AN INVESTIGATION INTO THE IMPORTANCE OF CONSIDERING PROTECTION PERFORMANCE DURING POWER SYSTEM OUT-OF-STEP CONDITIONS

by

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ABSTRACT

The performance of power system protection is affected by out-of-step conditions in that system. Protection relays such as distance relays may detect an out-of-step condition and consequently operate to trip unfaulted lines. The tripping of unfaulted lines interrupts supply to loads and exacerbates an already existing stability problem.

To prevent distance-relay operation during out-of-step conditions, distance protection can incorporate out-of-step blocking protection. The purpose of the out-of-step blocking protection is to detect an out-of-step condition and, upon detection, block distance-relay operation.

In the research the following were investigated:

1) The effect of out-of-step conditions on distance-protection performance

2) The performance of distance protection incorporating out-of-step blocking protection, during out-of-step conditions

A nine-bus IEEE benchmark network was chosen for the purposes of the research. The nine-bus network is representative, simple and small. It is a benchmark which is often used in comparative studies in the power system field. The nine-bus network data taken from reference [22] (see Table 3.1 in Chapter 3) were consistently used for every study done.

Mathematical protection models representing the behaviour of distance protection incorporating out-of-step blocking protection were modelled in such a way as to simulate the protection of every line in the nine-bus network. These models were included in the power system model representing the nine-bus network.

Two types of stability studies were done to investigate protection performance: a dynamic-stability study and a transient-stability study.

In modelling the protection in the stability studies, it was found that a cascade effect of switching unfaulted lines can occur due to relay operation. Results also show that distance-protection performance improves with the application of out-of-step blocking protection.

The research covers the following topics:

1) Dynamic stability
2) Transient stability
3) Distance protection
4) Out-of-step blocking protection

Results are discussed. An important conclusion reached is the need to take protection performance into account in routine stability studies. It will be shown that this may change the outcome of a stability study.

For the sake of completeness, suggestions are made for further research.

DEFINITIONS

Impedance-type characteristic: A distance relay using an impedance-type characteristic is on the verge of operating at a given constant value V divided by I, which may be expressed as an impedance. The operation of this relay is independent of the phase angle between V and I and can therefore be represented as a circle on an R-X diagram, with its centre at the origin [5].

Mho-type characteristic: A distance relay using an mho type-characteristic is similar to a relay using an impedance-type characteristic, except that the operation is dependent on the phase angle between measured voltage and measured current. When plotted on an R-X diagram the mho type characteristic is a circle with the circumference passing through the origin. The relay is thus directional and operates to clear faults in the forward direction [5].

Reactance-type characteristic: A distance relay using a reactance-type characteristic is designed to measure only the reactive component of a line. On an R-X plane the reactance-type characteristic is a straight line parallel to the R-axis. Any measured reactance below the straight line will cause the relay to operate [5].

Blinders: Blinders are angle-impedance distance-relay units. Blinders are used to block protection operation for certain areas where tripping is not desired [6].

Pick-up current: When a relay operates to open or close a contact, it is referred to as a "pick-up" action. The smallest value of measured current that will cause such an operation is called the "pick-up current" [6].

Supervisory signal input: A supervisory signal input supervises the equipment to which it is connected. For example, a distance relay has a supervisory signal controlled by an out-of-step blocking relay. If the distance relay attempts to operate during out-of-step conditions, the supervisory signal input (controlled by the out-of-step blocking relay which detects the out-of-step condition) will block the operation of the distance relay.

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CHAPTER 1: INTRODUCTION

The performance of power system protection is affected by out-of-step conditions in that system. Protection relays such as distance relays may detect an out-of-step condition and consequently operate to trip unfaulted lines. The tripping of unfaulted lines interrupts supply to load and exacerbates an already existing stability problem.

In 1983 and 1984 out-of-step conditions in the WSCC (Western System Co-ordinating Council) power system caused distance-relay operation. This operation resulted in the tripping of unfaulted lines. The undesired operation of distance protection gave rise to a study on the coordination of distance protection and out-of-step blocking protection [1].

Stability problems in the operation of the Queensland Electricity Commission System led to the contemplation of protection performance through the application of a protection scheme [2]. Such a protection scheme had to provide for:

1) the detection of an out-of-step condition;
2) the blocking of distance protection; and
3) the tripping of lines at selected locations, called split locations, in the event of an out-of-step condition.

With view to the application of this protection scheme, protection was modelled and stability studies were done. Distance protection was modelled to determine where out-of-step blocking protection would be required. Out-of-step blocking protection was modelled to determine the setting requirements for out-of-step detection. From the stability studies, split locations were determined.

In November 1990 the author experienced a situation where a condition of instability led to the undesired operation ("misoperation") of distance protection in the ESKOM power system. The structure of the ESKOM power system is shown in Figure 1.1.

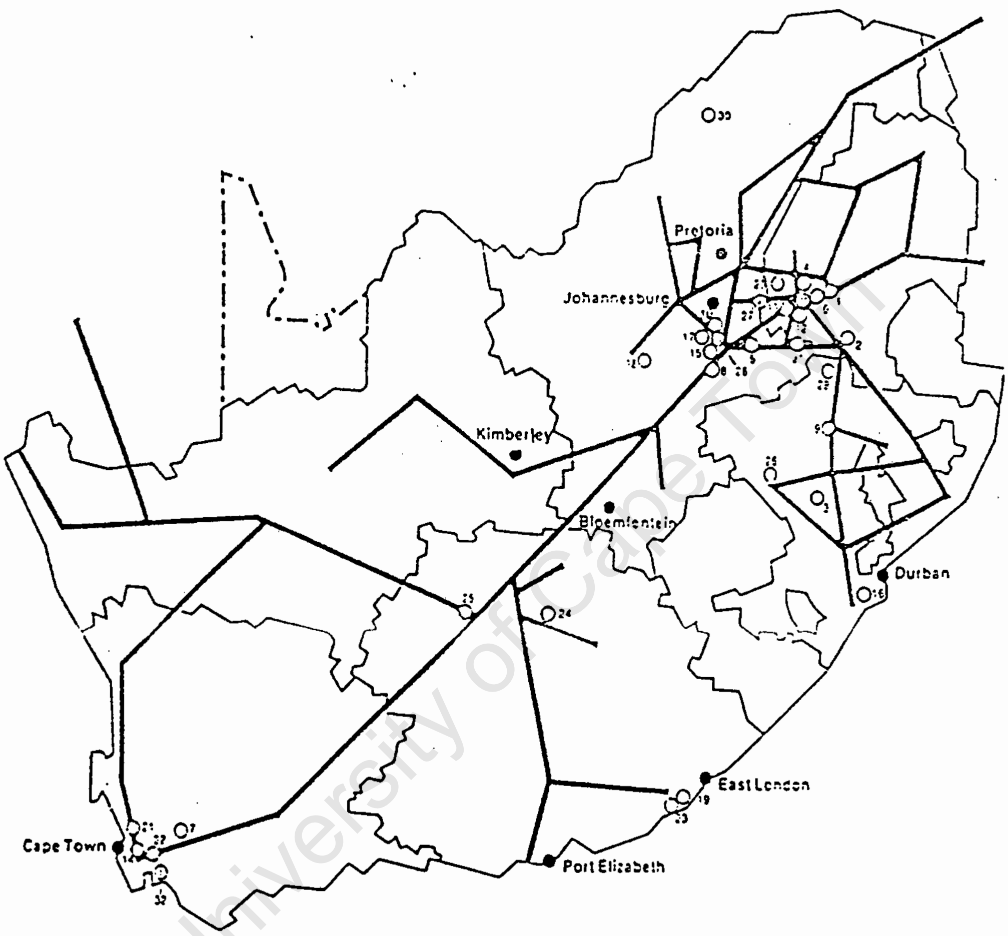


Figure 1.1: Structure of the ESKOM power system.

The power system is characterised by a major capacity of coal-fired power stations in the north. A nuclear power station and a pumped storage scheme are situated in the south. The power generated in the south is not sufficient to supply the local load, however, and power therefore has to be imported from the north, over a distance of ±1 400 km.

On 8 November 1990 overvoltage protection tripped two critical lines linking the north to the south. The tripping of these lines induced negative-sequence current, and protection tripped a third line. The result was an out-of-step condition between the north and the south. Most of the distance relays in the ESKOM power system are not equipped with out-of-step blocking protection therefore several distance-protection relays operated. As a consequence, cascade tripping of unfaulted transmission lines occurred in the south and caused a complete system blackout on the southern part of the system.

Conclusions drawn from the above are:

1) Distance-protection performance is affected during out-of-step conditions. An out-of-step condition may lead to the misoperation of distance protection, which will cause the tripping of unfaulted lines.
2) To investigate protection performance during out-of-step conditions, protection must be modelled.
3) To investigate protection performance, the models representing the protection must be included in stability studies.

The above conclusions, and the fact that routine stability studies on the ESKOM power system does not include protection-performance evaluation by means of protection models, led to a further investigation into protection performance during out-of-step conditions.

The research covers the following aspects:

1) Dynamic stability
2) Transient stability
3) Distance protection
4) Out-of-step blocking protection

1.1 Methodology

The research was performed by using a power system simulator program called PSS/E (Power System Simulator for Engineers). PSS/E has a library of mathematical models. This library contains, amongst others, models representing the behaviour of generators, excitation systems, loads, transmission lines, transformers and protection.

A nine-bus IEEE benchmark network was chosen for the purposes of the research (see Figure 1.2). The nine-bus network is representative, simple and small. It is a benchmark which is often used in comparative studies in the power system field. The nine-bus network data taken from reference [22] (see Table 3.1 in Chapter 3) were consistently used for every study done.

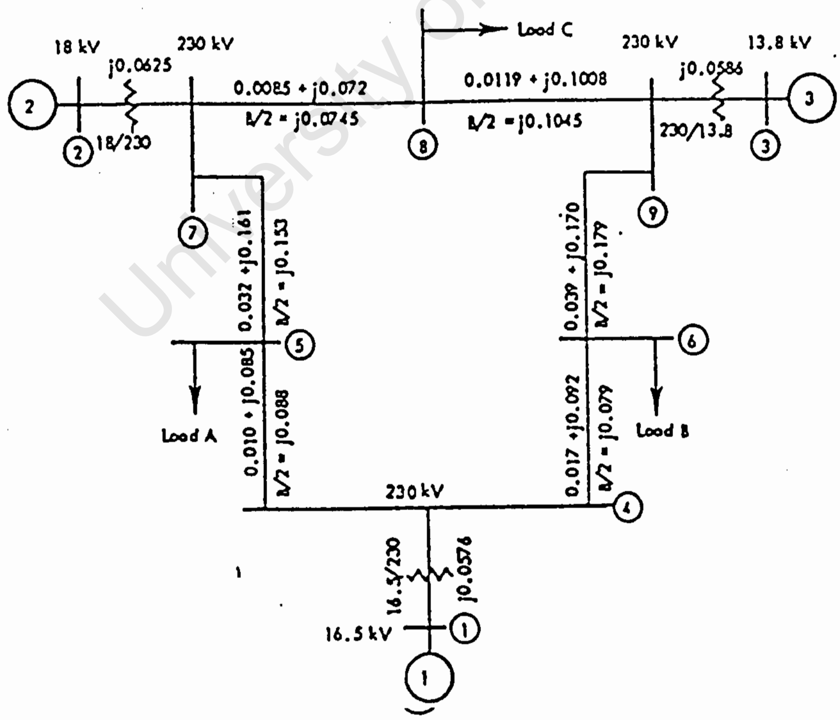


Figure 1.2 : The nine-bus benchmark network

The following protection were modelled, applied and investigated:

1) Distance protection
2) Out-of-step blocking protection

Distance protection is primarily used for the protection of high-voltage transmission lines where:

1) high-speed protection
   and
2) discrimination between fault locations

are necessary. For this reason, distance-protection performance during out-of-step conditions was investigated.

Out-of-step blocking protection is primarily used to detect an out-of-step condition and, upon detection, block distance protection. The performance of distance protection incorporating out-of-step blocking protection was also investigated in the research.

Dynamic instability and transient instability initiate system oscillations. These oscillations may affect the performance of the protection in the nine-bus network. For this reason, dynamic-stability and transient-stability studies were done on the nine-bus network to investigate the protection performance. Various stability studies were done to obtain the worst cases for dynamic and transient stability respectively (see Table 5.1 in Chapter 5). For these stability studies the effect of excitation control was investigated. Excitation control may decrease the damping at a generator, thus making the generator more sensitive to dynamic instability [3]. In the case of transient instability, the presence of excitation control may increase the stability limit of the system, thereby making the system more stable [3].

The effect of power system stabiliser control, when present at each generator, was not investigated. The presence of power system stabiliser control will improve the stability of a power system and, in the case of the nine-bus network, this will defeat the object of obtaining the worst cases for dynamic and transient stability respectively.

To do a dynamic-stability study, a change in load was simulated. Due to the presence of high-gain excitation control at each generator, the small disturbance was sufficient to cause dynamic instability*.

To do a transient-stability study, a three-phase fault close to the generator at bus 3 was simulated. For this simulation there was no excitation control on the nine-bus network. (The simulation of various stability studies indicated that the presence of excitation control at each generator keeps the system from becoming transiently unstable. Without excitation control, the nine-bus network was found to be sensitive to severe disturbances, resulting in the system becoming transiently unstable.)

1.2 Limitations of the research.

The nine-bus network is a small and simple system. This could limit conclusions regarding distance-protection performance during out-of-step conditions.

1.3 Plan of development

* High-gain excitation tends to decrease the damping at a generator, thus making the generator more sensitive to dynamic instability [3].

In Chapter 2 the synchronous stability of the power system is discussed. Two types are presented namely:

1) Dynamic stability
2) Transient stability

Dynamic instability and transient instability conditions were simulated for the purposes of the research. In Chapter 2 it is shown that these conditions cause oscillations that may affect the performance of system protection.

Chapter 3 presents the nine-bus network used for the purposes of the research. The mathematical models representing the nine-bus network are presented.

Chapter 4 deals with protection and its performance during system out-of-step conditions. Distance protection and out-of-step blocking protection, and their respective mathematical models, are presented.

Chapter 5 presents and discuss the results of the dynamic-stability and transient-stability studies carried out.

Chapter 6 is a summary of the research. The results obtained in the research are summarised and discussed. Suggestions are made regarding further research.

CHAPTER 2: SYNCHRONOUS STABILITY OF A POWER SYSTEM

2.1 Introduction

Synchronous stability of a power system is a concept used in AC electric power systems. "Synchronous stability" denotes a condition in which the various machines of the system remain "in step" with one another. "Synchronous instability" denotes a condition in which the various machines of the system fall "out of step" with on another.

An out-of-step condition can occur between one machine and the rest of the system, or between groups of machines.

Following a system disturbance, the generator's electrical parameters (rotor angle, electrical power, terminal voltage, etc.) oscillate for some time. The oscillations are reflected as fluctuations in the power flow over the transmission lines. If the system is stable, the oscillations caused by the disturbance will be damped, eventually resulting in new operating conditions. If damping is not sufficient, the system will become unstable.

The fluctuations in power flow over the transmission lines causes voltage and current to vary over wide ranges. This variation of voltage and current can affect protection performance, for example that of distance protection, on the system and may consequently cause the opening of unfaulted lines. An interconnected system can "break up" due to distance-protection operation and thus become unable to provide support to areas which become isolated.

Common features of a power system displaying unstable behaviour are:

1) long-distance transmission lines;
2) load centres that are widely separated and partially supplied by remote generation, the angular displacements between remote generators and those near the load centre being large; and
3) lines ("ties") between load areas are long and the interchange of power requires large power angle differences.

2.2 Types of synchronous instability in a power system.

Two types of synchronous instability in a power system can be identified, namely:

1) Dynamic instability
2) Transient instability

The main difference between these types of instability, is the time frame within which they develop. Dynamic instability occurs within a period of one second to one minute. Transient instability occurs within a period of zero to one second.

2.2.1) Dynamic instability

Dynamic stability is the ability of a generator to remain in synchronism when exposed to small disturbances such as a gradual change in load [4].

Small speed deviations from synchronous speed occur continually during normal operation when a generator is subjected to slow or gradual changes. The speed deviations cause rotor angle and electrical power output oscillations. If the oscillations diminish in time due to sufficient system damping, the system is said to be dynamically stable. If the oscillations increase in time due to a lack of system damping, the system is said to be dynamically unstable.

During slow or gradual changes in a system the motion of each generator rotor in the system is expressed as

$$M.\frac{d^2\delta}{dt^2}+\frac{D}{\omega_s}.\frac{d\delta}{dt}+K=0 \tag{2.1}$$

where

K = - (Pm - Pe)

D = damping power coefficient

ω_s = synchronous speed of the rotor

M = inertia constant of the generator

δ = angular displacement of the rotor

Pm = mechanical power supplied by prime mover

Pe = electrical power output of machine.

Substituting $\delta = e^{st}$, the solution to equation (2.1) becomes

$$\delta = e^{at} * e^{\pm\sqrt{b}.t} \tag{2.2a}$$

$$a=\frac{-D}{2M\omega_s} \tag{2.2b}$$

$$b=\frac{(\frac{D}{\omega_s})^2-4MK}{2M} \tag{2.2c}$$

With $\frac{D^2}{\omega_s^2}$ < 4MK, the roots are complex and the response is oscillatory. The generator will be unstable for D <0. Figure 2.1 shows an oscillatory increase in rotor angle δ due to insufficient damping.

A rotor deviation from synchronous speed will change the electrical power output of the machine. The relationship can be expressed by means of the power-angle equation:

$$Pe = Pmax \times \sin\delta \tag{2.3}$$

where

Pmax = maximum electrical power output of the generator.

Figure 2.2 shows the electrical power output **Pe** oscillating with an increase in rotor angle δ.

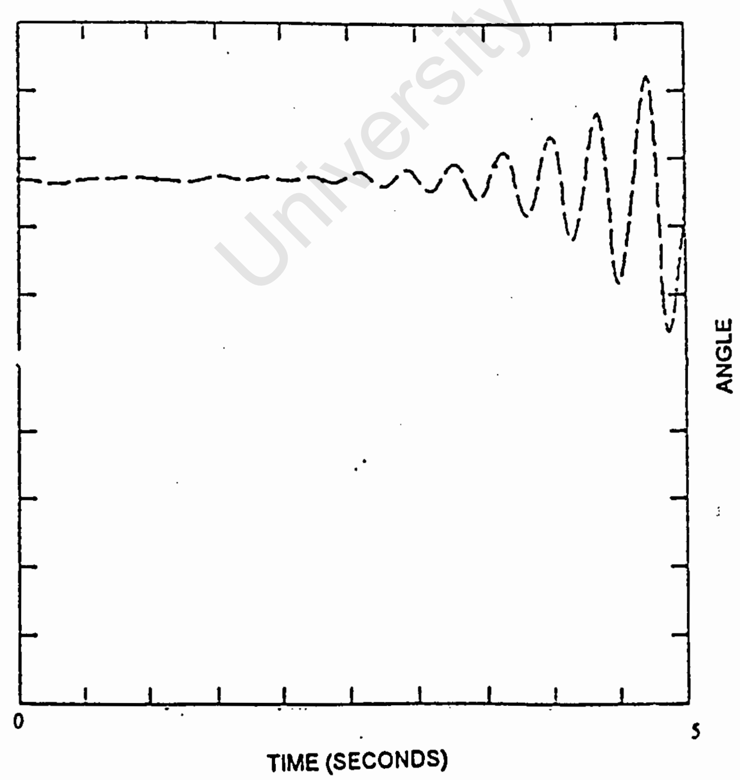


Figure 2.1: Dynamic instability (Angle vs time)

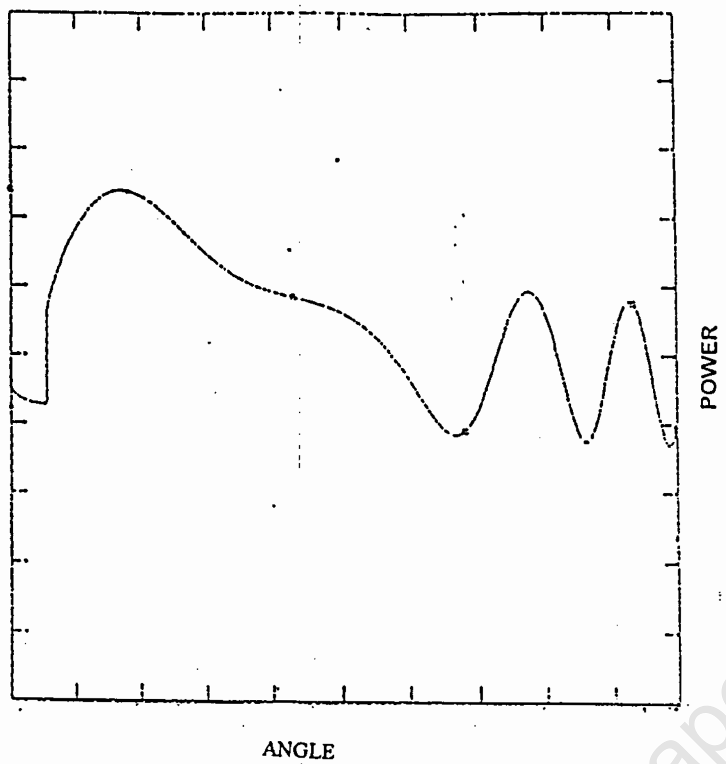


Figure 2.2: Power vs angle

2.2.2) Transient instability

Transient stability is the ability of a generator to remain in synchronism when exposed to severe disturbances [4]. Severe disturbances are:

1) a fault on a heavily loaded line, which requires the opening of the line;
2) tripping of a heavily loaded generator; and
3) abrupt dropping of a large load.

When a generator is subjected to a major disturbance, a sudden change in generator output will occur. At the instant of the disturbance, the terminal voltage and power output of the generator will change. As a result, there will be a difference between the mechanical power and the electrical power. In order to eliminate this difference the rotor speed will change; consequently the rotor angle will change. Figure 2.3 shows the power-angle curve of a generator. If the rotor angle increases to beyond 90°, the power output at the generator terminals will decrease, with a consequent increase in speed. With this condition, stability will be lost.

