|$ to be as close as possible to 0 pu which will ensure that the impedance locus enters the out-of-step tripping inner characteristic for the purpose of detection[3]; and
- $\%R_{enter}$ to be as close as possible to 100% as most relay types are designed to allow detection when the impedance enters the characteristics close to the R-axis; and
- $\%R_{exit}$ to be as close as possible to 100% as most relay types are designed to allow detection when the impedance locus exits the characteristics close to the R-axis; and
- the impedance to enter and exit the ROW in such a way as to allow detection according to the detection methodology of the type of relay chosen.

4.3.2 Relay reach settings

The forward and reverse reach settings are calculated from the following:

1. the transmission line angle
2. $|Zf_{largest\ dist\ relay\ char}|$ = forward reach of largest distance relay characteristic
3. $|Zr_{largest\ dist\ relay\ char}|$ = reverse reach of largest distance relay characteristic
4. $R_{enter\text{-}actual}$
5. $X_{enter\text{-}actual}$
6. $R_{exit\text{-}actual}$
7. $X_{exit\text{-}actual}$

[3] Many out-of-step tripping relay types exist [1, 9, 13, 14, 30, 40-43, 49]. These types of relays require that the impedance enter an inner zone to allow detection.

- 4, 5, 6 and 7 are determined as explained under section 4.3.1b.

Using the above quantities the forward and reverse reach settings are calculated as follows:

4.3.2a Out-of-step blocking protection

Zf = $|Zf| \angle \varphi l$---(4.4)

Zr = $|Zr| \angle 180° + \varphi l$--(4.5)

where

Zf = blocking relay forward reach

Zr = blocking relay reverse reach

φl = line angle of line on which blocking relay will be located

= $\tan^{-1} \dfrac{Xl}{Rl}$ --(4.6)

- for $X_{enter\text{-}actual} < 0$ and $X_{exit\text{-}actual} < 0$:

$|Zf|$ = |maximum forward reach specified for the out-of-step protection used| --------(4.7)

$|Zr|$ = the greater of $\sqrt{(R_{enter\text{-}actual}{}^2 + X_{enter\text{-}actual}{}^2)}$ and $\sqrt{(R_{exit\text{-}actual}{}^2 + X_{exit\text{-}actual}{}^2)}$---------(4.8)

or

= |maximum reverse reach specified for the out-of-step protection used|

if calculated $|Zr| \leq |Zr_{largest\ dist\ relay\ char}|$

or

if calculated $|Zr|$ > |maximum reverse reach specified|

- for $X_{enter\text{-}actual} > 0$ and $X_{exit\text{-}actual} > 0$:

$|Zf|$ = the greater of $\sqrt{(R_{enter\text{-}actual}{}^2 + X_{enter\text{-}actual}{}^2)}$ and $\sqrt{(R_{exit\text{-}actual}{}^2 + X_{exit\text{-}actual}{}^2)}$ ---(4.9)

or

= |maximum forward reach specified for the out-of-step protection used|

if calculated $|Zf| \leq |Zf_{largest\ dist\ relay\ char}|$

or

if calculated $|Zf| > |$maximum forward reach specified$|$

$|Zr|$ = $|$maximum reverse reach specified for the out-of-step protection used$|$ ------(4.10)

- for $X_{enter\text{-}actual} > 0$ and $X_{exit\text{-}actual} < 0$:

$|Zf|$ = $\sqrt{(R_{enter\text{-}actual}{}^2 + X_{enter\text{-}actual}{}^2)}$ --(4.11)

or

= $|$maximum forward reach specified for the out-of-step protection used$|$

if $\sqrt{(R_{enter\text{-}actual}{}^2 + X_{enter\text{-}actual}{}^2)} \leq |Zf_{largest\ dist\ relay\ char}|$

or

if calculated $|Zf| > |$maximum forward reach specified$|$

$|Zr|$ = $\sqrt{(R_{exit\text{-}actual}{}^2 + X_{exit\text{-}actual}{}^2)}$--(4.12)

or

= $|$maximum reverse reach specified for the out-of-step protection used$|$

if $\sqrt{(R_{exit\text{-}actual}{}^2 + X_{exit\text{-}actual}{}^2)} \leq |Zr_{largest\ dist\ relay\ char}|$

or

if calculated $|Zr| > |$maximum reverse reach specified$|$

- for $X_{enter\text{-}actual} < 0$ and $X_{exit\text{-}actual} > 0$:

$|Zf|$ = $\sqrt{(R_{exit\text{-}actual}{}^2 + X_{exit\text{-}actual}{}^2)}$--(4.13)

or

= $|$maximum forward reach specified for the out-of-step protection used$|$

if $\sqrt{(R_{exit\text{-}actual}{}^2 + X_{exit\text{-}actual}{}^2)} \leq |Zf_{largest\ dist\ relay\ char}|$

or

if calculated $|Zf| > |$maximum forward reach specified$|$

$|Zr|$ = $\sqrt{(R_{enter\text{-}actual}{}^2 + X_{enter\text{-}actual}{}^2)}$--(4.14)

or

= $|$maximum reverse reach specified for the out-of-step protection used$|$

if $\sqrt{(R_{enter\text{-}actual}{}^2 + X_{enter\text{-}actual}{}^2)} \leq |Zr_{largest\ dist\ relay\ char}|$

or

if calculated $|Zr| > |$maximum reverse reach specified$|$

where

$\lvert Zf_{inner} \rvert$	=	inner zone forward reach for blocking relay
	=	as specified for the out-of-step protection used---------------(4.15)
	or	
	=	$\lvert Zf_{largest\ dist\ relay\ char} \rvert$ if calculated $\lvert Zf_{inner} \rvert \le \lvert Zf_{largest\ dist\ relay\ char} \rvert$
$\lvert Zr_{inner} \rvert$	=	inner zone reverse reach for blocking relay
	=	as specified for the out-of-step protection used---------------(4.16)
	or	
	=	$\lvert Zr_{largest\ dist\ relay\ char} \rvert$ if calculated $\lvert Zr_{inner} \rvert \le \lvert Zr_{largest\ dist\ relay\ char} \rvert$
Rl+jXl	=	line impedance of line on which blocking relay will be located

4.3.2b Out-of-step tripping protection

$$Zf = \lvert Zf \rvert \angle \varphi l \qquad (4.17)$$

$$Zr = \lvert Zr \rvert \angle 180° + \varphi l \qquad (4.18)$$

where

Zf	=	tripping relay forward reach
Zr	=	tripping relay reverse reach
φl	=	line angle of line on which tripping relay will be located
	=	$\tan^{-1} \frac{Xl}{Rl}$ ---------------(4.19)

- for $X_{enter\text{-}actual} < 0$ and $X_{exit\text{-}actual} < 0$:

$\lvert Zf \rvert$	=	|maximum forward reach specified for the out-of-step protection used| ------(4.20)
$\lvert Zr \rvert$	=	the greater of $\sqrt{(R_{enter\text{-}actual}^2 + X_{enter\text{-}actual}^2)}$ and $\sqrt{(R_{exit\text{-}actual}^2 + X_{exit\text{-}actual}^2)}$------(4.21)
		or
	=	|maximum reverse reach specified for the out-of-step protection used|
		if calculated $\lvert Zr \rvert$ > |maximum reverse reach specified|

- for $X_{enter\text{-}actual} > 0$ and $X_{exit\text{-}actual} > 0$:

$|Zf|$ = the greater of $\sqrt{(R_{enter\text{-}actual}^2 + X_{enter\text{-}actual}^2)}$ and $\sqrt{(R_{exit\text{-}actual}^2 + X_{exit\text{-}actual}^2)}$ -(4.22)

or

= |maximum forward reach specified for the out-of-step protection used|

if calculated $|Zf|$ > |maximum forward reach specified|

$|Zr|$ = |maximum reverse reach specified for the out-of-step protection used| -------(4.23)

- for $X_{enter\text{-}actual} > 0$ and $X_{exit\text{-}actual} < 0$:

$|Zf|$ = $\sqrt{(R_{enter\text{-}actual}^2 + X_{enter\text{-}actual}^2)}$ --(4.24)

or

= |maximum forward reach specified for the out-of-step protection used|

if calculated $|Zf|$ > |maximum forward reach specified|

$|Zr|$ = $\sqrt{(R_{exit\text{-}actual}^2 + X_{exit\text{-}actual}^2)}$--(4.25)

or

= |maximum reverse reach specified for the out-of-step protection used|

if calculated $|Zr|$ > |maximum reverse reach specified|

- for $X_{enter\text{-}actual} < 0$ and $X_{exit\text{-}actual} > 0$:

$|Zf|$ = $\sqrt{(R_{exit\text{-}actual}^2 + X_{exit\text{-}actual}^2)}$--(4.26)

or

= |maximum forward reach specified for the out-of-step protection used|

if calculated $|Zf|$ > |maximum forward reach specified|

$|Zr|$ = $\sqrt{(R_{enter\text{-}actual}^2 + X_{enter\text{-}actual}^2)}$--(4.27)

or

= |maximum reverse reach specified for the out-of-step protection used|

if calculated $|Zr|$ > |maximum reverse reach specified|

where

$|Zf_{inner}|$ = inner zone forward reach for tripping relay

= as specified for the out-of-step protection used---------------(4.28)

$|Zr_{inner}|$ = inner zone reverse reach for tripping relay

= as specified for the out-of-step protection used---------------(4.29)

Rl+jXl = line impedance of line on which tripping relay will be located

4.3.3 Relay timer settings

The timer setting for a protection relay operating zone is calculated by determining the time (duration) for which the impedance remains in that operating zone. This is done by using a mathematical model representing the out-of-step protection relay characteristics in an impedance plane. The model is included in the power system model and a stability study is done. For the stability study done the impedance locus entry and exit times into and out of the operating zone are recorded. The duration that the apparent impedance stays within the operating zone represents the timer setting required to allow detection for the particular stability study done.

For out-of-step blocking protection the entry and exit times are recorded during that time when the system is experiencing power oscillations. The reason for this is that out-of-step blocking relays should detect during power oscillating conditions in order to block undesired distance relay operation.

For out-of-step tripping protection, the entry and exit times are recorded during that time when the system becomes unstable. The reason for this is that out-of-step tripping relays should detect only when the system becomes unstable and not while the system is experiencing power oscillations.

Figure 4.2 illustrates the method by showing concentric type characteristics with two operating zones (operating zone 1 and operating zone 2). Each of the operating zones require a timer setting. Depending on whether the timer settings are to be calculated for an out-of-step blocking relay or an out-of-step tripping relay, the times t1, t2 and t3 are recorded during that time when the relay should detect.

With the recorded times t1, t2 and t3 known, the timer settings for the respective operating zones shown within Figure 4.2 are calculated as follows:

T-operating zone 1	=	t2 - t1 ---(4.30)
T-operating zone 2	=	t3 - t2 ---(4.31)

where

T-operating zone 1	=	timer for operating zone 1
T-operating zone 2	=	timer for operating zone 2
t1	=	time at which the impedance enters the operating zone 1
t2	=	time at which the impedance exits operating zone 1 and enters operating zone 2
t3	=	time at which the impedance exits operating zone 2 and enters operating zone 1

4.4 Case study: Determining and testing the reliability of the new approach

Out-of-step protection was applied to the Eskom system, using the new approach. The methods presented to analyse the impedance locus behaviour were used to determine relay locations and calculate relay settings. Due to the number of calculations involved, all the calculations and examples are contained in Appendix E.

The stability study used to demonstrate the application method (choice of locations and calculating settings) as well as evaluate the out-of-step protection performance, is the stability study presented in Chapter 3, under section 3.3.1.

As in the case of demonstrating the existing approach and its limitations, the use of a single stability study was found to be sufficient to illustrate the new application approach and demonstrate the methods of studying the impedance locus to determine locations and calculate settings. However, as mentioned in section 1.4, no 10 of Chapter 1, a single study would not be sufficient in practice to determine the most suitable locations and settings for the relays.

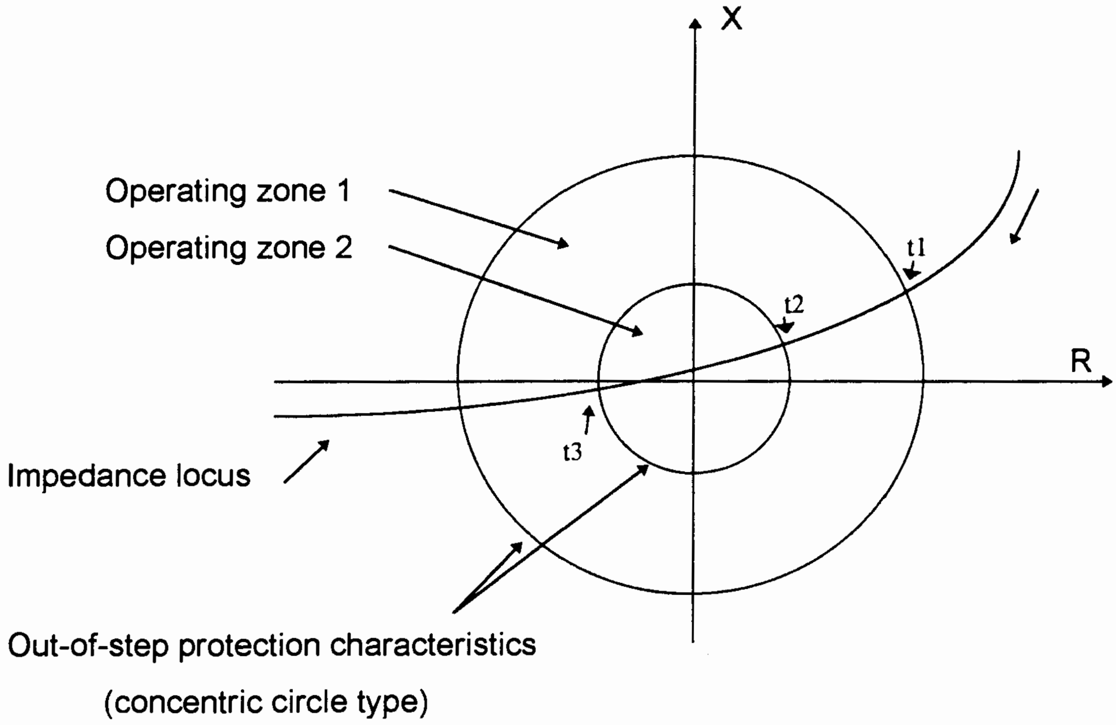

Figure 4.2: Calculating the timer settings

The protection performance was recorded and evaluated by including mathematical models, representing the behaviour of the protection relays, in the power system model. Appendix B contains a description of the mathematical models used to represent the protection behaviour. The protection relays were located at the locations identified in Appendix E with the reach and timer settings also calculated in Appendix E. A summary of the protection performance results are presented under section 4.4.1. Appendix F provides details of the protection performance results.

4.4.1 Verification and protection performance results

According to the stability study results shown in Figure 3.1, Chapter 3, the system underwent power oscillations before it became unstable. For this reason, it was expected that the impedance 'seen' by both the out-of-step blocking and the out-of-step tripping relays at their respective locations in the system would pass through the relay characteristics a number of times.

- The performance of the out-of-step blocking and tripping protection was evaluated by determining the percentage of correct detection for the total number of locations where correct detection should take place. The percentage was therefore calculated as follows:

$$\% \text{ detection} = \frac{\text{number of locations where correct detection took place}}{\text{number of locations where protection is located}} \times 100\%$$

Out-of-step blocking protection

The purpose of the out-of-step blocking protection is to detect when the impedance enters the characteristic zones and stays there long enough to allow the zone timers to expire. This will enable distance relay blocking every time there is a possibility of undesired operation of distance relays.

In the stability study done, the impedance passed through the out-of-step blocking protection characteristics more than once. Table 4.2 provides a summary of the out-of-step blocking protection evaluation results. The percentage of detection is 100% as shown in Table 4.2 which means that detection for the purpose of blocking took place at all the locations. Even though one would expect perfect performance because the same stability study done for the purpose of evaluation was also used for setting the relays, the improvement in protection performance is evident. Furthermore, with reference to section 1.4 no 10 of Chapter 1, one stability study was used only to illustrate the new approach and the improvement in protection performance. As mentioned under section 1.4 no 10 of Chapter 1, in practice the application of out-of-step protection should be done with more than one stability study. The more stability studies used, the more reliable the protection.

Note that only the results for the portion of the Eskom system shown in Figure C1, in Appendix C was evaluated. Appendix F provides details of the protection performance results.

Table 4.2: Out-of-step blocking protection evaluation results

Total number of locations where out-of-step blocking protection was applied	23
Total number of locations where out-of-step blocking protection detected	23
% detection	100%
Reasons for nondetection	• None

Out-of-step tripping protection

The purpose of the out-of-step tripping protection is to **not** detect during power swing conditions but detect during system out-of-step conditions. This will enable it to send a tripping signal to selected locations to initiate islanding.

As in the case of the out-of-step blocking protection, the impedance passed through the out-of-step tripping protection characteristics more than once. Table 4.3 provides a summary of the out-of-step tripping protection evaluation results. The percentage of detection is 100% which means that non detection during power oscillations took place and detection during system instability took place. The protection performance was therefore correct at all the locations. Note that as for the out-of-step blocking protection evaluation, only the results for a portion of the Eskom system shown in Figure C1, in Appendix C was evaluated. Appendix F provides a detailed presentation of the protection performance results.

Table 4.3: Out-of-step tripping protection evaluation results

Total number of locations where out-of-step tripping protection was applied	4
Total number of locations where out-of-step tripping protection detected	4
% detection	100%
Reasons for nondetection	• None

4.5 Discussion of verification and protection performance results for the case study presented under section 4.4.

Both the out-of-step blocking and tripping protection relays performed correctly according to the simulation results.

The out-of-step blocking relays applied within the power system detected during power oscillations. As a results no undesired operation of distance relays occurred.

The out-of-step tripping relays did not detect during the power oscillation conditions but did detect when the system became unstable. This performance of the out-of-step tripping relays is correct as out-of-step tripping relays should only detect and operate when the system is unstable.

From the above findings, the manner in which the out-of-step protection was applied according to the new approach, shows an improvement on the existing approach presented in Chapter 3. Even though the test regarding the new approach's reliability was done based on only one stability study, a definite improvement in protection performance took place. For the one stability study done and using the existing approach, only 41, 67% of all out-of-step blocking relays and 33,33 % of all out-of-step tripping relays detected correctly. For the same stability study done and using the new approach, a 100 % of all out-of-step blocking relays and 100 % of all out-of-step tripping relays detected correctly. As already mentioned before, even though one would expect perfect performance because the same stability study done for the purpose of evaluation was also used for setting the relays, the improvement in protection performance is evident. With reference to section 1.4 no 10 of Chapter 1, one stability study was used only to illustrate the new approach and the improvement in protection performance. As mentioned under section 1.4 no 10 of Chapter 1, it is necessary in practice to make use of more than one stability study when applying out-of-step protection. The more studies, the more reliable the protection becomes.

4.6 Summary and conclusions

In this chapter a new approach of applying out-of-step protection, which involves the studying of the impedance locus behaviour at all locations, was presented. In summary the approach entails the following:

1. The modelling of the power system (the actual power system); and

2. Studying the apparent impedance at all the locations within the power system.

The new approach was developed based on the limitations and shortcomings of the existing approach. Table 4.1 at the beginning of this chapter provides a comparison between the existing approach and the new approach.

The new approach was illustrated, tested and investigated by means of a case study in which out-of-step protection was applied to an actual power system. An investigation of the case study results indicated the following regarding the new approach:

Both the out-of-step blocking and tripping protection relays performed correctly because:

1. Results regarding the behaviour of the electrical quantities of the power system was used to determine locations and settings. A two machine equivalent system approach to interpret results were not used; and
2. Studying the impedance locus behaviour at all locations is an indication of what an impedance type relay will 'see' during system unstable conditions. Location and setting decisions by the protection engineer are therefore based directly on what the relay will 'see'.

The conclusions from this chapter are the following:

1. Studying the actual behaviour of the power system electrical quantities provides more accurate results for applying out-of-step protection. The reason for this is that the electrical quantities of an actual system does not necessarily behave similarly to the behaviour of the electrical quantities of a two machine system; and

2. Applying out-of-step protection according to the new approach shown an improvement on the existing approach presented in Chapter 3. Table 4.4 shows a comparison between the protection performance results for the case studies done in chapters 3 and 4. It can be seen that the use of the new approach resulted in improved protection performance compared with the protection performance when applying the protection using the existing approach.

Table 4.4: Comparison between the protection performance results for the case studies done in chapters 3 and 4

Case study	**Blocking protection**	**Tripping protection**
Case study Chapter 3 (existing approach)	% detection = 41,67 %	% detection = 33,33 %
Case study Chapter 4 (new approach)	% detection = 100 %	% detection = 100 %

CHAPTER 5

REAL CASE APPLICATION OF THE NEW APPROACH

In 1996 and 1997 Eskom investigated the use of out-of-step tripping protection and in 1997 out-of-step tripping protection was applied to the Eskom transmission system, using the new approach and methods of calculating reach and timer settings as presented in Chapter 4. In this chapter this real case application of out-of-step tripping protection to the Eskom system is presented (Detail regarding this investigation is documented in reference [39].

For this real case application of the new approach the following input information from Eskom was required:

1. a range of stability study results[1];
2. the pre-selected relay locations[2];
3. the out-of-step tripping relay to be used; and
4. the out-of-step tripping philosophy and scheme design to be used as well as protection coordination philosophies applicable to out-of-step tripping protection.

Figure 5.1 shows a block diagram with the Eskom input requirements to enable the use of the new approach. The diagram also shows at what stage final results were determined and verification of the application took place.

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[1] The block diagram under section 1.1 in Chapter 1 illustrates the procedure followed when applying out-of-step protection. It can be seen that the system stability analysis investigation (block 1) serves as an input for the out-if-step protection application process (block 2).

[2] At the time when the individual analysis of the stability study results were done, only the new methods of calculating reach and timer settings were testes and accepted by Eskom. As a result locations for the out-of-step tripping relays were pre-selected according to the approach presented under section (5.1.2).

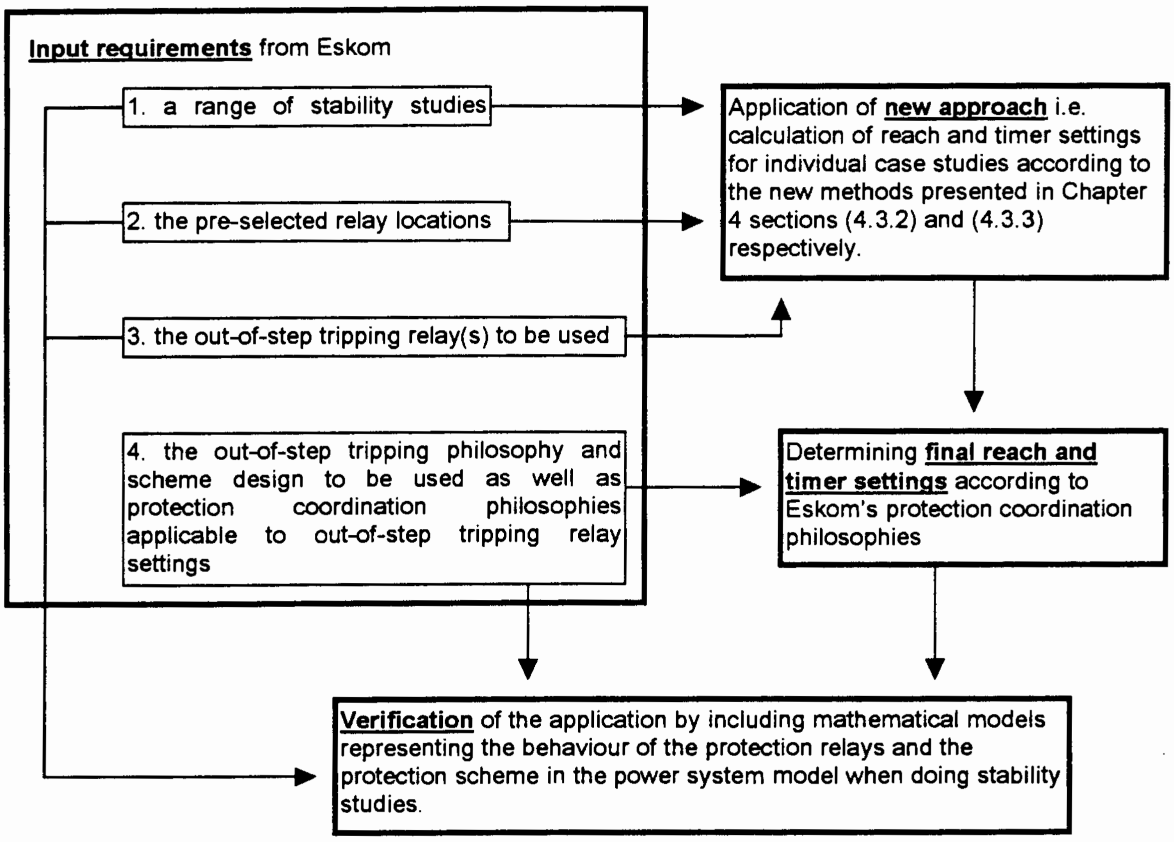


Figure 5.1: Block diagram showing the Eskom input requirements to enable the use of the new approach.

The application involved the following:

1. Modelling the Eskom power system for the purpose of system dynamic analysis.
2. Doing system stability studies to identify those studies which will be representative of most unstable scenarios within the Eskom system (four stability studies were identified which were used in the application process).
3. Analysing each of the four stability studies to determine suitable locations and settings for the individual stability studies. The settings were calculated according to the new methods presented in Chapter 4.
4. Analysing the overall results obtained under 3. to identify final locations and settings to comply with the protection coordination and application philosophies used by Eskom.

5. Verifying the choice of locations and settings by doing the four stability studies with protection models, representing the protection behaviour, included in the power system model. In addition to the four stability studies an accelerated simulation of the 7 June 1996 incident was also used to verify the out-of-step protection application.

5.1 Presenting the input information from Eskom to apply out-of-step tripping protection

The following sections present work done by Eskom. To illustrate and enable the use of the new approach, this work was needed as input information.

5.1.1 Presenting the stability studies [39]

Numerous stability studies were done to determine the conditions and contingencies for which the system will become unstable. From the range of stability studies that were done, four studies were identified to be representative of most system conditions and contingencies which will produce instability in the Eskom system. The four stability studies are those listed in Table 5.1.

Table 5.1 Stability studies representative of most system conditions and contingencies which will produce instability in the Eskom system

Case 1:	Busbar fault at Hydra during peak load conditions	Protection clearance by switching the following lines: • Beta series compensated • Droërivier series compensated 1&2 • Droërivier 3
Case 2:	Busbar fault at Hydra during minimum load conditions	Protection clearance by switching the following lines: • Beta series compensated • Droërivier series compensated 1&2 • Droërivier 3
Case 3:	Busbar fault at Grootvlei during peak load conditions Second busbar fault 1 second later at Alpha 765 kV during peak load conditions	Protection clearance by switching the following lines: • Leander • Perseus • Atlas • Zeus 1 Protection clearance by switching the following: • Alpha transformers 1&2 • Beta 765 kV 1&2 lines
Case 4:	Busbar fault at Beta during peak load conditions	Protection clearance by switching the following: • Beta transformers 1&2 • Perseus 1&2 lines • Hydra series compensated line

The angle results for these cases are shown in Figures 5.2a, 5.2b, 5.2c and 5.2d respectively.

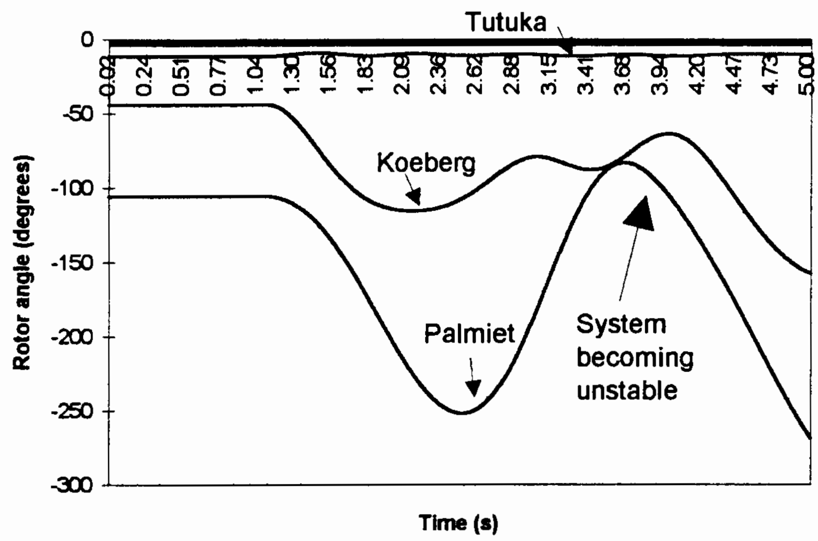


Figure 5.2a: Angle oscillation results for Case 1

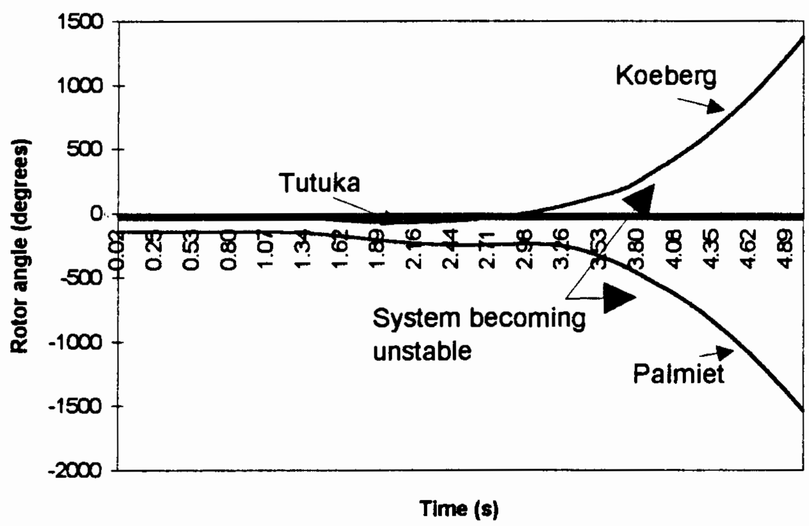


Figure 5.2b: Angle oscillation results for Case 2

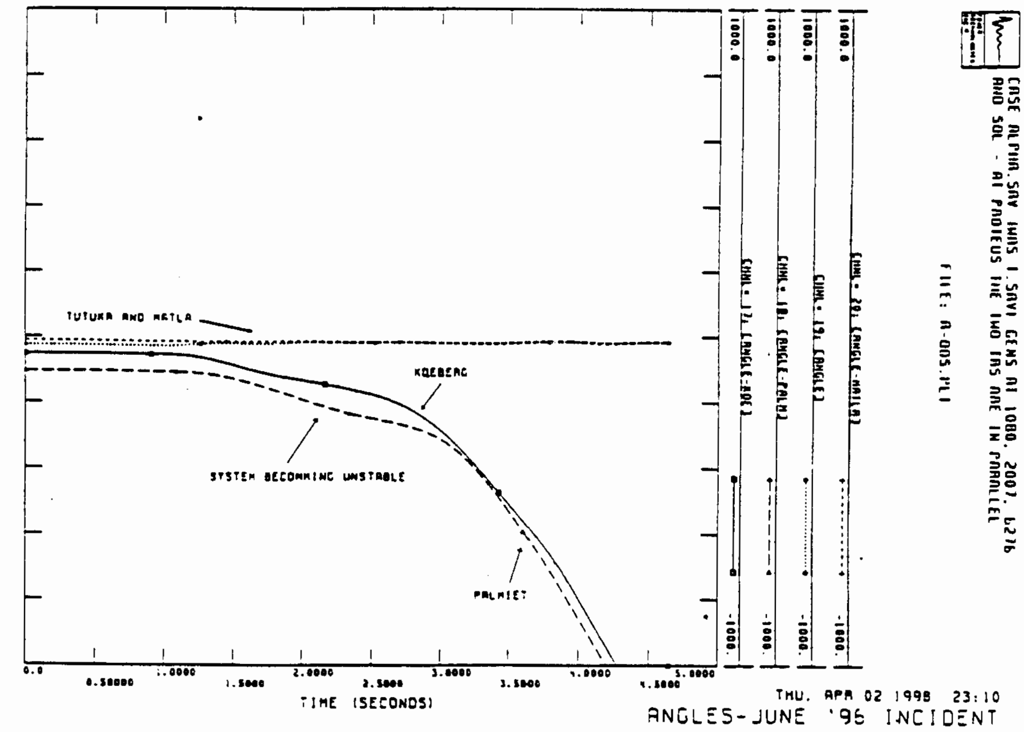


Figure 5.2c: Angle oscillation results for Case 3 (courtesy of Eskom report reference [37])

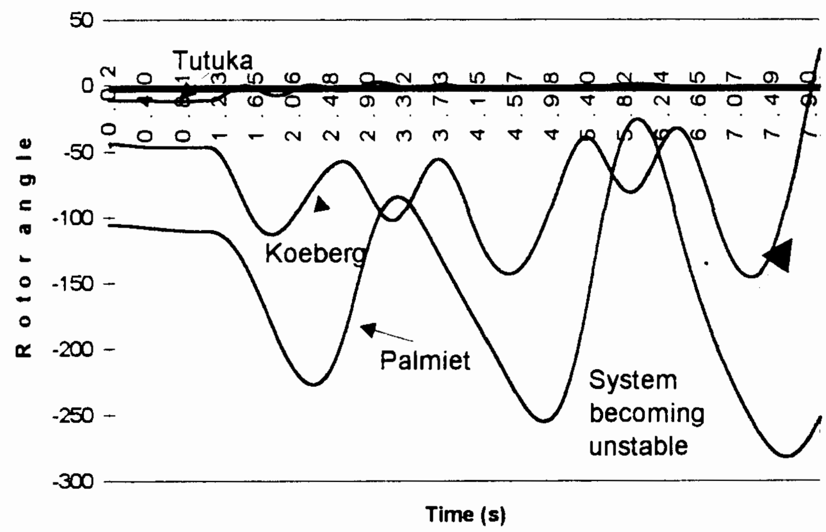


Figure 5.2d: Angle oscillation results for Case 4

5.1.2 Presenting the pre-selected out-of-step tripping relay locations [39]

At the time when the individual analysis of the stability study results were done, only the new methods of calculating the reach and timer settings were tested and accepted by Eskom. As a result, the choice of location(s) of the out-of-step tripping relays were made as follows:

2. For each of the four stability studies the impedance locus at the locations where the electrical centre is located was studied.
3. Based on the 'appearance' of the impedance loci as well as the detection philosophy for the out-of-step tripping relay used, locations were chosen.
4. The choice of locations were to be tested in the verification process.

The out-of-step tripping relay locations selected in this manner are listed in Table 5.2. From points 1 to 4 above it can be seen that neither the existing approach not the new approach was used in determining the locations. It was a strategic decision by Eskom to locate the relays at the locations listed in Table 5.2. The decision was based of points 1 to 4 above as well as what was found to be the most suitable location for the purpose of islanding (the islanding investigation is a separate investigation as indicated under section 1.1 in Chapter 1).