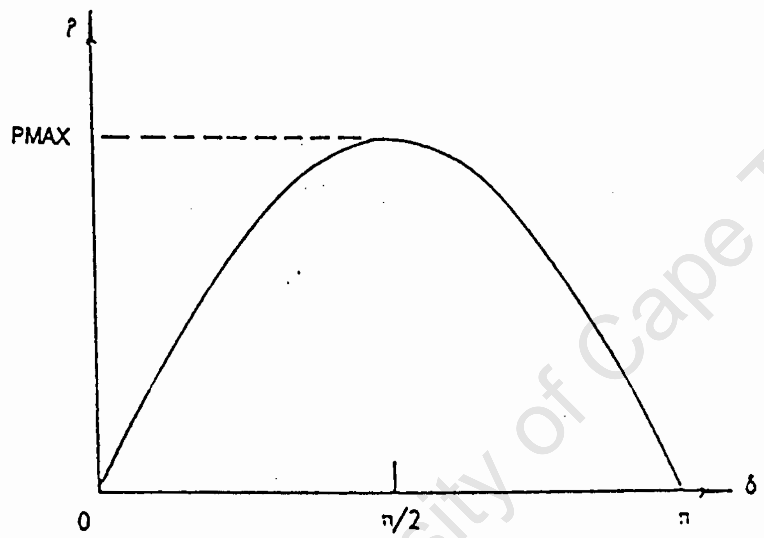


Figure 2.3: Power-angle curve of a generator

A severe disturbance on a power system necessitates a large and sudden change in the output of each generator. The equation representing the motion of each generator rotor can be expressed as

$$M.\frac{d^2\delta}{dt^2}+K=0 \tag{2.4}$$

where

$K = -(Pm - Pe)$

M = inertia constant of the generator

δ = angular displacement of the rotor

Pm = mechanical power supplied by prime mover

Pe = electrical power output of machine.

The damping term of the generator is neglected because of the following:

1) Due to the inertia of the machine, the rotor angle, δ, cannot change instantaneously.
2) The time frame of less than one second, within which transient instability can occur, is not large enough to allow the damping term (change in rotor angle δ) to become significant.

Substituting $\delta = e^{st}$, the solution to equation (2.4) becomes

$$\delta = e^{\pm\sqrt{\frac{-K}{M}}.t} \qquad (2.5)$$

The generator will be unstable if K <0. This will result in a constant rotor-angle increase (See Figure 2.4).

In section 2.2.1 it was shown that a rotor deviation from synchronous speed will change the electrical power output of the machine. Equation (2.3) shows this relationship. The electrical power oscillation with an increase in rotor angle is shown in Figure 2.2.

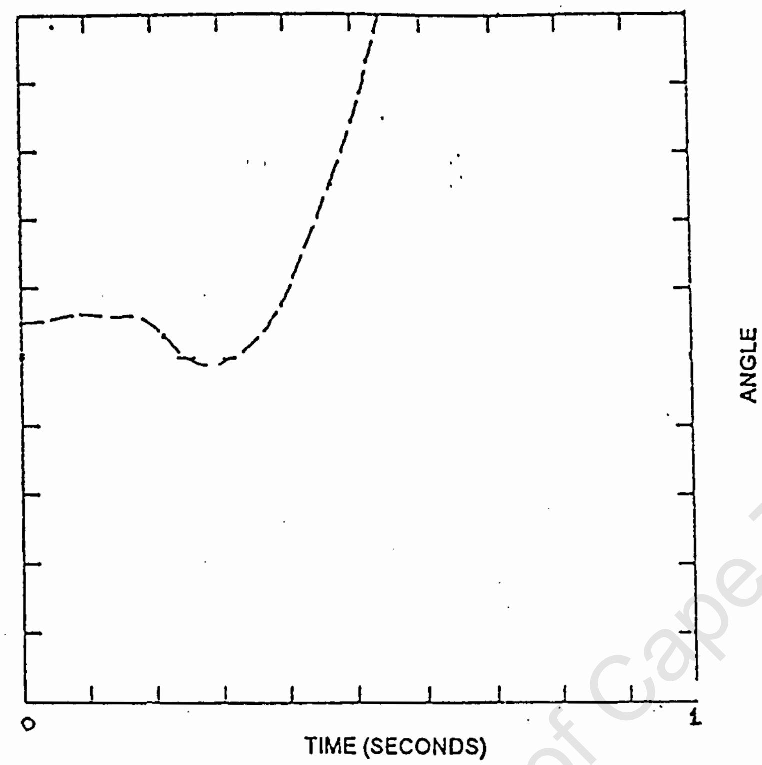


Figure 2.4: Transient instability (angle vs time)

Dynamic-stability and transient-stability studies were done on the nine-bus network (see Figure 1.2 in Chapter 1) to investigate distance-protection performance. Various stability studies were done to obtain the worst cases for dynamic and transient stability respectively (see Table 5.1 in Chapter 5). For these stability studies the effect of excitation control was investigated. Excitation control may decrease the damping at a generator, thus making the generator more sensitive to dynamic instability [3]. In the case of transient instability, the presence of excitation control may increase the stability limit of the system, thereby making the system more stable [3].

The effect of power system stabiliser control, when present at each generator, was not investigated. The presence of power system stabiliser control will improve the stability of a power system and, in the case of the nine-bus network, this will defeat the object of obtaining the worst cases for dynamic and transient stability respectively.

To do the dynamic-stability study, a change in load was simulated. High-gain excitation control was present at each generator and a small disturbance was sufficient to cause dynamic instability*. Due to the reduced damping, the small oscillations caused by the change in load were not sufficiently damped.

To do a transient-stability study, a three-phase fault close to the generator at bus 3 was simulated. For this simulation, there was no excitation control on the nine-bus network. The presence of excitation control at each generator makes the nine-bus network insensitive to severe disturbances. (The simulation of various stability studies indicated that the presence of excitation control at each generator keeps the system from becoming transiently unstable. Without excitation control, the nine-bus network was found to be sensitive to severe disturbances, resulting in the system becoming transiently unstable.)

2.3 Summary

In this chapter power-system synchronous stability was discussed. "Synchronous stability" denotes a condition in which the various machines of the system remain "in step" with one another. "Synchronous instability" denotes a condition in which the various machines of the system fall "out of step" with one another.

* High-gain excitation control tends to decrease the damping at a generator, thus making the generator more sensitive to dynamic instability [3].

Two types of power system instability were presented namely:

1. Dynamic instability
2. Transient instability

The main differences between these types of instability are the time frame within which they develop and the type of disturbance which will cause instability.

Dynamic instability, which occurs within a period of one second to one minute, is the ability of a generator to remain in synchronism when exposed to small disturbances such as a gradual change in load.

Transient instability, which occurs within a period of zero to one second, is the ability of a generator to remain in synchronism when exposed to severe disturbances such as major short circuits.

It was shown that the generator's electrical parameters (rotor angle, electrical power, terminal voltage, etc.) oscillate for some time following a system disturbance. If the system is stable, the oscillations caused by the disturbance will be damped, eventually resulting in new operating conditions. If damping is not sufficient, the system will become unstable.

The chapter also dealt with the simulation of dynamic and transient instability on the nine-bus network. Various stability studies were done to obtain the worst cases for dynamic and transient stability respectively (see Table 5.1 in Chapter 5). For these stability studies the effect of excitation control was investigated. Excitation control may decrease the damping at a generator, thus making the generator more sensitive to dynamic instability [3]. In the case of transient instability, the presence of excitation control may increase the stability limit of the system, thereby making the system more stable [3].

The effect of power system stabiliser control, when present at each generator, was not investigated. The presence of power system stabiliser control will improve the stability of a power system and, in the case of the nine-bus network, this will defeat the object of obtaining the worst cases for dynamic and transient stability respectively.

To do a dynamic-stability study, a small change in load was simulated. Each generator was equipped with high-gain excitation control.

To do a transient-stability study, a three-phase fault close to a generator was simulated. Excitation control was not present on the system for this study.

CHAPTER 3: THE POWER SYSTEM MODEL

3.1 Introduction

Power-system modelling involves the solution of algebraic and differential equations describing the following:

1) Each rotating machine
2) Generator excitation controls
3) Turbines and their governing systems
4) The transmission network
5) Loads at transmission substations

The process of solving the algebraic equations for given loads and generator power outputs is referred to as the "load flow calculation". The process of integrating the differential equations to produce plots of the dynamic behaviour of quantities such as rotor angle or protection behaviour as a function of time is called the "dynamic simulation".

For this research both the load flow and the dynamic simulation calculations were done by means of a computer program namely the PSS/E (Power System Simulator for Engineers). The data for the Working Case are contained in two files, namely the network data file and the dynamic data file. These files contain the network data and mathematical models representing the behaviour of the power system.

The load flow calculation deals with the positive-sequence model of all the system components. The quantities determined by a load flow calculation are the following:

1) The magnitude of the voltage at every bus
2) The phase of the voltage at every bus
3) The active and reactive power output of each generator
4) The real power, reactive power and current flow in each transmission line and transformer

The dynamic simulation of physical processes in a power system involves solving systems of algebraic and differential equations representing a mathematical model of the network. This involves the calculation of time derivatives and the performance of numerical integration at time **t**. The time is then advanced by an interval,**dt**, and the process is repeated until the end of a predetermined time.

The steps in a dynamic simulation are:

1) the construction of a set of differential equations describing the behaviour of the system;
2) the determination of a set of constants and parameters describing the condition of the system at a particular instant;
3) the integration of the differential equations with the values determined in 2) as initial conditions.

3.2 The nine-bus network and its mathematical representation.

The network used for the purposes of this research is shown in Figure 3.1. Generator, line, transformer and load data are listed in Table 3.1. This data were consistently used for every study done. This network is used as a benchmark for comparative studies in the power system field.

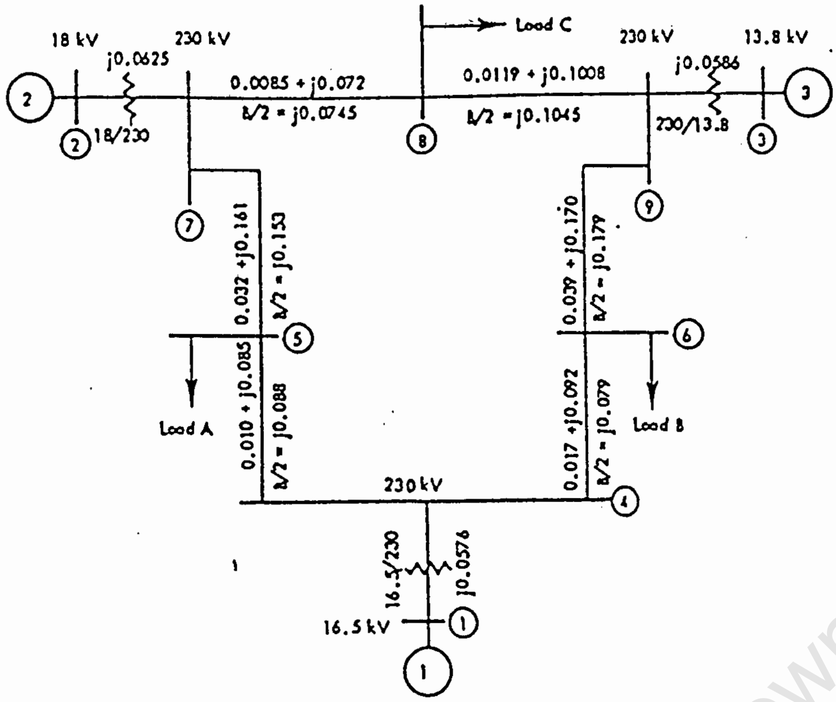


Figure 3.1: The nine-bus network

The nine-bus network is representative, simple and small. Power plant equipment such as static var compensators, series and shunt compensation equipment, etc., are not present in this network. Due to its simplicity, the effect of power system stabiliser control, when present at each generator, was not investigated. Only generators, generator excitation controls, transmission lines, transformers and loads were modelled* .

In addition to the nine-bus network model, distance protection and out-of-step blocking protection were modelled. The protection was modelled in such a way as to simulate the protection of every transmission line in the nine-bus network. Protection and protection modelling is discussed in Chapter 4.

* *Various stability studies were done to obtain the worst cases for dynamic and transient stability respectively (see Table 5.1 in Chapter 5). For these stability studies the effect of excitation control was investigated. Excitation control may decrease the damping at a generator, thus making the generator more sensitive to dynamic instability [3]. In the case of transient instability, the presence of excitation control may increase the stability limit of the system, thereby making the system more stable [3].*

The effect of power system stabiliser control, when present at each generator, was not investigated. The presence of power system stabiliser control will improve the stability of a power system and, in the case of the nine-bus network, this will defeat the object of obtaining the worst cases for dynamic and transient stability respectively.

Table 3.1: Data for the nine-bus network

GENERATOR	DATA				LINE	DATA				
DESCRIPTION	1	2	3	DESCRIPTION	4-5	5-7	7-8	8-9	6-9	4-6
Inertia H	6.396	3.302	2.382	R	0.010	0.032	0.009	0.012	0.039	0.017
Speed damping D	0.00	0.00	0.00	X	0.085	0.161	0.072	0.101	0.170	0.092
Xd	1.581	1.651	1.680	B	0.088	0.153	0.025	0.105	0.179	0.079
Xq	1.531	1.59	1.610		TRFR	DATA				
Xd'	0.380	0.232	0.232	DESCRIPTION	1-4		2-7		3-9	
Xq'	0.955	0.380	0.320	X	0.057		0.063		0.059	
Xd"	0.252	0.171	0.171	Rating (MVA)	100		100		100	
Xq"	0.248	0.171	0.171	Voltage (kV)	230 /	16,5	230 /	18	230 /	13,8
Xl	0.291	0.102	0.095							
T'do	5.390	5.900	5.890		LOAD	DATA				
T'qo	1.500	0.535	0.600	DESCRIPTION	A		B		C	
T"do	0.053	0.033	0.034	P	125		90		100	
T"qo	0.135	0.078	0.080	Q	50		30		35	
				System	base	=	100	MVA		

The PSS/E has a library of models which can represent almost every element in a power system. This library contains models for generators, excitation systems and loads. The models provided by the PSS/E were found to represent the behaviour of the nine-bus network adequately.

The Working Case, used by the PSS/E to do simulations for the purposes of the research, contains models for generators, excitation controls, transmission lines, transformers and loads.

The generator model.

To represent the dynamic behaviour of the generator, each generator was represented by a model available in the PSS/E called **GENROU**.

This model assumes the generator to be directly connected to a bus. The generator boundary-condition is a function of real power output and voltage magnitude at the generator bus, expressed as

$$\mathrm{Real}(vk, ik^{*}) = Pk \qquad (3.1)$$
$$|vk| = Vsched$$

where

k = the generator bus
Pk = real power output at bus k
Vsched = regulated voltage set-point of the generator
vk = voltage at bus k
ik = current inflow at bus k.

The **GENROU** model represents a round-rotor synchronous machine. It has a field circuit, one damper winding in the direct axis and two damper windings in the quadrature axis (see Figure 3.2). The model takes into account for both transient and subtransient effects. It adequately predicts the system stability following large and small disturbances, and it is generally used in stability studies as data for this model are readily available. Typical data needed for this model are:

1) transient and subtransient time constants in both the d-axis and the q-axis;
2) inertia;
3) speed damping; and
4) steady-state, transient and subtransient reactance for both the d-axis and the q-axis.

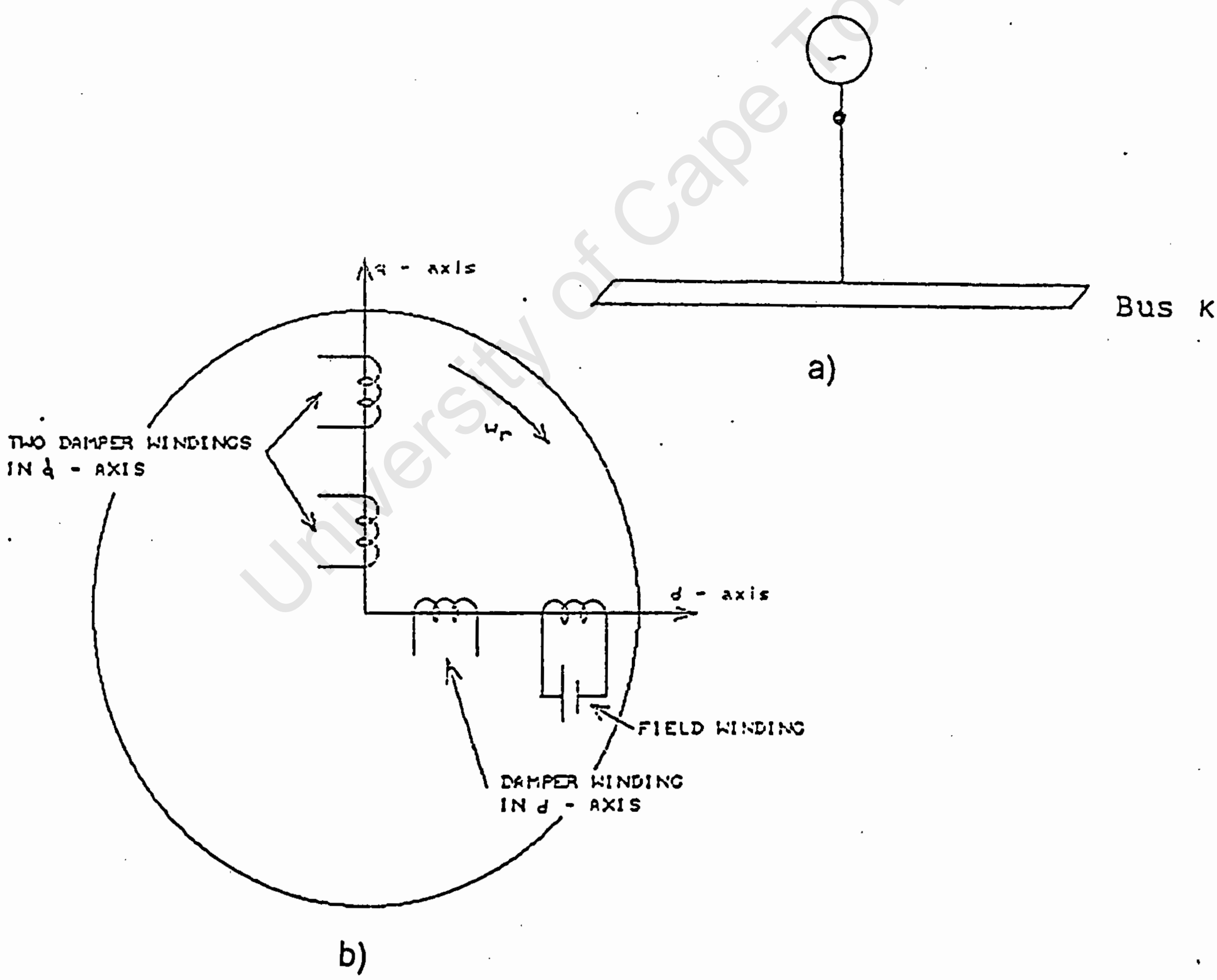


Figure 3.2: The **GENROU** model.

a) One-line diagram of generator model

b) Schematic diagram of generator model

Typical assumptions for a model such as **GENROU** are:

1) In the stator voltage equations the rate of change of the stator flux linkages are neglected
2) $\omega \approx \omega_s$
3) X"q = X"d

Synchronous machine equations for a model similar to **GENROU** are

$$\tau''_{qo} \cdot \frac{dE''_d}{dt} = E''_d - (X_q - X''_q) I_q \tag{3.2}$$

$$\tau''_{do} \cdot \frac{d\Phi_D}{dt} = -\Phi_D + E'_q + (X'_d - X_l) I_d \tag{3.3}$$

$$\tau''_{do} \cdot \frac{dE'_q}{dt} = E_{fd} - (1 + Kd) E'_q + X_{xd} I_d + Kd \Phi_D \tag{3.4}$$

$$E''_q = K1 E'_q + K2 \Phi_D \tag{3.5}$$

$$E''^2 = E''^2_q + E''^2_d \tag{3.6}$$

where

E_{fd}	=	exciter output voltage
E''_d	=	d-axis subtransient flux linkage
E''_q	=	q-axis subtransient flux linkage
τ''_{qo}, τ''_{do}	=	open-circuit subtransient time constants
Φ_D	=	direct-axis damping-winding flux-linkage
X''_q, X''_d	=	q-axis and d-axis subtransient reactances

X_l = leakage reactance

I_q, I_d = q-axis and d-axis current

$$K1 = \frac{(X''_d - X_l)}{(X'_d - X_l)} \tag{3.7}$$

$$K2 = (1 - K1) \tag{3.8}$$

$$K_d = \frac{(Xd - X'd)(X'd - X''d)}{(X'd - Xl)^2} \tag{3.9}$$

$$X_{xd} = \frac{(Xd - X'd)(X''d - X''l)}{(X'd - Xl)} \tag{3.10}$$

The swing equation and the electrical torque complete the description of the synchronous machine.

$$\frac{2H}{\omega_r} \cdot \frac{d\omega}{dt} = Tm - Te - D\omega \tag{3.11}$$

$$\frac{1}{\omega_r} \cdot \frac{d\delta}{dt} = \omega - 1 \tag{3.12}$$

where

$$Te = E''q * Iq + E''d * Id \tag{3.13}$$

The block diagram of the model represented by these equations can be seen in Figure 3.3.