Table 5.2: Out-of-step tripping relay locations

Substation (SS)	**Transmission line (s) leaving the substation**
At Droërivier SS	• Droërivier-Hydra series compensated 400 kV lines
	• Droërivier-Muldersvlei series compensated 400 kV
	• Droërivier-Bacchus series compensated 400 kV line;
At Aries SS	• Aries-Kronos series compensated 400 kV line
	• Aries-Helios series compensated 400 kV line

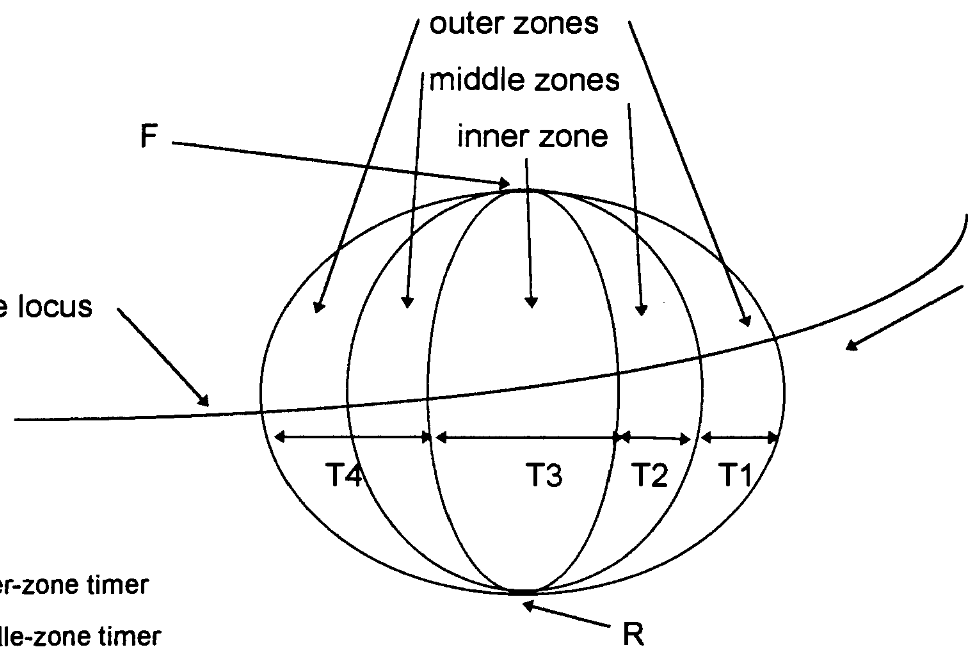
5.1.3 Presenting the out-of-step tripping relay used [39]

Eskom uses the OST1000 out-of-step tripping protection relay from General Electric [44]. It uses the characteristic type shown in the Figure 5.3 and detection takes place as follows (for more detail about the relay refer to reference [44]):

<u>Detection 'on the way in':</u> When the impedance enters the outer zone, the outer zone timer T1 will start. When the impedance enters the middle zone, after the outer zone timer has expired, the middle zone timer T2 will start. When the impedance enters the inner zone, after the middle zone timer has expired, an

inner zone timer T3 will start. Detection will take place after the inner zone timer has expired [44].

<u>Detection 'on the way out':</u> In addition to detection 'on the way in', a timer T4 will start when the impedance enters the middle zone for the second time after the inner zone timer has expired. Detection will take place when the impedance exists the characteristics after the timer T4 has expired [44].



T1 = Outer-zone timer
T2 = Middle-zone timer
T3 = Inner-zone timer
T4 = Timer for detection on the way out
F = Forward reach
R = Reverse reach

Figure 5.3: The GE OST1000 relay characteristics used by Eskom

For the application presented in this chapter Eskom used detection 'on the way' in. Timer T4 is therefore not used. In addition, Eskom set the timer T3 to be 10 msec in all application cases. The settings for the OST1000 relay which determines the size of the outer, middle and inner zones respectively are calculated according to the setting method presented in the OST1000 relay manual (refer to reference [44]).

5.1.4 Presenting the out-of-step tripping protection philosophy and scheme design used as well as the protection coordination philosophies applicable to out-of-step tripping relay settings [39]

In summary the out-of-step tripping philosophy and scheme design entails (The philosophy and scheme design was selected by Eskom in accordance with Eskom's protection coordination and application philosophies as well as the necessary requirements to allow islanding during unstable conditions for all possible stability studies investigated and not investigated [39].

- The choice of out-of-step tripping relay locations to be pre-selected according to the approach presented under section (5.1.2)

- OST1000 GE out-of-step tripping relays to be installed with a 'tripping on the way in' detection:

- Relays to be duplicated at their locations. A two out of two detection (main one and main two) should initiate operation (tripping of breaker).

- The required tripping scheme to be the following:

  <u>At each chosen location:</u>

  If any one of the relay 'pairs' should detect an out-of-step condition, tripping of breakers at the location should to take place which will enable islanding at that location.

  The above imply that when system instability is detected by out-of-step tripping relays at only one location, system separation will only take place at that one location. When detection takes place at all locations, system separation should be enabled at all locations. This is acceptable because investigations indicated that when system instability is detected at one of the locations, it will be detected at the other locations, unless the contingency which caused instability also resulted in the non availability of measurement at one of the other locations. This approach was chosen because a telecommunication system for the purpose of intertripping is not available at all locations within the Eskom system.

- Final reach settings for out-of-step tripping relays

  For each location, the maximum forward and reverse reach calculated for all stability study cases to be taken as the final forward and reverse reach setting respectively. The reason for this approach is because the maximum reach will also enable detection for those cases where a smaller reach setting would have been sufficient. The approach suggests that the relay characteristics should rather be larger than smaller to enable detection of all possible unstable conditions.

- Final timer settings for out-of-step tripping relays

  For each location, the minimum T1 and T2 timer setting (refer to section (5.1.3)) for all stability study cases, to be taken as the final T1 and T2 timer setting respectively. The reason for this approach is because the minimum timer setting will also enable detection for those cases where the rate of change of the impedance may be faster that what the minimum timer has been calculated for. The approach suggests that the relay timers should time out faster rather than slower as this decreases the risk of an unstable condition not being detected.

5.2 The calculation of the relay reach and timer settings according to the new methods in the new approach presented in this thesis [39]

5.2.1 Out-of-step tripping relay reach settings

With the locations being pre-selected, the ROWs for each location as well as the respective $R_{enter\text{-}actual}$, $X_{enter\text{-}actual}$, $R_{exit\text{-}actual}$, and $X_{exit\text{-}actual}$ values at each location for each study had to be determined before reach settings could be calculated. The following steps were therefore followed:

Step 1: Determining the ROWs

The ROWs were determined according to the specification presented under section (4.3.1b), Chapter 4. This specification is used when ROWs should be selected to determine whether locations are suitable for out-of-step tripping protection. For clarity the specification is repeated:

Xa = the maximum forward reach specified by the relay manufacturer which will be within the design limit of the relay type to be used;

Xb = the maximum reverse reach specified by the relay manufacturer which will be within the design limit of the relay type to be used;

Rl = Rr

= the maximum allowable resistive reach which will avoid load encroachment.

ROW's Rl and Rr boundaries

Eskom's National Control allows lines to be loaded up to their 90° thermal limit after which load shedding to deload the line becomes a consideration. The load encroachment border should therefore allow for this operating condition. This is done by calculating the apparent impedance in the impedance plane which corresponds to the 90° thermal limit loading of the line at those locations where relays were to be located.

The 90° MVA thermal limits for the lines at the locations where relays were to be located are listed in Table 5.3. The apparent impedance loading in ohms primary and pu are also listed.

Table 5.3: 90° line loading (MVA, Ohms primary, pu)

Location	90° thermal ratings (MVA) (all 400 kV lines)	90° impedance loading limit (Ohms primary) = 400 kV^2/line rating MVA	90° impedance loading limit (pu) = imp (ohms)/1600 (system base impe)
Aries-Kronos	876	183	0,11
Aries-Helios	876	183	0,11
Droërivier-Hydra	1124	142	0,09
Droërivier-Bacchus	1028	156	0,10
Droërivier-Muldersvlei	1028	156	0,10

The ROW's Rl and Rr boundaries for the respective locations were chosen to be those listed in Table 5.3.

ROW's Xa and Xb boundaries

Maximum forward and reverse reach settings for the OST1000 relay (x25 Tap and 1 Amp secondary) should not exceed 93,75 ohms secondary according to the relay specifications [44]. Using the CT and VT ratios at the respective locations where relays are to be located (listed in Table 5.4) the pu Xa and Xb boundaries for the ROWs were calculated.

Table 5.4: pu Xa and Xb boundaries for the ROWs

Location	CT ratio (VT ratio: 400 kV :110 V)	Maximum Ohms settings (x25 Tap and 1 Amp secondary)	ROW's Xa and Xb boundaries note: |Xa| = |Xb|
Aries-Kronos	1200 : 1	93,75 Ohms sec	0,178 pu
Aries-Helios	1200 : 1	93,75 Ohms sec	0,178 pu
Droërivier-Hydra	1600 : 1	93,75 Ohms sec	0,133 pu
Droërivier-Bacchus	1600 : 1	93,75 Ohms sec	0,133 pu
Droërivier-Muldersvlei	1600 : 1	93,75 Ohms sec	0,133 pu

Step 2: Determining $R_{enter\text{-}actual}$, $X_{enter\text{-}actual}$, $R_{exit\text{-}actual}$, and $X_{exit\text{-}actual}$

The $R_{enter\text{-}actual}$, $X_{enter\text{-}actual}$, $R_{exit\text{-}actual}$, and $X_{exit\text{-}actual}$ entry and exit values were calculated according to the method presented under section (4.3.1b), Chapter 4. This method was explained to be the following: $R_{enter\text{-}actual}$, $X_{enter\text{-}actual}$, $R_{exit\text{-}actual}$ and $X_{exit\text{-}actual}$ are determined by capturing (monitoring) the R and X values of the impedance locus as it crosses the ROW boundaries. This can be done within a power system simulation tool (PSS/E in the case on the research) when doing a stability study. A mathematical model representing the boundaries of the ROW can be included in the power system model. For the purpose of out-of-step tripping protection The $R_{enter\text{-}actual}$, $X_{enter\text{-}actual}$, $R_{exit\text{-}actual}$ and $X_{exit\text{-}actual}$ are captured only for those times when detection for the purpose of tripping should take place i.e. during those times when the power system becomes unstable. The times when detection should take place were obtained from the rotor angle oscillation results shown in Figure 5.2. Table 5.5 lists the $R_{enter\text{-}actual}$, $X_{enter\text{-}actual}$, $R_{exit\text{-}actual}$, and $X_{exit\text{-}actual}$ during that time when detection during each of the four unstable cases should take place i.e. when the system becomes unstable.

Step 3: Calculating the relay reach settings

The reach settings for each stability study were calculated using the new method presented in Chapter 4 under section 4.3.2b. Table 5.5 also lists the calculated reach settings required for the individual stability study cases. Note that for cases 1 and 2 the contingencies involved the loss of the 400 kV supply to Droërivier SS. For this reason the relays located at Droërivier will not 'see' any impedance and therefore not detect the instability. As an example the reach settings for case 4 at the Droërivier-Bacchus location is shown:

Reach settings for out-of-step tripping protection at Droërivier-Bacchus - Case 4

To allow the out-of-step tripping relay at Droërivier-Bacchus to detect power system unstable conditions during a contingency such as the one simulated in case 4, the forward and reverse reaches in the impedance plane are calculated as follows (Figure 5.4 shows the impedance locus and the ROW to enable the calculation of the reach settings. Figure 5.5 shows the relay characteristics, with calculated reach settings, in the impedance plane):

$Zf = |Zf| \angle \varphi l$ (eq. 4.17)

$= 0{,}101 \text{ pu } \angle 81{,}56°$

$Zr = |Zr| \angle 180° + \varphi l$ (eq. 4.18)

$= 0{,}129 \text{ pu } \angle 180° + 81{,}56°$

where

Zf = forward reach

$|$maximum forward reach specified for the out-of-step protection used$|$ = 0,178 pu [Table 5.4]

Zr = reverse reach

$|$maximum reverse reach specified for the out-of-step protection used$|$ = 0,178 pu [Table 5.4]

$R_{enter\text{-}actual}$ = -0,099 pu [from Table 5.5]

$X_{enter\text{-}actual}$ = -0,083 pu [from Table 5.5]

$R_{exit\text{-}actual}$ = 0,099 pu [from Table 5.5]

$X_{exit\text{-}actual}$ = 0,019 pu [from Table 5.5]

$X_{enter\text{-}actual} < 0$ and $X_{exit\text{-}actual} > 0$ therefore:

$|Zf| = \sqrt{(R_{exit\text{-}actual}^2 + X_{exit\text{-}actual}^2)}$ (eq. 4.26)

$= 0{,}101$ pu

$X_{enter\text{-}actual} < 0$ and $X_{exit\text{-}actual} > 0$ therefore:

$|Zr|$ = the greater of $\sqrt{(R_{enter\text{-}actual}^2 + X_{enter\text{-}actual}^2)}$ and $\sqrt{(R_{exit\text{-}actual}^2 + X_{exit\text{-}actual}^2)}$

$= 0{,}1290$ pu (eq. 4.27)

φl = line angle

$$= \tan^{-1}\frac{Xl}{Rl} \quad \text{(eq. 4.19)}$$

$$= \tan^{-1}\frac{0{,}0407}{0{,}0060}$$

$= 81{,}61°$

Rl+jXl = line impedance

$= 0{,}0060 + j\,0{,}0407$ [from Table A1, in Appendix A]

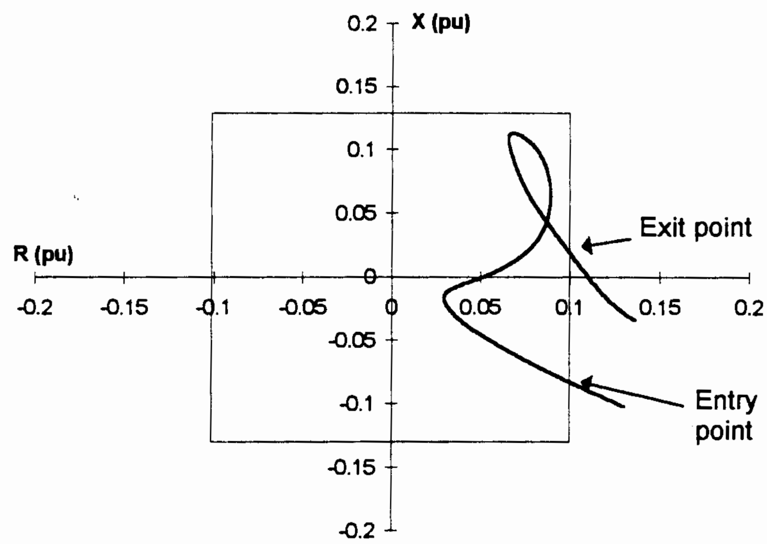


Figure 5.4: ROW and impedance 'seen' at Droërivier-Bacchus - Case 4

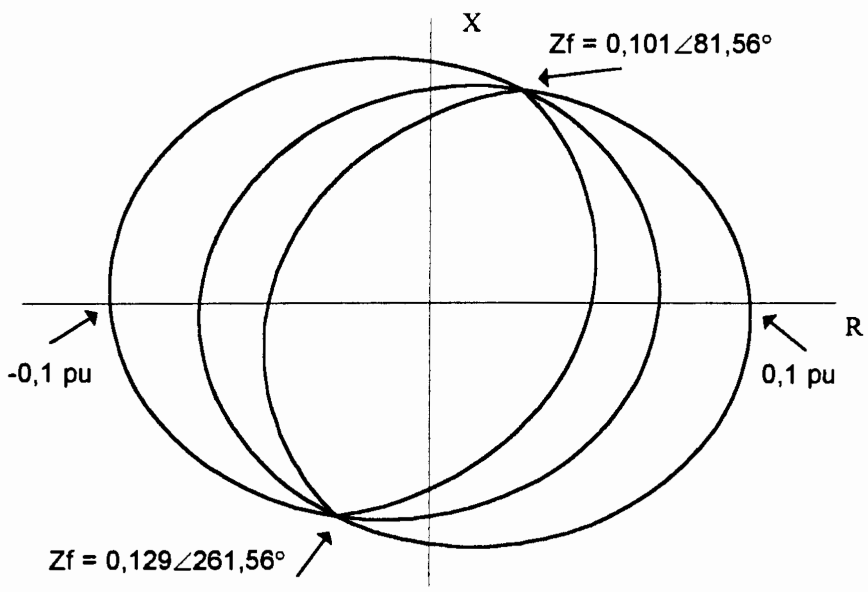


Figure 5.5: Out-of-step tripping protection characteristics with forward and reverse reaches, load encroachment outer boundaries also shown. The settings for the OST1000 relay which determines the size of the outer, middle and inner zones respectively were calculated according to the setting method presented in the OST1000 relay manual [44].

5.2.2 Out-of-step tripping relay timer settings

The timer settings for each stability study were calculated using the new method presented in Chapter 4 under section 4.3.3. With the reach settings known and the size of the outer, middle and inner zones respectively known, the OST1000 relay characteristics were mathematically modeled at the chosen locations using the available mathematical models for protection in the PTI PSS/E library of models. The stability studies were repeated and the times when the impedance locus entered and exited the various characteristic zones were recorded within PSS/E for each respective stability study case. Figure 5.6 shows typical relay characteristics for an OST1000 relay. The entry and exist times (t1, t2 and t3) recorded during a stability study is shown. The recorded times in PSS/E (t1, t2 and t3) as well as the calculated T1 and T2 timer settings for the respective stability study cases, are listed in Table 5.6.

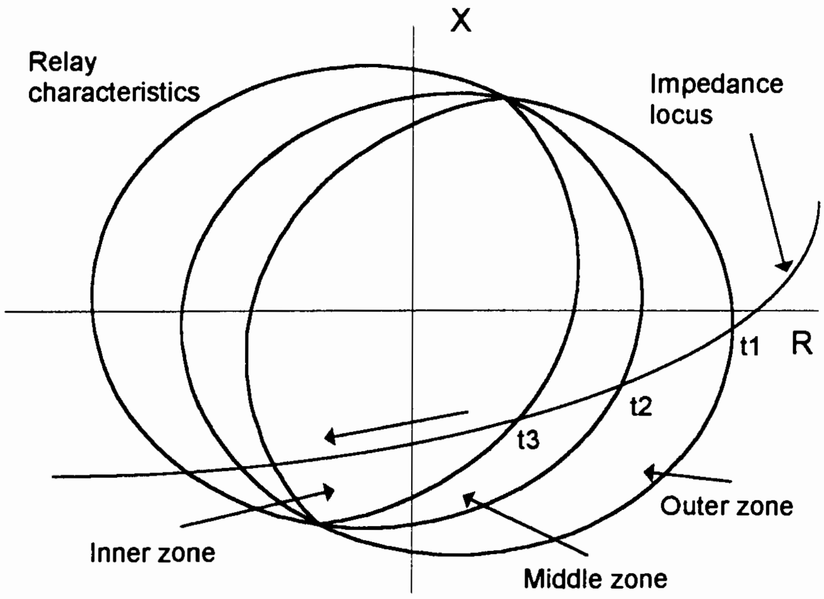


Figure 5.6: Times recorded on PSS/E simulation to calculate timer settings

As an example the timer setting calculations for case 4 at the Droërivier-Bacchus location is shown:

<u>Timer settings for the out-of-step tripping protection at Droërivier-Bacchus-case 4</u>

Figure 5.7 shows the protection characteristics, with the impedance 'seen' at Bacchus-Droërivier during the out-of-step condition simulated in case 4. The zone entry times as recorded in PSS/E are also shown.

From Figure 5.7 the timers T1 and T2 are calculated as follows:

T1	=	t2 - t1	(eq. 4.30)
	=	7,05 - 6,98	
	=	70 ms	
T2	=	t3 - t2	(eq. 4.31)
	=	7,16 - 7,05	
	=	110 ms	

where

T1	=	ost1000 outer-zone timer
T2	=	ost1000 middel-zone timer

t1	=	6,98 s	[From Table 5.6]
t2	=	7,05 s	[From Table 5.6]
t3	=	7,16 s	[From Table 5.6]

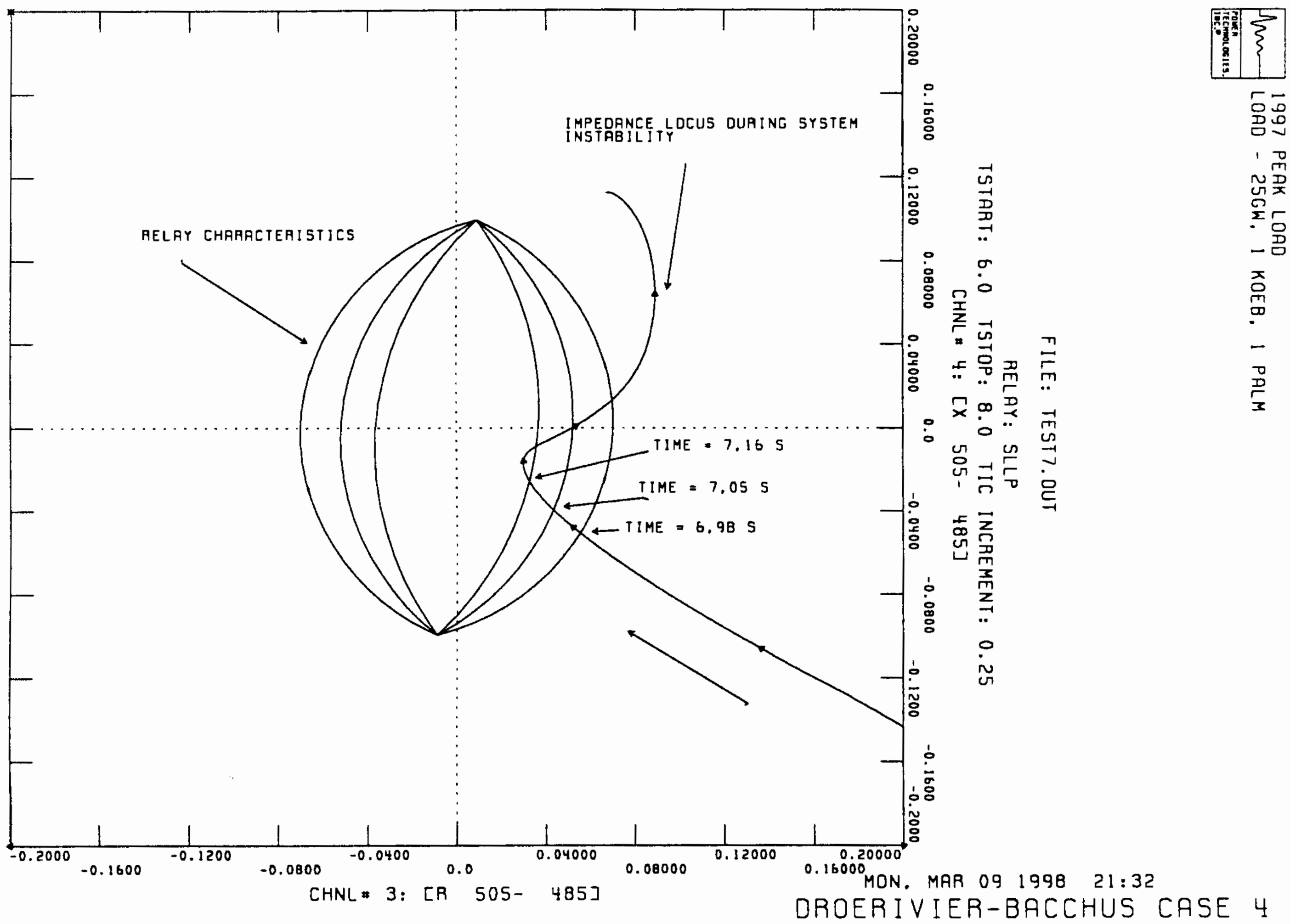


Figure 5.7: Impedance locus and out-of-step tripping protection characteristics at Bacchus-Droërivier - Case 4

Table 5.5: R + jX ROW entries and exits and calculated reach settings

	Locations	R + jX entry (pu)	R + jX exit (pu)	|Zf| (pu)	angle (degrees)	|Zr| (pu)	angle (degrees)
Case 1	Aries-Kronos	-0,100-j0,004	-	0,178	76,68	0,101	256,68
system	Aries-Helios	0,120-j0,010	-	0,178	75,80	0,120	255,80
unstable	Droërivier-Hydra	-	-	-	85,47	-	265,47
t>3,5 s	Droërivier-Bacchus	-	-	-	81,56	-	261,56
	Droërivier-Muldersvlei	-	-	-	81,88	-	261,88
Case 2	Aries-Kronos	-0,119-j0,019	-0,118-j0,040	0,178	76,68	0,125	256,68
system	Aries-Helios	0,119-j0,002	0,119-j0,246	0,122	75,80	0,119	255,80
unstable	Droërivier-Hydra	-	-	-	85,47	-	265,47
t>3,5 s	Droërivier-Bacchus	-	-	-	81,56	-	261,56
	Droërivier-Muldersvlei	-	-	-	81,88	-	261,88
Case 3	Aries-Kronos	-0,119+j0,086	-0,117-0,015	0,147	76,68	0,118	256,68
system	Aries-Helios	-0,000-j0,177	0,119-j0,092	0,178	75,80	0,177	255,80
unstable	Droërivier-Hydra	-0,039+j0,133	-0,118-j0,055	0,133	85,47	0,130	265,47
t>2,5 s	Droërivier-Bacchus	0,017-j0,132	0,024+j0,130	0,132	81,56	0,133	261,56
	Droërivier-Muldersvlei	0,043-j0,132	0,119-j0,066	0,133	81,88	0,133	261,88
Case 4	Aries-Kronos	-0,109+j0,024	did not exit	0,112	76,68	0,178	256,68
system	Aries-Helios	0,119-j0,109	0,110-j0,041	0,178	75,80	0,118	255,80
unstable	Droërivier-Hydra	0,119-j0,094	0,119+j0,001	0,119	85,47	0,133	265,47
t>6,5 s	Droërivier-Bacchus	0,099-j0,083	0,099+j0,019	0,101	81,56	0,129	261,56
	Droërivier-Muldersvlei	0,119-j0,098	0,118-j0,049	0,133	81,88	0,133	261,88

Table 5.6: Zone entry and exit times as well as calculated timer settings

	Locations	t1 (s)	t2 (s)	t3 (s)	T1 (s)	T2 (s)
Case 1	Aries-Kronos	1,32	1,39	2,2	0,07	0,81
system	Aries-Helios	4,2	4,25	4,74	0,05	0,49
unstable at	Droërivier-Hydra	-	-	-	-	-
t>3,5 s	Droërivier-Bacchus	-	-	-	-	-
	Droërivier-Muldersvlei	-	-	-	-	-
Case 2	Aries-Kronos	3,12	3,16	3,48	0,04	0,32
system	Aries-Helios	2,96	2,99	3,06	0,03	0,07
unstable at	Droërivier-Hydra	-	-	-	-	-
t>3,5 s	Droërivier-Bacchus	-	-	-	-	-
	Droërivier-Muldersvlei	-	-	-	-	-
Case 3	Aries-Kronos	2,58	2,59	2,68	0,01	0,09
system	Aries-Helios	2,65	2,69	2,87	0,04	0,18
unstable at	Droërivier-Hydra	2,65	2,66	2,82	0,01	0,16
t>2,5 s	Droërivier-Bacchus	2,65	2,66	2,80	0,01	0,14
	Droërivier-Muldersvlei	2,61	2,63	2,81	0,02	0,18
Case 4	Aries-Kronos	6,92	7,05	7,195	0,13	0,15
system	Aries-Helios	6,95	7,05	7,13	0,09	0,08
unstable at	Droërivier-Hydra	7,03	7,07	7,19	0,04	0,13
t>6,5 s	Droërivier-Bacchus	6,98	7,05	7,16	0,07	0,11
	Droërivier-Muldersvlei	7,02	7,07	7,19	0,05	0,13

5.3 Final choice for reach and timer settings according to Eskom's protection philosophies presented under section (5.1.4) [39]

With reference to Eskom's protection application philosophies presented under section (5.1.4) above the maximum forward and reverse reach calculated for all four stability study cases, were taken as the final forward and reverse reach setting respectively. The final forward and reverse reach value, taken from Table 5.5 are listed in Table 5.7.

Table 5.7: Final reach settings for the specific locations

Locations	Forward reach	Reverse reach
Aries-Kronos	0,178 $\angle 76,68°$	0,178 $\angle 256,68°$
Aries-Helios	0,178 $\angle 75,80°$	0,177 $\angle 255,80°$
Droërivier-Hydra	0,133 $\angle 85,47°$	0,133 $\angle 265,47°$
Droërivier-Bacchus	0,133 $\angle 81,56°$	0,133 $\angle 261,56°$
Droërivier-Muldersvlei	0,133 $\angle 81,88°$	0,133 $\angle 261,88°$

With reference to Eskom's protection application philosophy presented under section (5.1.4) above the minimum T1 and T2 timer setting for all four stability study cases, were taken as the final T1 and T2 timer setting respectively. The final T1 and T2 timer settings, taken from Table 5.6 are listed in Table 5.8.

Table 5.8: Final timer settings for the specific locations

Locations	T1 (s)	T2 (s)
Aries-Kronos	0,01	0,09
Aries-Helios	0,03	0,07
Droërivier-Hydra	0,01	0,16
Droërivier-Bacchus	0,01	0,14
Droërivier-Muldersvlei	0,02	0,18

5.4 Verifying the locations, settings and application [39]

Using the final reach and timer settings determined from the overall analysis the behaviour of the protection was mathematically modeled at the chosen locations. The protection was modelled to behave according to Eskom's out-of-step tripping protection scheme design presented under section (5.1.4). The available mathematical models for protection in the PTI PSS/E library of models were used.

The chosen locations and settings were verified by repeating the four stability study cases. The results indicated that all the out-of-step tripping relays operated at their respective locations. The relays did not detect during power oscillating conditions but did detect during those times when the system became unstable. The results of the verification therefore indicated correct application (locations, settings and out-of-step protection scheme-design).

In addition to the four stability study cases, the protection locations, settings and the out-of-step protection scheme design for the Eskom system were also verified by simulating an accelerated version of the system unstable incident that occurred within the Eskom system on 7 June 1996[3]. The results indicated that even though relays at some of the locations did not operate, the protection scheme operated correctly for the purpose of islanding. It was therefore conclude that the out-of-step protection application is correct because relays at the remaining locations operated to allow correct performance of the overall protection scheme. (The possibility of nonoperation of relays during instability scenarios not covered in the selection of stability studies used to determine locations and settings were discussed under section 1.4 no 10 of Chapter 1.)

A summary of the verification results i.e. status of detection and at what time detection took place can be seen in Table 5.9.

Table 5.9 also shows protection performance for the accelerated simulation of the June 1996 incident. Figure 5.8 shows the angle oscillations during the June 1996 incident. It can be seen in Figure 5.8 that system oscillations occurred before the system became unstable. The accelerated simulation of the incident was done over a period of 5 seconds even though the actual time during the incident was approximately 45 minutes [37]. According to the 5 second simulation the system

[3] Note that the simulation of the 7 June 1996 incident was not used for calculating settings. The reason for this is that the simulation was not completed at that time when settings were calculated. However, during the commissioning period, an accelerated simulation of the incident was completed and could therefore be used to verify the out-of-step tripping protection application.

went unstable after 2 seconds and for the purpose of verification, detection of instability must take place during this time.

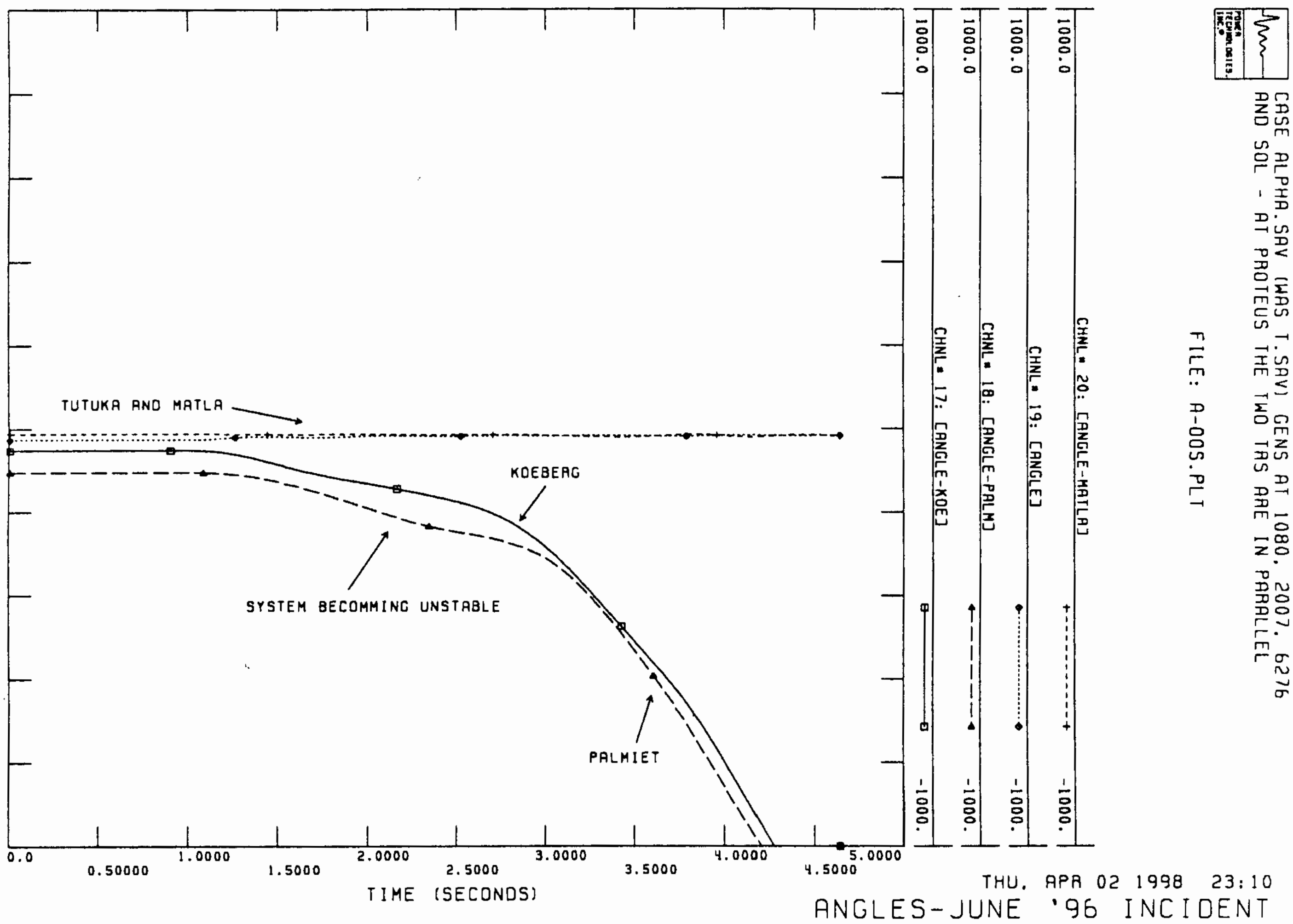


Figure 5.8 Angle oscillation results for the June 1996 incident (courtesy of Eskom report reference [37])

Table 5.9a: Relay performance for case 1

	Locations	Relay performance	Comment	Protection performance according to philosophy
Case 1	Aries-Kronos	No detection during oscillations (t < 3,5 s). Detection during instability at t = 4,691 s	The tripping protection did not detect to initiate operation during power oscillations but did detect to initiate operation during system instability.	The relays at both the locations at Aries detected and system separation was initiated at Aries.
system unstable at	Aries-Helios	No detection during oscillations (t < 3,5 s). Detection during instability at t = 4,771 s	As above	In the case of Droërivier the system is already separated because of the contingency.
t>3,5 s	Droërivier-Hydra	No detection during oscillations (t < 3,5 s). No detection during instability (t > 3,5 s).	The tripping protection did not detect to initiate operation during power oscillations or system instability. The contingency involved the loss of transmission lines to Droërivier and measurement for the purpose of protection could not take place.	Islanding therefore took place when the system became unstable which indicate correct application of out-of-step tripping protection.
	Droërivier-Bacchus	No detection during oscillations (t < 3,5 s). No detection during instability (t > 3,5 s).	As above	
	Droërivier-Muldersvlei	No detection during oscillations (t < 3,5 s). No detection during instability (t > 3,5 s).	As above	

Table 5.9b: Relay performance for case 2

	Locations	Relay performance	Comment	Protection performance according to philosophy
Case 2 system unstable at t>3,5 s	Aries-Kronos	No detection during oscillations (t < 3,5 s). Detection during instability at t = 3,536 s	The tripping protection did not detect to initiate operation during power oscillations but did detect to initiate operation during system instability.	The relays at both the locations at Aries detected and system separation was initiated at Aries. In the case of Droërivier the system is already separated because of the contingency. Islanding therefore took place when the system became unstable which indicate correct application of out-of-step tripping protection.
	Aries-Helios	No detection during oscillations (t < 3,5 s). Detection during instability at t = 3,618 s	As above	
	Droërivier-Hydra	No detection during oscillations (t < 3,5 s). No detection during instability (t > 3,5 s).	The tripping protection did not detect to initiate operation during power oscillations or system instability. The contingency involved the loss of transmission lines to Droërivier and measurement for the purpose of protection could not take place.	
	Droërivier-Bacchus	No detection during oscillations (t < 3,5 s). No detection during instability (t > 3,5 s).	As above	
	Droërivier-Muldersvlei	No detection during oscillations (t < 3,5 s). No detection during instability (t > 3,5 s).	As above	

Table 5.9c: Relay performance for case 3

	Locations	Relay performance	Comment	Protection performance according to philosophy
Case 3 system unstable at t>2,5 s	Aries-Kronos	No detection during oscillations (t < 2,5 s). Detection during instability at t = 2,936 s	The tripping protection did not detect to initiate operation during power oscillations but did detect to initiate operation during system instability.	The relays at both the locations at Aries detected. The relays at the three locations at Droërivier also detected. System separation was therefore initiated at both Aries and Droërivier. Islanding therefore took place when the system became unstable which indicate correct application of out-of-step tripping protection.
	Aries-Helios	No detection during oscillations (t < 2,5 s). Detection during instability at t = 2,796 s	As above	
	Droërivier-Hydra	No detection during oscillations (t < 2,5 s). Detection during instability at t = 2,826 s	As above	
	Droërivier-Bacchus	No detection during oscillations (t < 2,5 s). Detection during instability at t = 2,796 s	As above	
	Droërivier-Muldersvlei	No detection during oscillations (t < 2,5 s). Detection during instability at t = 2,817 s	As above	

Table 5.9d: Relay performance for case 4

	Locations	Relay performance	Comment	Protection performance according to philosophy
Case 4	Aries-Kronos	No detection during oscillations (t < 6,5 s). Detection during instability at t = 7,236 s	The tripping protection did not detect to initiate operation during power oscillations but did detect to initiate operate during system instability.	The relays at both the locations at Aries detected. The relays at the three locations at Droërivier also detected. System separation was therefore initiated at both Aries and Droërivier. Islanding therefore took place when the system became unstable which indicate correct application of out-of-step tripping protection.
system unstable at	Aries-Helios	No detection during oscillations (t < 6,5 s). Detection during instability at t = 7,318 s	As above	
t>6,5 s	Droërivier-Hydra	No detection during oscillations (t < 6,5 s). Detection during instability at t = 7,246 s	As above	
	Droërivier-Bacchus	No detection during oscillations (t < 6,5 s). Detection during instability at t = 7,217 s	As above	
	Droërivier-Muldersvlei	No detection during oscillations (t < 6,5 s). Detection during instability at t = 7,207 s	As above	

Table 5.9e: Relay performance for the June 1996 incident

	Locations	Relay performance	Comment	Protection performance according to philosophy
June 1996 incident	Aries-Kronos	No detection during oscillations (t < 2 s). Detection during instability at t = 2,450 s	Tripping protection did not detect to initiate operation during oscillations but did detect to initiate operation during instability.	The relays at one of the locations at Aries detected. System separation was therefore initiated at Aries.
system unstable at t>2 s	Aries-Helios	No detection during oscillations (t < 2 s). No detection during instability (t > 2 s)	Tripping protection did not detect to initiate operation during oscillations. The protection also did not detect to initiate operation during instability. The reason for this is that for the particular system condition, the instability was not observed at Aries-Helios.	The relays at one of the locations at Droërivier detected. System separation was therefore initiated at Droërivier.
refer to Figure (5.7) and ref [37]	Droërivier-Hydra	No detection during oscillations (t < 2 s). No detection during instability (t > 2 s)	Tripping protection did not detect to initiate operation during oscillations. The protection also did not detect to initiate operation during instability. The reason for this is that for the particular system condition, the instability was not observed at Droërivier-Hydra.	Islanding therefore took place when the system became unstable which indicate correct application of out-of-step tripping protection. Note that the out-of-step tripping protection scheme operated correctly even though some of the relays did not observe instability.
	Droërivier-Bacchus	No detection during oscillations (t < 2 s). Detection during instability at t = 2,380 s	Tripping protection did not detect to initiate operation during oscillations but did detect to initiate operation during instability.	
	Droërivier-Muldersvlei	No detection during oscillations (t < 2 s). No detection during instability (t > 2 s)	Tripping protection did not detect to initiate operation during oscillations. The protection also did not detect to initiate operation during instability. The reason for this is that the Droërivier-Muldersvlei line was not in service when the incident took place. No measurement was therefore available to allow detection.	

5.5 Summary and conclusions

In this chapter a real case application of the new approach was presented (Detail regarding this investigation is documented in reference [39]). The real case involves the application of out-of-step tripping protection to the Eskom system which took place in 1997. Eskom used the new approach to calculate reach and timer settings for their out-of-step tripping relays. For this real case application the locations were pre-selected. The locations, settings and scheme design were verified through simulation by doing the stability studies used to determine settings. In addition to these stability studies, an accelerated simulation of the actual incident that occurred in June 1996 was also done.

The verification results were presented in this chapter. The results indicated that the choice of locations, settings and protection scheme design for the purpose of islanding would be suitable for most unstable conditions (including the incident that occurred on the 7 June 1996) within the Eskom system.

As a result of the investigation and protection performance results presented in this chapter, Eskom tested and commissioned their out-of-step tripping relays at the locations listed in Table 5.2. The relays were set with the reach and timer settings listed in Tables 5.7 and 5.8 respectively. The testing and commissioning of the relays took place in May of 1997.

From this chapter the following can be concluded:

1. The new approach is reliable because application was tested with a number of stability studies and correct protection performance for the purpose of islanding resulted in each case;

2. It is believed that the new approach could be acceptable for any power system or utility because it proved to be successful for the Eskom system. The reason for this is that the Eskom power system, just like other power systems and

utilities, also experiences a variety of operating conditions and disturbances and its configuration is typical of a power system that experiences stability related constraints.

CHAPTER 6

SUMMARY, DISCUSSION AND CONCLUSIONS

6.1 Summary

In this research the application of out-of-step blocking and tripping protection was investigated. The motivation for the research was provided by system unstable incidents that occurred in Eskom, the electricity utility of South Africa.

Detailed out-of-step protection investigations indicated that the out-of-step blocking and tripping protection applied according to a method which is based on an existing approach failed to detect the unstable conditions. The investigations indicated problems with regard to the following:

- Locations of out-of-step tripping protection;
- Out-of-step tripping-relay forward and reverse reach settings;
- Out-of-step blocking and tripping protection timer settings; and
- Characteristic types used for the purposes of out-of-step blocking and tripping protection.

In summary, the detailed investigations showed that the existing approach of applying out-of-step blocking and tripping protection is not adequate as it does not allow the necessary observability[1] and correct detection of rotor-angle unstable conditions [38,39].

The existing approach (presented in Chapter 3) appears to involve the following according to literature:

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[1] The use of the term observability are in the context of local "observation" i.e. the trajectory of an impedance locus as 'seen' by an impedance type relay. It does not refer to "observability and controllability" of power system states.

1. the approach is based on the behaviour of the electrical quantities (voltage, current, rotor angle, etc.) of a two machine power system;
2. the tripping relay locations are selected based on the location of an electrical centre (also known as the voltage zero), determined from stability studies;
3. in many cases out-of-step blocking protection is located at all the locations where distance relays are located;
4. a source impedance, or equivalent impedance representing system impedance in front of and behind a location is used to calculate the forward and reverse reach settings respectively for a relay located at that location; and
5. a maximum swing frequency, determined from stability studies, is used to calculate relay timer settings.

The existing approach was tested and investigated by means of a case study in which out-of-step protection was applied to an actual power system. The case study results indicated the following regarding the existing approach:

1. During system instability, the electrical quantities of an actual power system does not necessarily behave similar to the behaviour of the electrical quantities of a two machine system;

2. The assumption that all distance relays should be equipped with out-of-step blocking protection may be over-cautious because many such blocking relays may be redundant in many stability events;

3. The use of an electrical centre area to identify locations for out-of-step tripping relays are not reliable to ensure observability of unstable conditions;

4. The use of equivalent impedances to calculate reach settings ignores dynamic influences within the real system that affects system impedance; and

5. The use of swing frequencies ignores the dynamic influences within the power system which affects the voltage and current measured by the relay at the relay location.

In summary it is believed that too many assumptions are made in the existing approach and it seems that there is a need to either improve the existing approach or to identify and develop a new approach for applying out-of-step protection.

Therefore, from limitations and shortcomings identified in the investigation of the existing approach, a new approach, based on the studying of the impedance locus at all locations, was developed. In summary the new approach entails the following: (Chapter 4 presents the new approach in detail)

1. mathematical modelling of the power system (the actual power system); and
2. studying the impedance locus behaviour at all relay locations.

The new approach was tested and investigated by means of a case study in which out-of-step protection was applied to an actual power system. An investigation of the case study results indicated the following regarding the new approach:

Both the out-of-step blocking and tripping protection relays performed correctly because:

1. Results regarding the behaviour of the electrical quantities of the power system was used to determine locations and settings. A two machine equivalent system approach to interpret results were not used; and
2. Studying the impedance locus behaviour at all distance relay locations is an indication of what an impedance type relay will 'see' during system unstable conditions. Location and setting decisions by the protection engineer are therefore based directly on what the relay will 'see'.

As additional support for the new approach, a real case application of out-of-step tripping protection to the Eskom system was presented in Chapter 5. This real case is an Eskom investigation which took place in 1996 and 1997. Eskom investigated the use of out-of-step tripping protection and in 1997 out-of-step tripping protection was applied to the Eskom transmission system, using the new approach and methods of calculating reach and timer settings as presented in Chapter 4. Eskom tested and commissioned their out-of-step tripping relays at the locations identified according to the new approach. The relays were also set with the reach and timer settings calculated according the new approach. The testing and commissioning of the relays took place in May of 1997 (Detail regarding this investigation is documented in reference [39].

6.2 Discussion

The existing approach of applying out-of-step protection to a power system seems to be using many assumptions. With regard to out-of-step blocking protection locations, it is assumed in most cases that all distance protection relays require blocking, irrespective of whether all distance relays will undergo undesired operation or not. In the identification of out-of-step tripping protection locations, an electrical centre area is determined which in itself is derived from an equivalent two machine system approach.

When determining the reach settings for out-of-step protection relays, the existing approach seems to be making use of an equivalent two machine system approach, with calculated equivalent impedances to represent the actual power system impedance.

The timer settings are calculated from a rotor angle swing frequency. Firstly it is assumed that this frequency is the same as the rate of change of the impedance 'seen' by any relay within the system. Secondly the approach seems to base its calculation of timer settings on the assumption that the impedance loci 'seen' by relays during unstable conditions are circular.

From the above a number of comments can be made regarding the reliability of the existing approach when wanting to ensure correct application of out-of-step protection (a more detail discussion is presented in Chapter 3):

1. An equivalent two machine system approach is not suitable when dealing with the application of out-of-step protection because results obtained are not representative of real case scenarios;

2. The use of equivalent impedances ignores the influence of parallel lines, static and dynamic compensation element such as SVC, shunt capacitor and reactor banks and series capacitor banks, and other aspects determining the configuration and dynamic behaviour of a power system. It therefore provides false information regarding reach setting requirements.

3. The use of a rotor angle swing frequency incorrectly assumes that the rate of change of impedance 'seen' by an out-of-step relay has the same frequency. In addition it was found in the research that the rate of change of the impedance is not constant. It is therefore easy to calculate incorrect timer settings.

Even though the existing approach may have its advantages, it seems to over simplify the procedure of applying out-of-step protection to a power system. When considering the effect of incorrect performance of this protection during incidents when it is called upon to operate correctly, should be proof enough that the application of the protection should not be made that simple. In addition one can add the number of incorrect performances of out-of-step protection relays (instability not detected) as further support that the existing approach may not be the best approach. With fast, powerful computers and new advanced computer software available for power system analysis, more detail analyses are possible which is also less time consuming than in the past.

The new approach identified in the research is new, original and effective because attention is given to the impedance locus 'seen' by a relay at its location. The impedance locus is studied using methods developed in the research. These methods were developed to identify correct locations for out-of-step blocking and tripping relays and to calculate correct settings which would ensure correct detection.

It should, however, be noted that both the existing approach and the new approach are techniques for linking relay settings to the results of power system stability studies. A technique could never include the full range of events which may occur in a power system that could lead to system instability. The main reason for this is that a power system model, and not the actual power system, is studied. It is therefore always possible that the expert(s) performing the stability investigation may miss an incident that could lead to instability on the actual power system. A margin of insecurity will therefore always exist i.e. for that percentage of system unstable cases which may not have been covered during the stability study investigation and therefore not covered in the selection of stability studies used, nonoperation of the protection could still occur. It is therefore important to include as many stability studies as possible in the stability investigation.

A specific technique of linking the individual stability study results with the relay settings could either improve or weaken the reliability of the protection to perform correctly during an unstable incident. Two case studies presented in the thesis show that the technique used in the new approach improves the reliability of the protection to perform correctly during an unstable incident.

6.3 Conclusions

The conclusions drawn from the research are the following:

1. Assumptions made in the existing approach seem to be the following:

    - voltage zeros are used to determine tripping relay locations;
    - blocking relays are located at all distance relay locations;
    - equivalent impedances are used to determine reach settings; and
    - swing frequencies are used to determine timer settings.

    These assumptions could lead to incorrect performance of out-of-step protection;

2. The four assumptions made in the existing approach over-simplify the procedure of applying out-of-step protection;

3. There is a need to either improve the existing approach or identify a new and better approach. An example of improving the existing approach could be anything which eliminates some or all of its limitations identified in Chapter 3. References [12] and [20] presents cases where improvements on the existing approach were studied. Examples of new and better approach could be either the use of the new approach presented in this thesis or the use of the phasor angle measurement technique presented in references [24, 46, 47, 48];

4. Applying out-of-step protection according to the new approach presented in this thesis shows an improvement of protection performance during unstable conditions;

5. The new approach presented in this thesis is reliable because a real case application was tested with a number of stability studies and correct protection

performance resulted in each case (refer to the real case application in Chapter 5)[2];

6. Even though the new approach was only tested on the Eskom system, the new approach could be acceptable for any complex power system or utility. The reason for this is that the Eskom power system is a complex power system, just like other power systems and utilities. In addition, the Eskom system's configuration is also typical of a power system that experiences stability related constraints i.e. long transmission lines connecting generator power stations and supplying power over long distances along parallel paths to load demand areas;

7. The new approach increases the reliability of out-of-step protection and thus increases confidence in the correct performance and application thereof. When considering the revenue loss during a system blackout which resulted mainly because out-of-step protection did not operate correctly for the purpose of islanding, extra expenditure to enable the use of the new approach could be justified; and

8. In practice, new locations and settings, based on the new approach, should 'avert' incorrect protection operation during an actual incident which, with the 'old' locations and settings, based on the existing approach, could respond inappropriately in response to the disturbance.

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[2] The real case application (locations, settings and protection scheme design) were verified by repeating the selection of stability studies used. The results indicated that all the out-of-step tripping relays performed correctly at their respective locations and the protection scheme design operated correctly to allow system islanding.

In addition to the selection of stability studies used, the protection locations, settings and the out-of-step protection scheme design for the Eskom system were also verified by simulating the system unstable incident that occurred within the Eskom system on 7 June 1996. The results indicated that even though relays at some of the locations did not operate the protection scheme operated correctly for the purpose of islanding. The out-of-step protection application is therefore correct for the unstable incident because relays at the remaining locations operated to allow correct performance of the overall protection scheme for the purpose of islanding (the possibility of nonoperation of relays during unstable cases not covered in the selection of stability studies used to determine locations and settings were discussed under section 1.4 no 10 of Chapter 1.)

APPENDIX A

THE ESKOM SYSTEM AND ESKOM'S CAPE SYSTEM

A1: The Eskom system

The Eskom system is shown in Figure A1. At present Eskom (the electricity supply utility of South Africa) supplies approximately 96% of the electricity used in South Africa.

South Africa has vast coal deposits in the Mpumalanga highveld. For economic reasons most of Eskom's generation is therefore concentrated near these coalfields.

With the widely dispersed load centres in South Africa, the concentration of power generation in the Mpumalanga highveld poses problems in the operation of a system where power has to be transmitted over long distances to load centres in different parts of the country; for example from Johannesburg to Cape Town (1 200 km), from Johannesburg to Durban (600 km) and from Johannesburg to the Northern Province (300 km). In addition to the coal-fired power stations in the Mpumalanga highveld, Eskom therefore also has a nuclear power station (Koeberg) just outside Cape Town, two pumped storage power stations - one in the Cape (Palmiet) and one in Natal (Drakensberg) - and a remotely situated coal-fired power station in the Northern Province (Matimba).

Power is distributed to the load centres via a combination of 765, 400, 275 and 220 kV lines. Some of these lines span distances of 400 km or more. Due to the great distances over which power must be transmitted, many 400 kV lines are 40-70% series-compensated. In many cases large static var compensators (with an operating range of approximately 300 Mvar) and shunt capacitor and reactor devices are located en route to the load centres to improve power flow via the long-distance transmission lines and to provide reactive power support (assist in system voltage control).

In addition to the transmission network in South Africa, Eskom also has tie lines connecting it with the neighbouring utilities north of South Africa. At present Eskom (at Matimba Power Station) is connected with Zesa (Zimbabwe) via a 400 kV AC line which spans a distance of approximately 420 km. Eskom (at Spitskop Substation) is also connected with BPC (Botswana) via three 132 kV lines. A third 400 kV AC interconnection exists between Eskom (at Aries Substation) and NamPower (Namibia) and a fourth interconnection consists of two 132 kV lines between Eskom (at Komatipoort Substation) and EDM (Mozambique).

A2: Eskom's Cape system

The main supply to the Cape system as well as the Cape system is shown in Figure A2. Table A1 lists the line impedance data for the Cape system. Hydra Substation is the main point of coupling between the northern generation pool and the Cape system. From Hydra Substation to the main load centre in the south there are two 400 kV parallel routes. These routes are known as the northern route and the southern/western route. As can be seen in Figure A2, the northern route consists of one single 400 kV line route between Hydra Substation and Koeberg Nuclear Power Station. The southern/western route is more secure as there are more 400 kV lines in parallel. The total distance between Hydra Substation and Koeberg Nuclear Power Station is approximately 800 km. Two generation stations are situated in the Cape system: Koeberg Nuclear Power Station and the Palmiet pumped storage scheme. The generating capacities of these power stations are 1 800 MW and 400 MW respectively. Koeberg Power Station has a four-loop control device performing the functions of both an excitation system and a stabiliser. Palmiet Power Station has an excitation control device. The Cape system also houses three large static var compensators (SVCs) for the purpose of voltage control, each with a capacity of 250 Mvar capacitive and 150 Mvar inductive. Two of these SVCs are located at Hydra Substation and the third is located at Muldersvlei Substation, situated close to Koeberg. The 1996 maximum recorded demand for the Cape system south of Hydra Substation was approximately 3 000 MW. The load types within the Cape system comprise industry, commercial, domestic, farming (small machines) and traction.

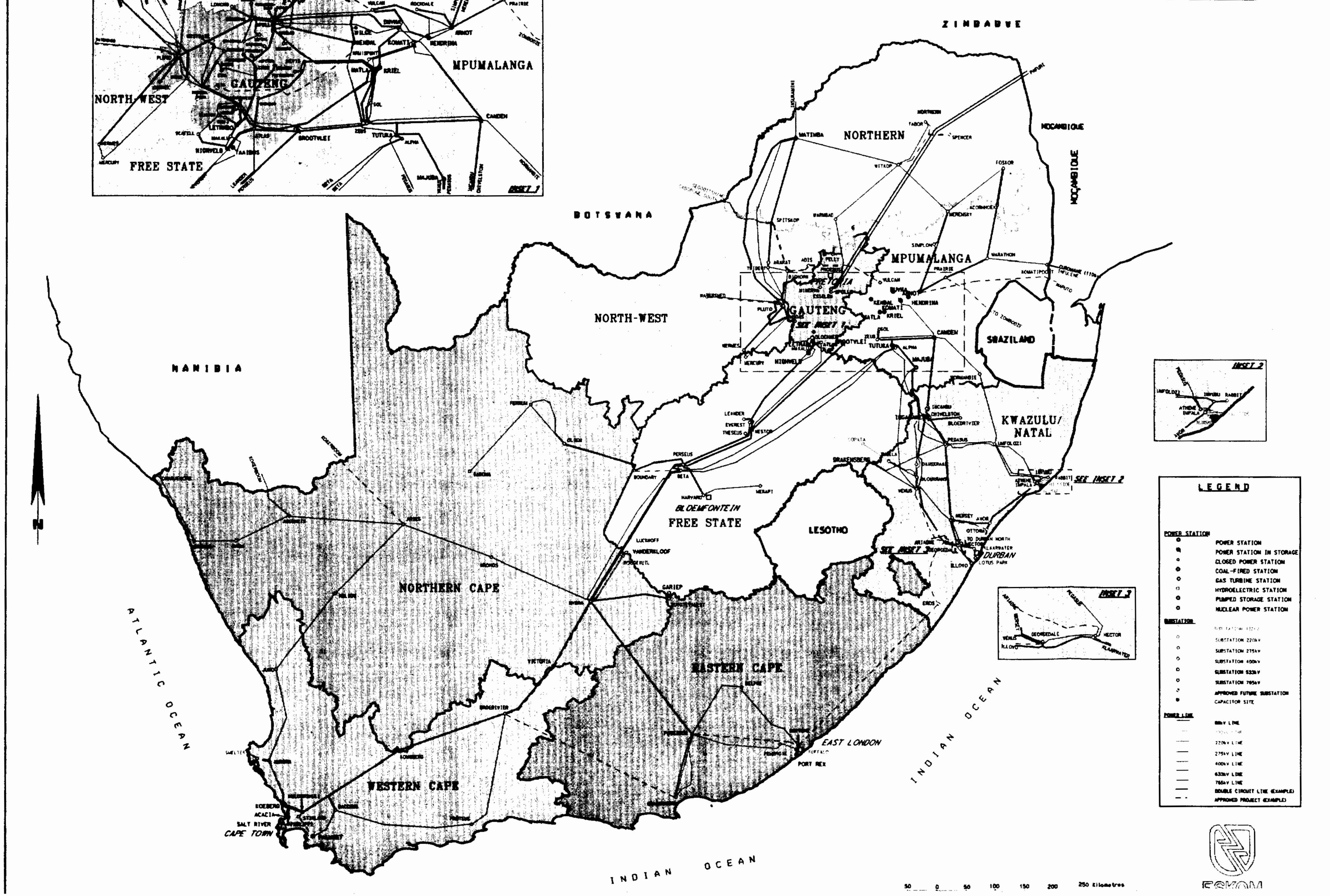
Power has to be imported from the Mpumalanga area over a distance of approximately 1 400 km to supply the Cape system load demand. Incidents that weaken this supply route may therefore produce system power swings or even out-of-step conditions. The stability study discussed in Chapter 3, section 3.3.1, represents one possible contingency which would weaken the system to a point where it becomes unstable.

Table A1: Line impedance data for the Cape system

Location	**Line impedance**		**Location**	**Line impedance**	
	Rline (pu)	**Xline (pu)**		**Rline (pu)**	**Xline (pu)**
Hydra-Kronos	0,0028	0,0119	Droërivier-Muldersvlei	0,0061	0,0424
Kronos-Hydra	0,0028	0,0119	Muldersvlei-Droërivier	0,0061	0,0424
Kronos-Aries	0,0024	0,0088	Droërivier-Proteus	0,0068	0,0393
Aries-Kronos	0,0024	0,0088	Proteus-Droërivier	0,0068	0,0393
Aries-Helios	0,0025	0,0098	Droërivier-Bacchus	0,0060	0,0407
Helios-Aries	0,0025	0,0098	Bacchus-Droërivier	0,0060	0,0407
Helios-Juno	0,0025	0,0104	Bacchus-Palmiet	0,0013	0,0159
Juno-Helios	0,0025	0,0104	Palmiet-Bacchus	0,0013	0,0159
Juno-Aurora	0,0028	0,0112	Bacchus-Muldersvlei	0,0017	0,0217
Aurora-Juno	0,0028	0,0112	Muldersvlei-Bacchus	0,0017	0,0217
Aurora-Koeberg	0,0013	0,0170	Muldersvlei-Koeberg 1	0,0006	0,0081
Koeberg-Aurora	0,0013	0,0170	Koeberg-Muldersvlei 1	0,0006	0,0081
Hydra-Droërivier 1	0,0038	0,0479	Muldersvlei-Koeberg 2	0,0006	0,0081
Droërivier-Hydra 1	0,0038	0,0479	Koeberg-Muldersvlei 2	0,0006	0,0081
Hydra-Droërivier 2	0,0038	0,0479	Muldersvlei-Acacia	0,0007	0,0091
Droërivier-Hydra 2	0,0038	0,0479	Acacia-Muldersvlei	0,0007	0,0091
Hydra-Droërivier 3	0,0037	0,0262	Acacia-Koeberg	0,0005	0,0063
Droërivier-Hydra 3	0,0037	0,0262	Koeberg-Acacia	0,0005	0,0063

Figure A1: Eskom power system

MAJOR TRANSMISSION SYSTEM AND PROVINCES



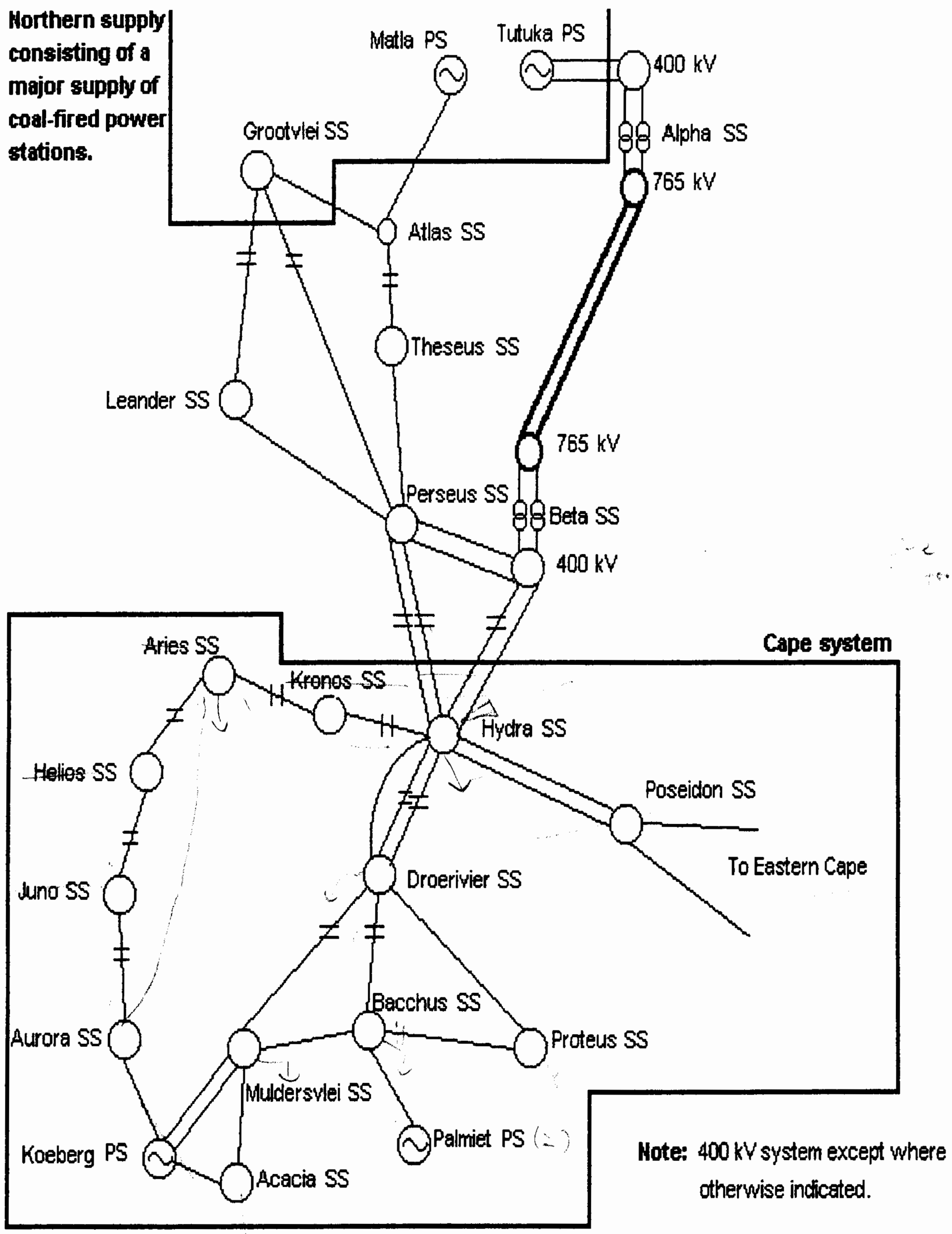


Figure A2: The main supply to the Cape system and the Cape system

APPENDIX B

OUT-OF-STEP BLOCKING AND TRIPPING PROTECTION

- **DETECTION METHODOLOGY**
- **MATHEMATICAL REPRESENTATION**

B1: Detection methodology (out-of-step blocking and tripping protection)

<u>Out-of-step blocking protection</u>

For the purposes of the research out-of-step blocking protection using two concentric circle characteristics and one characteristic timer (Tb) was used (see Figure B1 and refer to Chapter 1, section 1.4 no 7 for reason). The outer characteristic's forward reach and reverse reach as well as the characteristic timer are determined from setting procedures.

For the purposes of the research the following specifications were chosen:

1. The forward and reverse reach settings should not exceed 0,1 pu and -0,1 pu respectively.
2. The left and right boundaries of the outer characteristics should not exceed -0,1 pu and 0,1 pu respectively to avoid load encroachment.
3. The inner characteristic's forward reach and reverse reach are $\frac{1}{1,3}$ = 0,7692 less than the outer characteristic's forward reach and reverse reach respectively (In reference [15] it is stated that for a concentric circle type characteristic an outer reach is typically 1,3 times an inner reach).

Detection takes place when the following sequence of events have been completed:

1. The impedance enters the outer zone.
2. The impedance remains in the outer zone long enough to allow the zone timer to expire.
3. The impedance enters the inner zone.

Upon detection, a blocking signal is sent to the distance relay supervised by the blocking protection.

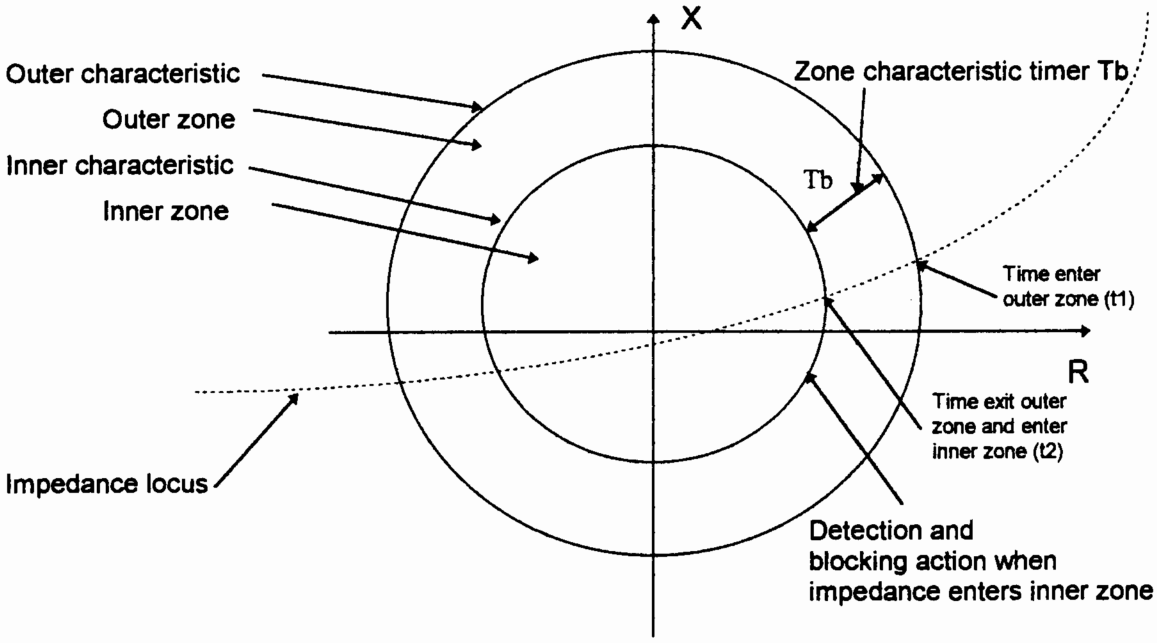


Figure B1: Out-of-step blocking protection

<u>Out-of-step tripping protection</u>

For the purposes of the research out-of-step tripping protection using two concentric circle characteristics and two characteristic timers - an outer-zone timer (Tto) and an inner-zone timer (Tti) - was used (see Figure B2 and refer to Chapter 1, section 1.4 no 7 for reason)[1]. The outer characteristic's forward reach and reverse reach as well as the two characteristic timers are determined from setting procedures.

[1] Even though the out-of-step tripping protection's detection methodology appears to be the same as that of the out-of-step blocking protection, differences between the detection methodologies do exist. The complete detection methodology of the out-of-step tripping protection is therefore presented.

For the purposes of the research the following specifications were chosen:

1. The forward and reverse reach settings should not exceed 0,1 pu and -0,1 pu respectively.
2. The left and right boundaries of the outer characteristics should not exceed -0,1 pu and 0,1 pu respectively to avoid load encroachment.
3. The inner characteristic's forward reach and reverse reach are $\frac{1}{1,3}$ = 0,7692 less than the outer characteristic's forward reach and reverse reach respectively.

Detection takes place when the following sequence of events have been completed:

1. The impedance enters the outer zone.
2. The impedance remains in the outer zone long enough to allow the outer-zone timer to expire.
3. The impedance enters the inner zone.
4. The impedance remains in the inner zone long enough to allow the inner-zone timer to expire.
5. The impedance exits the relay characteristics on the side opposite that which it entered.

Upon detection, tripping signals are sent to selected locations for the purpose of islanding.

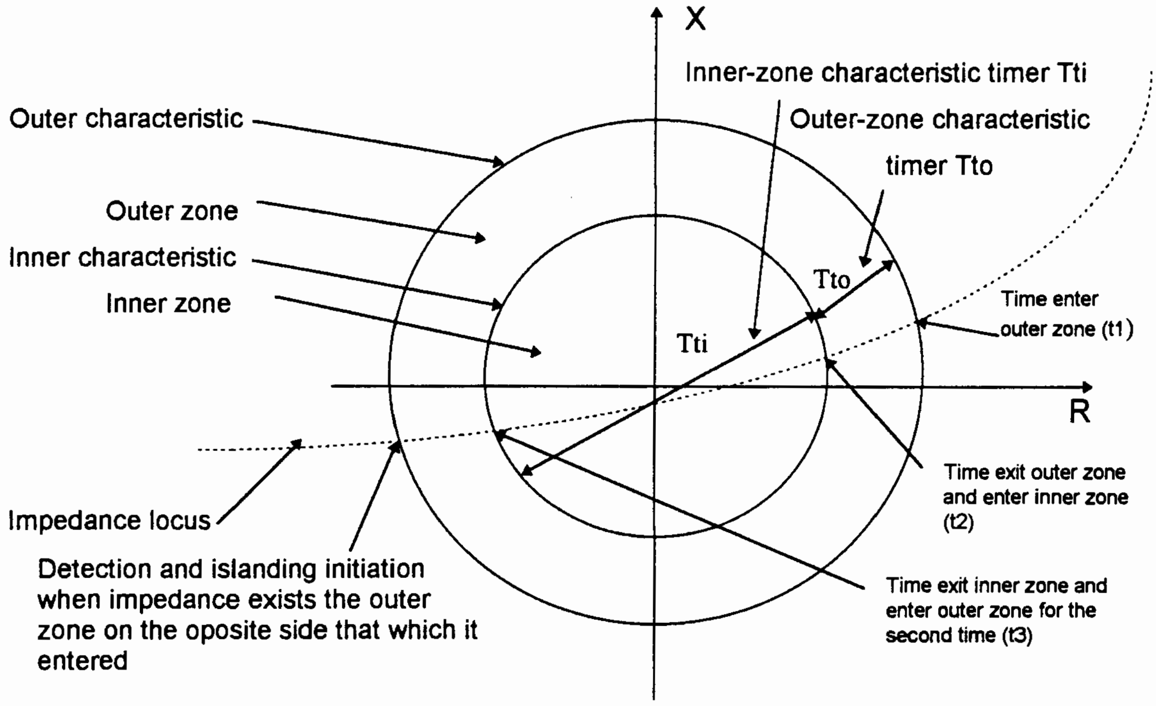


Figure B2: Out-of-step tripping protection

B2: Mathematical representation (out-of-step blocking and tripping protection)

The above out-of-step blocking and tripping protection were mathematically represented for the purpose of including the mathematical representation in the power system model during the verification of out-of-step protection application according to both the existing and the new out-of-step protection application approaches, discussed in Chapters 3 and 4 respectively. In Chapter 4 the mathematical representation of the characteristics was also used to determine the timer settings.