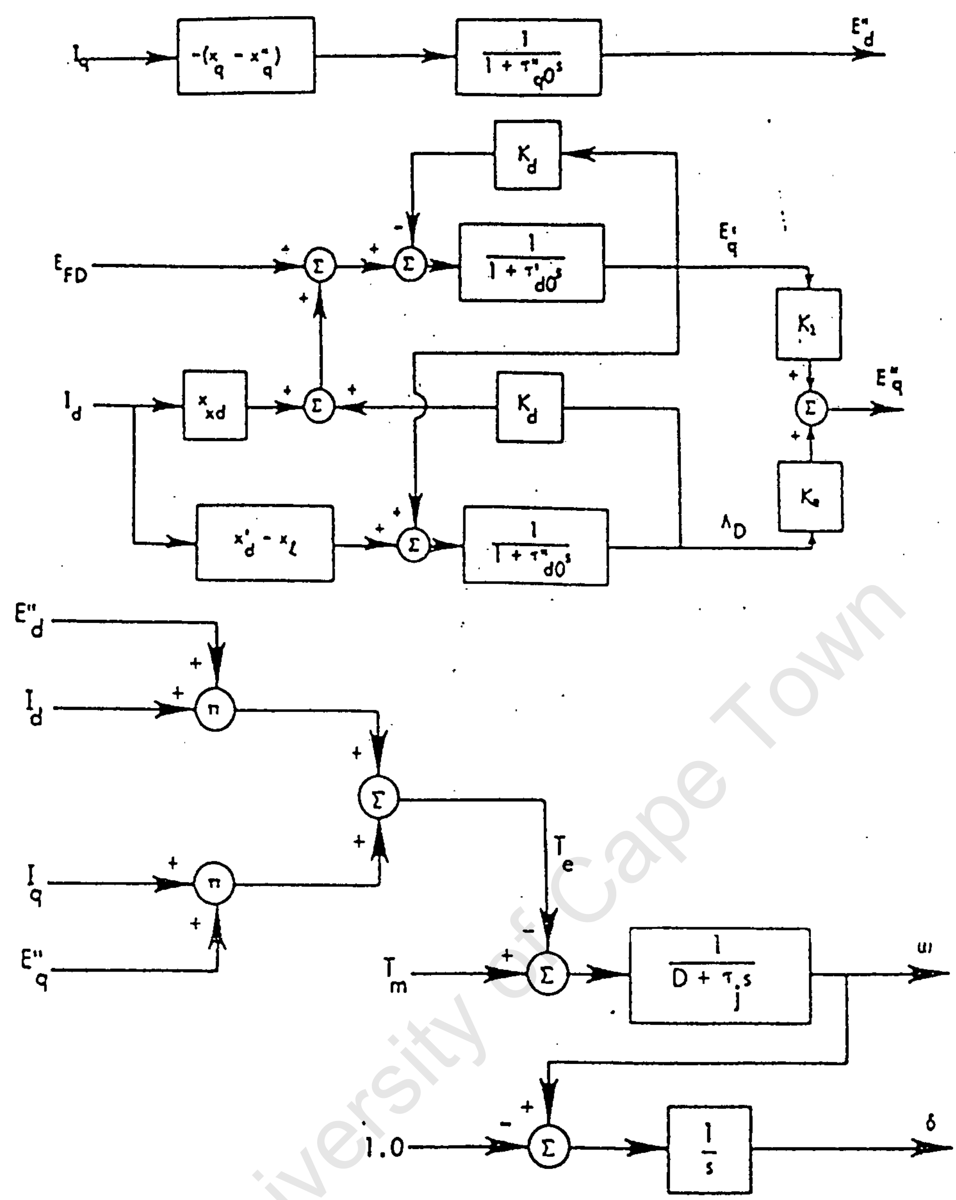


Figure 3.3 : Block diagram of synchronous machine

Model of the excitation system

The excitation system controls the generated emf of the generator and therefore controls the output voltage. The excitation control of each generator in the nine-bus network was represented by a model available in the PSS/E, called **SEXS**. This model does not represent any specific type of excitation system; it represents the general characteristics of a wide variety of excitation systems. It is particularly useful in cases where an excitation system whose detailed design is not known must be represented. The block diagram for this excitation system model can be seen in Figure 3.4. The mathematical equation to represent the block diagram can be expressed as:

$$E_{fd}=\frac{(1+T_A s)}{(1+T_B s)}*\frac{K}{(1+T_E)}*(Vref-Ve) \tag{3.14}$$

where

E_{fd}	=	exciter output voltage
T_A	=	time constant
T_B	=	time constant
K	=	constant
T_E	=	time constant
Vref	=	reference voltage
Ve	=	error voltage.

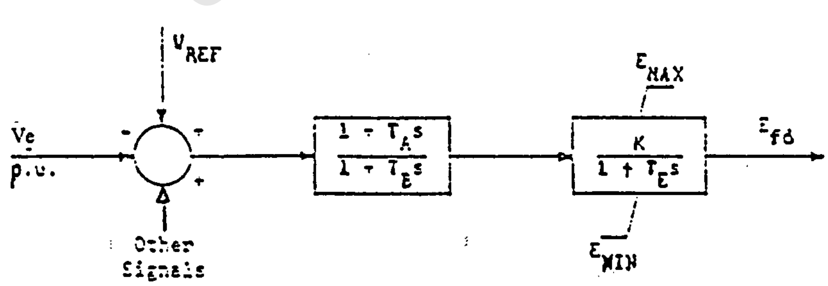


Figure 3.4 : Model of the excitation system

Model of the transmission lines and the transformers

Transmission lines and transformers were represented by the model shown in Figure 3.5. In representing a transmission line, the transformer turns ratio, T, and transformer phase-shift angle, ϕ, is equal to zero. In representing a transformer, the transmission-line shunt admittance **B** and series line resistance **R** are equal to zero.

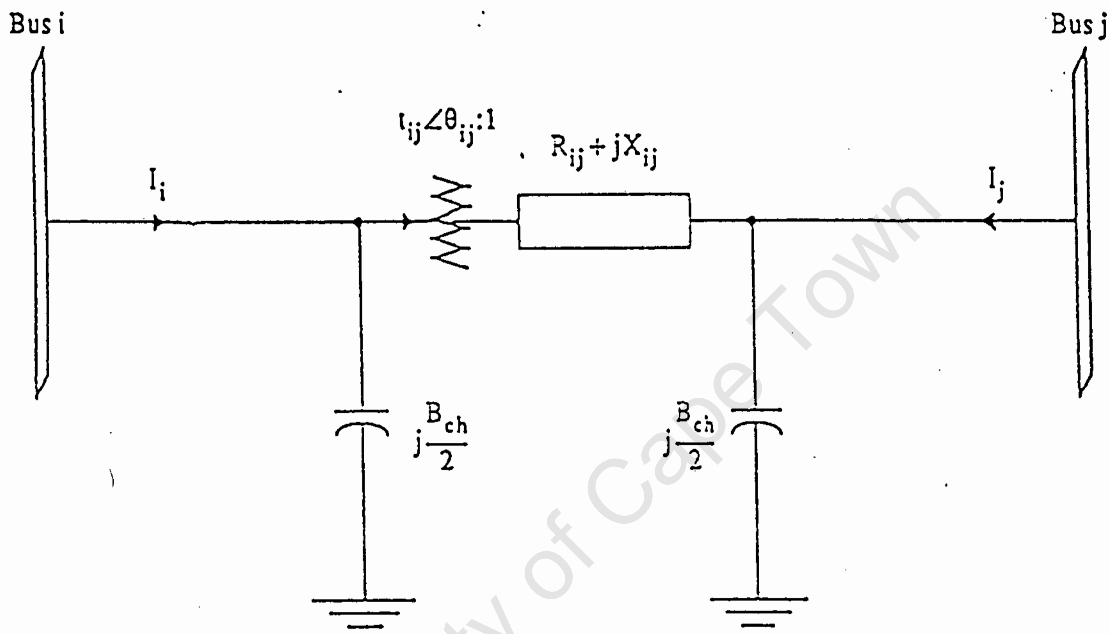


Figure 3.5: Model of the transmission line and the transformer

The load model.

Loads were modelled to represent real and reactive power consumption at the load buses:

$$\text{Real}\,(vk,ik^{*}) = -Pk \qquad (3.15)$$

$$\text{Imag}\,(vk,ik^{*}) = -Qk \qquad (3.16)$$

where

$Pk + jQk$ = net load and generation demand at bus k

vk = voltage at bus k

ik = current inflow at bus k.

In view of the size and simplicity of the nine-bus network, the dynamic behaviour of the loads were modelled as constant admittance. Loads represented as constant admittance* will provide conservative results regarding the stability of the nine-bus network, consequently the time that elapses before the system becomes unstable enables the effective investigation of protection performance during out-of-step conditions. Loads represented as constant power** or constant current*** reduce the stability limit, and thereby limiting the investigation of protection performance.

The loads were indicated by real and reactive parts of shunt admittance, such that the following equation is satisfied:

$$\frac{vk}{ik} = Gk + jBk \qquad (2.17)$$

$$= Yk$$

$$= \frac{vk^2}{Pk}$$

$$\Rightarrow \quad Pk \approx vk^2$$

where

$Gk + jBk$ = Yk = shunt admittance representation of real and reactive power consumption at load bus k

* For constant admittance representation the active and reactive power varies proportional with the square of the voltage in order to keep the impedance constant. These loads are dependent on voltage and current changes in the system and will therefore give conservative results [9].

** For constant power representation, the active and reactive power are assumed constant before during and after a system disturbance. These loads are independent of voltage and current changes in the system and will therefore give overpesimistic (worst case) results [9].

*** For constant current representation the active and reactive power varies proportional with voltage in order to keep the current constant. Loads represented as constant current usually represent a combination of constant power representation and constant admittance representation [9].

Pk	=	power consumption at load bus k
vk	=	voltage at bus k
ik	=	current inflow at bus k.

The real and reactive power values for the loads represented as constant admittance are the values corresponding to the nominal voltage. At voltage below nominal, this type of load will draw more current. The opposite applies for voltage above nominal. The result is a load change proportional to the square of the voltage.

3.3 Summary

In this chapter the network used for the purposes of the research was introduced. This network is a benchmark network used for comparative studies and is representative, simple and small.

The effect of power system stabiliser control, when present at each generator, was not investigated and therefore not modelled*.

The generators in the nine-bus network was represented by a model called **GENROU,** available in the PSS/E . The model takes into account both transient and subtransient effects and adequately predicts the system stability following large and small disturbances. It is generally used in stability studies as data for this model are readily available.

A model called **SEXS,** available in the PSS/E, was used to represent the excitation control of each generator. This model does not represent any specific type of

* Various stability studies were done to obtain the worst cases for dynamic and transient stability respectively (see Table 5.1 in Chapter 5). The presence of power system stabiliser control will improve the stability of a power system [3] and, in the case of the nine-bus network, this will defeat the object of obtaining the worst cases for dynamic and transient stability respectively.

excitation system; it represents the general characteristics of a wide variety of excitation systems. It is particularly useful in cases where an excitation system whose detailed design is not known must be represented.

Loads in the nine-bus network was represented by a voltage-dependent constant-admittance load model. Loads represented as constant admittance will provide conservative results regarding the stability of the nine-bus network, consequently the time that elapses before the system becomes unstable enables the effective investigation protection performance during out-of-step conditions. Loads represented as constant power or constant current reduce the stability limit, thereby limiting the investigation of protection performance..

The transmission lines and transformers were modelled by using an equivalent π model.

CHAPTER 4: THE PROTECTION MODEL

4.1. Introduction

Protection is one of the requirements of power system design to minimise damage to equipment. All power system equipment is protected by protection devices. The function of the protection device is to interrupt the operation of the protected equipment when an electrical failure occurs.

Protection performance and power system stability are closely related. Conditions of power system instability can influence the protection performance of a system. During an out-of-step condition, there are moments where the angle difference between the internal voltage phasors of the machines will be 180 degrees (see Appendix 1). The electrical conditions at that stage are very similar to those of a three-phase fault condition. Figure 4.1a shows the voltage and current loci for an out-of-step condition between two generators or between groups of generators. Figure 4.1b shows the impedance locus during out-of-step conditions.

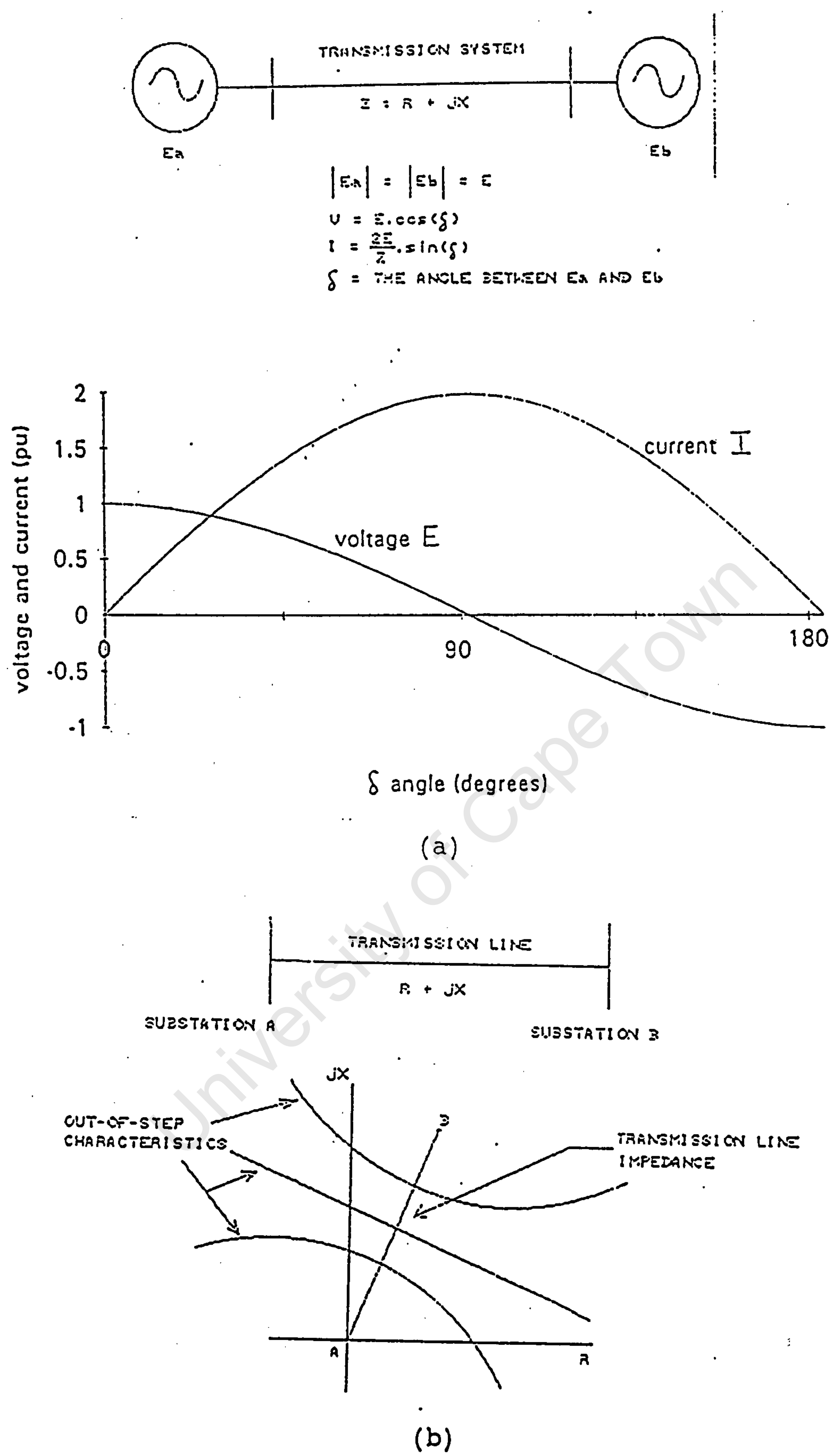


Figure 4.1: a) Voltage and current loci during an out-of-step condition.

b) Impedance locus during out-of-step conditions.

Undervoltage, overcurrent and distance relays used for line protection are designed to detect line fault conditions. During out-of-step conditions the performance of these protection relays may be affected and unfaulted lines may consequently be tripped.

Undervoltage and overcurrent protection

Undervoltage protection operates when a voltage below a set value is measured at the relay point. Overcurrent protection operates when a current above a set value is measured. The time delay in the operation of these relays, as well as the breaker tripping time, determines when a line is tripped. Figure 4.2 shows the operating characteristics of these relays. Figure 4.2 also illustrates undervoltage and overcurrent detection during out-of-step conditions.

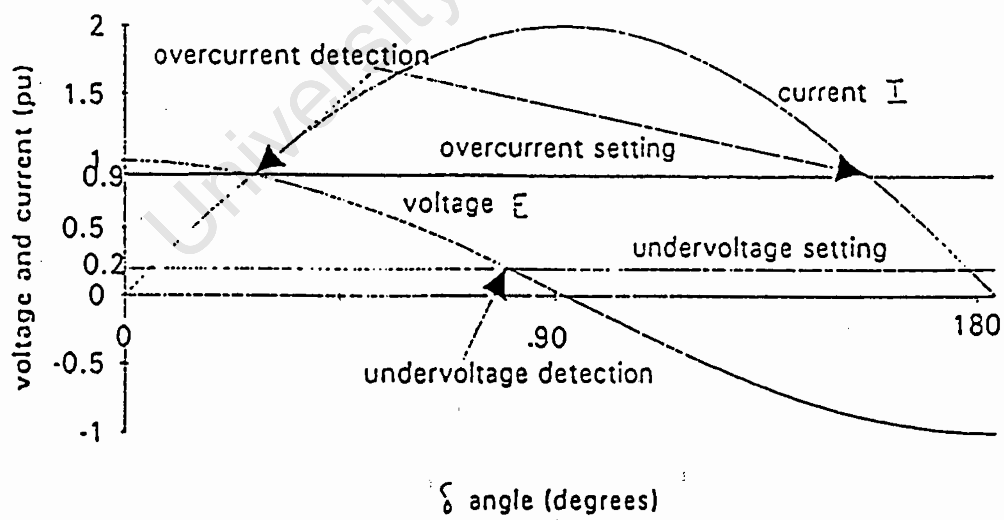


Figure 4.2 : Undervoltage and overcurrent detection during out-of-step conditions

Undervoltage and overcurrent relays are usually set for short fault-clearing times. This exacerbates the misoperation problem during out-of-step conditions. A longer time delay in the operation of these relays, can prevent them from tripping unfaulted lines during out-of-step conditions. Also, the current setting of an overcurrent relay can be set at a high value to prevent it from operating during out-of-step conditions.

Distance protection

Distance protection measures impedance. If the measured impedance is detected inside an operating zone, a zone timer will start. When the time allowed by the timer expires, the relay will operate to trip a breaker. The time delay in the operation of the relay, as well as the breaker tripping time, determines when the line will be tripped. Figure 4.3 shows the operating characteristic of a distance relay.

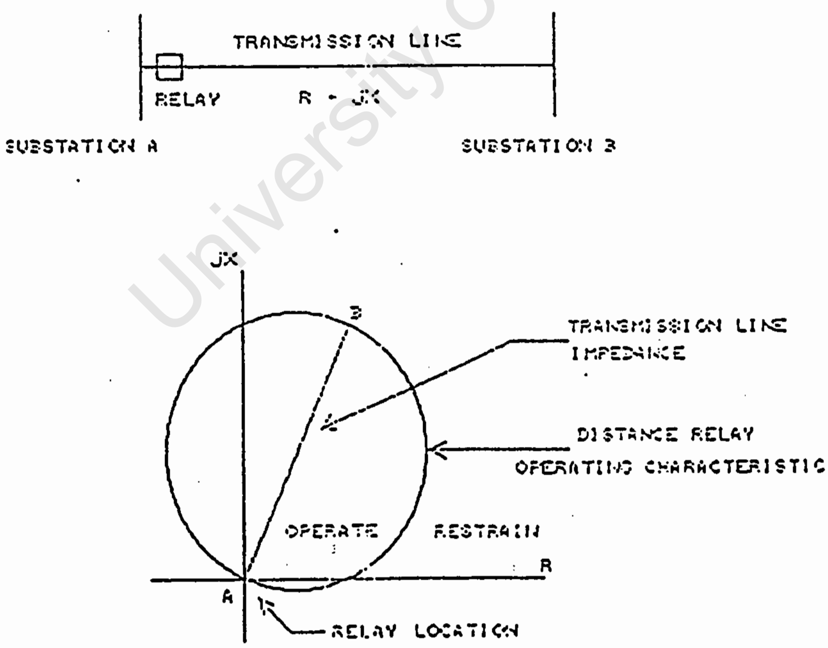


Figure 4.3: Operating characteristic of a distance relay

Due to the behaviour of voltage and current during out-of-step conditions (see Figure 4.1b), measured impedance may enter the operating zone of the distance relay. Figure 4.4 illustrates the out-of-step detection. If the measured impedance remains inside the operating zone long enough, the time allowed by the zone timer will expire and the protected line will be tripped.

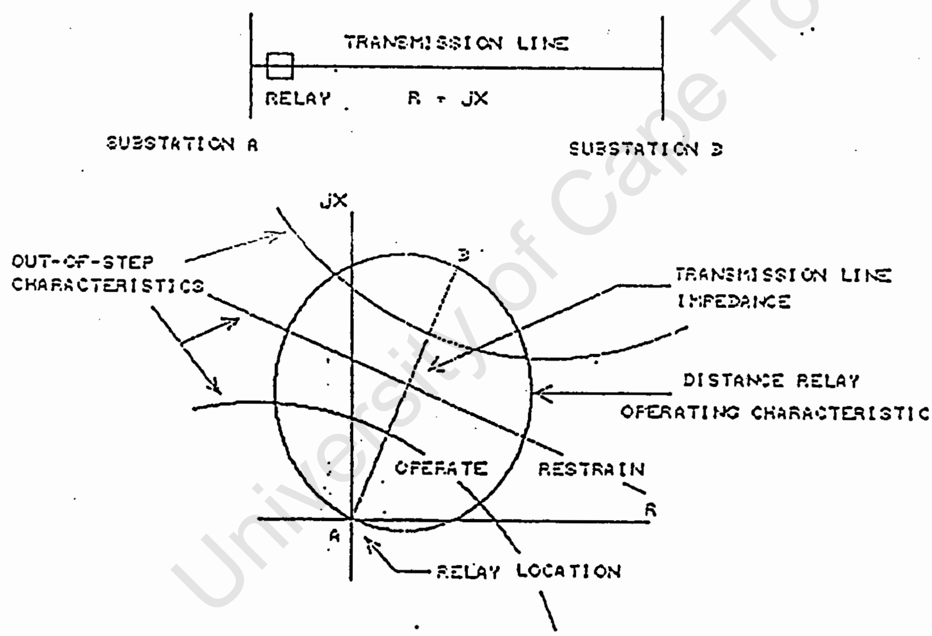


Figure 4.4: Distance relay detecting an out-of-step condition

To prevent distance-relay operation during out-of-step conditions, distance protection could incorporate out-of-step blocking protection. The blocking protection can be set to detect out-of-step conditions and block distance-protection operation.