For both out-of-step blocking and out-of-step tripping protection, examples are given to illustrate the use of the mathematical representation.

Out-of-step blocking protection

The mathematical equations representing the out-of-step blocking relay characteristics are as follows:

Outer characteristic:

$$Z_{radius\ (outer\ char)}^{2} = (R-a_o)^2 + (X-b_o)^2$$

where

$|Z_{radius\ (outer\ char)}|$ = absolute value of the radius of the outer circle characteristic

= $\frac{1}{2}$ x $(|Z_{forward\ reach\ (outer\ char)}| + |Z_{reverse\ reach\ (outer\ char)}|)$

$|Z_{forward\ reach\ (outer\ char)}|$ = absolute value of the outer characteristic forward reach

$|Z_{reverse\ reach\ (outer\ char)}|$ = absolute value of the outer characteristic reverse reach

R = variable R in the impedance (R/X) plane

X = variable X in the impedance (R/X) plane

$a_o + jb_o$ = circle offset-parameters for the outer zone

= $|Z_{offset\ (outer\ char)}| \angle \varphi_l$

$|Z_{offset\ (outer\ char)}|$ = absolute value of the offset from the origin due to forward and reverse reach settings

= $|Z_{forward\ reach\ (outer\ zone)}| - |Z_{radius\ (outer\ zone)}|$

φ_l = transmission-line angle determined from line resistance and reactance

Inner characteristic:

$$Z_{radius\ (inner\ char)}^{2} = (R-a_i)^2 + (X-b_i)^2$$

where

$|Z_{radius\ (inner\ char)}|$ = absolute value of the radius of the inner circle characteristic

	=	$\frac{1}{2}$ x ($\lvert Z_{\text{forward reach (inner char)}} \rvert$ + $\lvert Z_{\text{reverse reach (inner char)}} \rvert$)
$\lvert Z_{\text{forward reach (inner char)}} \rvert$	=	absolute value of the inner characteristic forward reach
	=	0,7692 x $\lvert Z_{\text{forward reach (outer char)}} \rvert$
$\lvert Z_{\text{reverse reach (inner char)}} \rvert$	=	absolute value of the inner characteristic reverse reach
	=	0,7692 x $\lvert Z_{\text{reverse reach (outer char)}} \rvert$
R	=	variable R in the impedance (R/X) plane
X	=	variable X in the impedance (R/X) plane
$a_i + jb_i$	=	circle offset-parameters for the inner zone
	=	$\lvert Z_{\text{offset (inner char)}} \rvert \angle \varphi_l$
$\lvert Z_{\text{offset (inner char)}} \rvert$	=	absolute value of the offset from the origin due to forward and reverse reach settings
	=	$\lvert Z_{\text{offset (outer char)}} \rvert$
φ_l	=	transmission-line angle determined from line resistance and reactance

The mathematical equation to represent the time for which the impedance remains in the outer zone is as follows:

$$t_{\text{monitor}} = t_{\text{exit (outer zone)}} - t_{\text{enter (outer zone)}}$$

where

t_{monitor}	=	time for which impedance remains in outer zone
$t_{\text{enter (outer zone)}}$	=	time at which impedance locus enters the outer zone
$t_{\text{exit (outer zone)}}$	=	time at which impedance locus exits the outer zone and enters the inner zone

The mathematical equations representing detection of the out-of-step blocking protection are as follows:

if

$$t_{\text{monitor}} \geq Tb$$

while

$\lvert R_{inner\ char} \rvert$	$<$	$\lvert R_{locus} \rvert$	$\leq$	$\lvert R_{outer\ char} \rvert$ and
$\lvert X_{inner\ char} \rvert$	$<$	$\lvert X_{locus} \rvert$	$\leq$	$\lvert X_{outer\ char} \rvert$

then detection when

$\lvert R_{locus} \rvert$	$<$	$\lvert R_{inner\ char} \rvert$ and
$\lvert X_{locus} \rvert$	$<$	$\lvert X_{inner\ char} \rvert$

where

Tb	=	zone timer setting for blocking protection
$R_{outer\ char} + jX_{outer\ char}$	=	impedance value in impedance plane representing a point on the outer characteristic boundary
$R_{inner\ char} + jX_{inner\ char}$	=	impedance value in impedance plane representing a point on the inner characteristic boundary
$R_{locus} + jX_{locus}$	=	impedance value representing a point on the impedance locus

Example: - Mathematical representation of the out-of-step blocking relay at Aries-Helios (settings calculated using Eskom's method which is based on the existing approach)

The out-of-step blocking protection characteristics are shown in Figure B3.

Outer characteristic:

$$Z_{radius\ (outer\ char)}^2 = (R-a_o)^2 + (X-b_o)^2$$

$$(0,05)^2 = (R-0,0025)^2 + (X-0,0097)^2$$

where

$$/Z_{radius\ (outer\ char)}/ = \frac{1}{2} \times (0,06 + 0,04) \qquad \text{[from Table C3b, Appendix C]}$$

$$= 0,05$$

$a_o + jb_o$ = *circle offset-parameters for the outer zone*

$$= /Z_{offset\ (outer\ char)}/\angle\varphi_l$$

$$= 0,01\angle 75,8°$$

$$= 0,0025 + j0,0097$$

$\lvert Z_{offset\ (outer\ char)} \rvert$	=	$\lvert Z_{forward\ reach\ (outer\ zone)} \rvert - \lvert Z_{radius\ (outer\ zone)} \rvert$	
	=	0,06 - 0,05	
	=	0,01	
φ_I	=	75,8°	[from Table C3b, Appendix C]

Inner characteristic:

$Z_{radius\ (inner\ char)}^2$	=	$(R-a_i)^2 + (X-b_i)^2$
$(0,038)^2$	=	$(R-0,0025)^2 + (X-0,0097)^2$
where		
$\lvert Z_{radius\ (inner\ char)} \rvert$	=	$\frac{1}{2}$ x $(\lvert Z_{forward\ reach\ (inner\ char)} \rvert + \lvert Z_{reverse\ reach\ (inner\ char)} \rvert)$
	=	$\frac{1}{2}$ x (0,0460 + 0,0310)
	=	0,038
$\lvert Z_{forward\ reach\ (inner\ char)} \rvert$	=	0,7692 x 0,06
	=	0,046
$\lvert Z_{reverse\ reach\ (inner\ char)} \rvert$	=	0,7692 x 0,04
	=	0,031
$a_i + jb_i$	=	$0,01\angle 75,8°$
	=	$0,0025 + j0,0097$

The mathematical equations representing detection of the out-of-step blocking protection are as follows:

if

$t_{monitor}$	$\geq$	(Tb = 15 ms)	[from Table C5a, Appendix C]

while

$\lvert R_{inner\ char} \rvert$	<	$\lvert R_{locus} \rvert \leq$	$\lvert R_{outer\ char} \rvert$ and
$\lvert X_{inner\ char} \rvert$	<	$\lvert X_{locus} \rvert \leq$	$\lvert X_{outer\ char} \rvert$

then detection when

$\lvert R_{locus} \rvert$	<	$\lvert R_{inner\ char} \rvert$ and
$\lvert X_{locus} \rvert$	<	$\lvert X_{inner\ char} \rvert$

where

Tb	=	zone timer setting for blocking protection
	=	15 ms [from Table C5a, Appendix C]
$R_{outer\ char} + jX_{outer\ char}$	=	impedance value in impedance plane representing a point on the outer characteristic boundary

$R_{inner\ char} + jX_{inner\ char}$	=	*impedance value in impedance plane representing a point on the inner characteristic boundary*
$R_{locus} + jX_{locus}$	=	*impedance value representing a point on the impedance locus*

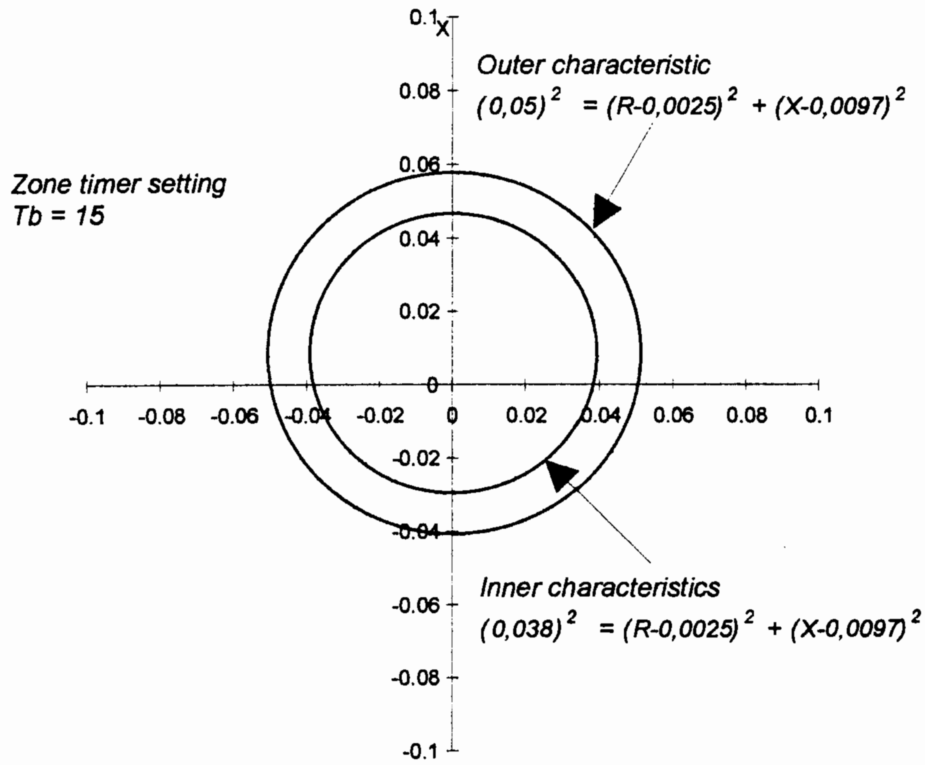


Figure B3: The out-of-step blocking protection characteristics

Out-of-step tripping protection

The mathematical equations representing the out-of-step tripping characteristics are as follows:

Outer characteristics:

$$Z_{radius\ (outer\ char)}^{2} = (R-a_o)^2 + (X-b_o)^2$$

where

$|Z_{radius\ (outer\ char)}|$ = absolute value of the radius of the outer circle characteristic

	=	$\frac{1}{2} \times (\lvert Z_{\text{forward reach (outer char)}} \rvert + \lvert Z_{\text{reverse reach (outer char)}} \rvert)$
$\lvert Z_{\text{forward reach (outer char)}} \rvert$	=	absolute value of the outer characteristic forward reach
$\lvert Z_{\text{reverse reach (outer char)}} \rvert$	=	absolute value of the outer characteristic reverse reach
R	=	variable R in the impedance (R/X) plane
X	=	variable X in the impedance (R/X) plane
$a_o + jb_o$	=	circle offset-parameters for the outer zone
	=	$\lvert Z_{\text{offset (outer char)}} \rvert \angle \varphi_l$
$\lvert Z_{\text{offset (outer char)}} \rvert$	=	absolute value of the offset from the origin due to forward and reverse reach settings
	=	$\lvert Z_{\text{forward reach (outer zone)}} \rvert - \lvert Z_{\text{radius (outer zone)}} \rvert$
φ_l	=	transmission-line angle determined from line resistance and reactance

Inner characteristic:

$$Z_{\text{radius (inner char)}}^2 = (R-a_i)^2 + (X-b_i)^2$$

where

$\lvert Z_{\text{radius (inner char)}} \rvert$	=	absolute value of the radius of the inner circle characteristic
	=	$\frac{1}{2} \times (\lvert Z_{\text{forward reach (inner char)}} \rvert + \lvert Z_{\text{reverse reach (inner char)}} \rvert)$
$\lvert Z_{\text{forward reach (inner char)}} \rvert$	=	absolute value of the inner characteristic forward reach
	=	$0{,}7692 \times \lvert Z_{\text{forward reach (outer char)}} \rvert$
$\lvert Z_{\text{reverse reach (inner char)}} \rvert$	=	absolute value of the inner characteristic reverse reach
	=	$0{,}7692 \times \lvert Z_{\text{reverse reach (outer char)}} \rvert$
R	=	variable R in the impedance (R/X) plane
X	=	variable X in the impedance (R/X) plane
$a_i + jb_i$	=	circle offset-parameters for the inner zone
	=	$\lvert Z_{\text{offset (inner char)}} \rvert \angle \varphi_l$
$\lvert Z_{\text{offset (inner char)}} \rvert$	=	absolute value of the offset from the origin due to forward and reverse reach settings

	=	$\lvert Z_{offset\ (outer\ char)} \rvert$
φ_l	=	transmission-line angle determined from line resistance and reactance

The mathematical equation to represent the time for which the impedance remains in the outer zone and inner zone respectively is as follows:

$$t_{monitor\ (outer\ zone)} = t_{exit\ (outer\ zone)} - t_{enter\ (outer\ zone)}$$
$$t_{monitor\ (inner\ zone)} = t_{exit\ (inner\ zone)} - t_{enter\ (inner\ zone)}$$

where

$t_{monitor\ (outer\ zone)}$	=	time that impedance spends in outer zone
$t_{monitor\ (inner\ zone)}$	=	time that impedance spends in inner zone
$t_{enter\ (outer\ zone)}$	=	time at which impedance enters the outer zone
$t_{exit\ (outer\ zone)}$	=	time at which impedance exits the outer zone and enters the inner zone
$t_{enter\ (inner\ zone)}$	=	time at which impedance enters the inner zone
$t_{exit\ (inner\ zone)}$	=	time at which impedance exits the inner zone and enters the outer zone

The mathematical equations representing detection of the out-of-step tripping protection are as follows:

If

$$t_{monitor\ (outer\ zone)} \geq Tto$$

while

$$\lvert R_{inner\ char} \rvert < \lvert R_{locus} \rvert \leq \lvert R_{outer\ char} \rvert$$
$$\lvert X_{inner\ char} \rvert < \lvert X_{locus} \rvert \leq \lvert X_{outer\ char} \rvert$$

and if

$$t_{monitor\ (inner\ zone)} \geq Tti$$

while

$$\lvert R_{locus} \rvert \leq \lvert R_{inner\ char} \rvert$$

$|X_{locus}| \quad \leq \quad |X_{inner\ char}|$

then detection when

$|R_{locus\text{-}exit}| \quad > \quad |R_{outer\ char}|$

$|X_{locus\text{-}exit}| \quad > \quad |X_{outer\ char}|$

and

$R_{locus\text{-}exit} > 0$ if $R_{locus\text{-}enter} < 0$ and vice versa

where

Tto = outer-zone timer setting for tripping protection

Tti = inner-zone timer setting for tripping protection

$R_{outer\ char} + jX_{outer\ char}$ = impedance value in impedance plane representing a point on the outer characteristic boundary

$R_{inner\ char} + jX_{inner\ char}$ = impedance value in impedance plane representing a point on the inner characteristic boundary

$R_{locus} + jX_{locus}$ = impedance value representing a point on the impedance locus

$R_{locus\text{-}enter} + jX_{locus\text{-}enter}$ = impedance value representing a point on the impedance locus when impedance enters the outer characteristic

$R_{locus\text{-}exit} + jX_{locus\text{-}exit}$ = impedance value representing a point on the impedance locus when impedance exits the outer characteristic

Example - Mathematical representation of out-of-step tripping relay at Bacchus-Droërivier (settings calculated using the new method in the new approach)

The out-of-step tripping protection characteristics are shown in Figure B4.

Outer characteristics:

$Z_{radius\ (outer\ char)}^2 \quad = \quad (R-a_o)^2 + (X-b_o)^2$

$(0{,}0999)^2 \quad = \quad (R-0{,}0006)^2 + (X-0{,}0001)^2$

where

$|Z_{radius\ (outer\ char)}| \quad = \quad \frac{1}{2} \times (0{,}1 + 0{,}0998)$ *[from Table E4b, Appendix E]*

$= \quad 0{,}0999$

$a_o + jb_o \quad = \quad 0{,}0006\angle 81{,}57°$

$= \quad 0{,}0006 + j0{,}0001$

$|Z_{offset\ (outer\ char)}| \quad = \quad 0{,}1 - 0{,}0999$

$$= 0,0001$$

$\varphi_I = 81,57°$ [from Table E4b, Appendix E]

Inner characteristic:

$$Z_{radius\ (inner\ char)}^2 = (R-a_i)^2 + (X-b_i)^2$$

$$(0,00769)^2 = (R-0,0006)^2 + (X-0,0001)^2$$

where

$$|Z_{radius\ (inner\ char)}| = \frac{1}{2} \times (|Z_{forward\ reach\ (inner\ char)}| + |Z_{reverse\ reach\ (inner\ char)}|)$$

$$= \frac{1}{2} \times (0,0769 + 0,0770)$$

$$= 0,0069$$

$$|Z_{forward\ reach\ (inner\ char)}| = 0,7692 \times 0,1$$

$$= 0,0769$$

$$|Z_{reverse\ reach\ (inner\ char)}| = 0,7693 \times 0,0998$$

$$= 0,0770$$

$$a_i + jb_i = |Z_{offset\ (inner\ char)}| \angle\varphi_I$$

$$|Z_{offset\ (inner\ char)}| = |Z_{offset\ (outer\ char)}|$$

$$= 0,0006\angle 81,57°$$

$$= 0,0006 + j0,0001$$

The mathematical equations representing detection of the out-of-step tripping protection are as follows:

If

$t_{monitor\ (outer\ zone)} \geq (Tto = 18\ ms)$ [from Table E5b, Appendix E]

while

$$|R_{inner\ char}| < |R_{locus}| < |R_{outer\ char}|$$

$$|X_{inner\ char}| < |X_{locus}| < |X_{outer\ char}|$$

and if

$t_{monitor\ (inner\ zone)} \geq (Tti = 450\ ms)$ [from Table E5b, Appendix E]

while

$$|R_{locus}| < |R_{inner\ char}|$$

$$|X_{locus}| < |X_{inner\ char}|$$

then detection when

$$|R_{locus}| \geq |R_{outer\ char}|$$

$$|X_{locus}| \geq |X_{outer\ char}|$$

and

$R_{locus\text{-}exit} > 0$ if $R_{locus\text{-}enter} < 0$ and vice versa

where

Tto	=	*outer-zone timer setting for tripping protection*
	=	*18 ms*
Tti	=	*inner-zone timer setting for tripping protection*
	=	*450 ms*
$R_{outer\ char} + jX_{outer\ char}$	=	*impedance value in impedance plane representing a point on the outer characteristic boundary*
$R_{inner\ char} + jX_{inner\ char}$	=	*impedance value in impedance plane representing a point on the inner characteristic boundary*
$R_{locus} + jX_{locus}$	=	*impedance value representing a point on the impedance locus*
$R_{locus\text{-}enter} + jX_{locus\text{-}enter}$	=	*impedance value representing a point on the impedance locus when impedance enters the outer characteristic*
$R_{locus\text{-}exit} + jX_{locus\text{-}exit}$	=	*impedance value representing a point on the impedance locus when impedance exits the outer characteristic*

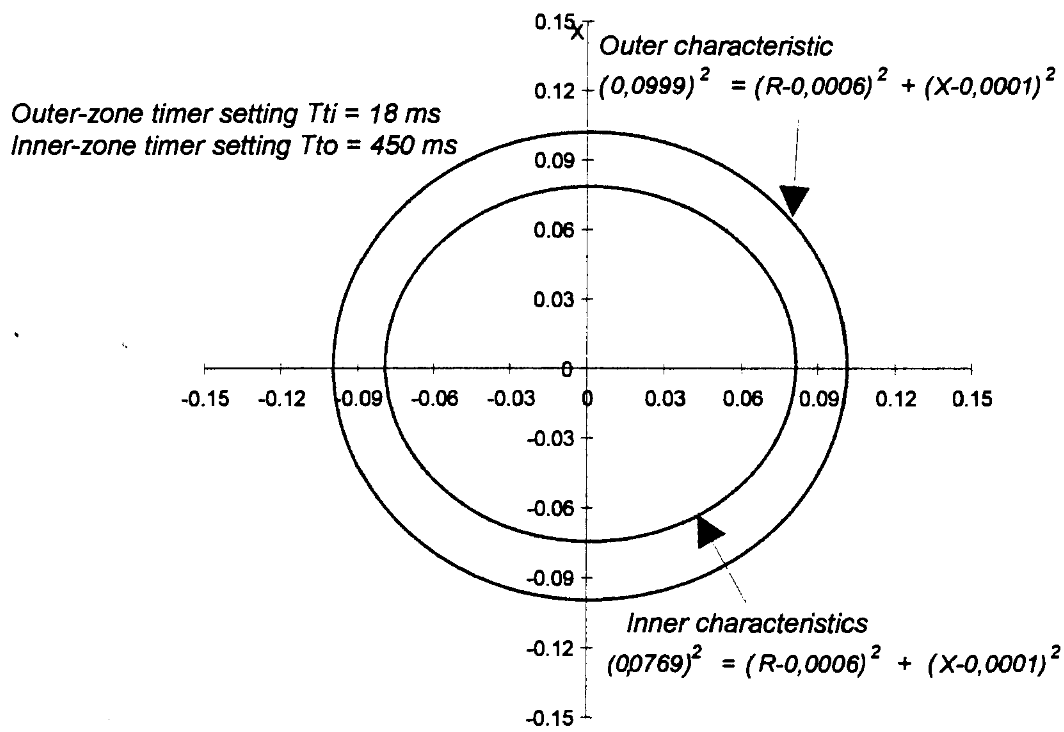


Figure B4: *Out-of-step tripping protection characteristics*

APPENDIX C

OUT-OF-STEP PROTECTION APPLICATION BASED ON THE EXISTING APPROACH AND USING ESKOM'S METHODS

Out of step was applied to the Eskom transmission system according to existing approach, using Eskom's methods of determining relay locations and calculating relay settings (reach and timer) (Eskom's methods are presented under section (3.3.2) in Chapter 3.)

The location and reach settings were selected and calculated for out-of-step blocking an tripping protection using concentric circle type characteristics. The protection type used for the purposes of the research is presented in Appendix B.

For those calculations and investigations that require stability study results, the stability study presented under section 3.3.1 in Chapter 3 was done to provide the necessary results.

Due to the size of the Eskom transmission system results for a portion of the system were presented as results for the remaining system are additional information and does not add any futher value to the thesis contribution. The portion of the Eskom transmission system for which results are presented, is shown in Figure C1.

C1 Locations

Out-of-step blocking protection

Out-of-step blocking protection was placed at all the locations in the Eskom transmission system. Table C1 lists the locations for the portion of the system shown in Figure C1.

Table C1: Locations of out-of-step blocking protection

LOCATIONS	
Hydra-Kronos	Droërivier-Muldersvlei
Kronos-Hydra	Muldersvlei-Droërivier
Kronos-Aries	Droërivier-Proteus
Aries-Kronos	Proteus-Droërivier
Aries-Helios	Droërivier-Bacchus
Helios-Aries	Bacchus-Droërivier
Helios-Juno	Bacchus-Palmiet
Juno-Helios	Palmiet-Bacchus
Juno-Aurora	Bacchus-Muldersvlei
Aurora-Juno	Muldersvlei-Bacchus
Aurora-Koeberg	Muldersvlei-Koeberg 1
Koeberg-Aurora	Koeberg-Muldersvlei 1
Hydra-Droërivier 1	Muldersvlei-Koeberg 2
Droërivier-Hydra 1	Koeberg-Muldersvlei 2
Hydra-Droërivier 2	Muldersvlei-Acacia
Droërivier-Hydra 2	Acacia-Muldersvlei
Hydra-Droërivier 3	Acacia-Koeberg
Droërivier-Hydra 3	Koeberg-Acacia

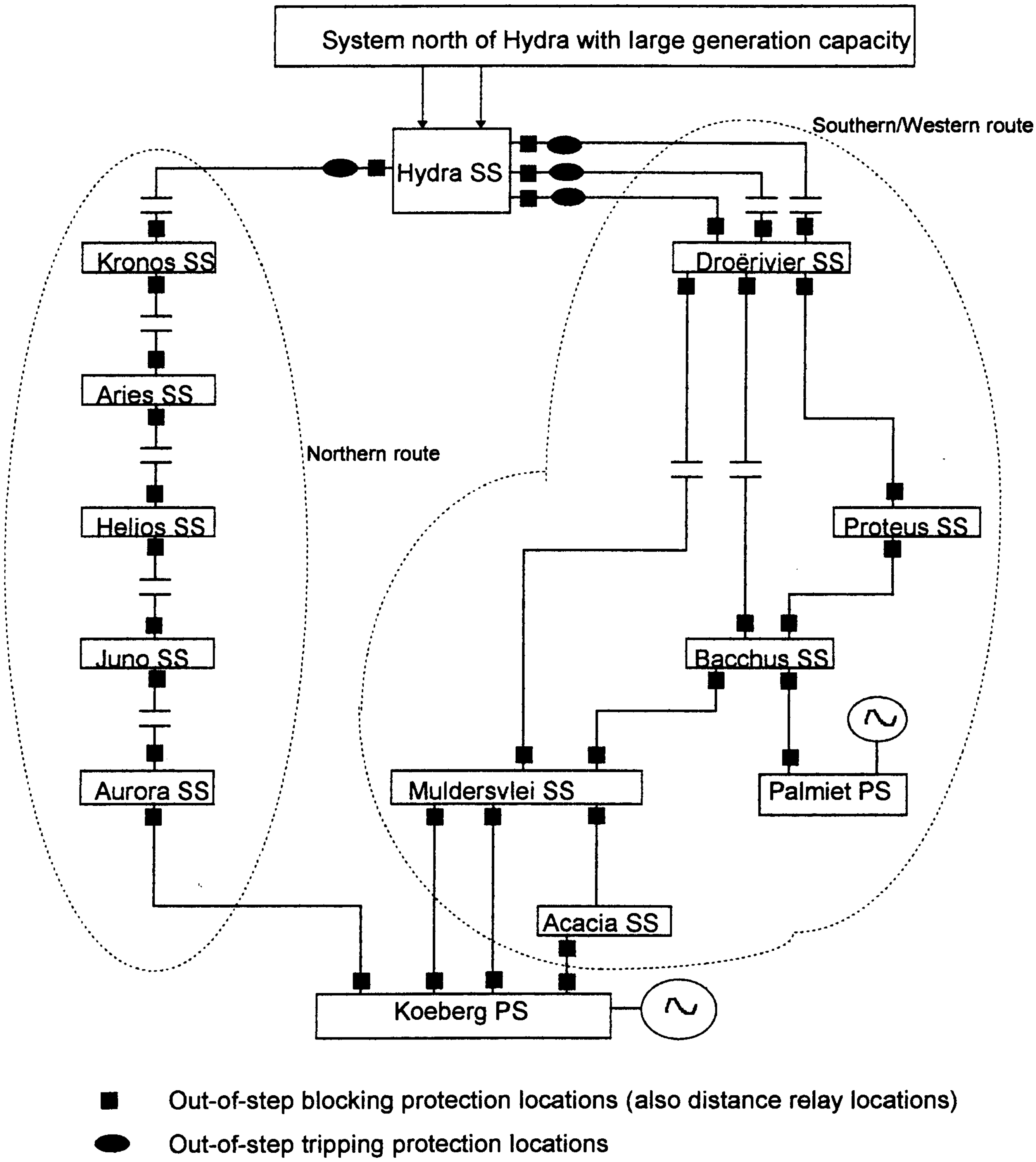


Figure C1: Portion of Eskom transmission system for which results are presented.

Out-of-step tripping protection

The voltage oscillations for the stability study done (refer to Chapter 3 section 3.3.1) can be seen in Figure C2. The voltage magnitudes for the substations in the northern and southern/western routes were plotted. From these plots it can be seen that the electrical centre in the northern route is located at Hydra Substation because the voltage magnitude is closest to zero at Hydra. The electrical centre in the southern/western route is also located at Hydra Substations because the voltage magnitude is closest to zero at Hydra.

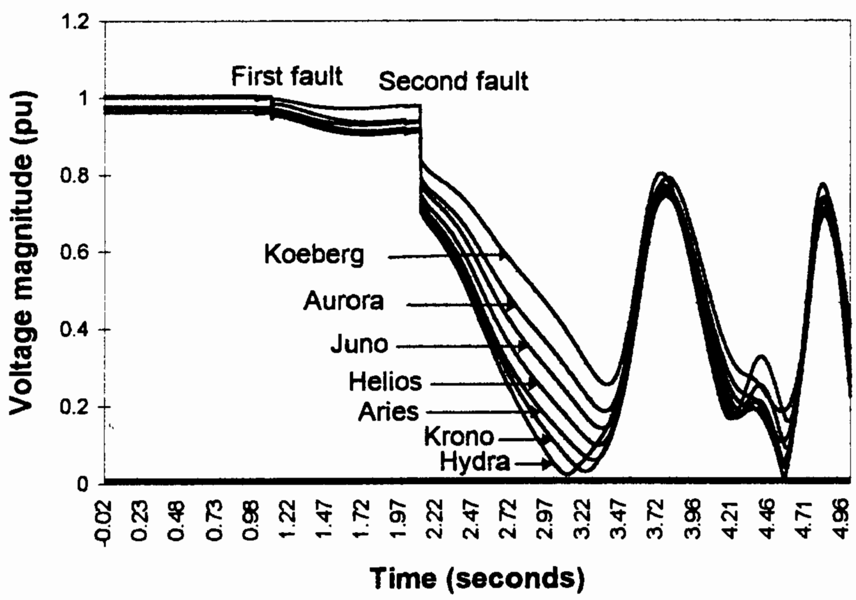


Figure C2a: Voltage oscillations in northern route

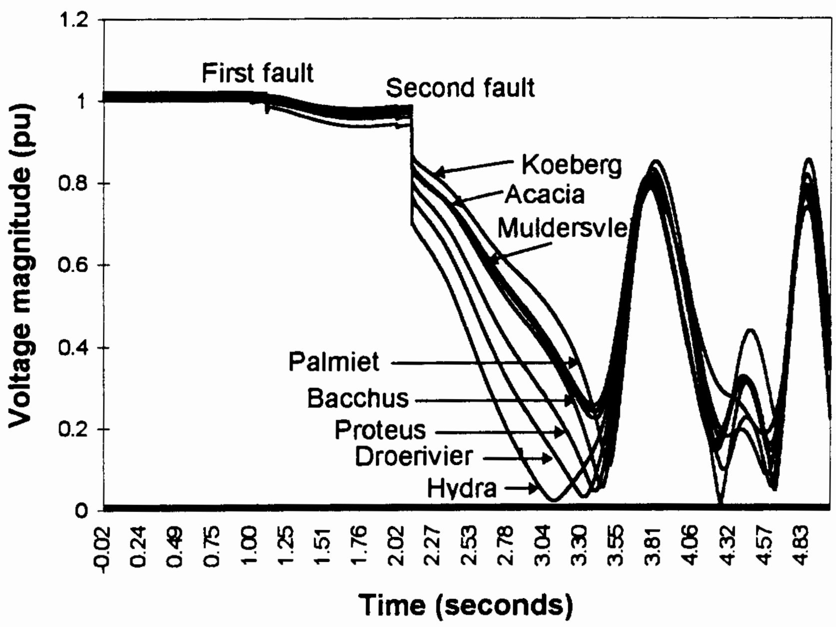


Figure C2b: Voltage oscillations in southern/western route

Out-of-step tripping protection was placed at the electrical centre location. Figure C1 shows the out-of-step tripping protection locations in the portion of the Eskom transmission system shown. These locations are also listed in Table C2.

Table C2: Locations of out-of-step tripping protection

LOCATIONS
Hydra-Kronos
Hydra-Droërivier 1
Hydra-Droërivier 2
Hydra-Droërivier 3

C2 Reach settings

The forward and reverse reaches for both the out-of-step tripping and the out-of-step blocking protection were calculated as explained under section (3.3.2b) in Chapter 3. Table C3a gives the Thevenin impedance calculated for the respective locations shown in Figure C1. Table C3b lists the reaches for the out-of-step blocking protection locations and Table C3c lists the reaches for the out-of-step tripping protection locations. These reaches were used to calculate the required zone characteristics for the blocking and tripping protection at the respective locations.

Two examples are given: firstly the reach calculation for the purpose of determining the reach settings for blocking protection located at Aries-Kronos and secondly the reach calculation for the purpose of determining the reach settings for tripping protection located at Hydra-Droërivier 1.

Example 1: Blocking protection reach settings at Aries-Kronos

With reference to Figure C3, the line impedance data listed in Table A1 in Appendix A, and the Thevenin impedance data listed in Table C3a, the reach settings were calculated as follows (Figure C4 shows the protection characteristics, with calculated reach settings, in the impedance plane):

Zf	=	$\lvert Zf\rvert \angle\varphi_l$
	=	$0{,}0398$ pu $\angle 74{,}74°$
Zr	=	$\lvert Zr\rvert \angle 180+\varphi_l$
	=	$0{,}0528$ pu $\angle 254{,}74°$

where

Zf	=	*forward reach*
Zr	=	*reverse reach*
$\lvert Zf\rvert$	=	*impedance forward reach*
	=	*ABS[(line impedance)+(Thevenin impedance in front of Kronos SS)]*
	=	$\lvert(0{,}0024 + j0{,}0088) + (0{,}0100 + j0{,}0290)\rvert$
	=	$\lvert 0{,}0124+j0{,}0378\rvert$
	=	$0{,}0398$ pu
$\lvert Zr\rvert$	=	*impedance reverse reach*
	=	*ABS(Thevenin impedance behind Aries SS)*
	=	$\lvert 0{,}0220+j0{,}0480\rvert$
	=	$0{,}0528$ pu
φ_l	=	*line angle*

$$= \tan^{-1}\frac{Xl}{Rl}$$

$$= \tan^{-1}\frac{0{,}0088}{0{,}0024}$$

$= 74{,}74°$

$Rl+jXl$ = *line impedance*

= *0,0024 + j0,0088 pu* *[from Table A1, Appendix A]*

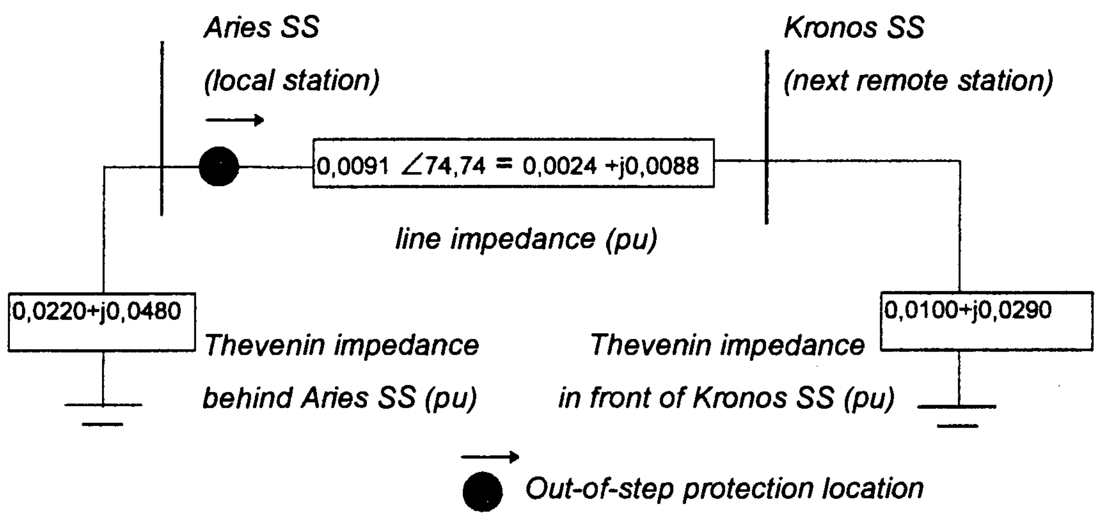


Figure C3: Forward and reverse reach calculation, Aries-Kronos

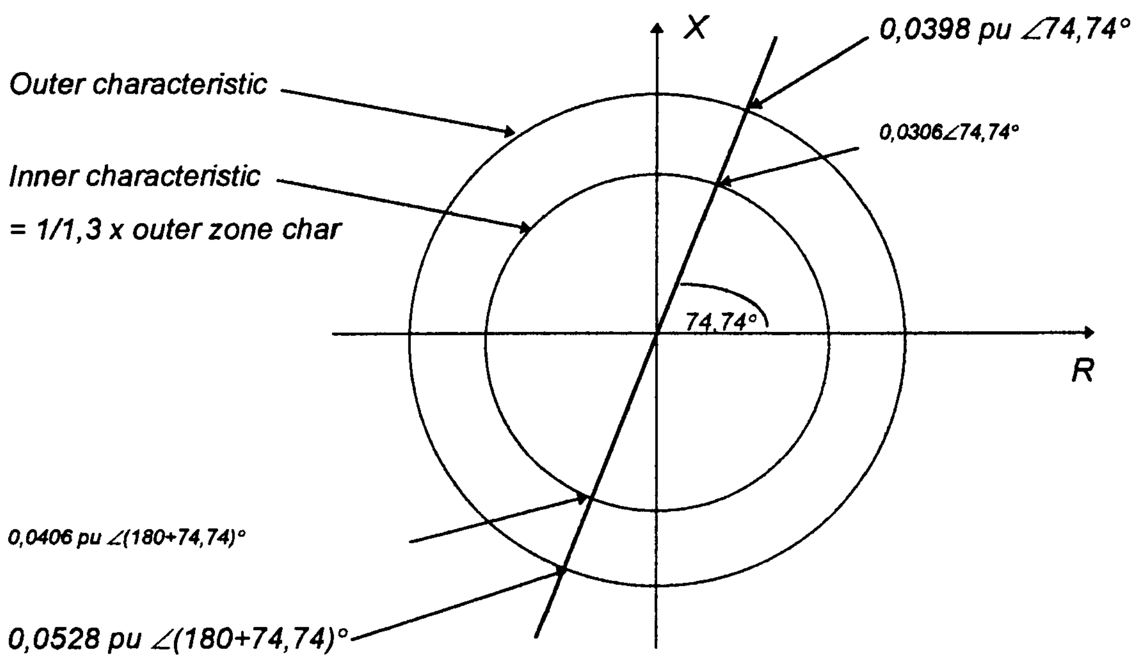


Figure C4: Reach settings for out-of-step blocking protection at Aries-Kronos

Example 2: *Tripping protection reach settings at Hydra-Droërivier 1*

With reference to Figure C5, the line impedance data listed in Table A1 in Appendix A, and the Theveinin impedance data listed in Table C3a, the reach settings were calculated as follows (Figure C6 shows the protection characteristics, with calculated reach settings, in the impedance plane):

$$Zf = |Zf|\angle\varphi_l$$
$$= 0{,}0680 \text{ pu } \angle 85{,}46°$$
$$Zr = |Zr|\angle 180+\varphi_l$$
$$= 0{,}0150 \text{ pu } \angle 256{,}46°$$

where

Zf	=	*forward reach*
Zr	=	*reverse reach*
$\|Zf\|$	=	*impedance forward reach*
	=	*ABS[(line impedance)+(Thevenin impedance in front of Droërivier SS)]*
	=	$\|(0{,}0038 + j0{,}0479) + (0{,}0080 + j0{,}0190)\|$
	=	$\|0{,}0120 + j0{,}0670\|$
	=	*0,0680 pu*
$\|Zr\|$	=	*impedance reverse reach*
	=	*ABS(Thevenin impedance behind Hydra SS)*
	=	$\|0{,}0070+j0{,}0130\|$
	=	*0,0150 pu*
φ_l	=	*line angle*
	=	$\tan^{-1}\dfrac{Xl}{Rl}$
	=	$\tan^{-1}\dfrac{0{,}0479}{0{,}0038}$
	=	*85,46°*
$Rl+jXl$	=	*line impedance*
	=	*0,0038 + j0,0479 pu* *[from Table A1, Appendix A]*

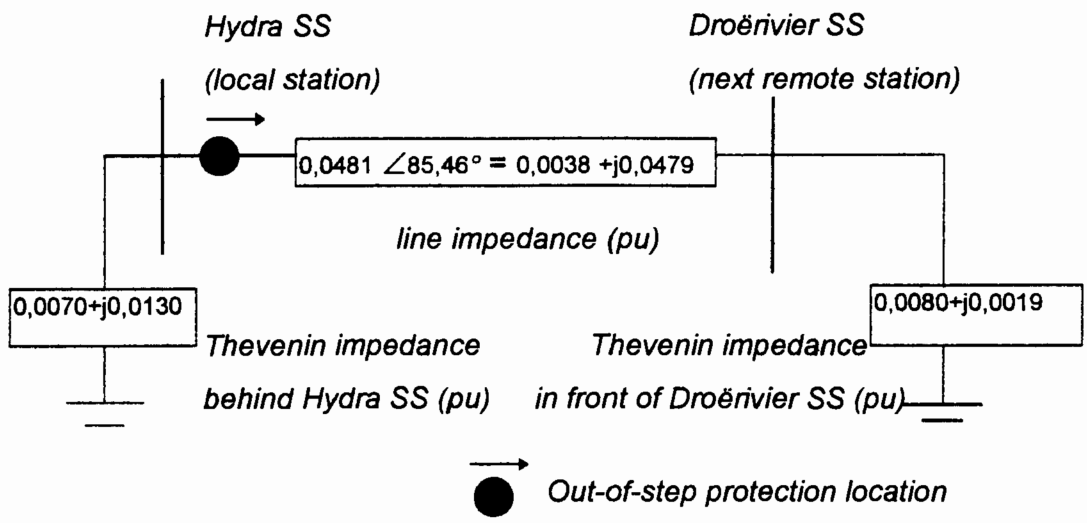


Figure C5: Forward and reverse reach calculation, Hydra-Droërivier 1

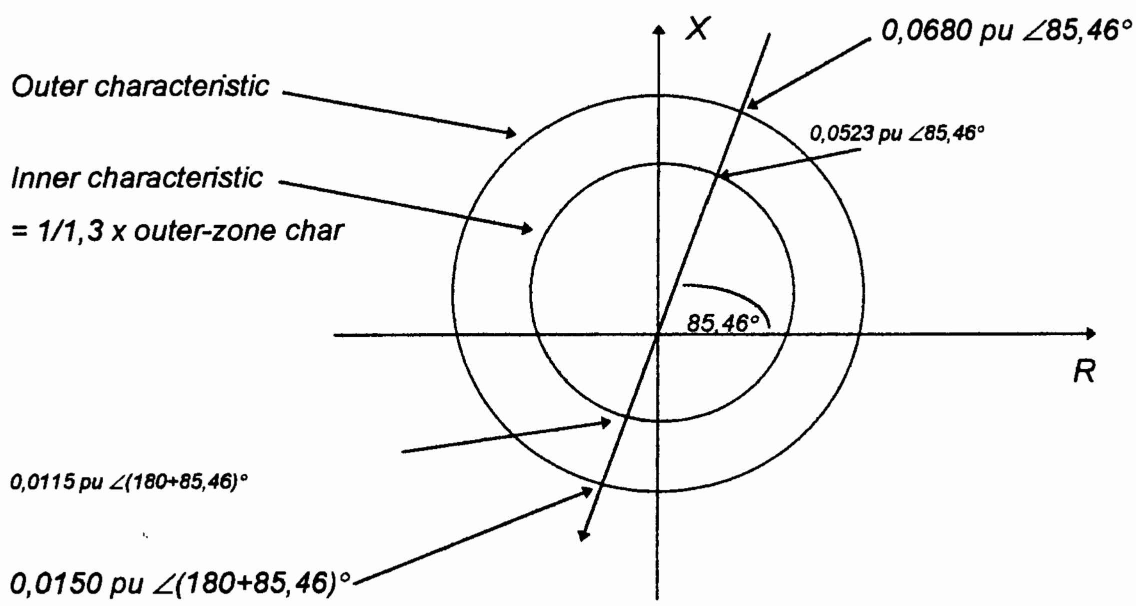


Figure C6: Reach settings for out-of-step tripping protection at Hydra-Droërivier 1

Table C3a: Thevinin impedance at respective locations in the system

Location (local - remote)	**Thevinin impedance behind local station (pu)**		**Thevinin impedance in front of remote station (pu)**	
	R	X	R	X
Hydra-Kronos	0,074	0,015	0,024	0,056
Kronos-Hydra	0,024	0,056	0,074	0,015
Kronos-Aries	0,010	0,029	0,022	0,048
Aries-Kronos	0,022	0,048	0,010	0,029
Aries-Helios	0,015	0,034	0,016	0,049
Helios-Aries	0,016	0,049	0,015	0,034

Table C3a (cont): Thevinin impedance at respective locations in the system

Location (local - remote)	Thevinin impedance behind local station (pu)		Thevinin impedance in front of remote station (pu)	
Helios-Juno	0,016	0,043	0,015	0,042
Juno-Helios	0,015	0,042	0,016	0,043
Juno-Aurora	0,019	0,054	0,012	0,030
Aurora-Juno	0,012	0,030	0,019	0,054
Aurora-Koeberg	0,024	0,045	0,008	0,018
Koeberg-Aurora	0,008	0,018	0,024	0,045
Hydra-Droërivier 1	0,007	0,013	0,008	0,019
Droërivier-Hydra 1	0,008	0,019	0,007	0,013
Hydra-Droërivier 2	0,007	0,013	0,008	0,019
Droërivier-Hydra 2	0,008	0,019	0,007	0,013
Hydra-Droërivier 3	0,007	0,013	0,008	0,017
Droërivier-Hydra 3	0,008	0,017	0,007	0,013
Droërivier-Muldersvlei	0,008	0,019	0,009	0,017
Muldersvlei-Droërivier	0,009	0,017	0,008	0,019
Droërivier-Proteus	0,007	0,017	0,022	0,057
Proteus-Droërivier	0,022	0,057	0,007	0,017
Droërivier-Bacchus	0,008	0,018	0,008	0,022
Bacchus-Droërivier	0,008	0,022	0,008	0,018
Bacchus-Palmiet	0,013	0,025	0,000	0,064
Palmiet-Bacchus	0,000	0,064	0,013	0,025
Bacchus-Muldersvlei	0,009	0,028	0,010	0,018
Muldersvlei-Bacchus	0,010	0,018	0,009	0,028
Muldersvlei-Koeberg 1	0,009	0,016	0,008	0,016
Koeberg-Muldersvlei 1	0,008	0,016	0,009	0,016
Muldersvlei-Koeberg 2	0,009	0,016	0,008	0,016
Koeberg-Muldersvlei 2	0,008	0,016	0,009	0,016
Muldersvlei-Acacia	0,008	0,016	0,010	0,020
Acacia-Muldersvlei	0,010	0,020	0,008	0,016
Acacia-Koeberg	0,011	0,021	0,008	0,016
Koeberg-Acacia	0,008	0,016	0,011	0,021

Table C3b: Forward and reverse reach settings at blocking protection locations

Location	Forward reach	Reverse reach	Line angle	Location	Forward reach	Reverse reach	Line angle
Hydra-Kronos	0,07	0,08	76,68	Droërivier-Muldersvlei	0,06	0,02	81,88
Kronos-Hydra	0,08	0,06	76,68	Muldersvlei-Droërivier	0,06	0,02	81,88
Kronos-Aries	0,06	0,03	74,75	Droërivier-Proteus	0,10	0,02	80,18
Aries-Kronos	0,04	0,05	74,74	Proteus-Droërivier	0,06	0,06	80,18
Aries-Helios	0,06	0,04	75,80	Droërivier-Bacchus	0,06	0,02	81,56
Helios-Aries	0,05	0,05	75,80	Bacchus-Droërivier	0,06	0,02	81,56
Helios-Juno	0,06	0,05	76,48	Bacchus-Palmiet	0,08	0,03	85,31
Juno-Helios	0,06	0,04	76,48	Palmiet-Bacchus	0,04	0,06	85,31
Juno-Aurora	0,04	0,06	75,96	Bacchus-Muldersvlei	0,04	0,03	85,52
Aurora-Juno	0,07	0,03	75,96	Muldersvlei-Bacchus	0,05	0,02	85,52
Aurora-Koeberg	0,04	0,05	85,63	Muldersvlei-Koeberg 1	0,03	0,02	85,76
Koeberg-Aurora	0,07	0,02	85,63	Koeberg-Muldersvlei 1	0,03	0,02	85,76

Table C3b (cont): Forward and reverse reach settings at blocking protection locations

Location	Forward reach	Reverse reach	Line angle	Location	Forward reach	Reverse reach	Line angle
Hydra-Droërivier 1	0,07	0,02	85,46	Muldersvlei-Koeberg 2	0,03	0,02	85,76
Droërivier-Hydra 1	0,06	0,02	85,47	Koeberg-Muldersvlei 2	0,03	0,02	85,76
Hydra-Droërivier 2	0,07	0,02	85,47	Muldersvlei-Acacia	0,03	0,02	85,59
Droërivier-Hydra 2	0,06	0,02	85,47	Acacia-Muldersvlei	0,03	0,02	85,59
Hydra-Droërivier 3	0,05	0,01	82,04	Acacia-Koeberg	0,02	0,02	85,10
Droërivier-Hydra 3	0,04	0,02	82,04	Koeberg-Acacia	0,03	0,02	85,10

Table C3c: Forward and reverse reach settings at tripping protection locations

Location	Forward reach	Reverse reach	Line angle
Hydra-Kronos	0,07	0,08	76,68
Hydra-Droërivier 1	0,07	0,02	85,46
Hydra-Droërivier 1	0,07	0,02	85,47
Hydra-Droërivier 3	0,05	0,01	82,04

C3 Timer settings

The timer settings for both the out-of-step blocking protection and the out-of-step tripping protection were calculated from the following equation:

$$T_{setting} = \frac{\Delta\theta}{360 * fs} \text{ seconds} \text{---------------------------(equation (3.6) in Chapter 3)}$$

where

$T_{setting}$ = timer setting for the operating zone(seconds)

$\Delta\theta$ = change in angle separation during that time when the apparent impedance is within the operating zone(in degrees)

fs = maximum swing frequency (Hz)

<u>fs</u>

The maximum swing frequency fs for the stability study presented under section (3.3.2c) was determined by calculating the swing frequencies at Koeberg and Palmiet Power Stations respectively. The electrical power oscillations at Koeberg and Palmiet respectively were used and are shown in Figure C7. The swing frequency for each oscillating cycle were calculated (the first two swing frequencies for Koeberg are shown in Figure C7).

The average swing frequencies for a given time range are those listed in Table C4. Figure C8 is a plot showing the change in swing frequency with time.

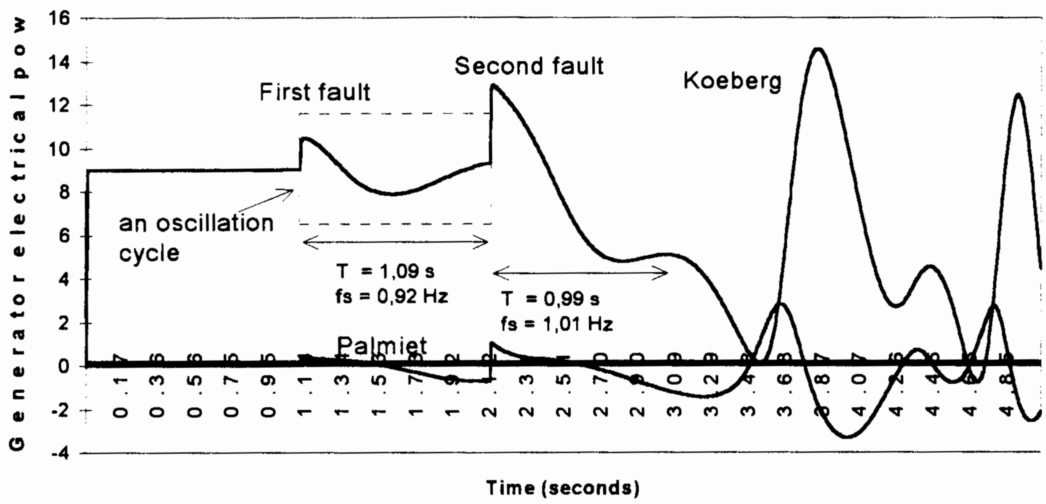


Figure C7: Calculating swing frequency

Table C4: Swing frequencies at Koeberg and Palmiet respectively

Time range(s)	Average swing frequency at Koeberg during time range (Hz)	Average swing frequency at Palmiet during time range (Hz)
0,00 - 1,10	0,00	0,00
1,10 - 2,10	0,31	0,56
2,10 - 3,50	0,65	0,65
3,50 - 4,50	0,89	1,85
4,50 - 5,00	1,09	2,78

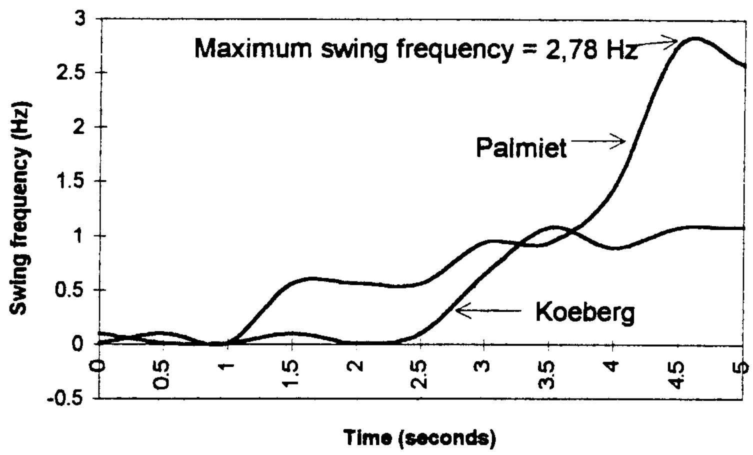


Figure C8: Change in swing frequency with time

From Figure C8 it is clear that the maximum swing frequency at which any of the out-of-step blocking or tripping protection should detect unstable conditions is 2,78 Hz.

<u>$\Delta\theta$</u>

For each relay location $\Delta\theta$ was calculated from the forward reach, the reverse reach and the difference in characteristic size between the inner and outer zone[1].

Two examples are given to illustrate the calculation of the timer settings: firstly the timer settings for blocking protection located at Aries-Kronos and secondly the timer settings for tripping protection located at Hydra-Droërivier 1.

Example 1: <u>*Blocking protection timer settings at Aries-Kronos*</u>

With reference to Figure C9, the reach settings listed in Table C3b, and the detection philosophy for out-of-step blocking protection used in this thesis (see Appendix B), the timer settings were calculated as follows:

[1] For both the out-of-step blocking and the out-of-step tripping relays used for the purposes of this research the outer zone radius = 1,3 x inner zone radius (refer to Appendix B).

$$T_{setting\ (outer\text{-}zone\ time\ Tb)} = \frac{\Delta\theta}{360 * fs} \text{ seconds}$$

$$= \frac{14{,}89^\circ}{360 * 2{,}78\,Hz}$$

$$= 0{,}0150 \text{ seconds}$$

where

$T_{setting\ (outer\ zone\ time\ Tb)}$	=	*timer setting (seconds) for blocking protection located at Aries-Kronos*
$\Delta\theta$	=	$\theta_B - \theta_A$
	=	$104{,}89^\circ - 90^\circ$
	=	$14{,}89^\circ$
θ_A	=	90°
θ_B	=	$2 \times \tan^{-1} \frac{outer \cdot char \cdot radius}{inner \cdot char \cdot radius})$
	=	$2 \times \tan^{-1} \frac{0{,}0450}{0{,}0346}$
	=	$104{,}89^\circ$
Outer char radius	=	$\frac{1}{2}(0{,}04 + 0{,}05)$ *[from Table C3b]*
	=	$0{,}0450$
Inner char radius	=	$\frac{1}{1{,}3}$ *x outer char radius*
	=	$0{,}0346$
fs	=	*maximum swing frequency*
	=	$2{,}78$ *Hz*

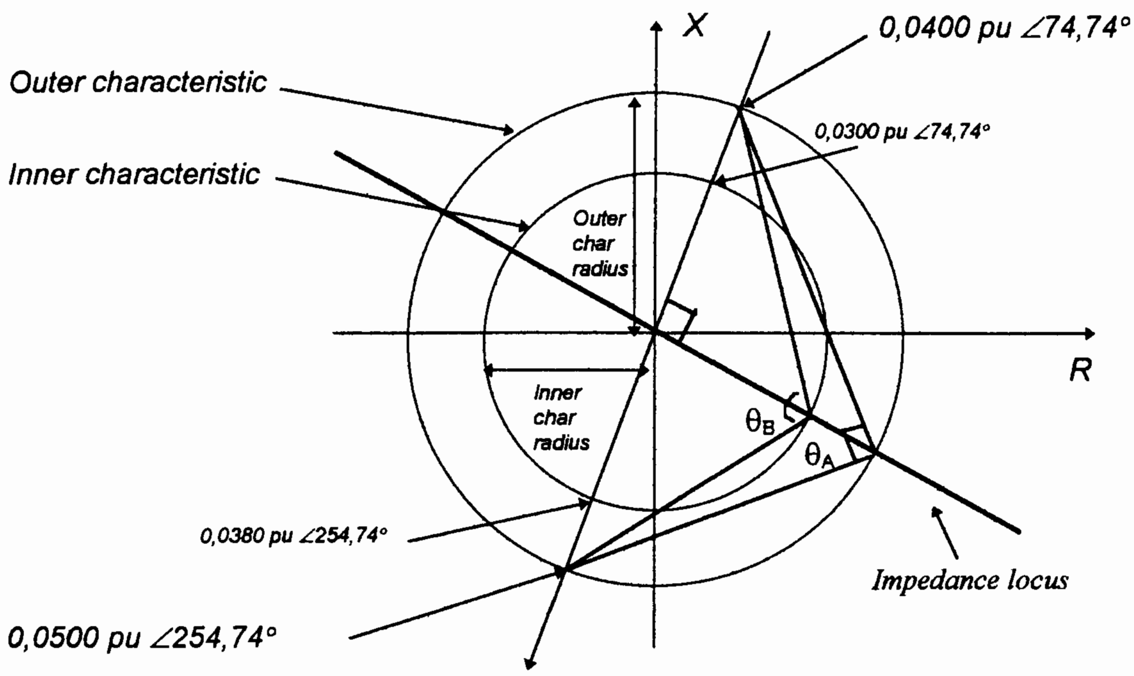


Figure C9: *Timer settings for out-of-step blocking relay at Aries-Kronos*

Example 2: *Tripping protection timer settings at Hydra-Droërivier 1*

With reference to Figures C10 and C11, the reach settings listed in Table C3c, and the detection philosophy for the out-of-step tripping relay used in this thesis (see Appendix B), the timer settings were calculated as follows:

$$T_{setting\ (outer\text{-}zone\ time\ Tto)} = \frac{\Delta\theta}{360 * fs} \text{ seconds}$$

$$= \frac{14{,}25^{\circ}}{360 * 2{,}78 Hz}$$

$$= 0{,}0150 \text{ seconds}$$

where

$T_{setting\ (outer\text{-}zone\ time\ Tto)}$ = *outer-zone timer setting (seconds) for the tripping relay located at Hydra-Droërivier 1*

$\Delta\theta$ = *portion of impedance trajectory ($\Delta\theta$) between two chosen points (degrees)*

= $\theta_B - \theta_{At}$

= $104{,}25^{\circ} - 90^{\circ}$

	=	*14,25°*
θ_A	=	*90°*
θ_B	=	$2 \times \tan^{-1} \frac{outer \cdot char \cdot radius}{inner \cdot char \cdot radius})$
	=	$2 \times \tan^{-1} \frac{0{,}0450}{0{,}0350}$
	=	*104,25°*
Outer char radius	=	$\frac{1}{2}$ (|Zf| + |Zr|)
	=	$\frac{1}{2}(0{,}0700 + 0{,}0200)$
	=	*0,0450 pu*
Inner char radius	=	$\frac{1}{1{,}3}$ x outer char radius
	=	*1/1,3 x 0,0450*
	=	*0,0350 pu*
fs	=	*2,78 Hz*

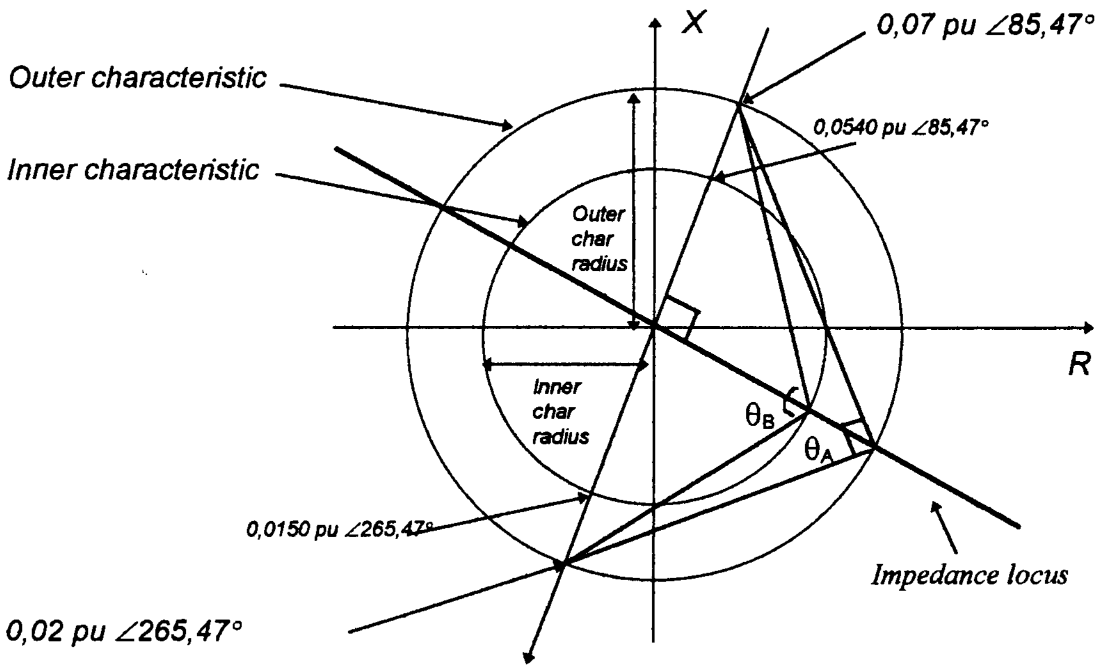


Figure C10: Timer settings for out-of-step tripping protection at Hydra-Droërivier 1

$T_{setting\ (inner\text{-}zone\ time\ Tti)} = \dfrac{\Delta\theta}{360 * fs}$ *seconds*

$= \dfrac{151{,}49°}{360 * 2{,}78\,Hz}$

$=$ *0,1510 seconds*

where (refer to Figure C11)

$T_{setting\ (inner\text{-}zone\ time\ Tti)}$ = *inner-zone timer setting (seconds) for the tripping relay located at Hydra-Droërivier 1*

$\Delta\theta$ = *portion of impedance trajectory ($\Delta\theta$) between two chosen points (degrees)*

$= \theta_{B2} - \theta_{iB}$

$= 255{,}75° - 104{,}25°$

$= 151{,}49°$

$\theta_B = 2 \times \tan^{-1} \dfrac{outer \cdot char \cdot radius}{inner \cdot char \cdot radius})$

$= 2 \times \tan^{-1} \dfrac{0{,}0450}{0{,}0350}$

$= 104{,}25°$

$\theta_{B2} = 360 - [2 \times \tan^{-1} \dfrac{outer \cdot char \cdot radius}{inner \cdot char \cdot radius}]$

$= 360 - [2 \times \tan^{-1} \dfrac{0{,}0450}{0{,}0350}]$

$= 255{,}75°$

Outer char radius $= \dfrac{1}{2}\,(|Zf| + |Zr|)$

$= \dfrac{1}{2}(0{,}0700 + 0{,}0200)$

$= 0{,}0450$

Inner char radius $= \dfrac{1}{1{,}3} \times$ *outer char radius*

$= \dfrac{1}{1{,}3} \times 0{,}0450$

$= 0{,}0350$

$fs = 2{,}78\ Hz$

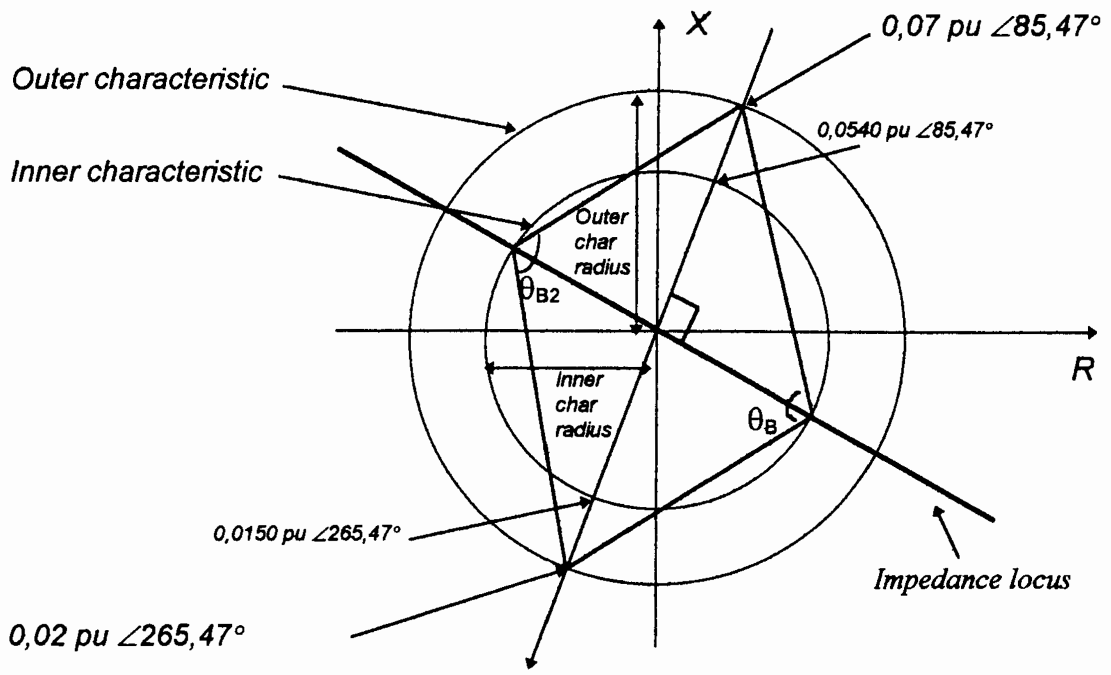


Figure C11: Timer settings for out-of-step tripping protection at Hydra-Droërivier 1

Timer settings were calculated for out-of-step blocking and tripping protection at their respective locations. The timers for the blocking and tripping relays are listed in Tables C5a and C5b respectively[2]. The locations are the locations for the portion of the transmission system shown in Figure C1.

[2] Note that all the outer-zone and inner-zone timers are the same because:

1. the outer zone characteristics are 1,3 times the inner zone characteristics for out-of-step blocking and tripping protection respectively (refer to appendix B); and
2. the maximum swing frequency is assumed to be the same everywhere in the system.

Table C5a: Out-of-step blocking protection timers

Location	Outer-zone timer Tb (ms)	Location	Outer-zone timer Tb (ms)
Hydra-Kronos	15	Droërivier-Muldersvlei	15
Kronos-Hydra	15	Muldersvlei-Droërivier	15
Kronos-Aries	15	Droërivier-Proteus	15
Aries-Kronos	15	Proteus-Droërivier	15
Aries-Helios	15	Droërivier-Bacchus	15
Helios-Aries	15	Bacchus-Droërivier	15
Helios-Juno	15	Bacchus-Palmiet	15
Juno-Helios	15	Palmiet-Bacchus	15
Juno-Aurora	15	Bacchus-Muldersvlei	15
Aurora-Juno	15	Muldersvlei-Bacchus	15
Aurora-Koeberg	15	Muldersvlei-Koeberg 1	15
Koeberg-Aurora	15	Koeberg-Muldersvlei 1	15
Hydra-Droërivier 1	15	Muldersvlei-Koeberg 2	15
Droërivier-Hydra 1	15	Koeberg-Muldersvlei 2	15
Hydra-Droërivier 2	15	Muldersvlei-Acacia	15
Droërivier-Hydra 2	15	Acacia-Muldersvlei	15
Hydra-Droërivier 3	15	Acacia-Koeberg	15
Droërivier-Hydra 3	15	Koeberg-Acacia	15

Table C5a: Out-of-step tripping protection timers

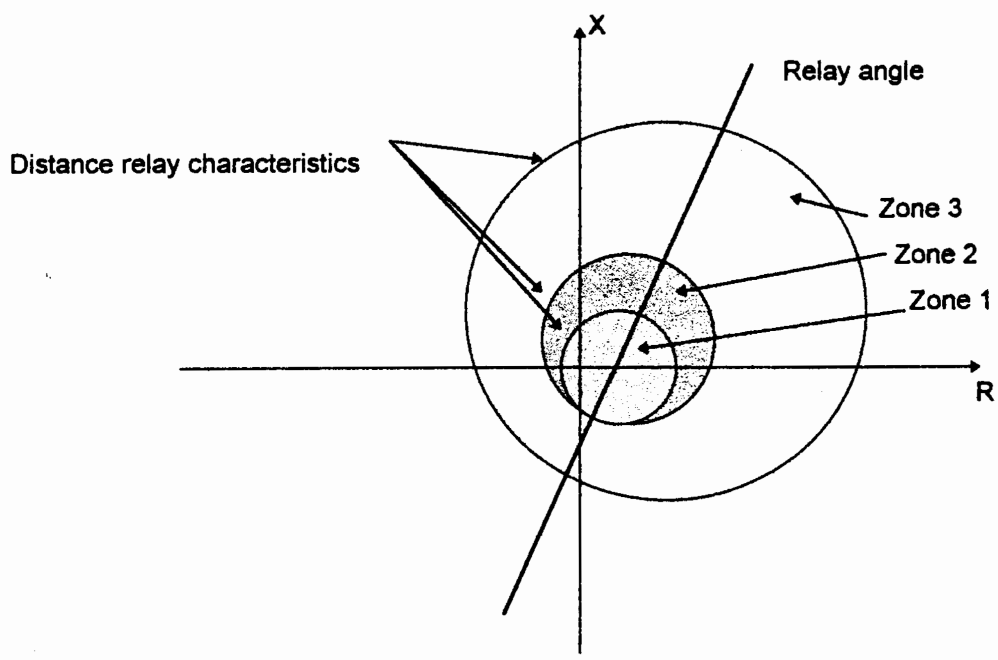
Location	Outer-zone timer Tto (ms)	Inner-zone timer Tti (ms)
Hydra-Kronos	15	151
Hydra-Droërivier 1	15	151
Hydra-Droërivier 1	15	151
Hydra-Droërivier 3	15	151

APPENDIX D

VERIFICATION AND PROTECTION PERFORMANCE PERFORMANCE RESULTS - CASE STUDY DONE IN CHAPTER 3

The protection performance was recorded and evaluated by including mathematical models, representing the behaviour of out-of-step protection relays as well as distance relays, in the power system model. The distance relays were modelled at each location within the Eskom transmission system. A mathematical model available in PSS/E was used. The distance relay characteristics, zone timer settings and calculation method for the reach settings are the following:

<u>Distance relay characteristics:</u>



<u>Zone timer settings:</u>

For each location the zone timer settings were fixed to be the following (typical distance relay zone timer settings used by Eskom):

Zone 1 timer =	instantaneous operation
Zone 2 timer =	0,4 seconds delay before operation
Zone 3 timer =	0,7 seconds delay before operation

<u>Calculation method for the reach settings</u>

The zone reach settings for the distance relays were calculated as follows:

Zone 1	=	80% x $\lvert Zl \rvert$
Zone 2	=	100% x $\lvert Zl \rvert$
Zone 3 forward	=	150% x $\lvert Zl \rvert$
Zone 3 reverse	=	10% x $\lvert Zl \rvert$

where

$\lvert Zl \rvert$ = line impedance

The stability study was done and the protection performance was recorded. The performance of the out-of-step blocking and tripping protection each time the impedance passed through the characteristics was evaluated as follows:

Detection:	Correct detection took place according to the detection methodology and philosophy presented in Appendix B for out-of-step blocking and triping relays respectively.
Nondetection and undesired operation of distance protection:	Detection by the out-of-step blocking relay did not take place and as a result undersired operation of distance protection took place

Nondetection with no undesired operation of distance protection:	Detection by the out-of-step blocking protection did not take place and undersired operation of distance protection did not take place.
Nondetection of instability:	Detection by the out-of-step tripping protection did not take place.