Undervoltage and overcurrent relays used for line protection, are primarily used:

1) for the protection of lower voltage transmission lines; or
2) to serve as back-up protection for the high-voltage transmission lines. (If the main protection, which is usually distance protection, fails to operate, for example, back-up protection should operate.)

Distance protection is primarily used for the tripping of high-voltage transmission lines where

1) high-speed tripping

   and

2) discrimination between fault locations

are essential.

For these reasons, distance-protection performance during out-of-step conditions was investigated during the research.

In addition to the above, the performance of distance protection incorporating out-of-step blocking protection was investigated. (As already mentioned, distance protection can incorporate out-of-step blocking protection to prevent misoperation during out-of-step conditions.)

4.2 Distance relays and out-of-step protection and their mathematical representations in the PSS/E.

4.2.1) Distance protection

Distance protection is based on voltage and current measurement. The ratio of the measured voltage and current is represented by:

$$Z_r = \frac{V_r}{I_r} \tag{4.1}$$

where

Zr = calculated impedance detected or "seen" by the relay
Vr = voltage measured at the relay point
Ir = current measured at the relay point.

The distance relay has a setting impedance, Zset, equivalent to the impedance of the section of the line to be protected and operates when the ratio of voltage and current is less than the setting impedance Zset.

Distance protection often have more than one protection zone. A conventional distance protection relay will have an instantaneous directional zone 1 protection as well as one or more time-delayed zones. Distance protection for a transmission line is shown in Figure 4.5.

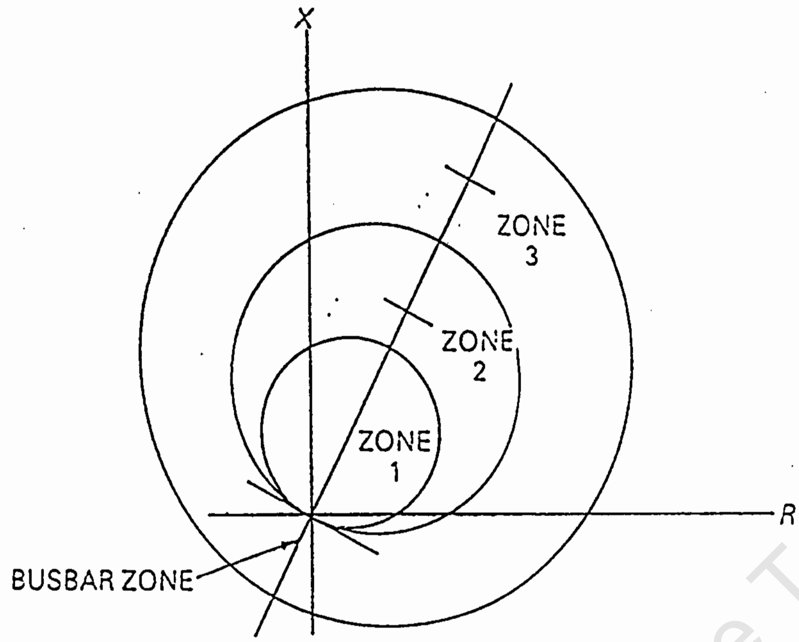


Figure 4.5: Distance protection for a transmission line

It is customary to select a relay setting of about 80% of the impedance of the protected line for zone 1 protection. Zone 1 protection is usually set to operate with no time delay (instantaneously).

The remaining part of the line, not covered by zone 1, is covered by a time-delayed zone 2 protection. The selected setting of the zone 2 protection normally covers the protected line plus 50% of the shortest adjacent line. The zone 2 time delay is set to allow for zone 1 protection plus circuit-breaker tripping time.

Zone 3 protection serves as back-up protection for all faults on the adjacent lines and has a longer time delay to allow for zone 2 protection plus circuit breaker tripping time. The zone 3 setting is usually selected to provide protection from a fault at the remote end of the second line section (see Figure 4.5).

Zone 3 protection sometimes has a setting which provides time-delayed back-up protection from busbar faults and "close-up" three-phase faults behind the relay which were not cleared by other protection schemes. This setting is usually set to 20% of the impedance of the protected line.

4.2.2) Out-of-step blocking protection

The change in impedance measured during an out-of-step condition is slow compared with the fast change in impedance during a fault condition. An out-of-step condition can therefore be detected of monitoring the rate of the change in measured impedance.

Out-of-step blocking protection is primarily used to block distance-protection operation when an out-of-step condition is detected. Distance-protection relays which are not blocked by out-of-step blocking protection are, however, sometimes used intentionally for tripping during out-of-step conditions. The reason for this is the need for system separation during out-of-step conditions.

A simple out-of-step blocking relay has two characteristic zones called the inner and outer zones (see Figure 4.6). When the measured impedance enter the outer zone, a timer is started. If the time allowed by this timer expires before the impedance enter the inner zone, an out-of-step condition is detected. Relay operation occurs as soon as the impedance enters the inner zone.

The setting of an out-of-step blocking relay must be coordinated with the setting of the distance relay that it must block. In many cases the inner zone is set to equal, or exceed the zone 3 characteristic of the distance relay. This enables the detection of an out-of-step condition before the distance relay detects impedance inside its operating zones.

The outer zone setting is higher. Typically it will be 1,3 times that of the inner zone to allow a sufficient timer setting.

Distance protection incorporating out-of-step blocking protection can be seen in Figure 4.6.

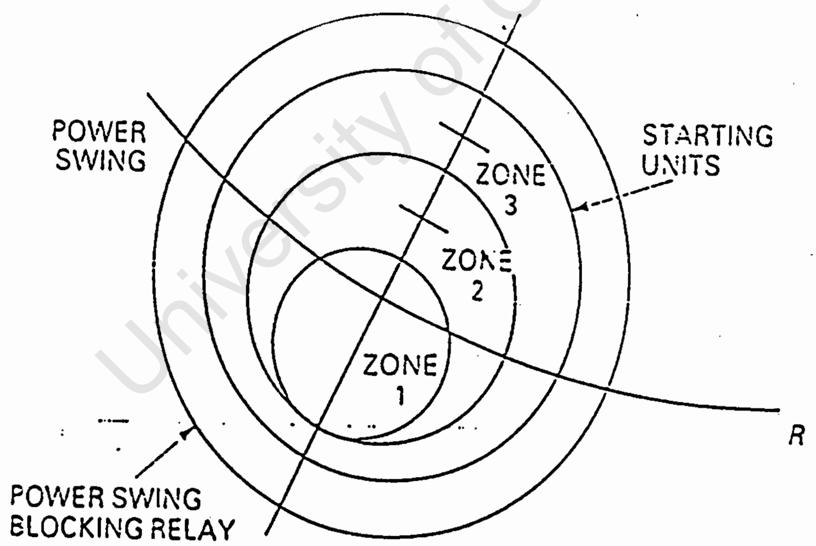


Figure 4.6: Distance protection incorporating out-of-step blocking protection

4.2.3) Mathematical representations in the PSS/E

In the PSS/E relays can be modelled by combining and manipulating the relay models available in the PSS/E library. The relays in the model library are not intended to be an exact representation of any one product of any relay manufacturer. They are intended to sufficiently represent the basic features of relays generally.

Distance relay and out-of-step blocking protection were modelled by using existing PSS/E models and were included in the Working Case representing the nine-bus network. The models chosen to represent the dynamic behaviour of the distance protection and out-of-step blocking protection, are **DISTR** and **CIRCOS** respectively.

1. DISTR Model

DISTR is a general model for distance relays, which has the following features and functions:

1) Mho, impedance or reactance characteristic*
2) Up to three independent circular zones for mho or impedance characteristics
3) Tripping of the monitored line (self-trip) as well as tripping of up to three remote lines (transfer trips)
4) Single-attempt reclosure for zone 1 faults
5) Supervisory signal input * to prevent tripping or force immediate tripping
6) Up to two straight-line blinders*
7) Minimum pick-up current logic*

* See section on definitions.

8) A tripping action opening the circuit breakers at both ends of a line simultaneously

9) A monitor-only mode (In this mode the model reports detection of faults on the monitored or remote lines, but will not cause tripping of these lines.)

The **DISTR** model will operate for the following condition:

$$Zr = \frac{V_r}{I_r} \qquad (4.2a)$$

$$< Zset$$

$$t \geq Tset \qquad (4.2b)$$

where

t = time that has elapsed since the first detection of impedance inside the impedance zone

Zr = impedance measured

Vr = voltage measured at the relay point

Ir = current measured at the relay point

Zset = impedance-zone reach-setting

Tset = impedance-zone timer-setting.

For the purposes of the research distance relays were modelled in such a way as to simulate to protect every line in the nine-bus system. The **DISTR** model was used to represent a distance relay which has the following features and functions:

1) Three time-delayed mho (circular) characteristics with a reverse reach* for zone 3 protection

* A zone 3 setting to provide backup protection for faults behind the relay.

2) A self-tripping operation of the monitored line

3) A supervisory signal input to prevent tripping

The graphical representation of the model is shown in Figure 4.6 and is represented by the following equations:

$$\mathbf{Z} = \frac{V}{I} \quad (4.3)$$

$$\mathbf{S1} = \mathbf{Z} - \mathbf{Z1} \quad (4.4a)$$

$$\theta 1 = 90^\circ \quad (4.4b)$$

$$\mathbf{S2} = \mathbf{Z} - \mathbf{Z2} \quad (4.5a)$$

$$\theta 2 = 90^\circ \quad (4.5b)$$

$$\mathbf{S31} = \mathbf{Z} - \mathbf{Z3} \quad (4.6a)$$

$$\mathbf{S32} = \mathbf{Z3r} - \mathbf{Z} \quad (4.6b)$$

$$\theta 3 = 90^\circ \quad (4.6c)$$

where

V	= measured voltage vector
I	= measured current vector
Z	= calculated measured impedance vector
Z1	= zone 1 reach-setting (vector)
Z2	= zone 2 reach-setting (vector)
Z3	= zone 3 reach-setting (vector)
Z3r	= zone 3 reverse reach-setting (vector)
θ1	= angle between **S1** and **Z**
θ2	= angle between **S2** and **Z**
θ3	= angle between **S31** and **S32**
S1, **S2**, **S31** and **S32**	= vectors

A self-tripping operation of the monitored line will take place when the following conditions are satisfied, provided that a supervisory signal to prevent tripping has not been received:

$$\theta 1 \geq 90^\circ \text{ and } t \geq Tset1; \text{ or} \quad (4.7a)$$

$$\theta 2 \geq 90^\circ \text{ and } t \geq Tset2; \text{ or} \quad (4.7b)$$

$$\theta 3 \geq 90^\circ \text{ and } t > Tset3 \quad (4.7c)$$

where

t = time that has elapsed since the first detection of impedance inside the impedance zone

Tset1 = zone 1 timer-setting

Tset2 = zone 2 timer-setting

Tset3 = zone 3 timer-setting

The time-delayed mho characteristic consists of:

- a zone 1, protecting 80% of the line;
- a zone 2, protecting the line and 50% of the shortest adjacent line; and
- a zone 3, providing protection up to the remote end of an adjacent line.

Zone 3 also provides protection behind the relay, from busbar faults and faults between the busbar and the relay.

The procedure of applying distance protection to the nine-bus network is set out in Appendix 2.

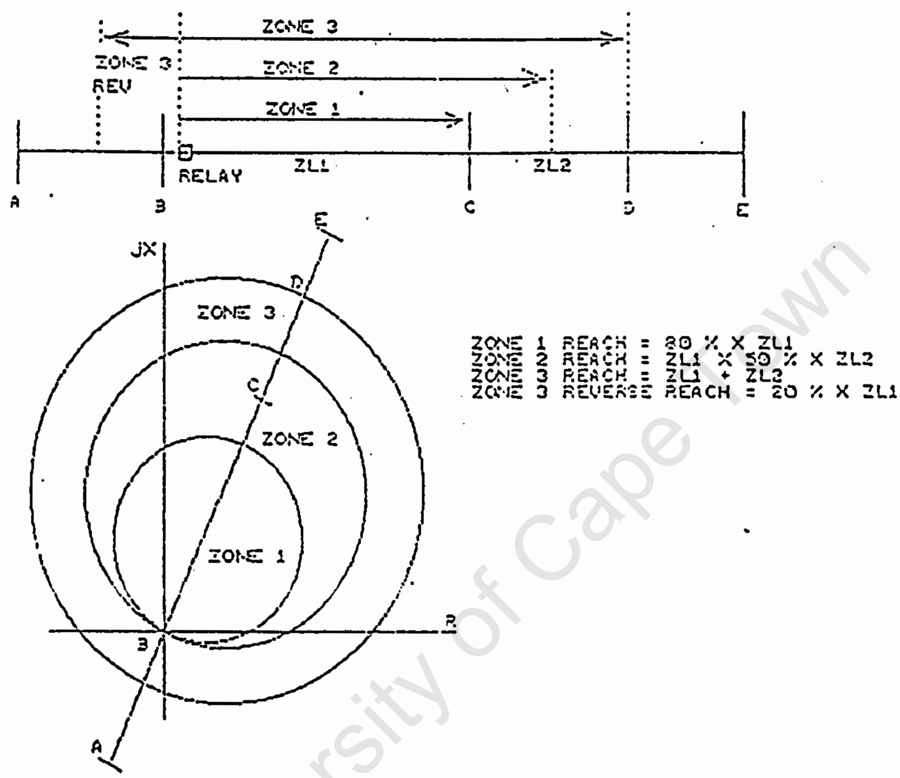
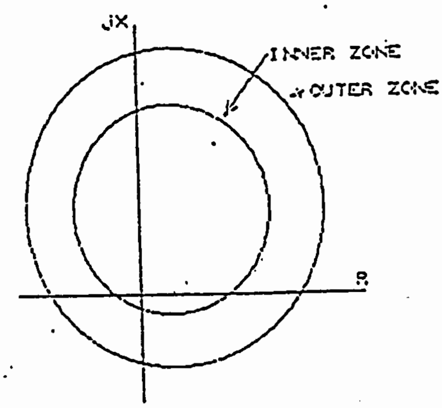


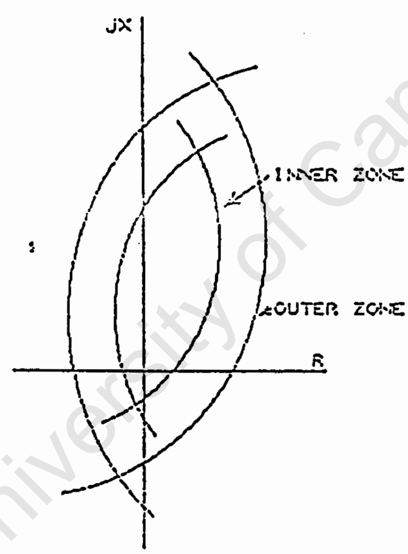
Figure 4.6 : **DISTR** model used for the purposes of the research

2. CIRCOS model

CIRCOS models out-of-step detection relays using a circular or lenticular type characteristic. The boundaries produce an inner zone surrounded by an outer zone (see Figure 4.7).



CIRCULAR TYPE CHARACTERISTIC
INNER ZONE SETTING = Zset-inner



LENTICULAR TYPE CHARACTERISTIC
INNER ZONE SETTING = Zset-inner

Figure 4.7: The **CIRCOS** model

The purpose of the out-of-step relay is to monitor the rate of change in measured impedance between the inner and the outer zones. A rapid change is interpreted as a fault condition. Conversely, a change in measured impedance which takes more than a specific time is interpreted as an out-of-step condition.

CIRCOS may be used to:

1) trip its "own" line;
2) transfer-trip up to three other lines; and to
3) control the supervisory input signal of another relay.

CIRCOS can be used in either a blocking mode or a tripping mode.

In the blocking mode **CIRCOS** is usually set to control the supervisory input signal of another relay, for example **DISTR**. As soon as **CIRCOS** detects an out-of-step condition, a blocking signal is sent to the supervisory input signal of **DISTR**.

When **CIRCOS** is in a tripping mode, it is not controlling a supervisory input signal of another relay. As soon as an out-of-step condition is detected, **CIRCOS** will therefore operate to trip local and/or remote lines.

The **CIRCOS** model will operate for the following conditions:

$$Zr = \frac{V_r}{I_r} < Zset(inner) \qquad (4.8a)$$

$$t_{oi} = f(\frac{dZr}{dt}) < T \qquad (4.8b)$$

where

Zr	= measured impedance
$\frac{dZr}{dt}$	= change in measured impedance
Vr	= voltage measured at the relay point
Ir	= current measured at the relay point

Zset(inner)	= inner-zone reach setting
t_{oi}	= duration of measured impedance between the outer and inner zone
T	= zone-timer setting

The timer setting **T** is determined on the basis of the swing frequency of the system during out-of-step conditions. This frequency is obtained from the stability studies by plotting power excursions of the system versus time. Typical swing frequencies are between 0.5 and 2.5 Hz.

For the purposes of the research, out-of-step blocking protection was represented by using **CIRCOS,** with the following features:

1) inner and outer circular characteristic zones; and
2) the control of the supervisory input of the DISTR model.

The model is shown in Figure 4.8 and is mathematically represented by the following equations:

$$\mathbf{Z} = \frac{V}{I} \tag{4.9}$$

$$\mathbf{S11} = \mathbf{Z - Zin} \tag{4.10a}$$

$$\mathbf{S12} = \mathbf{Zinr - Z} \tag{4.10b}$$

$$\theta 1 = 90^\circ \tag{4.10c}$$

$$\mathbf{S21} = \mathbf{Z - Zout} \tag{4.11a}$$

$$\mathbf{S22} = \mathbf{Zoutr - Z} \tag{4.11b}$$

$$\theta 2 = 90^\circ \tag{4.11c}$$

where

V	= measured voltage vector

I	= measured current vector
Z	= calculated measured impedance vector
Zin	= inner-zone reach-setting (vector)
Zinr	= inner-zone reverse reach-setting (vector)
Zout	= outer-zone reach-setting (vector)
Zoutr	= outer-zone reverse reach-setting (vector)
$\theta 1$	= angle between **S11** and **S12**
$\theta 2$	= angle between **S21** and **S22**
S11, **S12**, **S21** and **S22**	= vectors

Operation of the relay represented by this model, namely to control the supervisory input of the DISTR model by sending a blocking signal, will take place when the following conditions are satisfied:

$$\theta 1 \geq 90°; \qquad (4.12a)$$

$$\theta 2 \geq 90°; \text{ and} \qquad (4.12b)$$

$$t_{oi} \geq T \qquad (4.12c)$$

where

t_{oi}	= duration of measured impedance between the outer and inner zone
T	= zone-timer setting

The characteristic zones consist of

- an inner zone equal to the zone 3 setting of the distance protection; and
- an outer zone equal to 1.3 times the inner zone.

The procedure of applying out-of-step blocking protection to the nine-bus network is set out in Appendix 3.

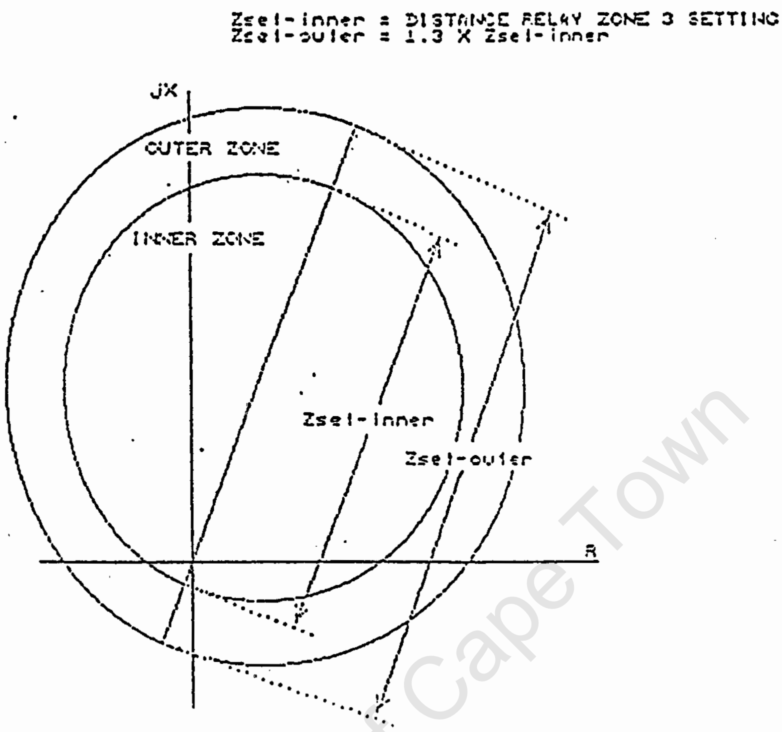


Figure 4.8: The **CIRCOS** model used for the purposes of the research

4.3 Summary

During out-of-step conditions voltage, current and power oscillations occur. These oscillations are balanced three-phase phenomena and at certain moments the electrical conditions are very similar to those of a three-phase fault condition.

Protection such as undervoltage, overcurrent and distance relays, is designed to detect fault conditions. It was shown that these protection relays may also operate during out-of-step conditions. The operation of these relays may consequently result in the tripping of unfaulted lines.