For those locations where nondetection took place, the reasons why the protection did not detect were investigated.

D1 Out-of-step blocking protection

In the stability study done, the impedance passed through the out-of-step blocking protection characteristics twice at every location: the first time during the initial power swing condition and the second time during the out-of-step condition. Table D1 shows the performance of the out-of-step blocking protection during each time the impedance passed through the characteristics. For those locations where nondetection took place, the reason is also given.

Table D1: Performance of out-of-step blocking protection

Location	Performance during power swing condition	Performance during out-of-step condition
Hydra-Kronos	Detection	Detection
Kronos-Hydra	Detection	Detection
Kronos-Aries	Detection	Detection
Aries-Kronos	Detection	Detection
Aries-Helios	Detection	Nondetection and undesired operation of distance protection: The zone timer setting is not sufficient to allow the timer to expire.
Helios-Aries	Detection	Detection
Helios-Juno	Detection	Detection
Juno-Helios	Detection	Nondetection and undesired operation of distance protection: The zone timer setting is not sufficient to allow the timer to expire.
Juno-Aurora	Detection	Nondetection and undesired operation of distance protection: The zone timer setting is not sufficient to allow the timer to expire.
Aurora-Juno	Detection	Nondetection and undesired operation of distance protection: The zone timer setting is not sufficient to allow the timer to expire.
Aurora-Koeberg	Detection	Detection
Koeberg-Aurora	Nondetection: The out-of-step blocking characteristics are not large enough to allow detection.	Detection
Hydra-Droërivier 1	Detection	Detection
Droërivier-Hydra 1	Detection	Nondetection and undesired operation of distance protection: Distance relay's largest characteristic encroached the out-of-step blocking characteristics.
Hydra-Droërivier 2	Detection	Detection
Droërivier-Hydra 2	Detection	Nondetection and undesired operation of distance protection: Distance relay's largest characteristic encroached the out-of-step blocking characteristics.
Hydra-Droërivier 3	Detection	Nondetection and undesired operation of distance protection: The zone timer setting is not sufficient to allow the timer to expire.
Droërivier-Hydra 3	Nondetection and undesired operation of distance protection: The zone timer setting is not sufficient to allow the timer to expire.	Nondetection and undesired operation of distance protection: The zone timer setting is not sufficient to allow the timer to expire.
Droërivier-Muldersvlei	Detection	Detection
Muldersvlei-Droërivier	Detection	Detection

Table D1 (cont): Performance of out-of-step blocking protection

Location	Performance during power swing condition	Performance during out-of-step condition
Droërivier-Proteus	Detection	Nondetection and undesired operation of distance protection: The out-of-step blocking characteristics are not large enough to allow detection.
Proteus-Droërivier	Detection	Nondetection and undesired operation of distance protection: The out-of-step blocking characteristics are not large enough to allow detection.
Droërivier-Bacchus	Detection	Detection
Bacchus-Droërivier	Detection	Detection
Bacchus-Palmiet	Detection	Detection
Palmiet-Bacchus	Detection	Detection
Bacchus-Muldersvlei	Nondetection and undesired operation of distance protection: The zone timer setting is not sufficient to allow the timer to expire.	Nondetection and undesired operation of distance protection: The zone timer setting is not sufficient to allow the timer to expire.
Muldersvlei-Bacchus	Nondetection and undesired operation of distance protection: The zone timer setting is not sufficient to allow the timer to expire.	Nondetection and undesired operation of distance protection: The zone timer setting is not sufficient to allow the timer to expire.
Muldersvlei-Koeberg 1	Nondetection with no undesired operation of distance protection: Impedance did not enter characteristics.	Nondetection with no undesired operation of distance protection: Impedance did not enter characteristics.
Koeberg-Muldersvlei 1	Nondetection with no undesired operation of distance protection: Impedance did not enter characteristics.	Nondetection with no undesired operation of distance protection: Impedance did not enter characteristics.
Muldersvlei-Koeberg 2	Nondetection with no undesired operation of distance protection: Impedance did not enter characteristics.	Nondetection with no undesired operation of distance protection: Impedance did not enter characteristics.
Koeberg-Muldersvlei 2	Nondetection with no undesired operation of distance protection: Impedance did not enter characteristics.	Nondetection with no undesired operation of distance protection: Impedance did not enter characteristics.
Muldersvlei-Acacia	Nondetection with no undesired operation of distance protection: Impedance did not enter characteristics.	Nondetection with no undesired operation of distance protection: Impedance did not enter characteristics.
Acacia-Muldersvlei	Nondetection with no undesired operation of distance protection: Impedance did not enter characteristics.	Nondetection with no undesired operation of distance protection: Impedance did not enter characteristics.
Acacia-Koeberg	Nondetection with no undesired operation of distance protection: Impedance did not enter characteristics.	Nondetection with no undesired operation of distance protection: Impedance did not enter characteristics.
Koeberg-Acacia	Nondetection with no undesired operation of distance protection: Impedance did not enter characteristics.	Nondetection with no undesired operation of distance protection: Impedance did not enter characteristics.

The locations that are shaded in Table D1 are the locations where power swing and out-of-step conditions were not detected and blocking could therefore not be initiated. The reasons, also indicated in Table D1, were as follows:

1. The timer setting was not sufficient to allow the timer to expire.

2. The out-of-step blocking characteristics were not large enough to allow detection.

3. Distance relay's largest characteristic encroached the out-of-step blocking characteristics.

4. The impedance never entered the relay characteristics.

1. <u>Zone timer setting not sufficient</u>

Figure D1 shows the impedance locus 'seen' by the out-of-step blocking protection at Juno-Helios. In Figure D1 it can be seen that after the impedance had entered the outer zone for the first time, it remained in the outer zone for a period of 118 ms. The timer setting for the blocking relay as calculated in Appendix C was 15 ms. On entering the outer zone for the second time, the impedance remained in the outer zone for a period of 14 ms. The impedance therefore passed through the characteristics at a faster rate than it did the first time.

Figures D2a and D2b show the change in the impedance 'seen' by the out-of-step blocking protection located at Juno-Helios. Figure D2b indicates the time for which the impedance remained within the characteristics each time. From Figure D2b it can be seen that upon the second entry the impedance stayed in the characteristics for 0,41 s compared with the first time, when it stayed there for 0,56 s. The second stay was therefore shorter, which indicates an increased rate of change of the impedance.

From the above it can be concluded that the rate of change of the impedance is not constant. In those cases where nondetection occurred, the rate of change of the impedance, when entering the outer zone, was more than the maximum swing frequency f_s used for calculation of the timer setting.

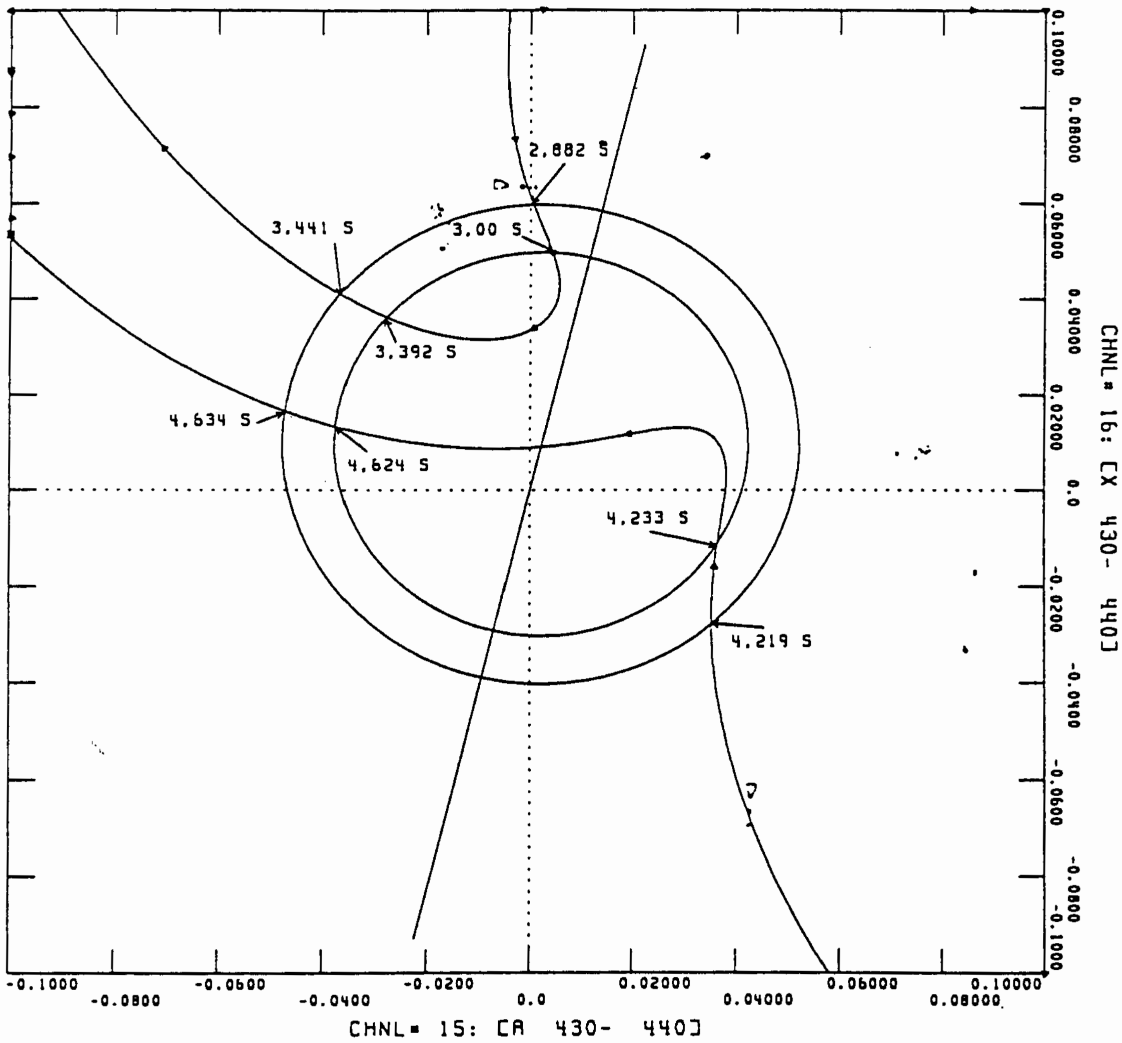


Figure D1: Impedance locus and out-of-step blocking protection characteristics for protection located at Juno-Helios

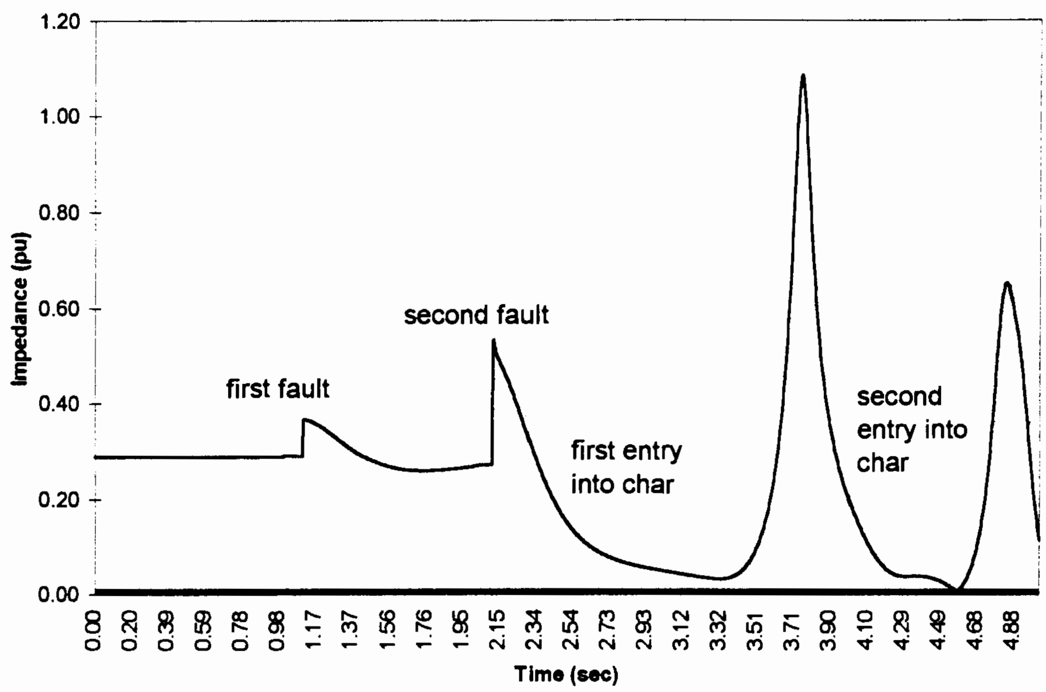


Figure D2a: Impedance change with time at Juno-Helios

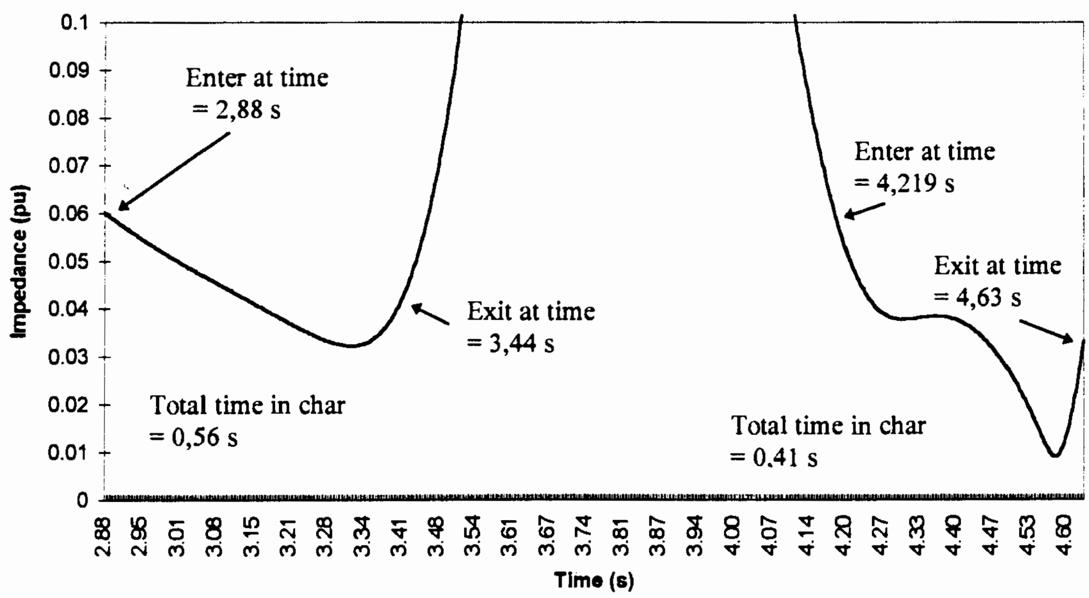


Figure D2b: Impedance entering the relay characteristics at Juno-Helios

2. The out-of-step blocking characteristics were not large enough

At five of the locations listed in Table D1 the impedance entered the out-of-step blocking's outer zone, remained inside the outer zone long enough to allow the timer to expire, but never entered the inner zone to enable detection of the power swing or out-of-step condition. As a consequence, the undesired operation of distance relays located at these locations occured.

Figure D3 shows the impedance locus 'seen' at the Droërivier-Hydra 1 location. It shows that the blocking protection detected the power swing when the impedance first entered the characteristics, but upon the second entry the blocking protection did not detect because the impedance did not enter the inner zone.

From the above it can be concluded that the reason for nondetection is that the out-of-step blocking characteristic was not large enough to allow detection.

3. Distance relay's largest characteristic encroached the out-of-step blocking characteristics.

At two locations the distance relay's characteristic reaches exceeded the blocking relay's characteristic reaches and undesired operation of the distance relay occured.

Figure D4 shows the relay characteristics of a distance relay located at the Droërivier-Hydra 1 location. The zone reach settings for the distance relay were calculated to be the following:

Zone 1	=	80% x $\lvert Zl \rvert$
	=	0,04 pu
Zone 2	=	100% x $\lvert Zl \rvert$
	=	0,05 pu

Zone 3 forward = 150% x $|Zl|$

= 0,06 pu

Zone 3 reverse = 10% x $|Zl|$

= 0,004 pu

where

$|Zl|$ = line impedance

= 0,0481 pu for the Droërivier-Hydra 1 line

In Figure D4 it can be seen that the zone 3 distance relay characteristic reach exceeds the out-of-step blocking protection reach. From the results of the case study it is clear that the impedance entered the zone 3 distance relay characteristic when it enters the out-of-step blocking's outer zone. Both the zone 3 distance relay timer and the out-of-step blocking timer started. In this cases the impedance did not enter the out-of-step blocking protection's inner zone because of the reason given under point 2 above. The distance relay zone 3 timer expired and undesired operation of the distance relay occured.

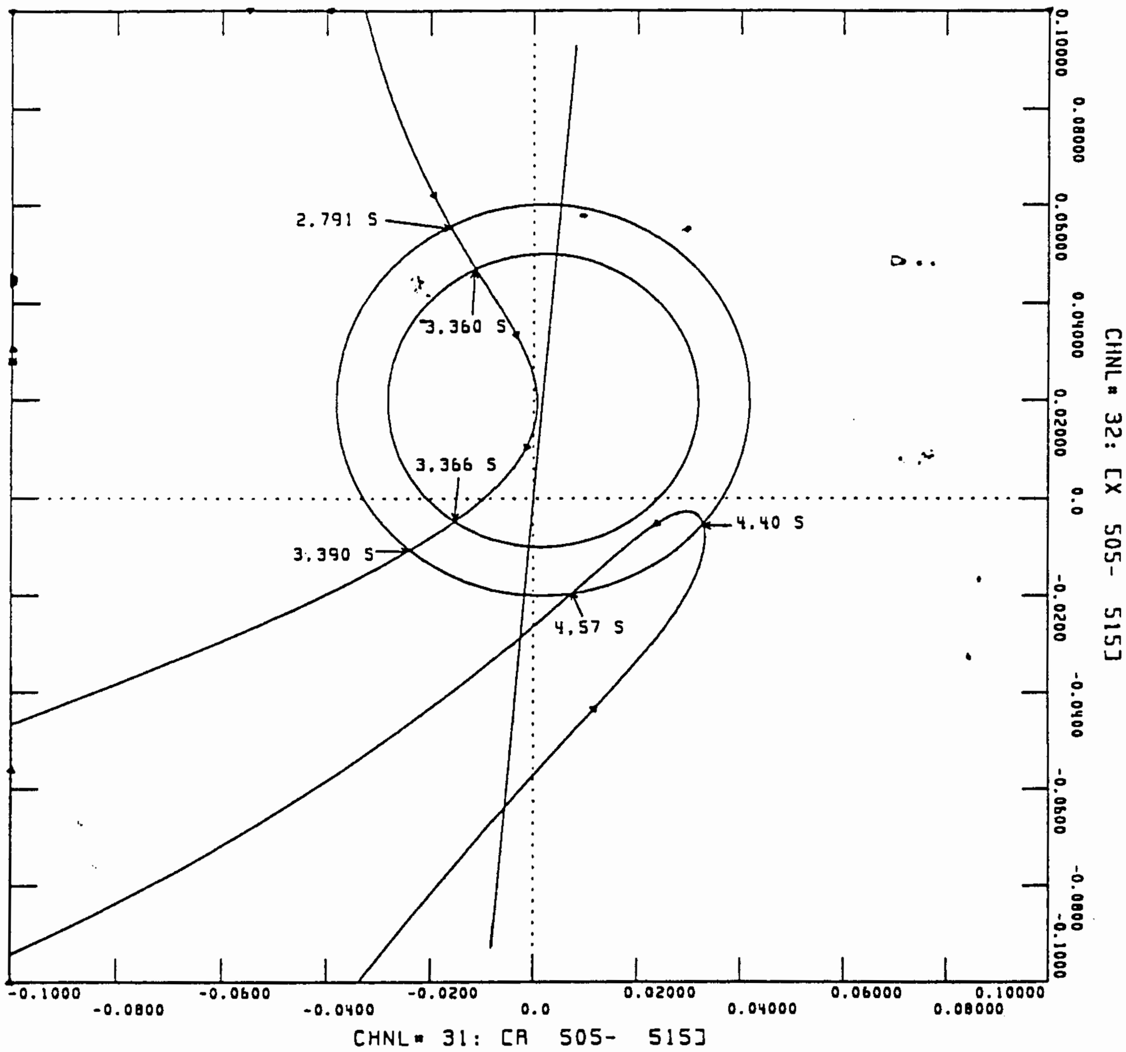


Figure D3: Impedance locus and out-of-step blocking protection characteristics for protection at Droërivier-Hydra 1

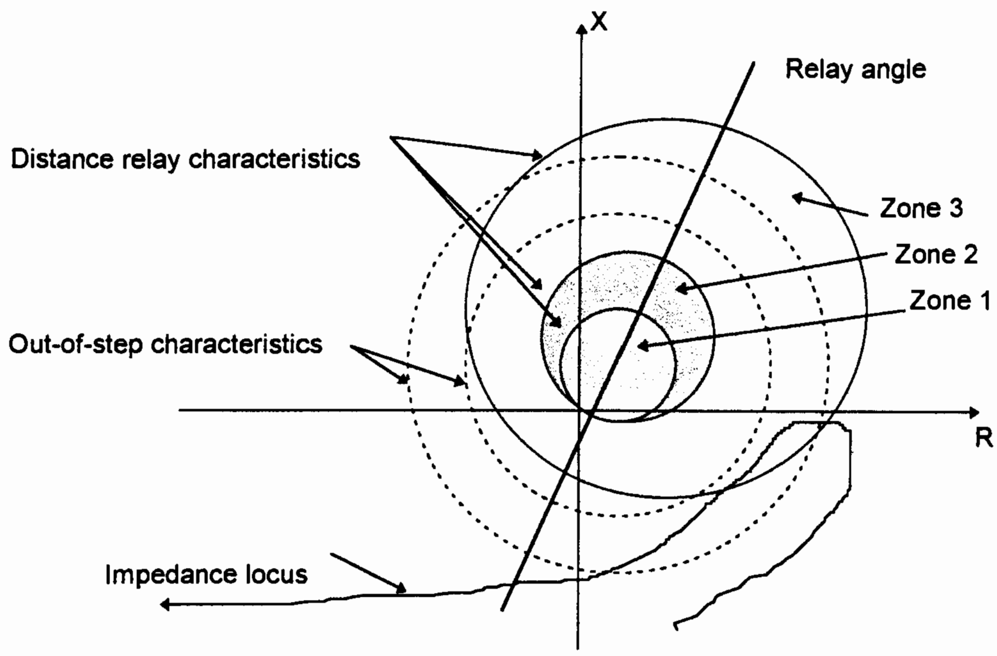


Figure D4: Distance relay and out-of-step blocking protection characteristics at Droërivier-Hydra 1

4. Impedance never enters the characteristics

The existing approach assumes that all the distance relays in the system will observe power oscillations and out-of-step conditions and as a results undesirable operation will occur. Out-of-step blocking protection is therefore typically located at all the locations where distance relays are located.

At eight of the locations listed in Table 3.1 nondetection occurred because the impedance never entered the blocking relay characteristics. The reason for this is that the impedance locus behaviour during power oscillations and out-of-step conditions is not observed at these locations. The apparent impedance calculated from the voltage and current at the relay location does not undergo oscillations severe enough to raise concern about possible undesired operation of the distance relay protection.

Figure D5a shows the impedance locus 'seen' at the Muldersvlei-Koeberg 1 location. Figure D5b shows the apparent impedance 'seen' by a distance relay located at Muldersvlei-Koeberg 1. The distance relay characteristics are shown in Figure D5b with reach settings calculated as follows:

Zone 1	=	80% x $\lvert Zl \rvert$
	=	0,008 pu
Zone 2	=	100% x $\lvert Zl \rvert$
	=	0,01 pu
Zone 3 forward	=	150% x $\lvert Zl \rvert$
	=	0,015 pu
Zone 3 reverse	=	10% x $\lvert Zl \rvert$
	=	0,001 pu

where

$\lvert Zl \rvert$	=	line impedance
	=	0,01 pu for the Muldersvlei-Koeberg 1 line

In Figure D5a it can be seen that the impedance never enters the out-of-step blocking characteristics. Figure D5b shows that the impedance never enters the distance relay characteristics and therefore does not introduce undesired operation of the distance relay during power oscillations or out-of-step conditions.

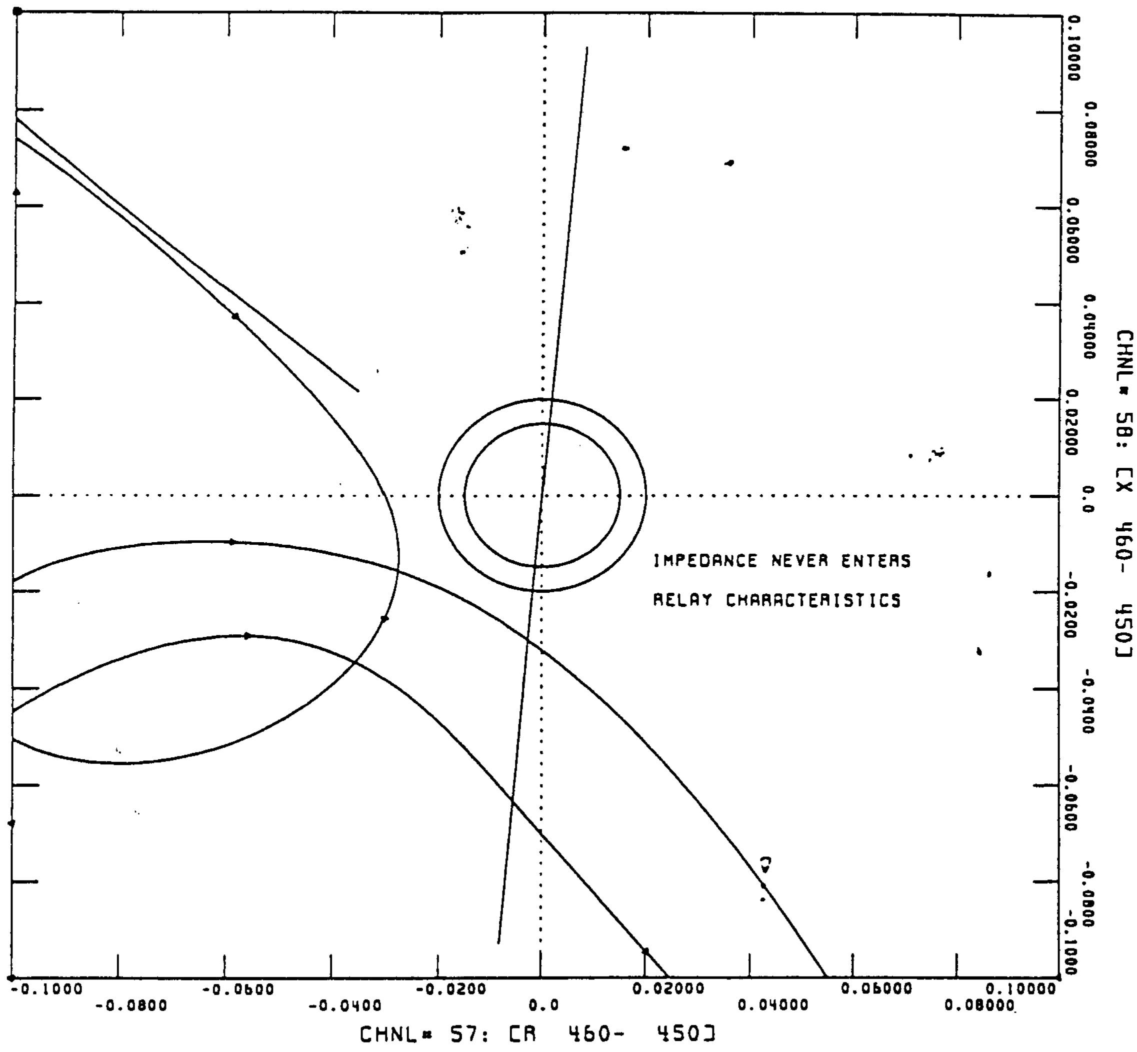


Figure D5a: Impedance locus and out-of-step blocking protection characteristics for protection at Muldersvlei-Koeberg 1

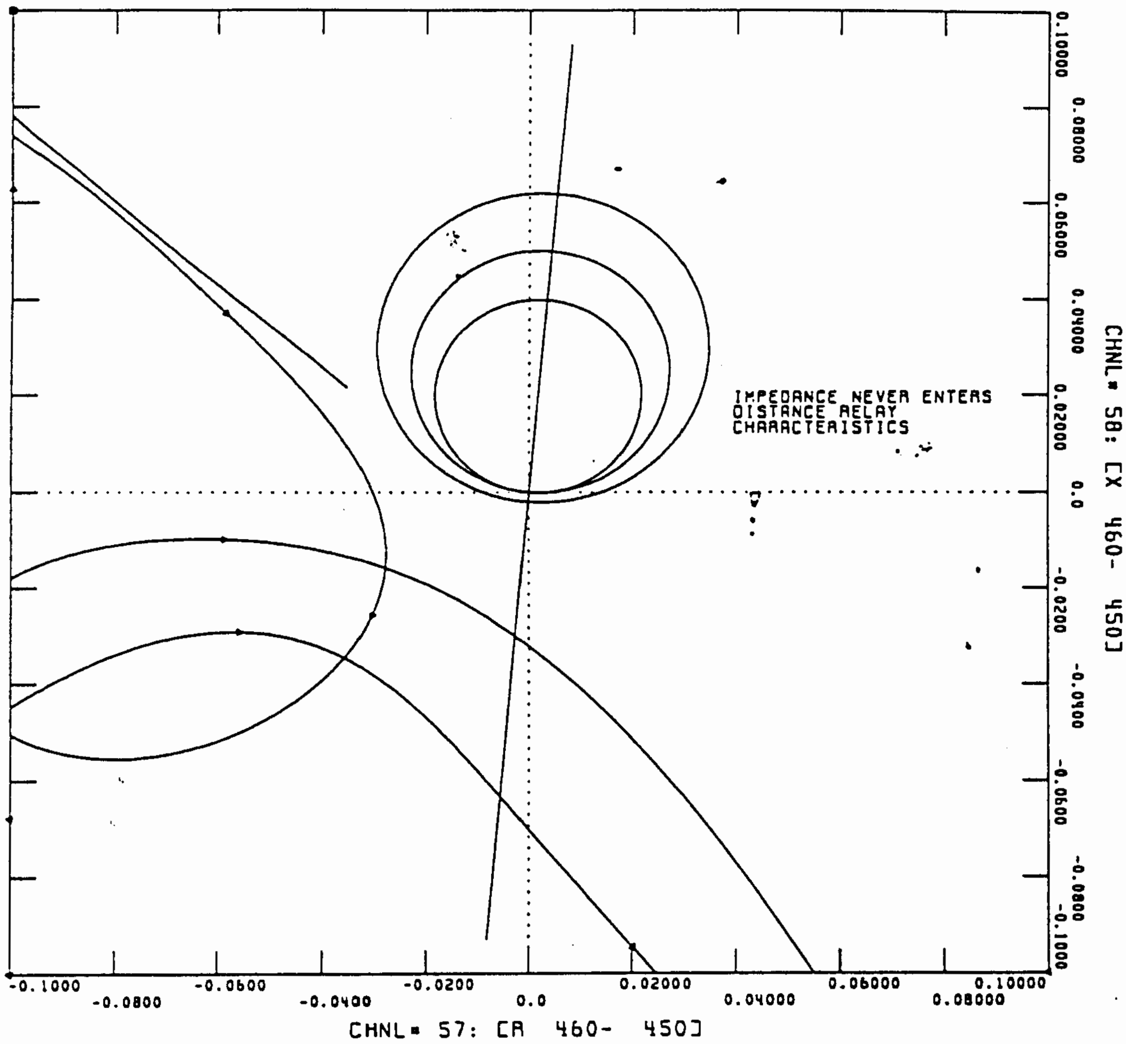


Figure D5b: Impedance 'seen' by a distance relay at Muldersvlei-Koeberg 1

D2 Out-of-step tripping protection

The purpose of the out-of-step tripping protection is to not detect power swing conditions but detect system out-of-step conditions. This will enable the out-of-step tripping protection to send a tripping signal to selected locations to initiate islanding.

As in the case of the out-of-step blocking protection, the impedance passed through the out-of-step tripping protection characteristics twice: the first time during the power swing condition and the second time during the out-of-step condition. Table D2 shows the performance of the out-of-step tripping protection in the stability study done. For those locations where detection did not take place, the reason is also given.

Table D2: Performance of the out-of-step tripping protection

Location	**Performance during power swing condition**	**Performance during out-of-step condition**
Hydra-Kronos	Detection	Detection
Hydra-Droërivier 1	Detection	Nondetection of instability: insufficient inner-zone timer setting
Hydra-Droërivier 3	Detection	Nondetection of instability: impedance locus behaviour did not allow detection

The out-of-step tripping protection at the locations that are shaded in Table D2 did not detect the out-of-step condition. As shown in Table D2, the reasons for nondetection were as follows:

1. The inner-zone timer setting was not sufficient to allow the timer to expire while the impedance passed through the inner zone.

2. The impedance locus behaviour did not allow detection.

1. Insufficient inner-zone timer setting

The impedance locus 'seen' by the out-of-step tripping relay located at Hydra-Droërivier 1 can be seen in Figure D6. This example will show insufficient inner-zone timer setting.

Upon the first entry (at time = 2,95 s) the impedance remained in the outer zone for 150 ms and in the inner zone for 300 ms. The timer settings given in Appendix C were calculated to be 15 ms and 151 ms for the outer-zone and inner-zone timers respectively. Both timers therefore expired, but the relay did not detect because the impedance locus did not exit the characteristic on the side opposite that which it originally entered. The relay performance was therefore correct.

Upon the second entry, during the out-of-step condition, the impedance remained in the outer and inner zone for 200 ms and 100 ms respectively. With the same timer settings (15 ms and 151 ms for the outer-zone and inner-zone timers respectively) the outer-zone timer expired but the inner-zone timer was set too slow. Due to an insufficient inner-zone timer setting, detection of the out-of-step condition therefore did not take place.

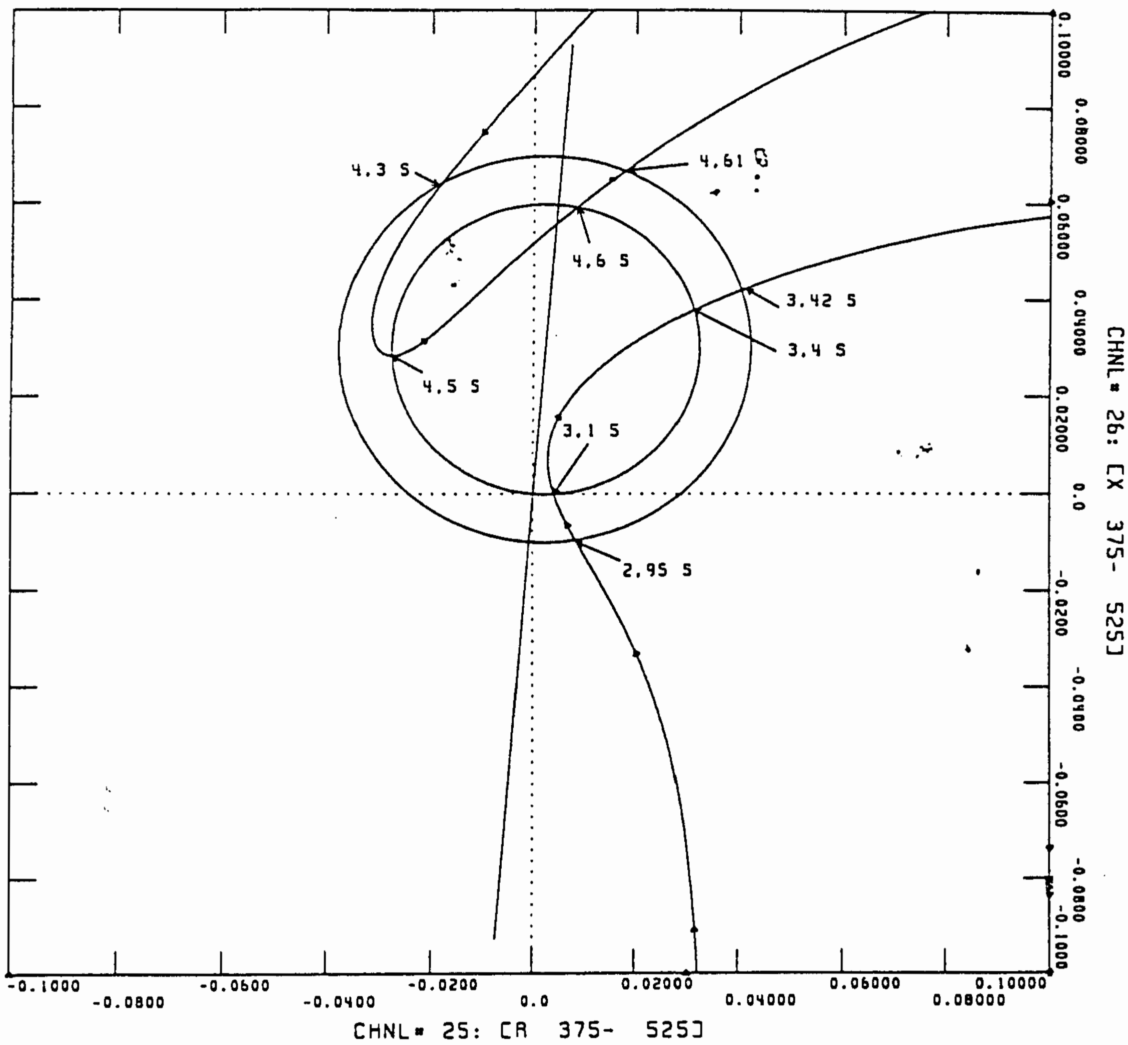


Figure D6: Impedance locus and out-of-step tripping protection characteristic for relay located at Hydra-Droërivier 1

2. <u>Out-of-step condition not observable to the out-of-step tripping protection.</u>

The impedance locus ‘seen’ by the out-of-step tripping protection located at Hydra-Droërivier 3 can be seen in Figure D7.

Upon the first entry (at time = 3 s) the impedance remained in the outer zone for 50 ms and in the inner zone for 250 ms. The timer settings given in Appendix C were calculated to be 15 ms and 151 ms for the outer-zone and inner-zone timers respectively. Both timers therefore expired, but the protection did not detect because the impedance locus did not exit the characteristics on the side opposite that which it originally entered. The protection performance was therefore correct.

However, during the out-of-step condition the impedance never entered the protection characteristics and the out-of-step condition could therefore not be detected.

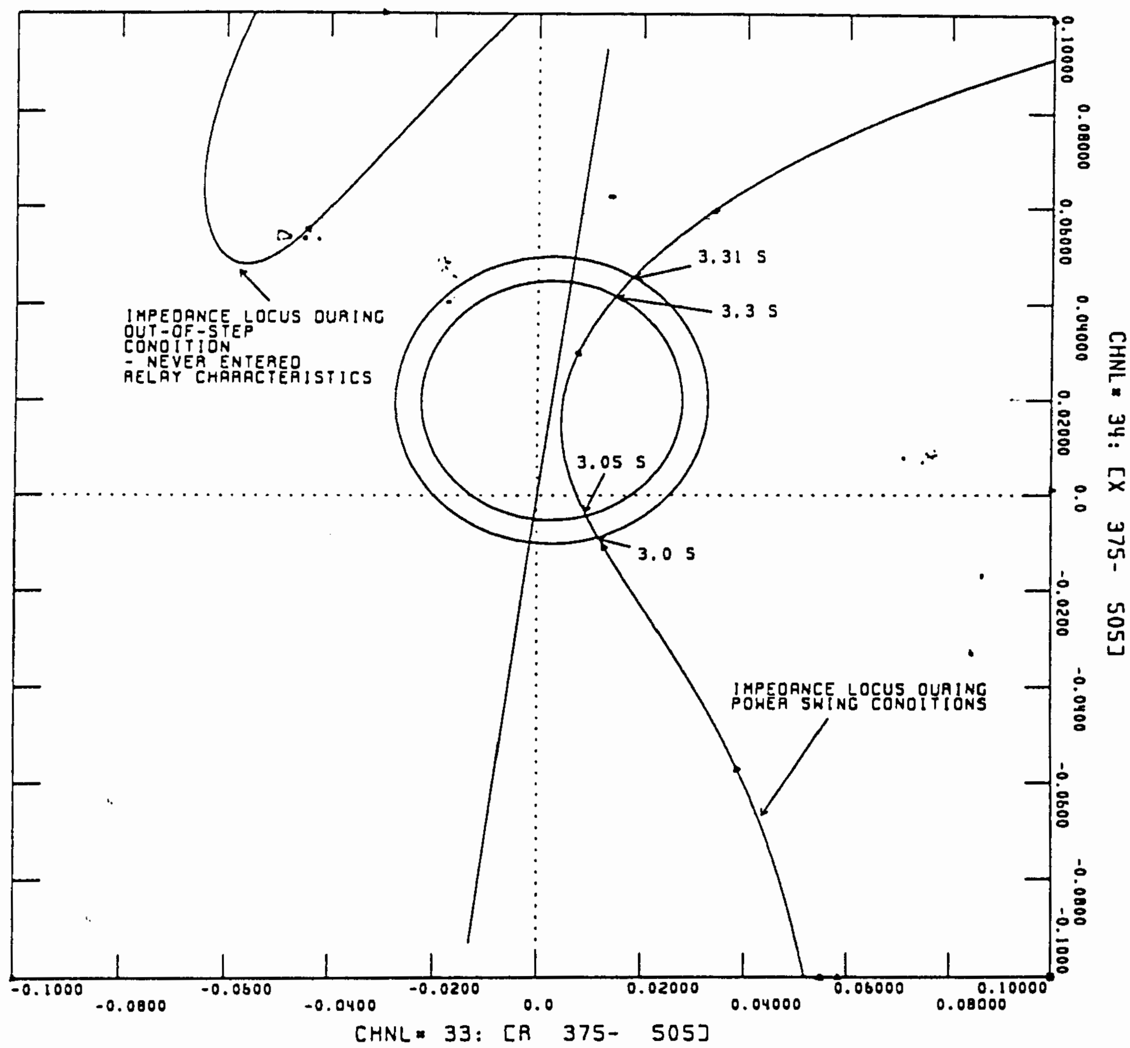


Figure D7: Impedance locus and out-of-step protection characteristics for protection located at Hydra-Droërivier 3

APPENDIX E

OUT-OF-STEP PROTECTION APPLICATION BASED ON THE NEW APPROACH AND IMPEDANCE LOCUS STUDY METHODS

Out of step protection was applied to the Eskom transmission system according to new approach, using the new methods of studying the impedance locus behaviour to determine relay locations and calculating relay settings (reach and timer).

The location and reach settings were selected and calculated for out-of-step blocking an tripping protection using concentric circle type characteristics. The protection type used for the purposes of the research is presented in Appendix B.

For those calculations and investigations that require stability study results, the stability study presented under section 3.3.1 in Chapter 3 was done to provide the necessary results.

Due to the size of the Eskom transmission system results for a portion of the system were presented as results for the remaining system are additional information and does not add any futher value to the thesis contribution. The portion of the Eskom transmission system for which results are presented, is shown in Figure C1, Appendix C.

E1 Locations

The impedance locus at all the distance relay locations in the Eskom transmission system was studied.

Out-of-step blocking protection

To identify the need for out-of-step blocking protection, the following criterion was used:

If $R_{l\text{-}zone\ 3} < R_d < R_{r\text{-}zone\ 3}$ and $X_{b\text{-}zone\ 3} < X_d < X_{a\text{-}zone\ 3}$ then the impedance locus is inside the boundaries defined by a distance relay zone 3 characteristic[1]. The forward and reverse reaches of the ROW are $X_{a\text{-}zone\ 3}$ and $X_{b\text{-}zone\ 3}$ respectively. $R_{l\text{-}zone\ 3}$ and $R_{r\text{-}zone\ 3}$ represent the left and right ROW boundaries respectively.

A distance relay zone 3 ROW with the following boundary values was chosen for every location (see Table E1):

$X_{a\text{-}zone\ 3}$	=	150% of abs(line impedance)
$X_{b\text{-}zone\ 3}$	=	10% of abs(line impedance)
$R_{r\text{-}zone\ 3}$	=	1/2 x (forward reach + reverse reach)
$R_{l\text{-}zone\ 3}$	=	$- R_{r\text{-}zone\ 3}$

[1] For the purposes of the research a distance relay zone 3 characteristic was assumed to be the largest distance relay characteristic.

Table E1: ROW boundaries to determine the need for out-of-step blocking protection

Location	Line impedance		Zone 3 forward reach ($+X_{a\text{-}zone3}$)	Zone 3 reverse reach ($X_{b\text{-}zone3}$)	Left boundary = -right boundary ($R_{l\text{-}zone3} = -R_{r\text{-}zone3}$)
	Rline	Xline	= 150% of abs(line impedance)	= 10% of abs(line impedance)	= 1/2 x (forward reach + reverse reach
Hydra-Kronos	0,0028	0,0119	0,0184	0,0012	0,0097
Kronos-Hydra	0,0028	0,0119	0,0184	0,0012	0,0097
Kronos-Aries	0,0024	0,0088	0,0137	0,0009	0,0072
Aries-Kronos	0,0024	0,0088	0,0137	0,0009	0,0072
Aries-Helios	0,0025	0,0098	0,0152	0,0010	0,0080
Helios-Aries	0,0025	0,0098	0,0151	0,0010	0,0080
Helios-Juno	0,0025	0,0104	0,0160	0,0010	0,0085
Juno-Helios	0,0025	0,0104	0,0160	0,0010	0,0085
Juno-Aurora	0,0028	0,0112	0,0173	0,0011	0,0092
Aurora-Juno	0,0028	0,0112	0,0173	0,0011	0,0092
Aurora-Koeberg	0,0013	0,0170	0,0255	0,0017	0,0136
Koeberg-Aurora	0,0013	0,0170	0,0255	0,0017	0,0136
Hydra-Droërivier 1	0,0038	0,0479	0,0722	0,0048	0,0385
Droërivier-Hydra 1	0,0038	0,0479	0,0722	0,0048	0,0385
Hydra-Droërivier 2	0,0038	0,0479	0,0722	0,0048	0,0385
Droërivier-Hydra 2	0,0038	0,0479	0,0722	0,0048	0,0385
Hydra-Droërivier 3	0,0037	0,0262	0,0397	0,0026	0,0211
Droërivier-Hydra 3	0,0037	0,0262	0,0397	0,0026	0,0211
Droërivier-Muldersvlei	0,0061	0,0424	0,0642	0,0042	0,0342
Muldersvlei-Droërivier	0,0061	0,0424	0,0642	0,0042	0,0342
Droërivier-Proteus	0,0068	0,0393	0,0598	0,0039	0,0319
Proteus-Droërivier	0,0068	0,0393	0,0598	0,0039	0,0319
Droërivier-Bacchus	0,0060	0,0407	0,0617	0,0041	0,0329
Bacchus-Droërivier	0,0060	0,0407	0,0617	0,0041	0,0329
Bacchus-Palmiet	0,0013	0,0159	0,0240	0,0016	0,0128
Palmiet-Bacchus	0,0013	0,0159	0,0240	0,0016	0,0128
Bacchus-Muldersvlei	0,0017	0,0217	0,0326	0,0021	0,0174
Muldersvlei-Bacchus	0,0017	0,0217	0,0326	0,0021	0,0174
Muldersvlei-Koeberg 1	0,0006	0,0081	0,0121	0,0008	0,0064
Koeberg-Muldersvlei 1	0,0006	0,0081	0,0121	0,0008	0,0064
Muldersvlei-Koeberg 2	0,0006	0,0081	0,0121	0,0008	0,0064
Koeberg-Muldersvlei 2	0,0006	0,0081	0,0121	0,0008	0,0064
Muldersvlei-Acacia	0,0007	0,00917	0,0136	0,0009	0,0072
Acacia-Muldersvlei	0,0007	0,0091	0,0136	0,0009	0,0072
Acacia-Koeberg	0,0005	0,0063	0,0094	0,0006	0,0050
Koeberg-Acacia	0,0005	0,0063	0,0094	0,0006	0,0050

For the purpose of identifying locations where out-of-step blocking is required, R_d and X_d as defined under section 4.1.1 in Chapter 4 were calculated. The results are listed in Table E2. Table E2 also indicates, with reference to Table E1, whether the criterion for the need for out-of-step blocking has been satisfied, indicating that there is a need for out-of-step blocking protection. The locations that are shaded in Table E2 are the locations where out-of-step blocking is needed.

Table E2: R_d and X_d as defined under section 4.1.1 in Chapter 4

Location	$Time_{enter}$ (s)	R_d	X_d	Criterion satisfied
Hydra-Kronos	< 3,5[2]	0,0043	0,0004	Yes
	> 3,5	0,0040	0,0331	No
Kronos-Hydra	< 3,5	-0,0044	0,0036	Yes
	> 3,5	-0,0019	-0,0188	No
Kronos-Aries	< 3,5	0,0043	-0,0036	Yes
	> 3,5	0,0019	0,0192	No
Aries-Kronos	< 3,5	-0,0060	0,0097	Yes
	> 3,5	-0,0012	-0,0100	No
Aries-Helios	< 3,5	0,0050	-0,0113	Yes
	> 3,5	0,0021	0,0113	Yes
Helios-Aries	< 3,5	-0,0058	0,0210	No
	> 3,5	0,0004	-0,0017	No
Helios-Juno	< 3,5	0,0056	-0,0201	No
	> 3,5	-0,0004	0,0017	Yes
Juno-Helios	< 3,5	-0,0050	0,0318	No
	> 3,5	-0,0007	0,0089	Yes
Juno-Aurora	< 3,5	0,0043	-0,0038	Yes
	> 3,5	0,0007	-0,0088	No
Aurora-Juno	< 3,5	-0,0029	0,0428	No
	> 3,5	-0,0019	0,0202	No
Aurora-Koeberg	< 3,5	-0,0063	-0,0418	No
	> 3,5	-0,0027	-0,0205	No
Koeberg-Aurora	< 3,5	0,0080	0,0601	No
	> 3,5	0,0366	0,0066	No
Hydra-Droërivier 1	< 3,5	0,0038	0,0011	Yes
	> 3,5	-0,0217	0,0312	Yes
Droërivier-Hydra 1	< 3,5	-0,0054	0,0044	Yes
	> 3,5	0,0126	-0,0150	No
Hydra-Droërivier 2	< 3,5	0,0038	0,0011	Yes
	> 3,5	-0,0217	0,0312	Yes
Droërivier-Hydra 2	< 3,5	-0,0054	0,0044	Yes
	> 3,5	0,0126	-0,0150	No
Hydra-Droërivier 3	< 3,5	0,0068	0,0024	Yes
	> 3,5	-0,0464	0,0533	No
Droërivier-Hydra 3	< 3,5	-0,0105	0,0074	Yes
	> 3,5	0,0254	-0,0245	No
Droërivier-Muldersvlei	< 3,5	0,0027	-0,0054	No
	> 3,5	-0,0038	0,0157	Yes
Muldersvlei-Droërivier	< 3,5	-0,0068	0,0473	Yes
	> 3,5	-0,0015	0,0253	Yes
Droërivier-Proteus	< 3,5	0,0128	-0,0045	No
	> 3,5	-0,0378	0,0182	No
Proteus-Droërivier	< 3,5	-0,0213	0,0101	Yes
	> 3,5	0,0279	-0,0143	No
Droërivier-Bacchus	< 3,5	0,00645	-0,0024	Yes
	> 3,5	-0,0168	0,0098	Yes
Bacchus-Droërivier	< 3,5	-0,0159	0,0038	Yes
	> 3,5	0,0014	-0,0034	Yes

[2] The system stability study results indicated that power swings occurred before 3,5 seconds. (Koeberg, being the larger power station, is not out-of-step eventhough Palmiet being the smaller power station is already out-of-step, refer to Chapter 3, section 3.3.1). After 3,5 seconds the system became unstable. (Koeberg and Palmiet power stations are out-of-step, refer to Chapter 3, section 3.3.1)

Table E2 (cont): R_d and X_d as defined under section 4.1.1 in Chapter 4

Location	$Time_{enter}$ (s)	R_d	X_d	Criterion satisfied
Bacchus-Palmiet	< 3,5	0,0032	-0,0030	No
	> 3,5	0,0003	0,0013	Yes
Palmiet-Bacchus	< 3,5	0,0048	0,0068	Yes
	> 3,5	0,0021	0,0145	Yes
Bacchus-Muldersvlei	< 3,5	-0,0024	-0,0055	No
	> 3,5	-0,0016	-0,0017	Yes
Muldersvlei-Bacchus	< 3,5	0,0103	0,0249	Yes
	> 3,5	0,0061	0,0138	Yes
Muldersvlei-Koeberg 1	< 3,5	-0,0287	-0,0391	No
	> 3,5	-0,0124	-0,0233	No
Koeberg-Muldersvlei 1	< 3,5	0,0313	0,0464	No
	> 3,5	0,0298	0,0107	No
Muldersvlei-Koeberg 2	< 3,5	-0,0287	-0,0391	No
	> 3,5	-0,0124	-0,0233	No
Koeberg-Muldersvlei 2	< 3,5	0,0313	0,0464	No
	> 3,5	0,0298	0,0107	No
Muldersvlei-Acacia	< 3,5	0,00169	-0,1108	No
	> 3,5	-0,0045	-0,0564	No
Acacia-Muldersvlei	< 3,5	-0,0039	0,1237	No
	> 3,5	0,0054	0,0665	No
Acacia-Koeberg	< 3,5	-0,0577	-0,0334	No
	> 3,5	-0,0395	-0,0073	No
Koeberg-Acacia	< 3,5	0,0597	0,0382	No
	> 3,5	0,0409	0,0100	No

Two examples are given to illustrate the method of identifying the need for out-of-step blocking protection: firstly Kronos-Hydra is evaluated and secondly Acacia-Koeberg is evaluated.

Example 1: *The need for out-of-step blocking protection at Kronos-Hydra*

The impedance 'seen' at Kronos-Hydra as obtained from the system stability study discussed in Chapter 3, section 3.3.1 can be seen in Figure E1. Figure E1 also shows the distance relay zone 3 ROW with the following boundary values:

$X_{a\text{-}zone\ 3}$	=	*150% of abs(line impedance)*	=	*0,0184 pu*
$X_{b\text{-}zone\ 3}$	=	*10% of abs(line impedance)*	=	*-0,0012 pu*
$R_{r\text{-}zone\ 3}$	=	*1/2 x (forward reach + reverse reach)*	=	*0,0098 pu*
$R_{l\text{-}zone\ 3}$	=	$- R_{r\text{-}zone\ 3}$	=	*-0,0098 pu*

with

Kronos-Hydra line impedance = *0,0028 + j0,0119 pu* *(from Table E1)*

From Figure E1 the following parameters were calculated:

During power swing condition (t < 3,5 s): (Koeberg, being the larger power station, is not out-of-step even though Palmiet being the smaller power station is already out-of-step, refer to Chapter 3, section 3.3.1)

R_d = -0,0044

X_d = 0,0036

During out-of-step condition (t > 3,5 s): (Both Koeberg Power Station and Palmiet Power Station are out-of-step, refer to Chapter 3, section 3.3.1)

R_d = -0,0019

X_d = -0,0188

From the above:

$R_{l\text{-zone }3} < (R_{d\ (power\ swing)} = -0{,}0044) < R_{r\text{-zone }3}$ and
$X_{b\text{-zone }3} < (X_{d\ (power\ swing)} = 0{,}0036) < X_{a\text{-zone }3}$

$R_{l\text{-zone }3} < (R_{d\ (out\text{-}of\text{-}step)} = -0{,}0019) < R_{r\text{-zone }3}$ and
$X_{b\text{-zone }3} > (X_{d\ (out\text{-}of\text{-}step)} = -0{,}0188) < X_{a\text{-zone }3}$

During the power swing condition (t < 3,5 s) the impedance entered the distance relay zone 3 ROW. During the out-of-step condition (t > 3,5 s) the impedance did not enter the distance relay zone 3 ROW. However, to avoid maloperation of a distance relay at Kronos-Hydra during power swing conditions, out-of-step blocking protection is needed.

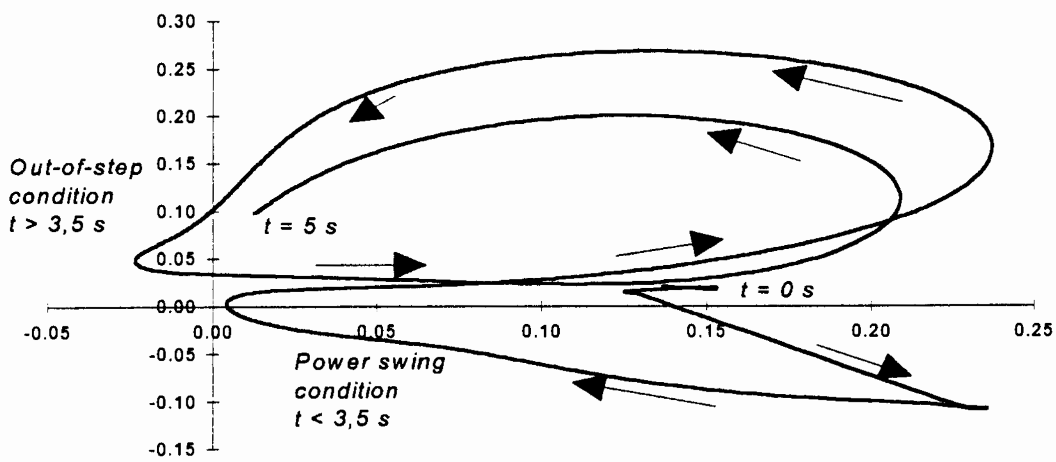


Figure E1: Impedance locus 'seen' at Hydra-Kronos

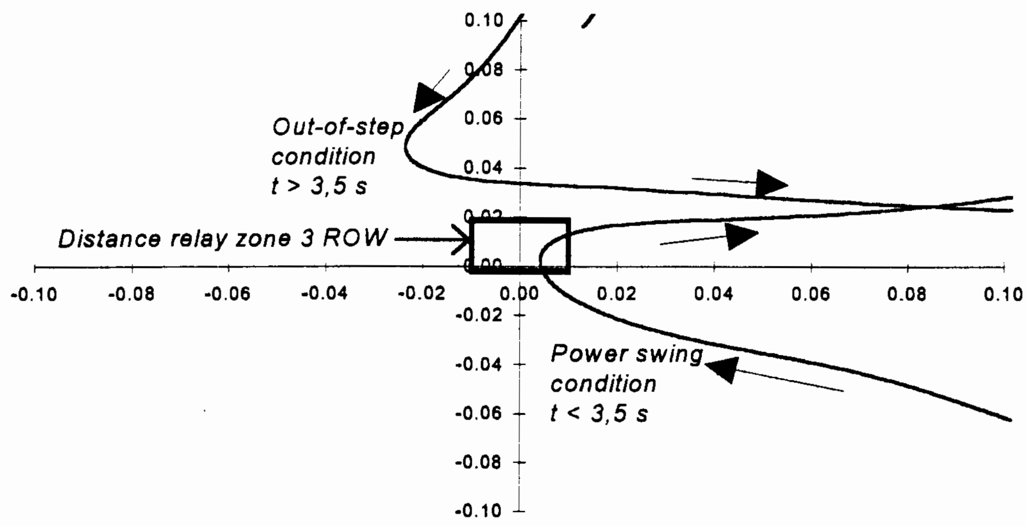


Figure E1 (cont): Impedance locus and distance relay zone 3 ROW at Hydra-Kronos

Example 2: <u>*The need for out-of-step blocking protection at Acacia-Koeberg*</u>

The impedance 'seen' at Acacia-Koeberg as obtained from the system stability study discussed in Chapter 3, section 3.3.1, can be seen in Figure E2. Figure E2 also shows the distance relay zone 3 ROW with the following boundary values:

$X_{a\text{-zone }3}$	=	*150% of abs(line impedance)*	=	*0,0095 pu*
$X_{b\text{-zone }3}$	=	*10% of abs(line impedance)*	=	*-0,0006 pu*
$R_{r\text{-zone }3}$	=	*1/2 x (forward reach + reverse reach)*	=	*0,0051 pu*
$R_{l\text{-zone }3}$	=	$- R_{r\text{-zone }3}$	=	*-0,0051 pu*

with

Acacia-Koeberg line impedance = *0,0005 + j0,0063 pu* *(from Table E1)*

From Figure E2 the following parameters were calculated:

During power swing condition (t < 3,5 s): (Koeberg, being the larger power station, is not out-of-step even though Palmiet being the smaller power station is already out-of-step, refer to Chapter 3, section 3.3.1)

R_d = -0,0577

X_d = -0,0334

During out-of-step condition (t > 3,5 s): (Both Koeberg Power Station and Palmiet Power Station are out-of-step, refer to Chapter 3, section 3.3.1)

R_d = -0,0395

X_d = -0,0073

From the above:

$R_{l\text{-}zone\ 3} > (R_{d\ (power\ swing)} = -0{,}0577) < R_{r\text{-}zone\ 3}$ and

$X_{b\text{-}zone\ 3} > (X_{d\ (power\ swing)} = -0{,}0334) < X_{a\text{-}zone\ 3}$

$R_{l\text{-}zone\ 3} > (R_{d\ (out\text{-}of\text{-}step)} = -0{,}0395) < R_{r\text{-}zone\ 3}$ and

$X_{b\text{-}zone\ 3} > (X_{d\ (out\text{-}of\text{-}step)} = -0{,}00731) < X_{a\text{-}zone\ 3}$

The impedance did not enter the distance relay zone 3 ROW during either the power swing condition (t < 3,5 s) or the out-of-step condition (t > 3,5 s). Out-of-step blocking protection is therefore not needed at Acacia-Koeberg.

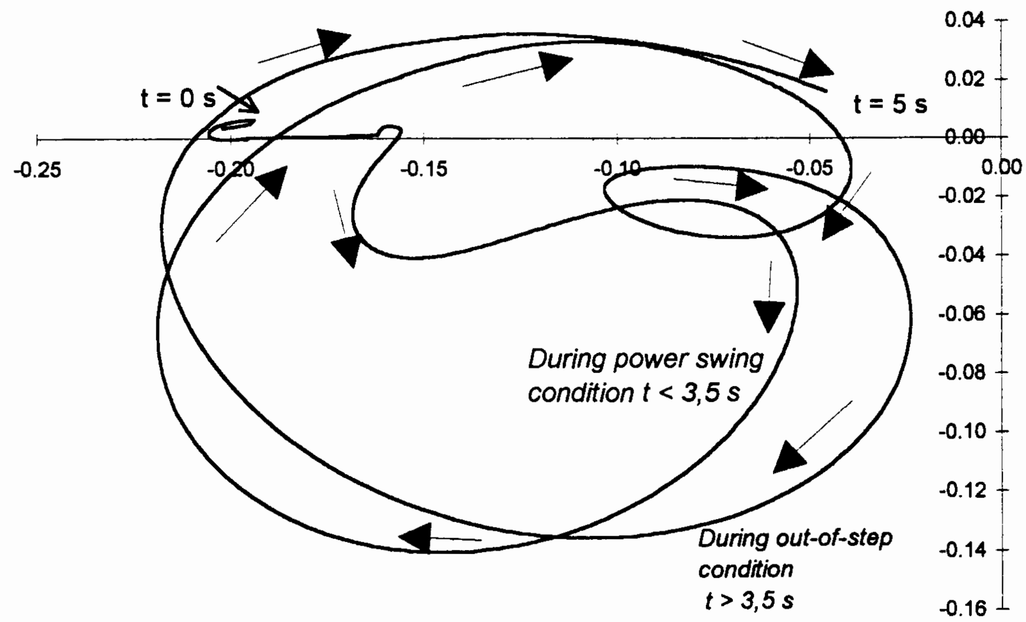


Figure E2: Impedance locus 'seen' at Acacia-Koeberg

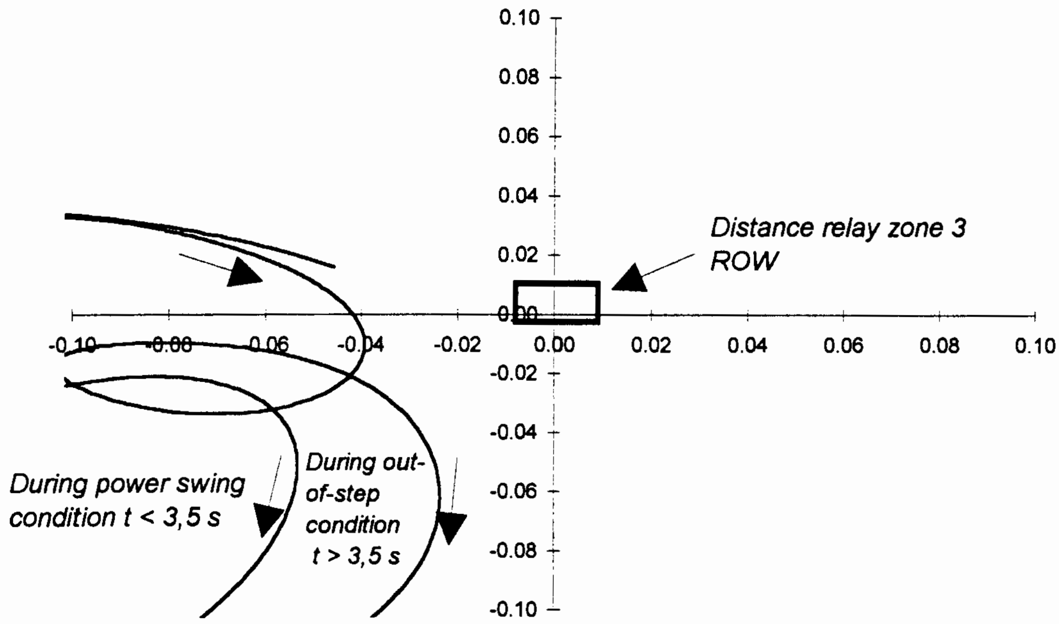


Figure E2 (cont): Impedance locus and distance relay zone 3 ROW at Acacia-Koeberg

Out-of-step tripping

To identify locations for out-of-step tripping protection, the following criterion was used:

- $R_l < R_{enter\text{-}actual} < R_r$ and $X_b < X_{enter\text{-}actual} < X_a$ to indicate that the impedance locus is inside the boundaries defined by an out-of-step tripping ROW.
- $|Z_d|$ to be as close as possible to 0 pu which will ensure that the impedance enters the out-of-step tripping inner characteristic for the purpose of detection[3].
- $\%R_{enter}$ not relevent because of the out-of-step tripping detection methodology used for the purposes of the research (refer to Appendix B).
- $\%R_{exit}$ not relevent because of the out-of-step tripping detection methodology used for the purposes of the research (refer to Appendix B).

[3] The out-of-step tripping protection type used for the purposes of the research requires that the impedance enter an inner zone to allow detection.

- The impedance to enter and exit the ROW in such a way as to allow detection according to the detection methodology of the type of out-of-step protection chosen. (For the purpose of the research the detection methodology is the following:
  if $R_{exit\text{-}actual} > 0$, then $R_{enter\text{-}actual} < 0$ and vice versa
  Refer to Appendix B)

An out-of-step tripping ROW with the following boundary values was chosen for every location:

$X_{a\text{-}OOS\text{-}ROW}$ = 0,1 pu (maximum forward reach setting as specified in Appendix B)
$X_{b\text{-}OOS\text{-}ROW}$ = -0,1 pu (maximum reverse reach setting as specified in Appendix B)
$R_{r\text{-}OOS\text{-}ROW}$ = 0,1 pu (limit to aviod load encroachment, used for the purposes of the research)
$R_{l\text{-}OOS\text{-}ROW}$ = -0,1 pu (limit to aviod load encroachment, used for the purposes of the research)

For the purpose of identifying locations for out-of-step tripping protection all the parameters defined under section (4.3.1b) in Chapter 4 were determined and calculated. The results are listed in Table E3[4]. The locations that are shaded in Table E3 are the locations where out-of-step tripping protection could be located according to the criterion presented above.

Any one, or all, of the locations that are shaded in Table E3 would be suitable for the location of out-of-step tripping relays. For the purposes of the research the following locations were used:

1. Helios-Aries
2. Helios-Juno
3. Bacchus-Droërivier
4. Bacchus-Muldersvlei

[4] Note that Table E3 lists the parameters as calculated after 3,5 seconds as the system then becomes unstable according to the results of the stability study discussed in Chapter 3 section 3.3.1 (both Koeberg Power Station and Palmiet Power Station are out of step).

Table E3: Parameter listing to identify out-of-step tripping protection locations

LOCATION	$R_{enter\text{-}actual}$	$X_{enter\text{-}actual}$	$\%R_{enter}$	$R_{exit\text{-}actual}$	$X_{exit\text{-}actual}$	$\%R_{exit}$	$\lvert Zd \rvert$
Hydra-Kronos	-0,0007	0,0990	0,7	0,0970	0,0232	97,0	0,0330
Kronos-Hydra	-0,0027	-0,0992	2,7	-0,0994	0,0201	99,4	0,0189
Kronos-Aries	0,0002	0,0989	0,2	0,0991	0,0101	99,1	0,0193
Aries-Kronos	-0,0020	-0,0989	2,0	-0,0970	-0,0102	97,0	0,0100
Aries-Helios	-0,0400	0,0984	40,0	0,0974	-0,0256	97,4	0,0114
Helios-Aries	0,0433	-0,0990	43,3	-0,0975	0,0242	97,5	0,0017
Helios-Juno	-0,0555	0,0995	55,5	0,0990	-0,0632	99,0	0,0017
Juno-Helios	0,0575	-0,0990	57,5	-0,0967	0,0495	96,7	0,0089
Juno-Aurora	-0,0726	0,0990	72,6	0,0989	-0,0865	98,9	0,0088
Aurora-Juno	0,0754	-0,0985	75,4	-0,0971	0,0699	97,1	0,0202
Aurora-Koeberg	-0,0997	0,0494	99,7	0,0640	-0,0969	64,0	0,0206
Koeberg-Aurora	0,0999	-0,0361	99,9	-0,0643	0,0954	64,3	0,0372
Hydra-Droërivier 1	0,0103	0,0986	10,3	0,0722	0,0983	72,2	0,0380
Droërivie -Hydra 1	-0,0329	-0,0988	32,9	-0,0919	-0,0901	91,9	0,0195
Hydra-Droërivier 2	0,0103	0,0986	10,3	0,0722	0,0983	72,2	0,0380
Droërivier-Hydra 2	-0,0329	-0,0988	32,9	-0,0919	-0,0901	91,9	0,0195
Hydra-Droërivier 3	-0,0556	0,0981	55,6	-0,0050	0,0988	5,0	0,0706
Droërivier-Hydra 3	0,0069	-0,0979	6,9	-0,0504	-0,0974	50,4	0,0352
Droërivier-Muldersvlei	-0,0519	0,0986	51,9	0,0963	-0,00892	96,3	0,0161
Muldersvlei-Droërivier	0,0805	-0,0997	80,5	-0,0958	0,0392	95,8	0,0253
Droërivier-Proteus	0,0991	0,0983	99,1	-0,0112	0,0958	11,2	0,0419
Proteus-Droërivier	-0,0998	-0,0640	99,8	0,0006	-0,0990	0,6	0,0313
Droërivier-Bacchus	0,0967	0,0730	96,7	-0,0144	0,0969	14,4	0,0194
Bacchus-Droërivier	-0,0970	0,0468	97,0	0,0335	-0,0936	33,5	0,0036
Bacchus-Palmiet	0,0862	-0,0958	86,2	-0,0990	0,0027	99,0	0,0013
Palmiet-Bacchus	-0,0878	0,0966	87,8	0,0962	0,0068	96,2	0,0146
Bacchus-Muldersvlei	-0,0961	0,0985	96,1	0,0789	-0,0949	78,9	0,0024
Muldersvlei-Bacchus	0,0967	-0,0991	96,7	-0,0699	0,0962	69,9	0,0198
Muldersvlei-Koeberg 1	-0,0993	-0,0176	99,3	-0,0995	-0,0507	99,5	0,0289
Koeberg-Muldersvlei 1	0,0992	-0,0687	99,2	0,0983	0,0595	98,3	0,0316
Muldersvlei-Koeberg 2	-0,0993	-0,0176	99,3	-0,0995	-0,0507	99,5	0,0289
Koeberg-Muldersvlei 2	0,0992	-0,0687	99,2	0,0983	0,0595	98,3	0,0316
Muldersvlei-Acacia	-0,095	-0,0495	95,0	0,0995	-0,0682	99,5	0,0565
Acacia-Muldersvlei	0,0986	0,0567	98,6	-0,0977	0,0758	97,7	0,0667
Acacia-Koeberg	-0,0993	0,0325	99,3	-0,0993	-0,0241	99,3	0,0401
Koeberg-Acacia	0,0996	-0,0279	99,6	0,0991	0,0302	99,1	0,0421

As an example Bacchus-Droërivier is evaluated to illustrate the method of identifying locations for out-of-step tripping protection.