Distance-protection performance during out-of-step conditions was investigated in this research. A distance-protection model available in the PSS/E was presented. The model, called **DISTR**, was chosen to represent a distance relay with three time-delayed mho characteristics.

To prevent the misoperation of distance protection during out-of-step conditions, out-of-step blocking protection are used to detect an out-of-step condition and block the distance protection. The PSS/E model used to represent out-of-step blocking protection is called **CIRCOS**. This model represents an out-of-step blocking relay with inner and outer circular characteristic zones and a function of controlling a supervisory input of a **DISTR** model.

Distance protection incorporating out-of-step blocking protection was modelled in such a way as to simulate the protection of every line in the nine-bus network. The procedures for the application of these types of protection to the nine-bus network are set out in Appendices 2 and 3 respectively.

The protection models presented in this chapter were included in the Working Case file. These models were used to represent the dynamic behaviour of the protection during the stability studies.

CHAPTER 5: CASE STUDIES AND RESULTS

5.1 Introduction

A loss of synchronism between generators will affect the protection of the system. Protection relays such as distance relays, may detect an out-of-step swing and may therefore operate to trip their breakers. Out-of-step blocking protection will block the operation of these distance relays during unstable conditions in the system.

Various stability studies were done to obtain the worst cases for dynamic and transient stability respectively. Various stability studies were done to obtain the worst cases for dynamic and transient stability respectively (see Table 5.1 in Chapter 5). For these stability studies the effect of excitation control was investigated. Excitation control may decrease the damping at a generator, thus making the generator more sensitive to dynamic instability [3]. In the case of transient instability, the presence of excitation control may increase the stability limit of the system, thereby making the system more stable [3].

The effect of power system stabiliser control, when present at each generator, was not investigated. The presence of power system stabiliser control will improve the stability of a power system and, in the case of the nine-bus network, this will defeat the object of obtaining the worst cases for dynamic and transient stability respectively.

These studies are listed in Table 5.1. The stability studies were done on the nine-bus network shown in Figure 5.1. The nine-bus network data taken from reference [22] (see Table 3.1 in Chapter 3) were consistently used for every study done.

Table 5.1: Stability studies done on the nine-bus network

	DYNAMIC	TRANSIENT
WITH EXCITATION CONTROL AT EACH GENERATOR	Increase in load at bus 5	3-phase fault on line 4-6 close to bus 4
	Increase in load at bus 6	3-phase fault on line 5-7 close to bus 7
	Increase in load at bus 8	3-phase fault on line 6-9 close to bus 9
WITHOUT EXCITATION CONTROL AT EACH GENERATOR	none	3-phase fault on line 4-6 close to bus 4
	none	3-phase fault on line 5-7 close to bus 7
	none	3-phase fault on line 6-9 close to bus 9

For dynamic stability, the worst case obtained was an increase in load at bus 8. For this study there was excitation control at each generator.

For transient stability, the worst case obtained was a three-phase fault close to the generator at bus 3. For this study, no excitation control was present at the generators.

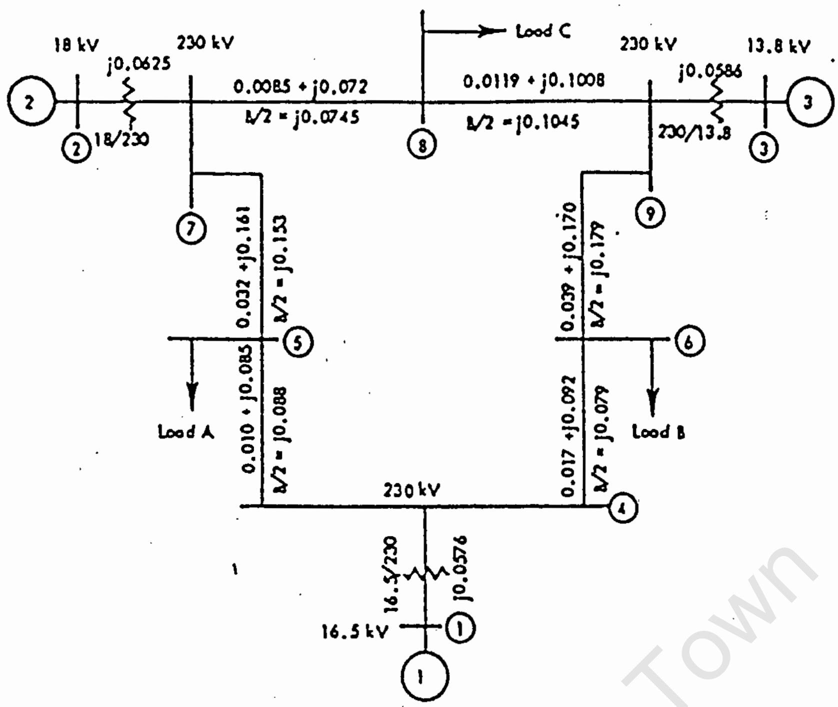


Figure 5.1: The nine-bus network

The worst cases for dynamic and transient stability respectively are discussed in the dynamic-stability study and the transient-stability study which follow. Both these cases demonstrate the influence which out-of-step conditions can have on distance-protection performance. These cases also show the improvement in distance protection-performance with the application of out-of-step blocking protection.

5.2 Case studies

CASE 1: Dynamic stability

To do a dynamic-stability study, a small increase in load at bus 8 was simulated. Due to the presence of high-gain excitation control at each generator, the small disturbance was sufficient to cause dynamic instability.*

* High-gain excitation control tend to decrease the damping at a generator, thus making the generator more sensitive to dynamic instability [3].

1. System behaviour without protection models

The load change in the system necessitated a sudden power change in the system. Due to the need for a sudden power change, small angular oscillations occurred at each generator. The generators could not damp these small angular oscillations and as a result increasing oscillations between the generators eventually developed. The increasing oscillations between the generators in the nine-bus network can be seen in Figure 5.2. The power, voltage and current oscillations caused by the angular oscillations between the generators, are shown in Figure 5.3. Measured impedance oscillations due to dynamic instability can be seen in Figure 5.4. Figure 5.4 also shows the circular characteristic of the impedance on an R-X plane.

Conclusion

With an increase in load at bus 8, system oscillations started and the system became dynamically unstable. Protection was not modelled and it is thus not possible to see the effect of these oscillations on the protection performance.

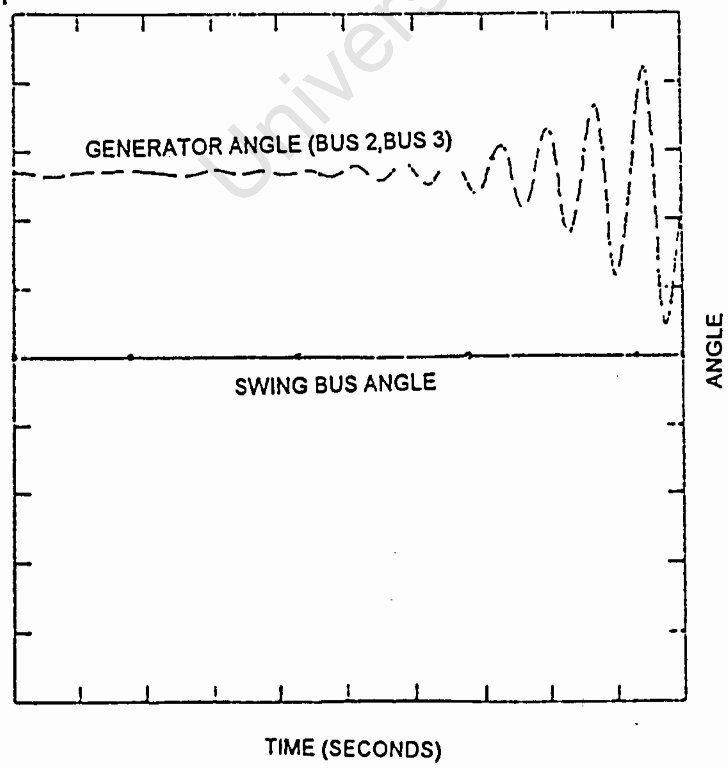
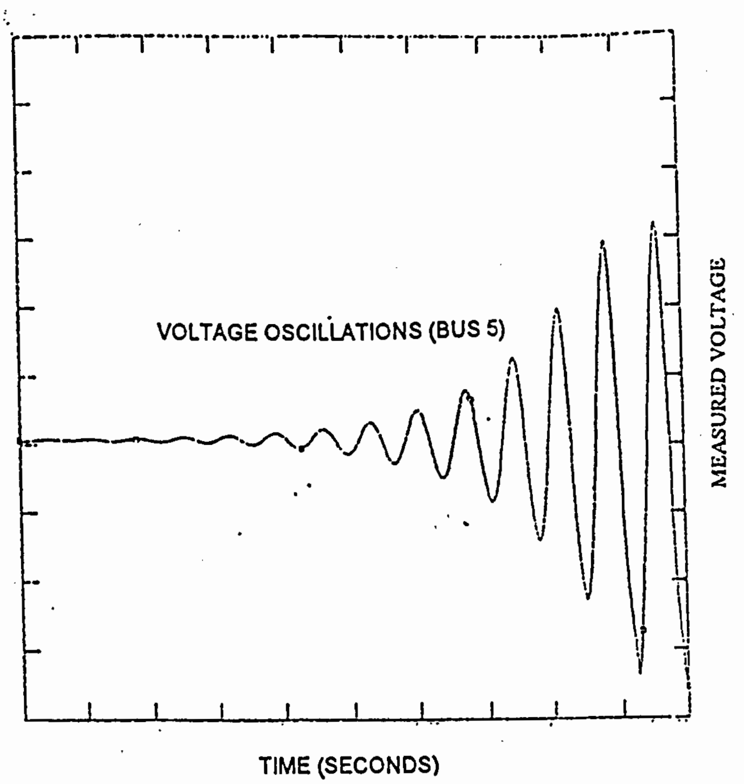
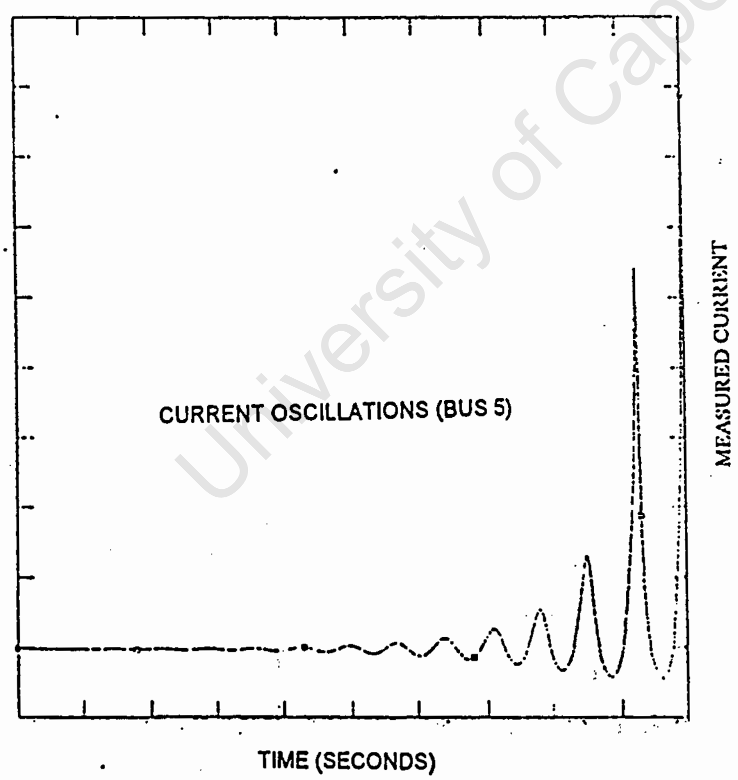


Figure 5.2: Increasing angular oscillations due to dynamic instability

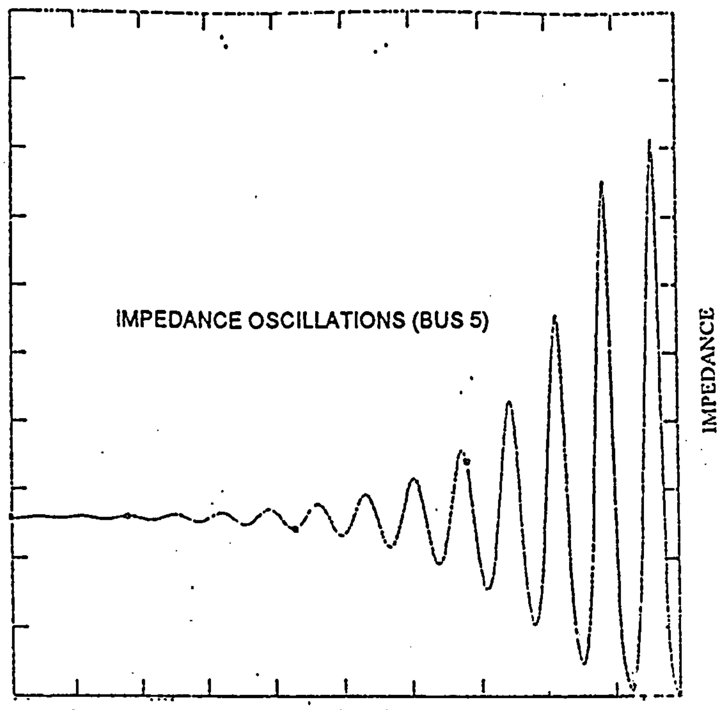


(a)

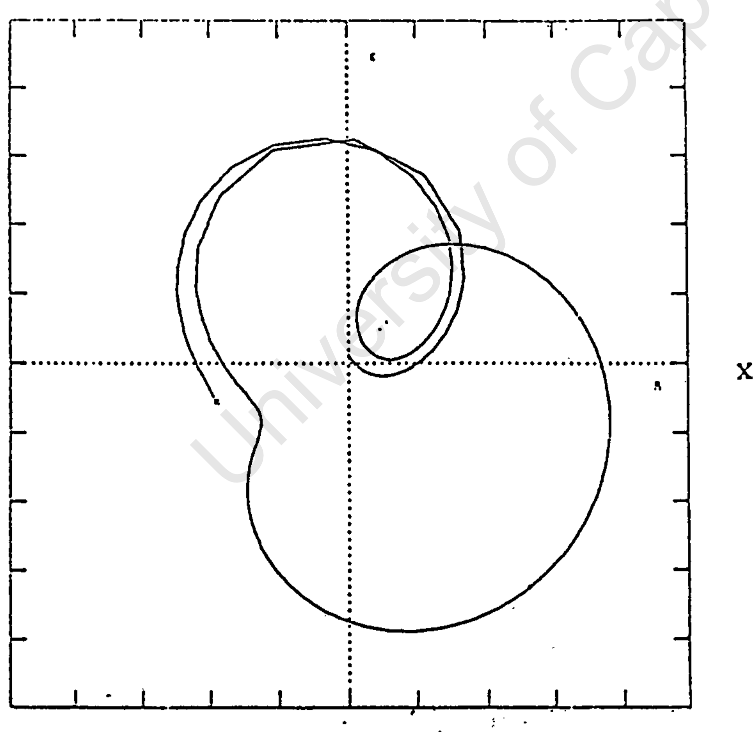


(b)

Figure 5.3: Voltage (a) and current (b) oscillations measured at bus 5



(a)



(b)

Figure 5.4: a) Measured impedance oscillations

b) Measured impedance on R-X plane

2. Distance protection performance.

Distance protection was modelled in such a way as to simulate the protection of every line in the nine-bus network. With the small change in load, system oscillations started and 4 seconds later the distance relays on lines 4-6, 4-5, 5-7 and 6-9 detected impedance entering their operating zones. For these relays, the zone timers then started. The time allowed by the zone timers for the relays on lines 4-6 and 4-5 expired and these lines were tripped. The impedance detected by the relays on lines 4-6 and 4-5 are shown in Figure 5.5.

With the switching of lines 4-5 and 4-6, the generator at bus 1 was separated from the system. The generators at buses 2 and 3 supplied the load at buses 5, 6 and 8 and the system was stable. The impedance detected by the relays on lines 5-7 and 6-9 left the operating zones and their zone timers were reset. The distance relays on lines 5-7 and 6-9 therefore never operated to trip these lines.

Table 5.2 summarises the distance-relay performance in case 1.

Conclusions

The dynamic stability study was repeated with distance protection modelled in this case. Several distance-protection relays detected impedance inside their characteristic zones and two of these distance relays tripped their lines. This action demonstrates the effect an out-of-step condition can have on protection performance. In this case unfaulted lines were tripped.

From a system point of view, protection performance saved the system from becoming dynamically unstable. In this case distance protection tripped two lines and therefore separated the two asynchronous areas. (The generator at bus 1 was separated from the rest of the system.) After the tripping of these two lines, the system was stable (see Figure 5.6).

Table 5.2: Distance-relay performance for case 1.

RELAY LOCATION	RELAY PERFORMANCE
5-4	z1 z2 z3 T
4-5	z1 z2 z3
4-6	z1 z2 z3
6-4	z1 z2 z3 T
9-6	z2 z3
6-9	z2 z3
9-8	n
8-9	z3
7-8	n
8-7	n
7-5	z2 z3
5-7	z2 z3

n = no detection

z1 = impedance detected in zone 1

z2 = impedance detected in zone 2

z3 = impedance detected in zone 3

T = distance-relay operation to open the line breakers

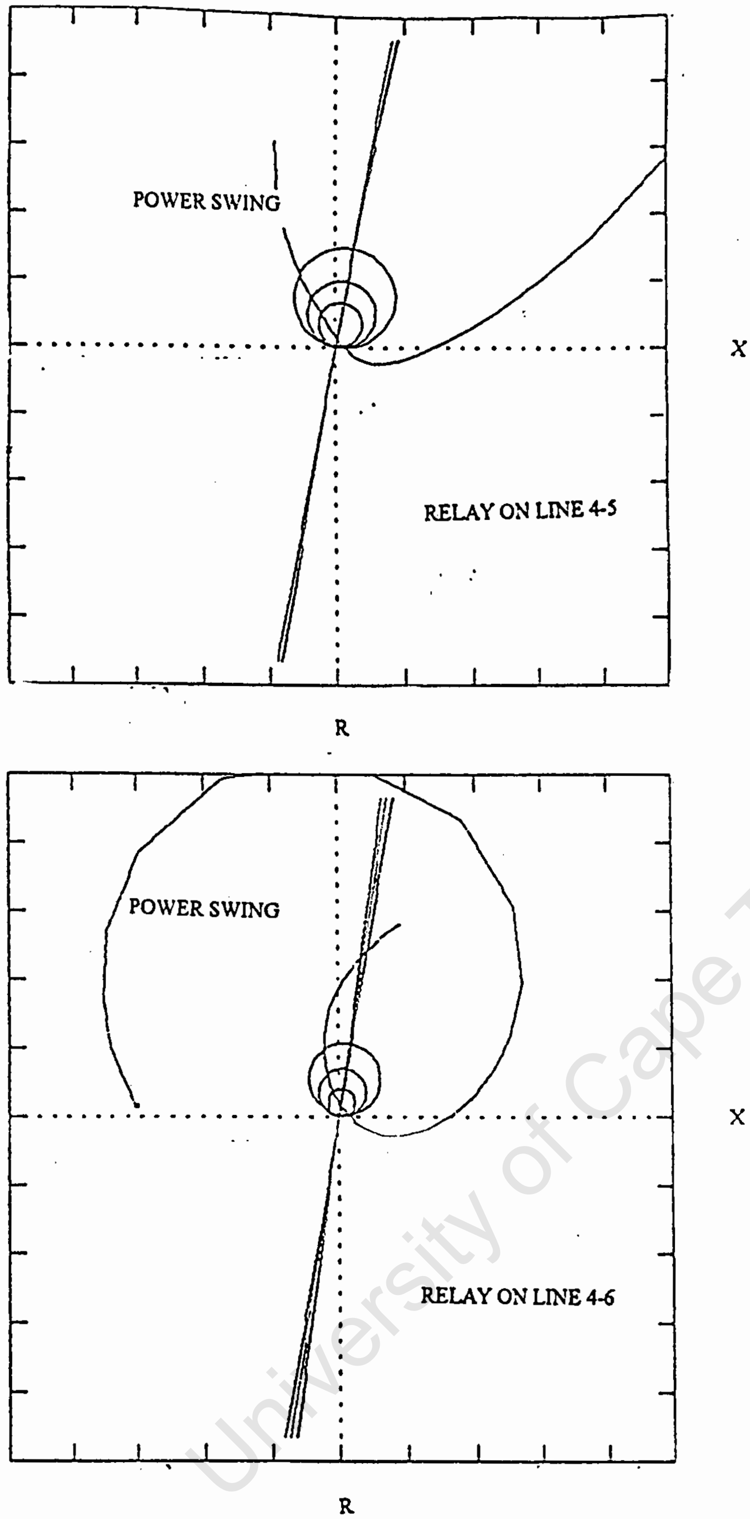


Figure 5.5: Relay characteristics and impedance loci of relays located on lines 4-5 and 4-6

3. Performance of distance protection performance incorporating out-of-step blocking protection

Out-of-step blocking protection was modelled in such a way as to simulate the supervision of every distance relay on the nine-bus system. In this simulation the blocking protection was modelled to detect an out-of-step condition and to block the operation of the distance protection.

The blocking and distance protection for lines 4-5, 4-6, 5-7 and 6-9 detected impedance entering their operating zones due to the oscillations caused by the small change in load on the nine-bus network. The time allowed by the timers of the blocking relays expired and an out-of-step condition was detected. The out-of-step blocking relays blocked the distance protection on lines 4-6, 4-5, 5-7 and 6-9 and no distance-protection misoperation occurred during the out-of-step condition. The impedance detected by the blocking relays on lines 4-5 and 4-6 is shown in Figure 5.7. The out-of-step blocking performance for case 2 is summarised in Table 5.3.