Example 3: *The suitability of Bacchus-Droërivier for out-of-step tripping protection*

The impedance 'seen' at Bacchus-Droërivier as obtained from the system stability study discussed in Chapter 3, section 3.3.1, can be seen in Figure E3. Figure E3 also shows the out-of-step tripping ROW with the following boundary values:

$X_{a\text{- }OOS\text{-}ROW} = 0,1$ *pu* *(maximum forward reach setting as specified in Appendix B)*

$X_{b\text{- }OOS\text{-}ROW} = -0,1$ *pu* *(maximum reverse reach setting as specified in Appendix B)*

$R_{r\text{- }OOS\text{-}ROW} = 0,1$ *pu* *(limit to aviod load encroachment, used for the purposes of the research)*

$R_{l\text{- }OOS\text{-}ROW} = -0,1$ *pu* *(limit to aviod load encroachment, used for the purposes of the research)*

From Figure E3 the following parameters were calculated:

During out-of-step condition (t>3,5 s): (Koeberg and Palmiet power stations are out-of-step, refer to Chapter 3, section 3.3.1)

$\lvert Zd \rvert$	= 0,003647		
$R_{enter\text{-}actual}$	= -0,0970	$R_{exit\text{-}actual}$	= 0,0335
$X_{enter\text{-}actual}$	= 0,0468	$X_{exit\text{-}actual}$	= -0,0936
$\%R_{enter}$	= 97,0%	$\%R_{exit}$	= 33,5%

From the above:

- $R_{l\text{-}OOS\text{-}ROW} < (R_{enter\text{-}actual} = -0{,}0970) < R_{r\text{-}OOS\text{-}ROW}$; and $X_{b\text{-}OOS\text{-}ROW} < (X_{enter\text{-}actual} = 0{,}0468) < X_{a\text{-}OOS\text{-}ROW}$
- $(R_{exit\text{-}actual} = -0{,}0970) < 0$ and $(R_{exit\text{-}actual} = 0{,}0335) > 0$
- $(\lvert Z_d \rvert = 0{,}003647$ pu$) \cong 0$ pu.
- $(\%R_{enter\text{-}actual} = 97{,}0\%) \cong 100\%$.
- $(\%R_{exit\text{-}actual} = 33{,}5\%)$ not close to 100%.

During the out-of-step condition (t > 3,5 s) the impedance entered the out-of-step tripping ROW in accordance with the criterion indicating that Bacchus-Droërivier is a suitable location for out-of-step tripping protection.

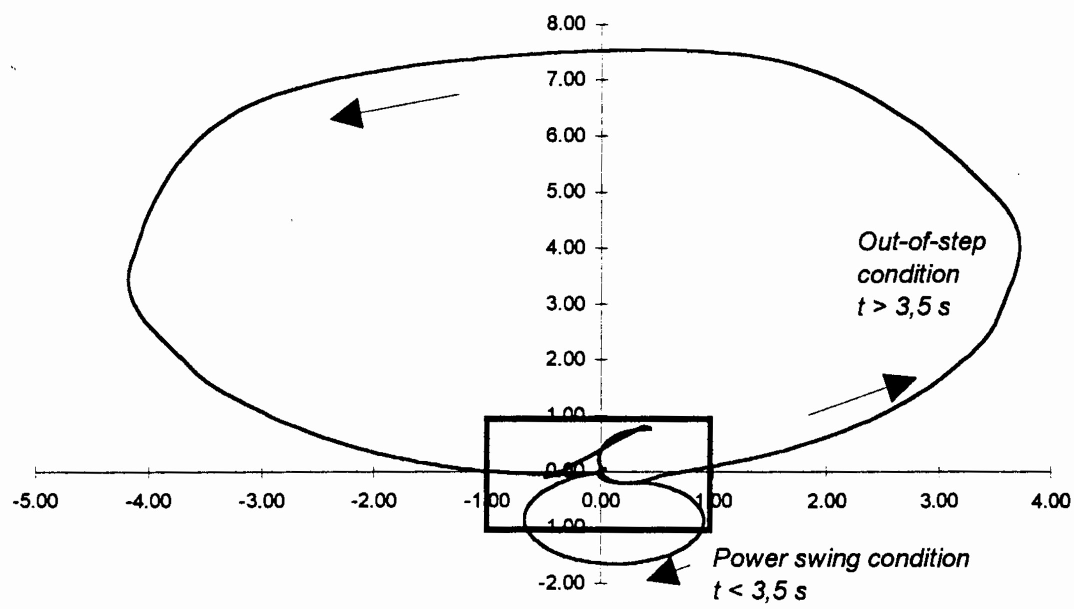


Figure E3: Impedance 'seen' at Bacchus-Droërivier

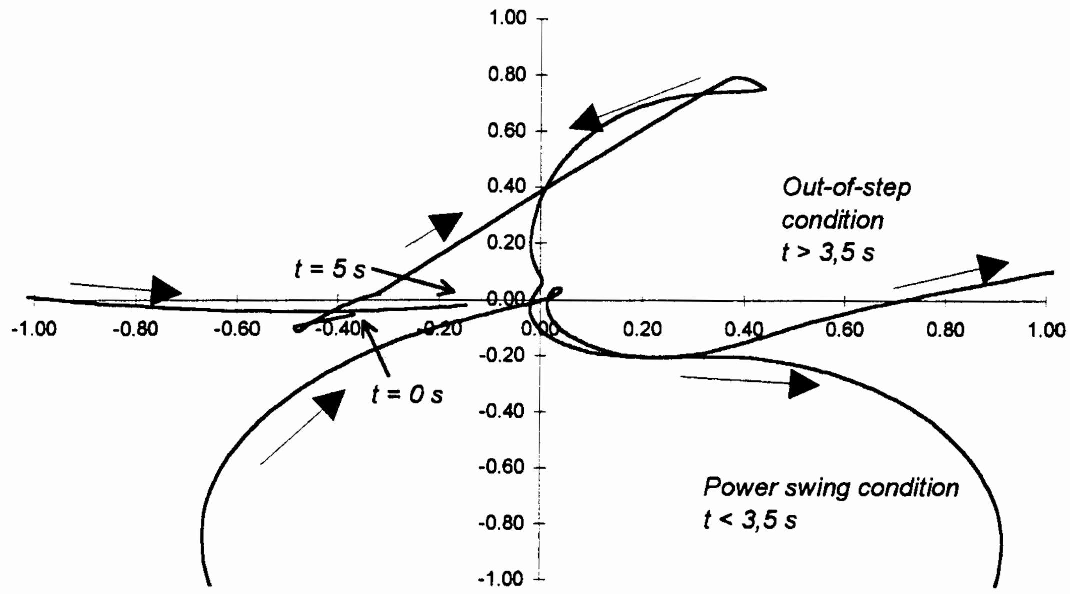


Figure E3 (cont): Impedance 'seen' at Bacchus-Droërivier (smaller scale)

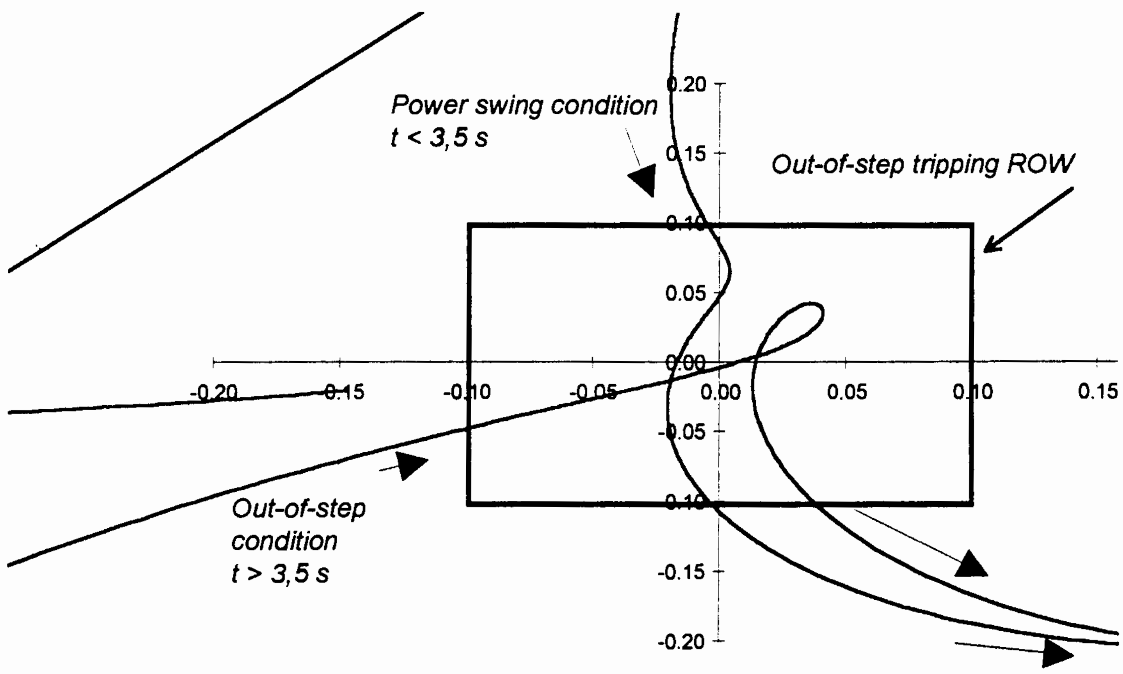


Figure E3 (cont): Impedance locus and out-of-step tripping ROW at Bacchus-Droërivier

E2 Reach settings

The blocking and tripping reach settings for the respective locations were calculated by using the method given under section 4.3.2, Chapter 4. Table E4 lists the calculated reach settings for out-of-step blocking and tripping protection respectively.

To illustrate the method of calculating the reach settings for out-of-step blocking or tripping, the reach settings for blocking protection located at Kronos-Hydra are calculated.

Example 1: <u>*Reach settings for out-of-step blocking protection at Kronos-Hydra*</u>

To allow the out-of-step blocking protection located at Kronos-Hydra to detect power system unstable conditions, the forward and reverse reaches in the impedance plane are calculated as follows (Figure E4 shows the relay characteristics, with calculated reach settings, in the impedance plane):

$$Zf = /Zf/\angle\varphi/$$
$$= 0{,}1\ pu\ \angle 76{,}76^\circ$$
$$Zr = /Zr/\angle 180^\circ{+}\varphi/$$
$$= 0{,}0990\ pu\ \angle 180^\circ{+}76{,}76^\circ$$

where

Zf = *forward reach*

/maximum forward reach specified for the out-of-step protection used/ = *0,1 pu*

$/Zf_{inner}/$ = $1/1{,}3 \times /Zf/$

Zr = *reverse reach*

/maximum reverse reach specified for the out-of-step protection used/ = *0,1 pu*

$/Zr_{inner}/$ = $1/1{,}3 \times /Zr/$

$R_{enter\text{-}actual}$ = *-0,0027 pu* *[from Table E3]*

$X_{enter\text{-}actual}$ = *-0,0992 pu* *[from Table E3]*

$R_{exit\text{-}actual}$ = *-0,0994 pu* *[from Table E3]*

$X_{exit\text{-}actual}$	=	$0,0201\ pu$			*[from Table E3]*
$\lvert Zf_{largest\ dist\ relay\ char}\rvert$	=	$0,0183\ pu$	=	$X_{a\text{-}zone3}$	*[from Table E1]*
$\lvert Zr_{largest\ dist\ relay\ char}\rvert$	=	$0,0012\ pu$	=	$X_{b\text{-}zone3}$	*[from Table E1]*

$X_{enter\text{-}actual} < 0$ *and* $X_{exit\text{-}actual} > 0$ *therefore:*

$$
\begin{aligned}
\lvert Zf\rvert &= \sqrt{(R_{exit\text{-}actual}{}^2 + X_{exit\text{-}actual}{}^2)} \\
&= \sqrt{(-0,0994^2 + 0,0201^2)} \\
&= 0,1014\ pu \\
&= 0,1\ pu \text{ because } 0,1014 > \lvert \text{maximum forward reach specified} \rvert
\end{aligned}
$$

$$
\begin{aligned}
\lvert Zf_{inner}\rvert &= 1/1,3 \times \lvert Zf\rvert \\
&= 1/1,3 \times 0,1\ pu \\
&= 0,0769\ pu
\end{aligned}
$$

$X_{enter\text{-}actual} < 0$ *and* $X_{exit\text{-}actual} > 0$ *therefore:*

$$
\begin{aligned}
\lvert Zr\rvert &= \sqrt{(R_{enter\text{-}actual}{}^2 + X_{enter\text{-}actual}{}^2)} \\
&= \sqrt{(-0,003^2 + -0,0992^2)} \\
&= 0,0990\ pu
\end{aligned}
$$

$$
\begin{aligned}
\lvert Zr_{inner}\rvert &= 1/1,3 \times \lvert Zf\rvert \\
&= 1/1,3 \times 0,0990\ pu \\
&= 0,0762\ pu
\end{aligned}
$$

$$
\begin{aligned}
\varphi l &= \text{line angle} \\
&= \tan^{-1}\frac{Xl}{Rl} \\
&= \tan^{-1}\frac{0,0119}{0,0028} \\
&= 76,76^\circ
\end{aligned}
$$

$$
\begin{aligned}
Rl + jXl &= \text{line impedance} \\
&= 0,0028 + j\,0,0119
\end{aligned}
$$

[from Table E1]

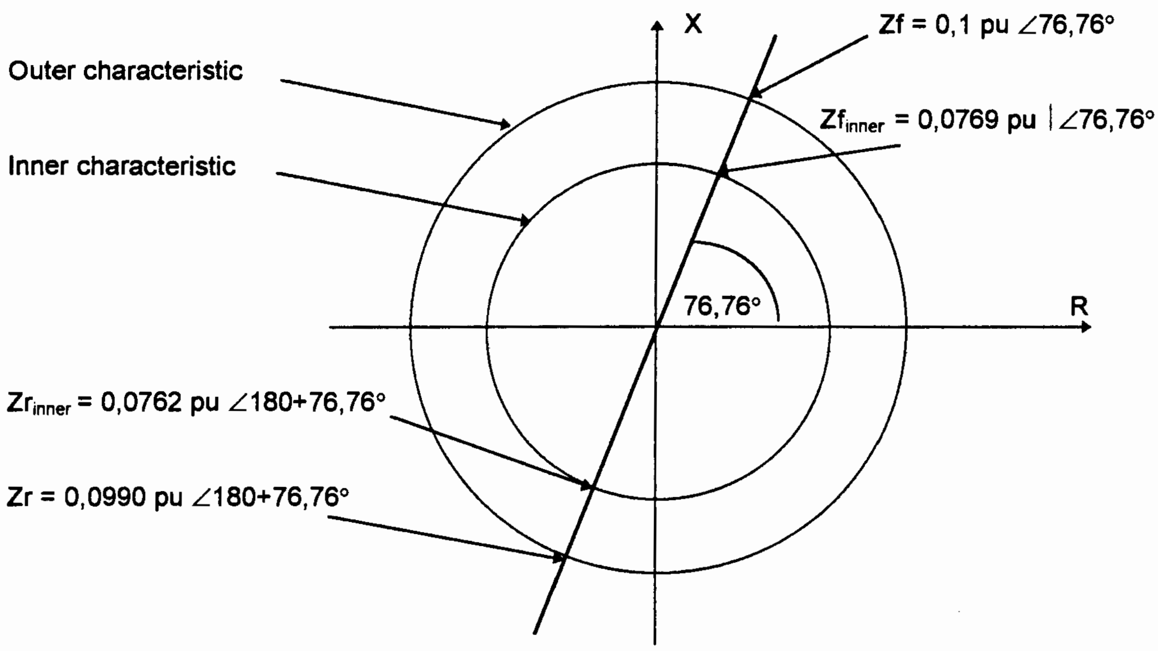


Figure E4: Out-of-step blocking protection characteristics with forward and reverse reaches

Table E4a: Maximum forward and reverse reach settings for out-of-step blocking protection

LOCATION	Impedance forward reach = $\|Zf\|$ (pu)	Impedance reverse reach = $\|Zr\|$ (pu)	Line angle = φ_{line} (degrees)
Hydra-Kronos	0,101812 i.e. 0,1	0,116547 i.e. 0,1	76,68
Kronos-Hydra	0,1014 i.e. 0,1	0,099237	76,76
Kronos-Aries	0,100487 i.e. 0,1	0,124943 i.e. 0,1	74,75
Aries-Kronos	0,124322 i.e. 0,1	0,09892	74,75
Aries-Helios	0,106219 i.e. 0,1	0,126606 i.e. 0,1	75,80
Helios-Juno	0,113932 i.e. 0,1	0,12837 i.e. 0,1	76,48
Juno-Helios	0,135336 i.e. 0,1	0,114487 i.e. 0,1	76,48
Juno-Aurora	0,122767 i.e. 0,1	0,13139 i.e. 0,1	75,96
Hydra-Droërivier 1	0,121966 i.e. 0,1	0,104581 i.e. 0,1	85,47
Droërivier-Hydra 1	0,104357 i.e. 0,1	0,1287 i.e. 0,1	85,47
Hydra-Droërivier 2	0,121966 i.e. 0,1	0,104581 i.e. 0,1	85,47
Droërivier-Hydra 2	0,104357 i.e. 0,1	0,1287 i.e. 0,1	85,47
Hydra-Droërivier 3	0,133327 i.e. 0,1	0,112087 i.e. 0,1	82,04
Droërivier-Hydra 3	0,106197 i.e. 0,1	0,113644 i.e. 0,1	82,04
Droërivier-Muldersvlei	0,111425 i.e. 0,1	0,10941 i.e. 0,1	81,88
Muldersvlei-Droërivier	0,12179 i.e. 0,1	0,128142 i.e. 0,1	81,88
Proteus-Droërivier	0,09977	0,118558 i.e. 0,1	80,18
Droërivier-Bacchus	0,121161 i.e. 0,1	0,100757 i.e. 0,1	81,56
Bacchus-Droërivier	0,1077 i.e. 0,1	0,099884	81,56
Bacchus-Palmiet	0,100168 i.e. 0,1	0,133265 i.e. 0,1	85,31
Palmiet-Bacchus	0,130539 i.e. 0,1	0,097975	85,31
Bacchus-Muldersvlei	0,137613 i.e. 0,1	0,123415 i.e. 0,1	85,52
Muldersvlei-Bacchus	0,119225 i.e. 0,1	0,138462 i.e. 0,1	85,52

Table E4b: Maximum forward and reverse reach settings for out-of-step tripping protection

LOCATION	**Impedance forward reach = $\lvert Zf \rvert$ (pu)**	**Impedance reverse reach = $\lvert Zr \rvert$ (pu)**	**Line angle = φ_{line} (degrees)**
Helios-Aries	0,123009 i.e. 0,1	0,108055 i.e. 0,1	75,80
Helios-Juno	0,113932 i.e. 0,1	0,12837 i.e. 0,1	76,48
Bacchus-Droërivier	0,1077 i.e. 0,1	0,099884	81,56
Bacchus-Muldersvlei	0,137613 i.e. 0,1	0,123415 i.e. 0,1	85,52

E3 Timer settings

With the reach settings known, the required zone timer settings for the out-of-step blocking and tripping protection respectively can be calculated. The calculation was done by:

- including mathematical models representing the relay characteristics in the power system model;
- doing the stability study presented in Chapter 3 under section 3.3.1 and recording the required entry and exit times; and
- calculating the timer settings according to the method presented under section 4.3.3 in Chapter 4.

The timer settings required for out-of-step blocking and out-of-step tripping protection at the selected locations are listed in Tables E5a and E5b respectively.

To illustrate the method of calculating the timer settings for out-of-step blocking and tripping protection, the timer settings for tripping protection located at Bacchus-Droërivier are calculated. Note that the method of calculating timer settings is the same for out-of-step blocking and out-of-step tripping protection.

Example 1: <u>*Timer settings for the out-of-step tripping protection at Bacchus-Droërivier*</u>

To allow the out-of-step tripping protection located at Bacchus-Droërivier to detect out-of-step conditions, the impedance 'seen' at the location, as determined from the stability study discussed in Chapter 3, must overlay the out-of-step tripping protection *characteristics. Figure E5 shows the protection characteristics, with the impedance 'seen' at Bacchus-Droërivier during the out-of-step condition.*

From Figure E5 the following is calculated:

Tto=	*t2 - t1*
=	*4,147 - 4,129*
=	*18 ms*
Tti =	*t3 - t2*
=	*4,597 - 4,147*
=	*450 ms*

where

Tto=	*outer-zone timer*
Tti =	*inner-zone timer*
t1 =	*4,129 s*
t2 =	*4,147 s*
t3 =	*4,597 s*

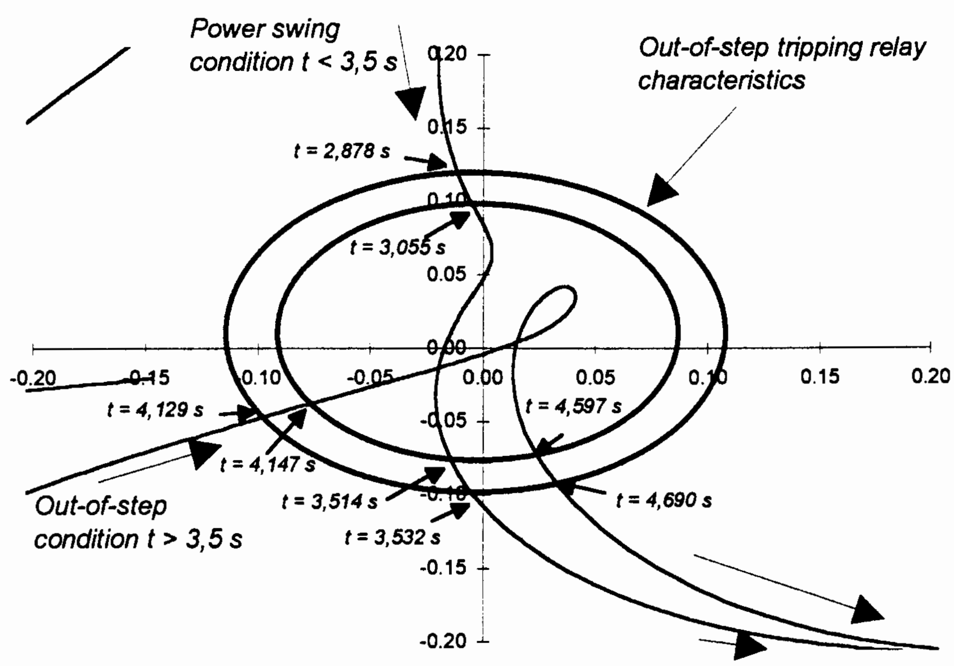


Figure E5: Impedance locus and out-of-step tripping protection characteristics at Bacchus-Droërivier

Table E5a: Maximum timer settings required for out-of-step blocking protection

LOCATION	Maximum required outer zone timer = Tb
Hydra-Kronos	75 ms
Kronos-Hydra	66 ms
Kronos-Aries	60 ms
Aries-Kronos	60 ms
Aries-Helios	39 ms
Helios-Juno	33 ms
Juno-Helios	33 ms
Juno-Aurora	30 ms
Hydra-Droërivier 1	42 ms
Droërivier-Hydra 1	27 ms
Hydra-Droërivier 2	42 ms
Droërivier-Hydra 2	27 ms
Hydra-Droërivier 3	84 ms
Droërivier-Hydra 3	36 ms
Droërivier-Muldersvlei	39 ms
Muldersvlei-Droërivier	39 ms
Proteus-Droërivier	21 ms
Droërivier-Bacchus	24 ms
Bacchus-Droërivier	18 ms
Bacchus-Palmiet	30 ms
Palmiet-Bacchus	33 ms
Bacchus-Muldersvlei	42 ms
Muldersvlei-Bacchus	36 ms

Table E5b: Maximum timer settings required for out-of-step tripping protection

LOCATION	Maximum required outer-zone timer = Tto	Maximum required inner-zone timer = Tti
Helios-Aries	42 ms	525 ms
Helios-Juno	33 ms	504 ms
Bacchus- Droërivier	18 ms	450 ms
Bacchus-Muldersvlei	42 ms	396 ms

F1 shows the performance of the out-of-step blocking protection each time the impedance passed through the characteristics.

Table F1: Performance of out-of-step blocking protection

Location	Performance during power swing condition	Performance during out-of-step condition
Hydra-Kronos	Detection	Detection
Kronos-Hydra	Detection	Detection
Kronos-Aries	Detection	Detection
Aries-Kronos	Detection	Detection
Aries-Helios	Detection	Detection
Helios-Juno	Detection	Detection
Juno-Helios	Detection	Detection
Juno-Aurora	Detection	Detection
Hydra-Droërivier 1	Detection	Detection
Droërivier-Hydra 1	Detection	Detection
Hydra-Droërivier 2	Detection	Detection
Droërivier-Hydra 2	Detection	Detection
Hydra-Droërivier 3	Detection	Detection
Droërivier-Hydra 3	Detection	Detection
Droërivier-Muldersvlei	Detection	Detection
Muldersvlei-Droërivier	Detection	Detection
Proteus-Droërivier	Detection	Detection
Droërivier-Bacchus	Detection	Detection
Bacchus-Droërivier	Detection	Detection
Bacchus-Palmiet	Detection	Detection
Palmiet-Bacchus	Detection	Detection
Bacchus-Muldersvlei	Detection	Detection
Muldersvlei-Bacchus	Detection	Detection

Table F1 shows that detection for the purpose of blocking took place at all the locations. As an example, Figure F1 shows the impedance 'seen' by the out-of-step blocking protection located at Aries-Kronos. It can be seen that upon the first and second entry into the characteristics the impedance remained in the outer zone for 90 ms and 60 ms respectively. The timer setting as calculated in Appendix E is 60 ms. The timer setting was therefore sufficient to allow detection for the purpose of blocking during both the power swing and the out-of-step conditions.

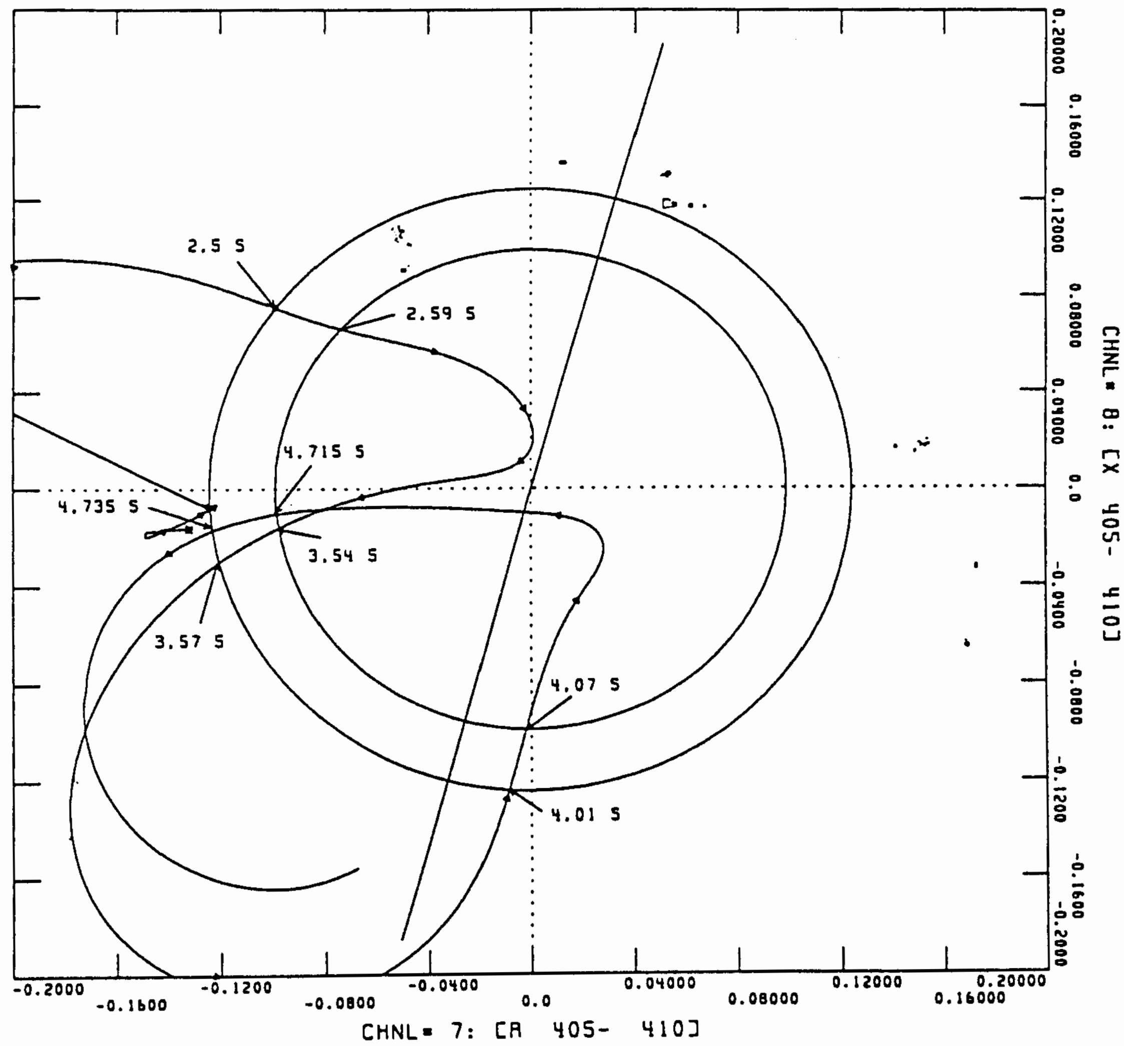


Figure F1: Impedance locus and out-of-step blocking protection characteristics for protection located at Aries-Kronos

F2 Out-of-step tripping protection

The purpose of the out-of-step tripping protection is to **not** detect during power swing conditions but detect during system out-of-step conditions. This will enable it to send a tripping signal to selected locations to initiate islanding.

As in the case of the out-of-step blocking protection, the impedance passed through the out-of-step tripping protection characteristics twice: the first time during the power swing condition and the second time during the out-of-step condition. Table F2 shows the performance of the out-of-step tripping protection in the stability study done.

Table F2: Performance of out-of-step tripping protection

Location	**Performance during power swing condition**	**Performance during out-of-step condition**
Helios-Aries	Detection	Detection
Helios-Juno	Detection	Detection
Bacchus-Droërivier	Detection	Detection
Bacchus-Muldersvlei	Detection	Detection

Table F2 shows that during the initial power swing detection did not take place at any of the locations. During the out-of-step condition the out-of-step tripping protection detected. Figure F2 shows the impedance 'seen' by the relay located at Helios-Juno. When the impedance passed through the protection characteristics the first time, it remained in the outer zone for 80 ms and in the inner zone for 980 ms. All the zone timers expired (timer settings as calculated in Appendix E are 33 ms and 504 ms for the outer-zone and inner-zone timers respectively). However, the impedance did not exit the characteristics on the side opposite that which it had entered and detection did not take place.

Upon the second entry into the characteristics, the impedance remained in the zones long enough to allow the timers to expire (70 ms in the outer zone and 530 ms in the inner zone), and the impedance exited the characteristics on the side opposite that which it had entered. Detection of the out-of-step condition therefore took place.

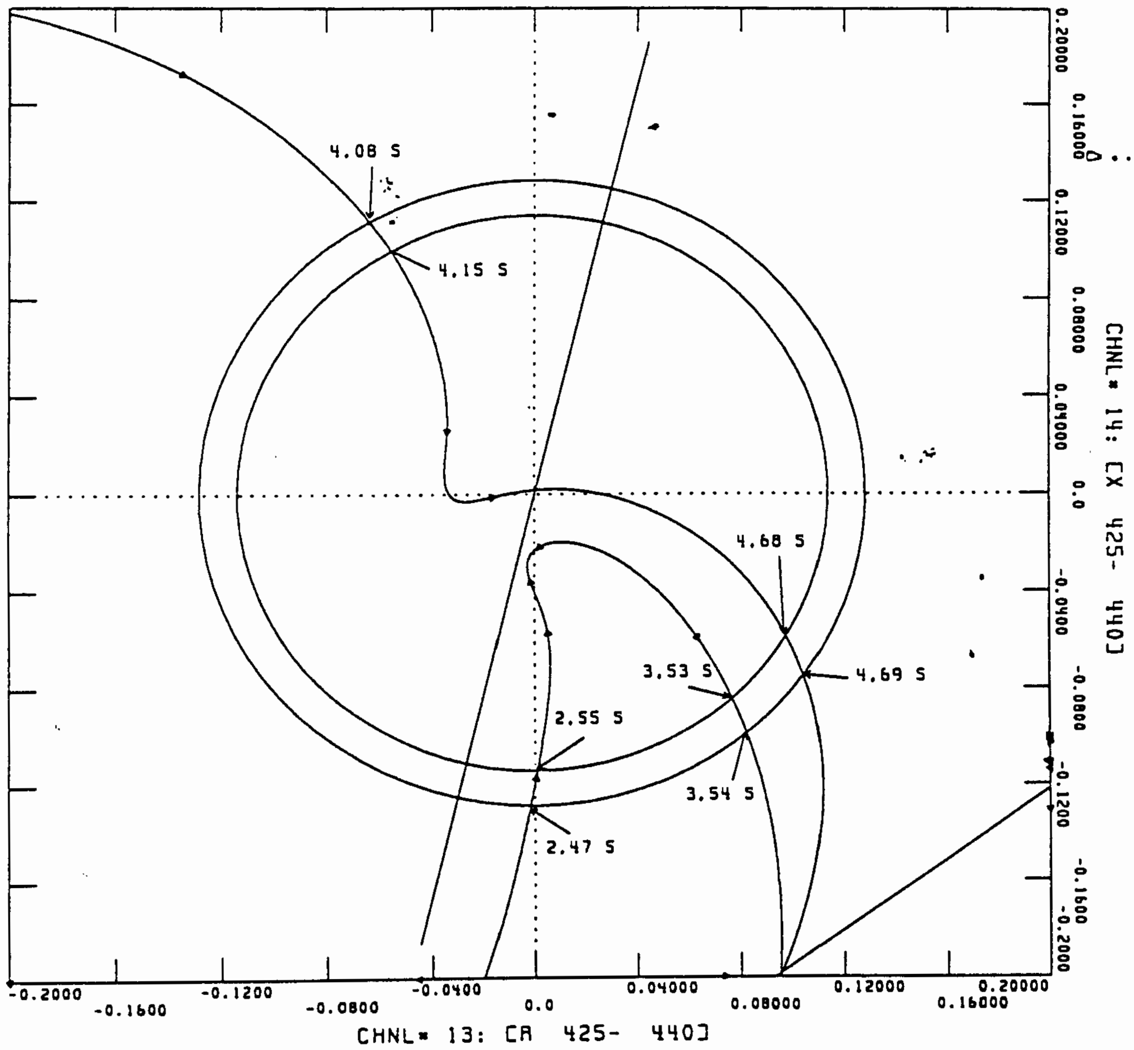


Figure F2: Impedance locus and out-of-step tripping protection characteristics for protection located at Helios-Juno

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Note: In some cases reference is made to specific pages of a document or book to which a previous reference has already been made. For these cases the detail regarding the document or book is repeated except for the page numbers.

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