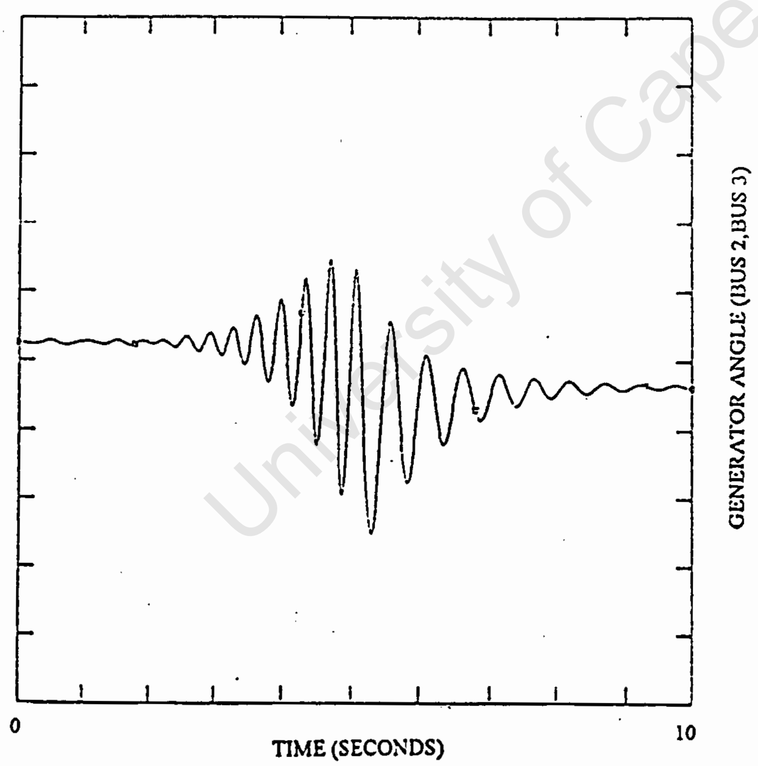


Figure 5.6: System stability due to distance-protection operation

Conclusion

In this case models representing distance protection incorporating out-of-step blocking protection were included in the dynamic-stability study done. It was therefore possible to investigate the protection performance of both distance protection and out-of-step blocking protection. The results show that the out-of-step blocking protection detected out-of-step conditions and that the distance protection was then blocked. The performance of the out-of-step blocking protection thus improved the performance of the distance protection.

From a system point of view, the performance of the out-of-step blocking protection caused the system to become dynamically unstable because, due to the blocking of all distance relays, the asynchronous areas were not separated.

Table 5.3 : Performance of out-of-step blocking protection in case 1.

RELAY LOCATION	RELAY PERFORMANCE
5-4	O I B
4-5	O I B
4-6	O I B
6-4	O I B
9-6	O I B
6-9	O I B
9-8	n
8-9	n
7-8	n
8-7	n
7-5	O I B
5-7	O I B

n = no detection

O = impedance entering outer characteristic

I = impedance entering inner characteristic

B = operation and blocking of distance relay

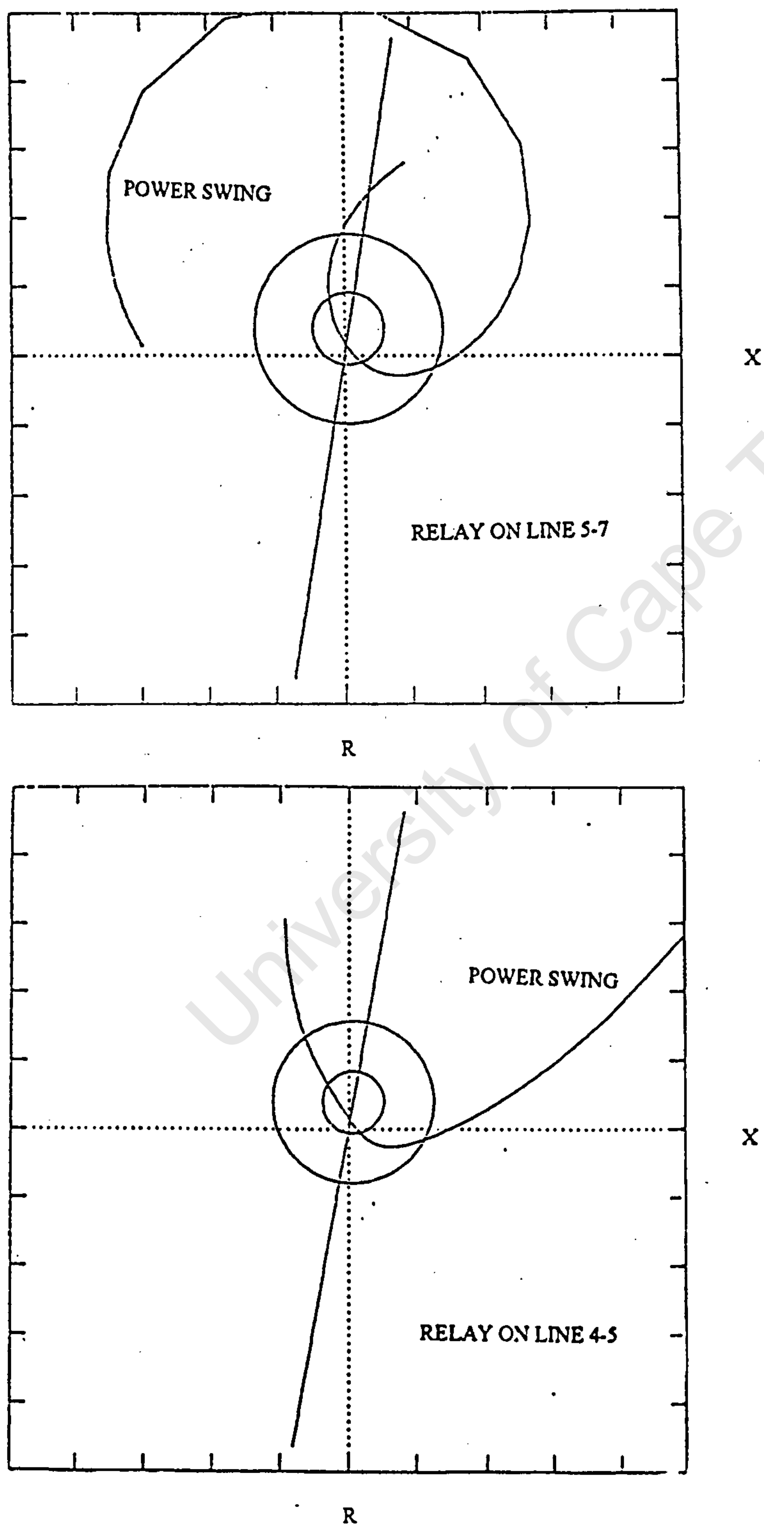


Figure 5.7: Relay characteristics and impedance loci of the out-of-step blocking relays on lines 5-7 and 4-5

CASE 2: Transient stability

A permanent three phase fault was simulated on line 6-9, close to generator 3. In this case, excitation control at each generator was not included in the Working Case.

1. System behaviour without protection models

The severe three-phase fault close to the generator at bus 3 resulted in a decrease of power output at this generator. The rotor speed accelerated, resulting in an increase in rotor angle (see Figure 5.8).

The fault was cleared by switching line 6-9, 0.11 seconds after the fault occurred. The power output of the generator at bus 3 recovered to a value higher than its initial condition due to the rotor acceleration. At this point the energy stored in the rotor due to the acceleration forced a further increase in the rotor angle. The increase in rotor angle resulted in a decrease in generator power output and stability was lost. The angle separation between the generator at bus 3 and the swing bus (bus 1) started to increase (see Figure 5.9). The increase in the rotor angle of the generator at bus 3 resulted in power, voltage and current oscillations. These oscillations can be seen in Figure 5.10.

The oscillations of the measured impedance due to transient instability are shown in Figure 5.11. These oscillations are also shown on an R-X plane. In Figure 5.11 it is evident that the locus follows a circular characteristic and can thus influence the performance of distance protection.

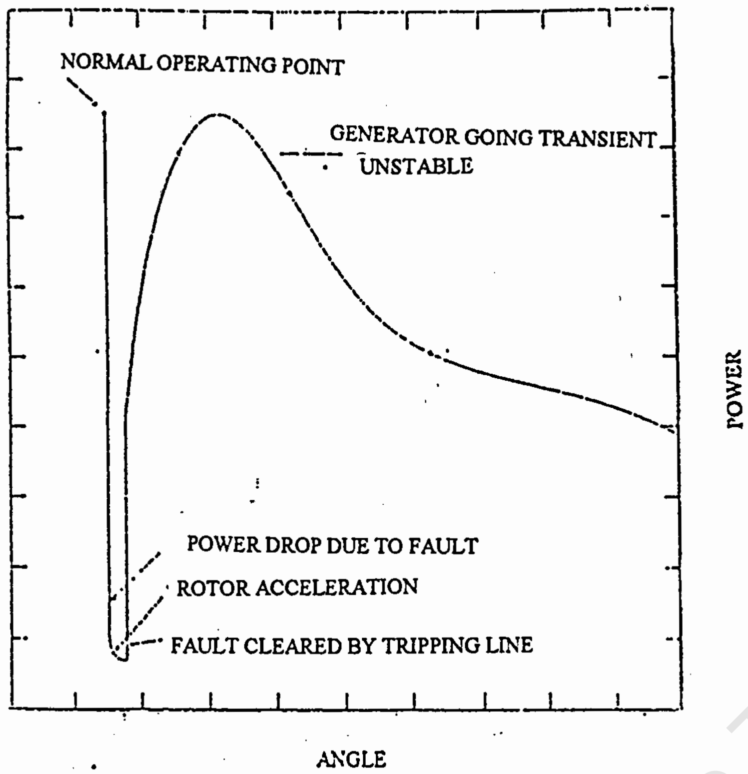


Figure 5.8: Power-angle curve for the generator at bus 3

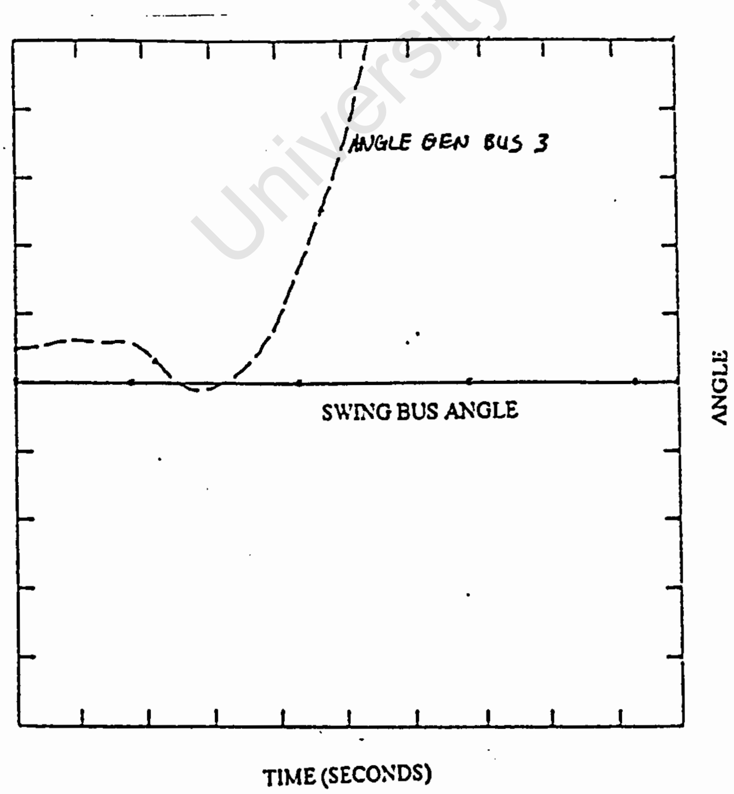


Figure 5.9: Increase in angle separation due to instability

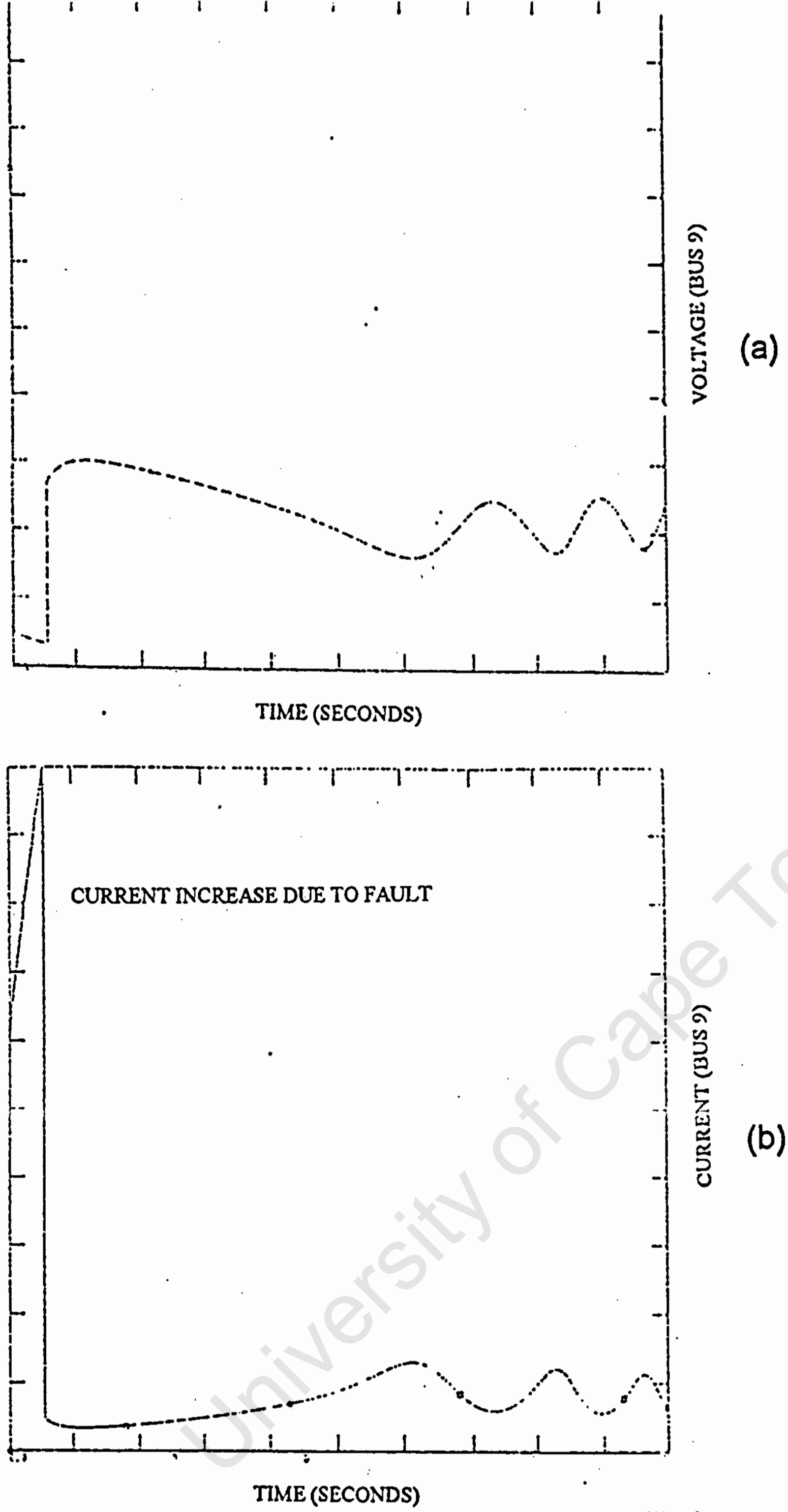


Figure 5.10: Voltage (a) and current (b) oscillations measured at bus 9

Conclusions

With the clearance of the fault on line 6-9, system oscillations started and the system became transiently unstable. Protection was not modelled and it is thus not possible to see the effect of these oscillations on the protection performance.

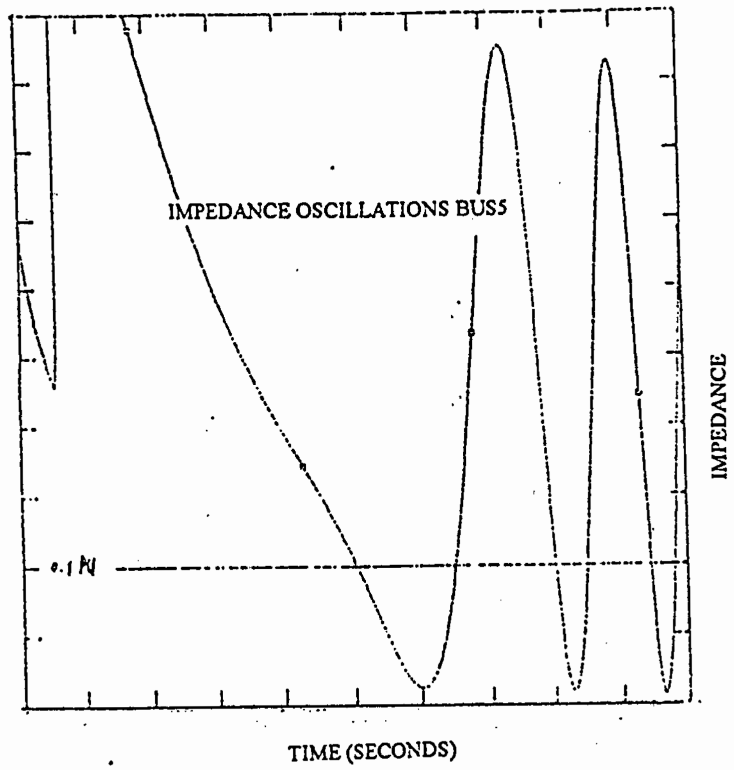


Figure 5.11: a) Oscillations of measured impedance at bus 5 on line 4-5

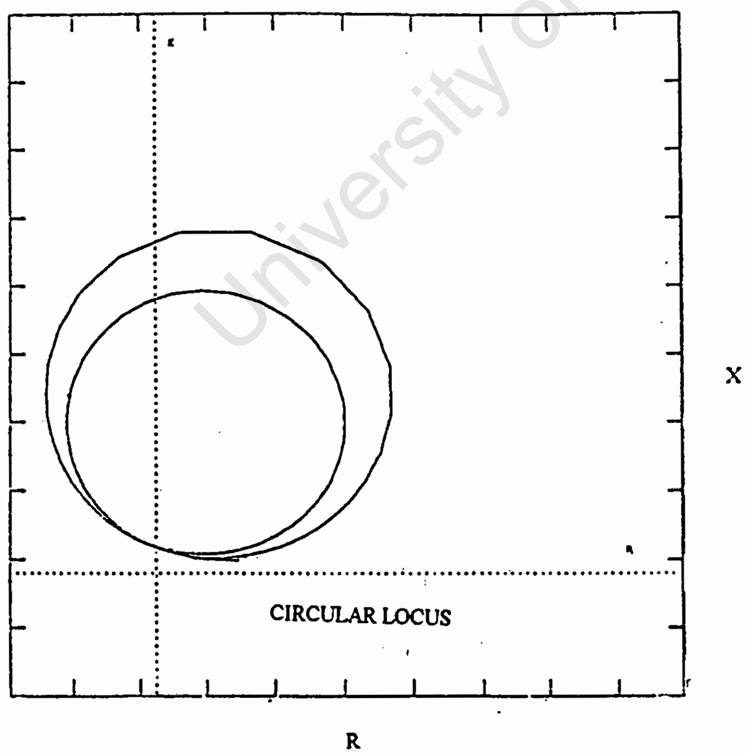


Figure 5.11 (cont.): b) Measured impedance on the R-X plane for relay at bus 5 on line 4-5

2. Distance-protection performance

To investigate the performance of distance protection during transient instability, distance protection was modelled in such a way as to simulate the protection of every line in the nine-bus system. The transient-stability study done in section 1 was then repeated.

The fault on line 6-9 was cleared by the distance protection on this line. Relays close to the fault location also detected impedance inside their operating zones (refer to Table 5.4). This was to be expected because these relays are back-up relays for faults on line 6-9. The relays did not operate because the fault was cleared by the relays on line 6-9.

After the fault was cleared, system oscillations started as explained in section 1. Distance relays on lines 4-5, 7-8, 8-9 and 5-7 detected impedance entering their operating zones. The zone timers for these relays started and eventually the relays on lines 5-7 and 4-5 operated. The impedance detected by these relays is shown in Figure 5.12.

With the switching of lines 5-7 and 4-5, the system was separated into two stable islands. The generator at bus 1 supplied the load at bus 6 and the generators at buses 2 and 3 supplied the load at bus 8. The load at bus 5 was no longer supplied. With the separation of the generator at bus 3 from the generator at the swing bus, the system became stable. Due to the stable operation, the impedance detected by the relays on lines 7-8 and 8-9 withdrew from the relays' operating zones and the timers for these relays were reset. Consequently line 8-9 was not switched. The distance-protection performance of the system is summarised in Table 5.4.

Table 5.4: Distance-relay performance for case 2

RELAY LOCATION	RELAY PERFORMANCE DURING FAULT	RELAY PERFORMANCE AFTER FAULT CLEARANCE
5-4	n	z1 z2 z3 T
4-5	n	z1 z2 z3 T
4-6	z3	n
6-4	n	n
9-6	z1 z2 z3 T	n
6-9	z2 z3	n
9-8	n	z1 z2 z3
8-9	z2 z3	z1 z2 z3
7-8	z2 z3	z2 z3
8-7	n	z2 z3
7-5	n	z1 z2 z3 T
5-7	n	z1 z2 z3 T

n = no detection

z1 = impedance detected in zone 1

z2 = impedance detected in zone 2

z3 = impedance detected in zone 3

T = distance-relay operation to open the line breakers

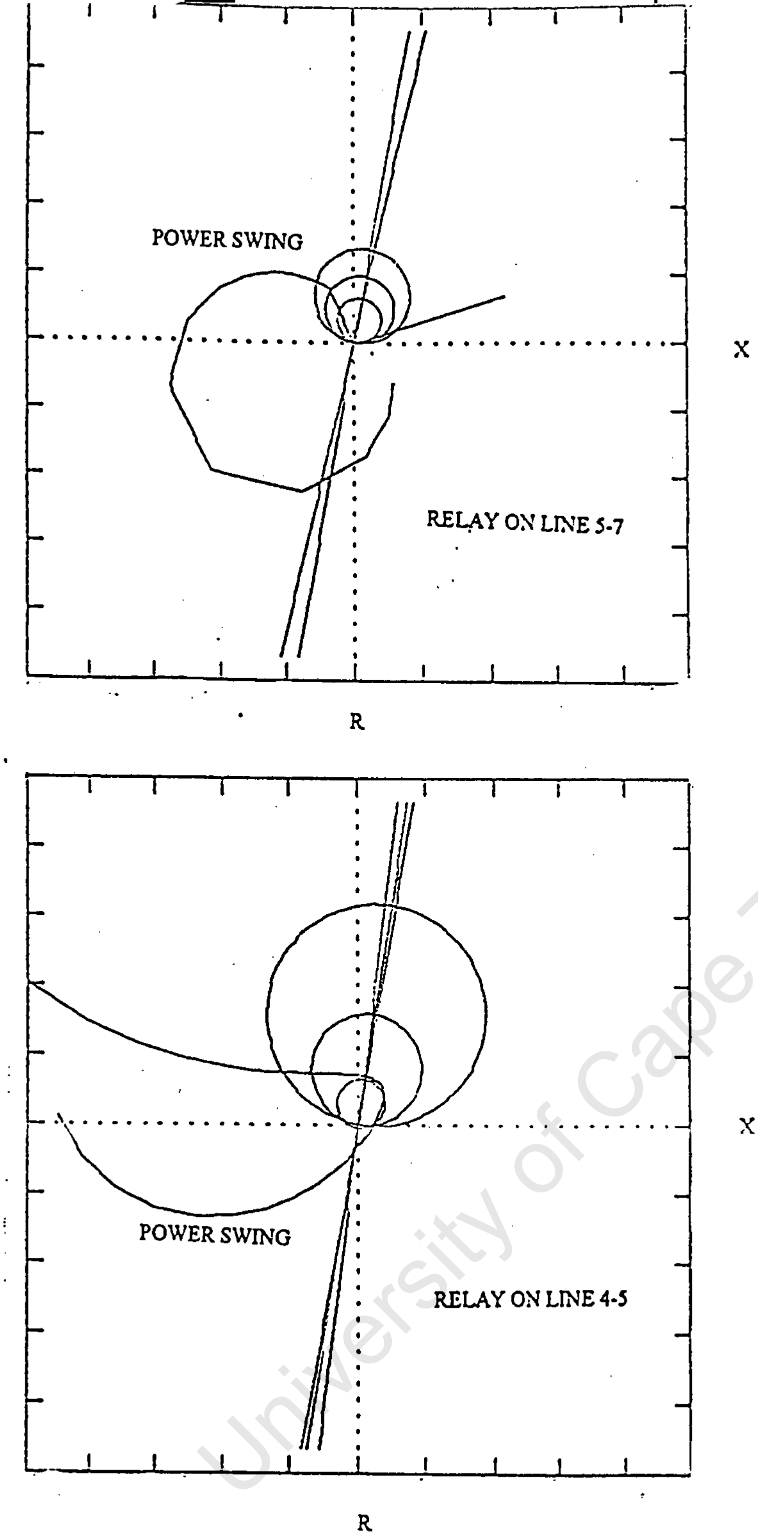


Figure 5.12: Relay characteristics and impedance loci of relays located on lines 5-7 and 4-5

Conclusions

In this case the transient-stability study was repeated, with distance protection modelled. The fault was cleared by tripping the faulted line. After tripping the faulted line, system oscillations started and several distance-protection relays detected impedance inside their characteristic zones. Two of these distance relays misoperated and tripped unfaulted lines.

From a system point of view, protection performance saved the system from becoming transiently unstable. The tripping of the two lines separated the two asynchronous areas. After the tripping of these two lines, the system was stable.

3. Performance of distance protection incorporating out-of-step blocking protection

Out-of-step blocking protection was modelled to simulate the supervision of every distance relay in the nine-bus network. In this simulation, the blocking relays were modelled to detect an out-of-step condition and to block the operation of the distance protection.

The transient-stability study was repeated and the fault on line 6-9 was cleared by the distance protection on this line. The fault condition was also detected by the relays close to the fault (refer to Table 5.4). This was to be expected because these relays are back-up relays for the fault on line 6-9, as mentioned in section 2. No back-up relay operation occurred.

With fault clearance, system oscillations started. The blocking relays and the distance relays on lines 4-5, 7-8, 8-9 and 5-7 detected impedance entering their operating zones. The time allowed by the timers for the blocking relays expired and an out-of-step condition was detected. With the detection of the out-of-step condition, the operation of the distance relays on lines 4-5, 7-8, 8-9 and 5-7 was blocked. Consequently no misoperation of distance relays occurred during the out-of-step condition. The impedance detected by the blocking relays on lines 5-4 and

5-7 can be seen in Figure 5.13. The out-of-step blocking performance is summarised in Table 5.5.

Conclusion

In this case models representing distance protection incorporating out-of-step blocking protection were included in the transient-stability study done. It was again possible to investigate the protection performance of both distance protection and out-of-step blocking protection. The results show that the out-of-step blocking protection detected out-of-step conditions and that the distance protection was then blocked. The performance of the out-of-step blocking protection thus improved the performance of the distance protection.

From a system point of view, the performance of the out-of-step blocking protection caused the system to become transiently unstable because, due to the blocking of all distance relays, the asynchronous areas were not separated.

5.3 Discussion of the results

Dynamic-stability and transient-stability studies were done on the nine-bus network.

The dynamic-stability study (case 1) showed typical dynamic instability. With a small change in load, speed deviations at the generators initiated system oscillations. Due to reduced damping in the network, caused by the excitation control at each generator, the oscillations increased and the system became dynamically unstable.

The transient-stability study (case 2) showed how a three phase fault close to the generator made the system transiently unstable. The generator at bus 3 initiated oscillations due to the disturbance. These oscillation were reflected as power, voltage and current oscillations over the transmission lines.

Due to the varying voltages and currents, several distance relays detected impedance inside their operating zones. During dynamic instability lines 4-5 and 4-6 were tripped. During transient instability lines 4-5 and 6-9 were tripped. In both these cases the period for which the impedance remained inside the operating zones of the distance relays for these lines was long enough to allow the time on the zone timers to expire.

With the application of out-of-step blocking protection, the performance of distance protection improved. In both the dynamic-stability and the transient-stability studies, the out-of-step blocking protection detected out-of-step conditions, and the distance protection was then blocked. Distance relays did not misoperate and unfaulted lines were not tripped.

From a system point of view, distance-protection performance saved the system from becoming unstable. During dynamic instability lines 4-5 and 4-6 were tripped, which separated the two asynchronous areas in case 1. During transient instability lines 4-5 and 6-9 were tripped, separating the two asynchronous areas in case 2. After the tripping of these lines, the system became stable.

Distance protection incorporating out-of-step blocking protection caused the system to become unstable in both case 1 and case 2. Due to the blocking of all the distance relays, lines 4-5 and 4-6 in case 1 and lines 4-5 and 6-9 in case 2 were not tripped. Consequently the asynchronous areas were not separated.

The conclusions drawn from the results are the following:

1) The modelling of protection in a stability study will provide an indication of the protection performance of the system during an out-of-step condition.

2) The modelling of out-of-step blocking protection shows an improvement in distance-protection performance during out-of-step conditions. The results show that the use of out-of-step blocking protection will eliminate the tripping of unfaulted lines.

3) Distance protection incorporating out-of-step blocking protection will enable better control of the system during out-of-step conditions.

4) Although the nine-bus network is a small and simple system, out-of-step conditions had adverse effects on its distance protection performance. This implies that the effects would be more serious in bigger and more complicated systems.

5) Taking protection performance into account in a stability study by modelling the protection will give an indication of the effect the protection performance can have on the stability of the system.

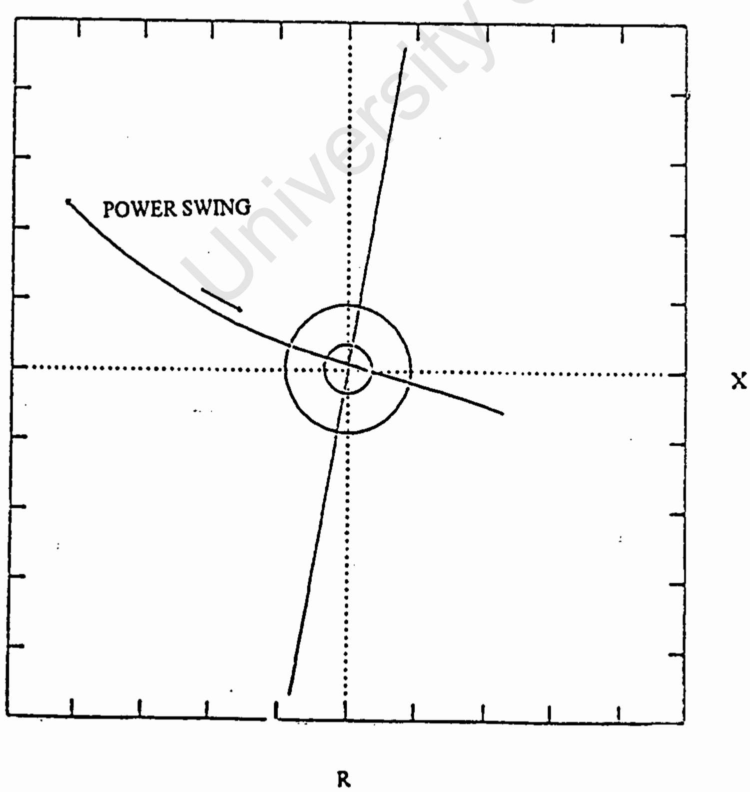


Figure 5.13: Relay characteristics and impedance loci of the out-of-step blocking relays on line 5-7

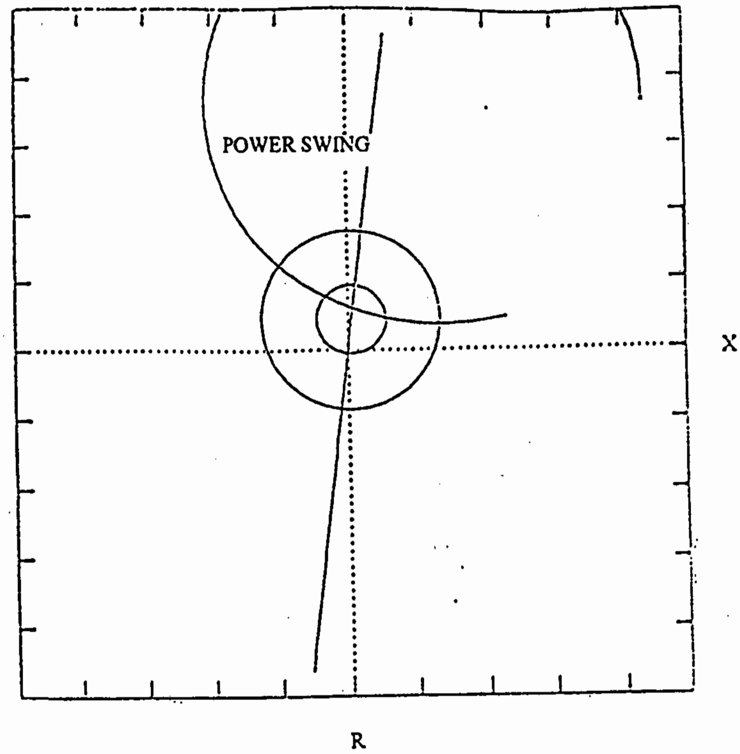


Figure 5.13 (cont.): Relay characteristics and impedance loci of the out-of-step blocking relays on line 4-5

Table 5.5: Performance of out-of-step blocking protection in case 2

RELAY LOCATION	RELAY PERFORMANCE DURING FAULT	RELAY PERFORMANCE AFTER FAULT CLEARANCE
5-4	n	O I B
4-5	n	O I B
4-6	n	n
6-4	n	n
9-6	n	n
6-9	n	n
9-8	n	O I B
8-9	n	O I B
7-8	n	O I B
8-7	n	O I B
7-5	n	O I B
5-7	n	O I B

n = no detection

O = impedance entering outer characteristic

I = impedance entering inner characteristic

B = operation and blocking of distance relay

5.4 Summary

In this chapter dynamic-stability and transient-stability studies were presented. The stability studies were done on the nine-bus network, to investigate

1. system performance without protection;
2. distance-protection performance; and
3. the performance of distance protection incorporating out-of-step blocking protection.

It was shown that system conditions of dynamic and transient instability will influence the performance of distance protection. In both cases distance relays on several lines detected impedance entering their operating zones. Distance relays then operated and cascade tripping of lines occurred.

With the use of out-of-step blocking protection, distance relay operation was blocked. In the conditions of system instability, the blocking relays detected out-of-step conditions. With the detection of out-of-step conditions, the operation of distance relays which detected impedance inside their operating zones was blocked. Consequently no cascade tripping of lines occurred during the out-of-step conditions.

CHAPTER 6: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

6.1 Summary

In the research the following were investigated:

1) The effect of out-of-step conditions on distance protection performance
2) Performance of distance protection incorporating out-of-step blocking protection, during out-of-step conditions

Distance protection measures impedance. If the measured impedance is detected inside an operating zone, a timer will start. When the time allowed by the timer expires, the relay will operate to trip a breaker.

The functions of out-of-step blocking protection are to detect an out-of-step condition by monitoring the rate of the change in measured impedance detected by the relay during an out-of-step condition and, upon detection, to block distance-protection operation.

To represent the dynamic performance of a real system in a simplified manner, a nine-bus benchmark network was chosen. The nine-bus network data taken from reference [22] (see Table 3.1 in Chapter 3) were consistently used for every study done. The network was represented by using existing models in the PSS/E. The generators were modelled by using a generator model called **GENROU** and the excitation system at each generator was modelled by using an excitation model called **SEXS.** Due to the size and simplicity of the nine-bus network, the effect of power-system stabiliser-control, when present at each generator, was not investigated and therefore not modelled. The loads were modelled as voltage-dependent constant-admittance loads and the transmission lines and transformers were modelled by using an equivalent π model.

Distance protection incorporating out-of-step blocking protection was modelled in such a way as to simulate the protection of every line in the nine-bus network. The PSS/E models chosen to represent the distance and out-of-step protection are called **DISTR** and **CIRCOS** respectively. The **DISTR** model was used to represent a distance relay with the following features:

1) Three time-delayed mho (circular) characteristics with a reverse reach for zone 3 protection,
2) a self-tripping operation of the monitored line; and
3) a supervisory signal input to prevent tripping.

Out-of-step blocking protection was represented by using **CIRCOS** with the following features:

1) inner and outer circular characteristic zones; and
2) the control of the supervisory input* of the **DISTR** model.

CIRCOS was set to control the supervisory input signal of another relay, in this case **DISTR**. As soon as **CIRCOS** detected an out-of-step condition, a blocking signal was sent to the supervisory input signal of **DISTR**.

Dynamic-stability and transient-stability studies were done on the nine-bus network to investigate the protection performance. Various stability studies were done to

* See section on definitions.

obtain the worst cases for dynamic and transient stability respectively (see Table 5.1 in Chapter 5). For these stability studies the effect of excitation control was investigated. Excitation control may decrease the damping at a generator, thus making the generator more sensitive to dynamic instability [3]. In the case of transient instability, the presence of excitation control may increase the stability limit of the system, thereby making the system more stable [3].

The effect of power system stabiliser control, when present at each generator, was not investigated. The presence of power system stabiliser control will improve the stability of a power system and, in the case of the nine-bus network, this will defeat the object of obtaining the worst cases for dynamic and transient stability respectively.

To do a dynamic-stability study, a change in load was simulated. Due to the presence of high gain-excitation control at each generator, the small disturbance was sufficient to cause dynamic instability* .

To do a transient-stability study, a three-phase fault close to the generator at bus 3 was simulated. For this simulation no excitation control was present on the nine-bus network. (The simulation of various stability studies indicated that the presence of excitation control at each generator keeps the system from becoming transiently unstable. Without excitation control, the nine-bus network was found to be sensitive to severe disturbances, resulting in the system becoming transiently unstable.)

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* High-gain excitation tends to decrease the damping at a generator, thus making it more sensitive to dynamic instability [3].

Summary of results

The dynamic-stability study (case 1) shows typical dynamic instability. With a small change in load, speed deviations at the generators initiated system oscillations. Due to reduced damping in the network, caused by the high-gain excitation control at each generator, the oscillations increased and the system became dynamically unstable.

The transient-stability study (case 2) shows how a three-phase fault close to the generator made the system transiently unstable. The generator at bus 3 initiated oscillations due to the disturbance. These oscillation were reflected as power, voltage and current oscillations over the transmission lines.

Due to the varying voltages and currents, several distance relays detected impedance inside their operating zones. During dynamic instability, lines 4-5 and 4-6 on the nine-bus network were tripped. During transient instability, lines 4-5 and 6-9 on the nine-bus network were tripped. In both these cases, the period for which the impedance remained inside the operating zones of the distance relays for these lines was long enough to allow the time on the zone timers to expire.

With the application of out-of-step blocking protection, distance protection performance was improved. In both the dynamic-stability and the transient-stability studies, the out-of-step blocking protection detected out-of-step conditions and the distance protection was then blocked. Consequently distance relays did not misoperate and unfaulted lines were not tripped.

6.2 Conclusions

The results obtained show that several distance-protection relays detected impedance inside their operating zones. These relays then operated and unfaulted lines were tripped.

The modelling of out-of-step blocking protection shows an improvement in distance-protection performance during conditions of instability. The results show that the use of out-of-step blocking protection will eliminate the tripping of unfaulted lines.

In conclusion:

1) The modelling of protection in a stability study will provide an indication of the protection performance of the system during an out-of-step condition.
2) The modelling of out-of-step blocking protection indicates that this will result in an improvement in distance-protection performance during out-of-step conditions. The results show that the use of out-of-step blocking protection will eliminate the tripping of unfaulted lines.
3) Distance protection incorporating out-of-step blocking protection will enable better control of the system during out-of-step conditions.
4) Although the nine-bus network is a small and simple system, out-of-step conditions had adverse effects on its distance-protection performance. This implies that the effects would be more serious in bigger and more complicated systems.
5) Taking protection performance into account during a stability study by modelling the protection will give an indication of the effect the protection performance can have on the stability of the system.

6.3 Recommendations for further study

When two generators or various groups of generators are out of step with one another, they must be separated into islands. These islands must be stable, with a sufficient generation-load balance. This research showed that if all distance protection is blocked during out-of-step conditions, the natural separation in the system cannot take place (See Chapter 5).

There are two possible solutions:

1) Distance-protection relays can intentionally not be blocked by out-of-step blocking protection. This will allow tripping at selected locations during out-of-step conditions.

2) In power systems where all distance-protection operation is blocked during out-of-step conditions, a new type protection called out-of-step tripping protection must detect out-of-step conditions and trip some local and/or remote lines. The tripping of elected lines allows system separation to take place during out-of-step conditions.

Further research into these solutions to control the stability problem is suggested.

APPENDIX 1 : LOCUS OF MEASURED IMPEDANCE DURING OUT-OF-STEP CONDITIONS.

Consider the one-line diagram in Figure A1.1, where a section of a transmission line is shown, with generating sources beyond each end of the line section.

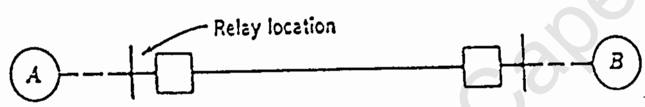


Figure A1.1: One-line diagram of a system to illustrate the out-of-step characteristics

Figure A1.1 shows the location of a relay whose response to an out-of-step condition between the two generating sources is to be studied. Each generating source may be either an actual generator or an equivalent generator representing a group of generators that remain in synchronism. (If generators within the same group lose synchronism with one another, this simple approach cannot be used and a network analysis study may be necessary.) The effects of shunt capacitance and of shunt loads are neglected. The generator reactance and generated voltage are assumed to remain constant.

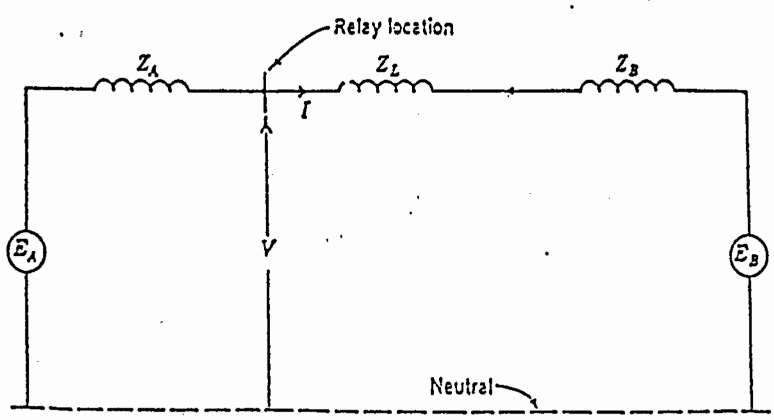


Figure A1.2: System constants and relay current and voltage for Figure A1.1

Figure A1.2 indicates the phase-to-neutral (positive-phase-sequence) impedance and the generated voltages of the system in Figure A1.1, as well as the phase current and phase-to-neutral voltage at the relay location.

The relay quantities can be derived as follows:

$$I=\frac{E_A-E_B}{Z_A+Z_L+Z_B} \tag{A.1}$$

$$V=E_A-IZ_A=E_A\frac{(E_A-E_B)Z_A}{Z_A+Z_L+Z_B} \tag{A.2}$$

$$\frac{V}{I}=Z=\frac{E_A}{E_A-E_B}*(Z_A+Z_L+Z_B)-Z_A \tag{A.3}$$

With E_B the reference, and E_A advancing in phase ahead of E_B by the angle θ, then

$$\frac{E_A}{E_A - E_B} = \frac{n(\cos\theta + j\sin\theta)}{n(\cos\theta + j\sin\theta) - 1} \tag{A.4}$$

with

magnitude of E_A = nE_B and where n is a scalar.

Equation (A.4) will solve as:

$$\frac{E_A}{E_A - E_B} = \frac{n[(n - \cos\theta) - j\sin\theta]}{(n - \cos\theta)^2 + \sin^2\theta} \tag{A.5}$$

With n = 1, the equation becomes:

$$\frac{E_A}{E_A - E_B} = \frac{1}{2}(1 - j\cot\frac{\theta}{2}) \tag{A.6}$$

Therefore, Z becomes :

$$Z = \frac{Z_A + Z_L + Z_B}{2}(1 - j\cot\frac{\theta}{2}) - Z_A \tag{A.7}$$

This value of **Z** is shown on the R-X diagram of Figure A1.3 for a particular value of θ less than 180°. Point **P** is a point on the out-of-step characteristic. All other points on the out-of-step characteristic will lie on the dash line through **P**. This line is the perpendicular bisector of the straight line connecting **A** and **B**.

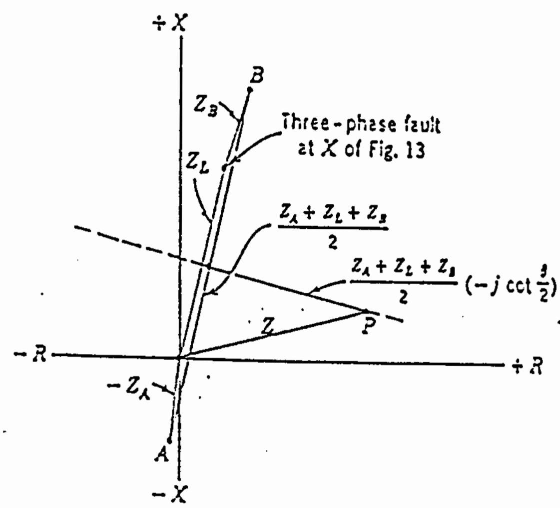


Figure A1.3: Calculated impedance of equation (A.7) for a value less than 180°

A three-phase fault on the line protected by the distance relay appears to the distance relay as a point on Z_L, as shown in Figure A1.3. Therefore, the point where the out-of-step characteristic intersects the impedance Z_L would also represent a three phase-fault at that point. In other words, at a particular instant during an out-of-step condition, the conditions are exactly the same as those of a three-phase fault at a point which is electrically approximately midway between generator **A** and generator **B**. This point is called the electrical centre or the impedance centre of the system. The point where the out-of-step characteristic intersects the total line impedance **AB** is reached when generator **A** has advanced to 180°, leading generator **B**.

Furthermore, all out-of-step characteristics are represented as circles with their centres on extensions of the total impedance line **AB** of Figure A1.3. The characteristic when n = 1 is represented by a circle with infinite radius. Any of these characteristics could be derived by successive calculations for a value of n, letting θ vary from 0 to 360° in the general formula:

$$Z=(Z_A+Z_L+Z_B)*n*\frac{(n-\cos\theta)-j\sin\theta}{(n-\cos\theta)^2+\sin^2\theta}-Z_A \qquad \text{(A.8)}$$

Figure A1.4 shows three out-of-step characteristics for $n>1$, $n=1$, and $n<1$. The total-system impedance line is again shown as **AB**.

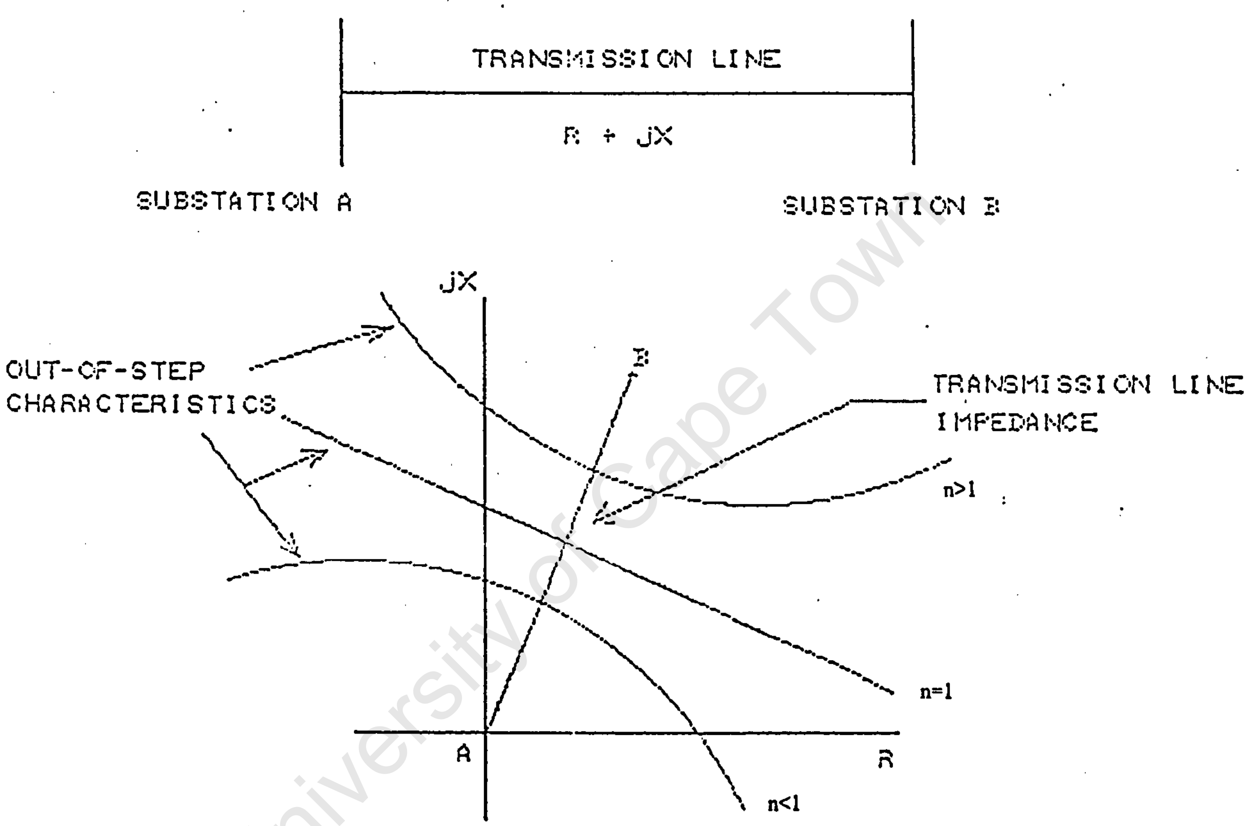


Figure A1.4: General out-of-step characteristics

APPENDIX 2: APPLICATION OF DISTANCE PROTECTION TO THE 9-BUS NETWORK.

Each distance-protection relay applied to the nine-bus network seen in Figure A2.1 has the following features and functions :

1) Three time-delayed mho characteristics
2) A self-tripping operation of the monitored line
3) A supervisory signal input to prevent tripping

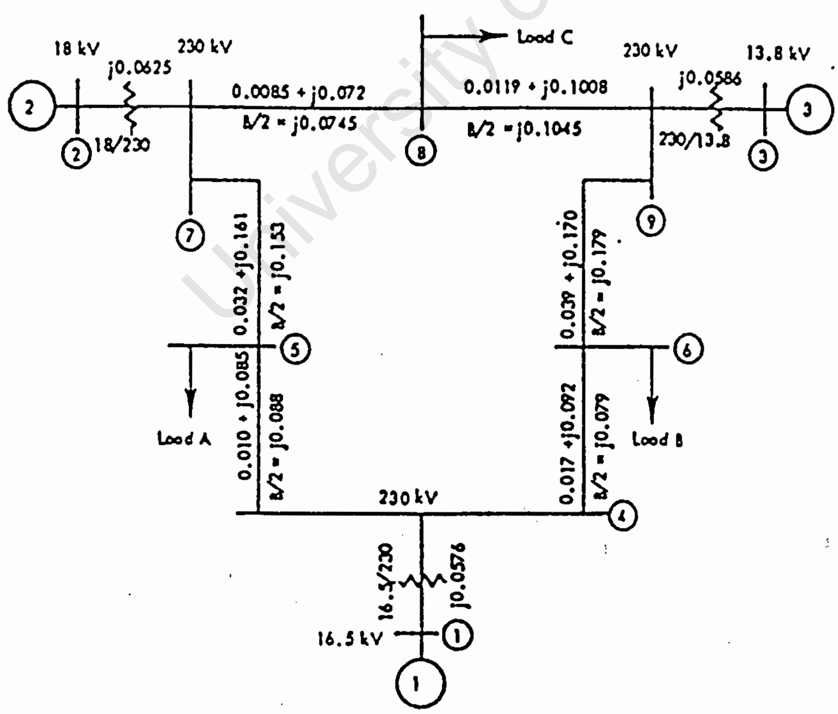


Figure A2.1: The nine-bus network

For an illustration of the application procedure, refer to Figure A2.2. The three time-delayed mho characteristics for the line in Figure A2.2 are set in the following way:

$$Z1 = 80\% * Zl1 \tag{A2.1}$$

$$Z2 = 100\% * Zl1 + 50\% * Zl2 \tag{A2.2}$$

$$Z3 = 100\% * Zl1 + 100\% * Zl2 \tag{A2.3}$$

$$Z3r = 20\% * Zl1 \tag{A2.4}$$

where

Z1	=	zone 1 setting
Z2	=	zone 2 setting
Z3	=	zone 3 setting
Z3r	=	zone 3 setting to protect behind the relay
Zl1,Zl2	=	impedance defined in Figure A2.2
ϕ	=	relay-characteristic angle setting

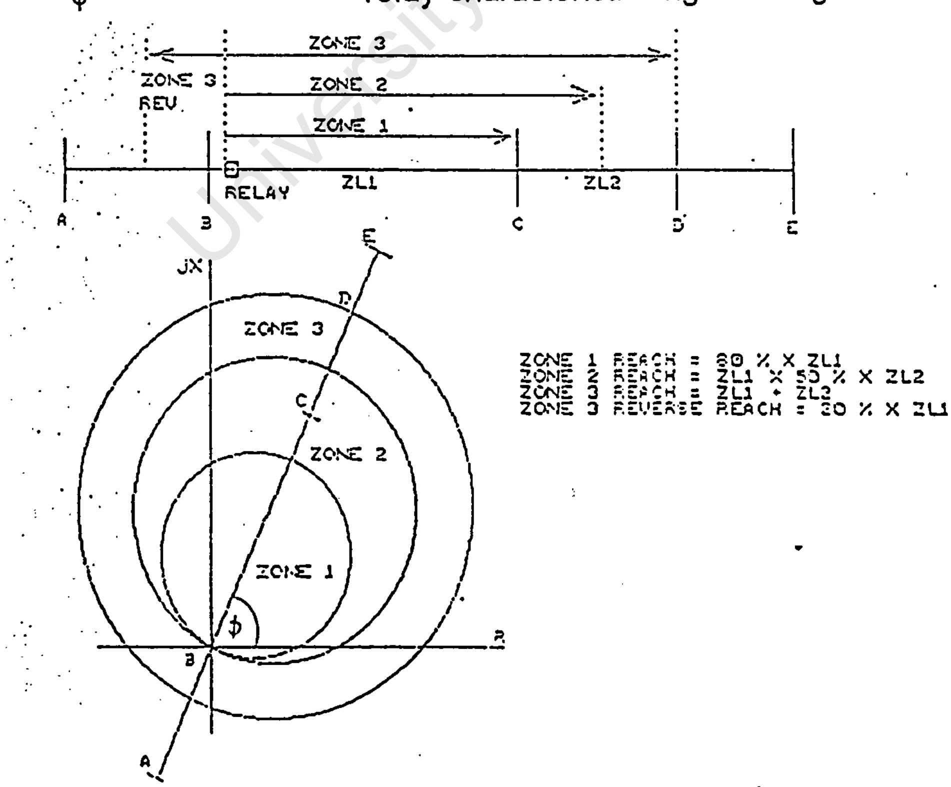


Figure A2.2: Zone characteristics for distance protection

Each mho characteristic has a zone timer. The timer settings chosen for each distance-protection relay are typical values used in practice. These timer settings are listed in Table A2.1.

Table A2.1: Timer setting used for every relay.

ZONE	TIMER SETTING (sec)
zone 1	instantaneous
zone 2	0.5
zone 3	1

Distance protection was applied to protect every line in the nine-bus network. The settings, calculated by using equations (A2.1 to A2.4), are listed in Table A2.2. Zl1 is the impedance of the protected line. Zl2 is the impedance of the line adjacent to the protected line in the forward direction. (To calculate the settings for a relay at bus 4 on line 4-6, for example, Zl1 will be the impedance of line 4-6 and Zl2 the impedance of line 6-9.)

The data in Tables A2.1 and A2.2, supplemented by a data sheet provided by PSS/E, are the data used by the **DISTR** model to represent each distance relay in the Working Case. The data sheet for the **DISTR** model can be seen in Figure A2.3. This data sheet contains data representing the distance relay at bus 4 on line 4-6. A breaker time of 100 msec was assumed for each case where distance protection was applied.

Table A2.2 : Settings of distance protection relays

RELAY LOCATION ♣	Z11 (pu)	Z12 (pu)	$\phi = \theta 11$ (deg)	Z1 = 80%*Z11 (pu)	Z2 = 100%*Z11 +50%*Z12 (pu)	Z3 = 100%*Z11+ 100%*Z12 (pu)	Z3rev = 20%*Z11 (pu)
4-6	0.09	0.17	80	0.07	0.18	0.32	0.02
4-5	0.08	0.16	83	0.07	0.17	0.30	0.02
6-9	0.17	0.10	77	0.14	0.23	0.33	0.03
5-7	0.16	0.07	79	0.13	0.22	0.28	0.03
9-8	0.10	0.07	83	0.08	0.14	0.21	0.02
7-8	0.07	0.10	83	0.06	0.12	0.21	0.01
6-4	0.09	0.08	80	0.07	0.14	0.21	0.02
5-4	0.08	0.09	83	0.07	0.13	0.21	0.02
9-6	0.17	0.09	77	0.14	0.22	0.32	0.03
7-5	0.16	0.08	79	0.13	0.21	0.30	0.03
8-9	0.10	0.17	83	0.08	0.19	0.33	0.02
8-7	0.07	0.16	83	0.06	0.15	0.28	0.01

♣ The first number indicates at which busbar the relay is located.

DISTR

Mho, Impedance Or Reactance Distance Relay

CALL DISTR (I,J,L) from CONET

Uses ICONs starting with # ________ I,

and CONs starting with # ________ J,

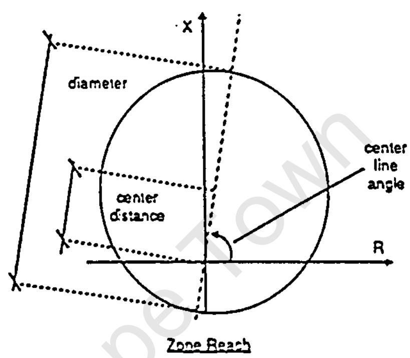
and VARs starting with # ________ L.

ICONs	#	Value	Description	
I		1	Ref # (Max Of 9)	
I+1		1	Type 1. Mho Distance Type 2. Impedance Distance Type 3. Reactance Distance	
I+2		0	0 - Monitor Only 1 - Monitor And Trip	
I+3		1	Resolution (Time Steps)	
I+4		4	From Bus #	Monitored Line,
I+5		6	To Bus #	Relay Is At
I+6		1	Circuit ID	"From" Bus End
I+7		0	From Bus #	First
I+8		0	To Bus #	Transfer
I+9		0	Circuit ID	Trip
I+10		0	From Bus #	Second
I+11		0	To Bus #	Transfer
I+12		0	Circuit ID	Trip
I+13		0	From Bus #	Third
I+14		0	To Bus #	Transfer
I+15		0	Circuit ID	Trip
I+16		X	Permissive Flag For Self Trip*	
I+17		X	Permissive Flag For Transfer Trip**	
I+18 . . I+35		X	ICONs Required For Internal Program Logic	

*Normally set to 1 in user input. Set to 0 and -1 by supervisory relay to effect blocking and force trip, respectively.

**Normally set to 1 in user input. Set to 0 to block transfer trip.

VARs	#	Description
L		Apparent R
L+1		Apparent X
L+2		Current
L+3 . . L+9		VARs Required For Internal Program Logic



DISTR

Mho, Impedance Or Reactance Distance Relay

(Continued)

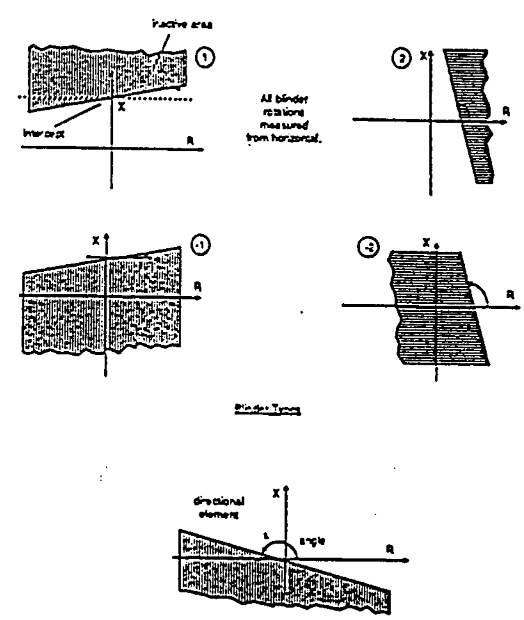


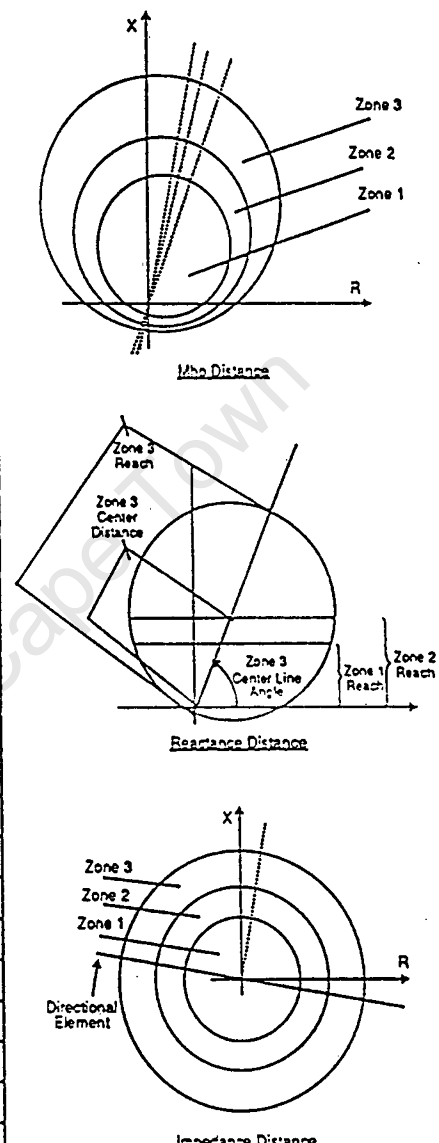
Figure A2.3: Data sheet for **DISTR** model, containing data to represent the relay at bus 4 on line 4-6 (data sheet taken from the PSS/E Program Operational Manual, Volume II, PTI, Appendix VII)

DISTR

Mho, Impedance Or Reactance Distance Relay

(Continued)

CONs	#	Value	Description
J		0	Zone 1 Operating Time (Cycles)
J+1		0·07	Zone 1 Reach (Diameter Or Reactance) In p.u.
J+2		80	Zone 1 Center Line Angle In Degrees (0 For Reactance Relay)
J+3		0·08	Zone 1 Center Distance (0 For Reactance Relay)
J+4		25	Zone 2 Pickup Time (Cycles)
J+5		0·18	Zone 2 Reach (Diameter Or Reactance) In p.u.
J+6		80	Zone 2 Center Line Angle (0 For Reactance Relay)
J+7		0·08	Zone 2 Center Distance (0 For Reactance Relay)
J+8		50	Zone 3 Pickup Time (Cycles)
J+9		0·32	Zone 3 Reach (Diameter)
J+10		80	Zone 3 Center Line Angle In Degrees
J+11		0·15	Zone 3 Center Distance In p.u.
J+12		0	Angle Of Directional Unit (Only For Impedance Relay)
J+13		0·1	Threshold Current In p.u.
J+14		0·1	Self Trip Breaker Time (Cycles)
J+15		0	Self Trip Reclosure Time (Cycles)
J+16		0	Transfer Trip Breaker Time (Cycles)
J+17		0	Transfer Trip Reclosure Time (Cycles)
J+18		0	1st Blinder Type (± 1 or ± 2)
J+19		0	1st Blinder Intercept (p.u.)
J+20		0	1st Blinder Rotation (Degrees)
J+21		0	2nd Blinder Type (± 1 or ± 2)
J+22		0	2nd Blinder Intercept (p.u.)
J+23		0	2nd Blinder Rotation (Degrees)



0, 'DISTR', first 16 ICONs, CON list/

Figure A2.3 (cont.) Data sheet for **DISTR** model, containing data to represent the relay at bus 4 on line 4-6 (data sheet taken from the PSS/E Program Operational Manual, Volume II, PTI, Appendix VII)

APPENDIX 3: APPLICATION OF OUT-OF-STEP BLOCKING PROTECTION TO THE NINE-BUS NETWORK.

Each out-of-step blocking protection applied to the nine-bus network seen in Figure A3.1 consists of

1) inner and outer circular characteristic zones and
2) a controled supervisory input of the **DISTR** model with which it is coordinated.

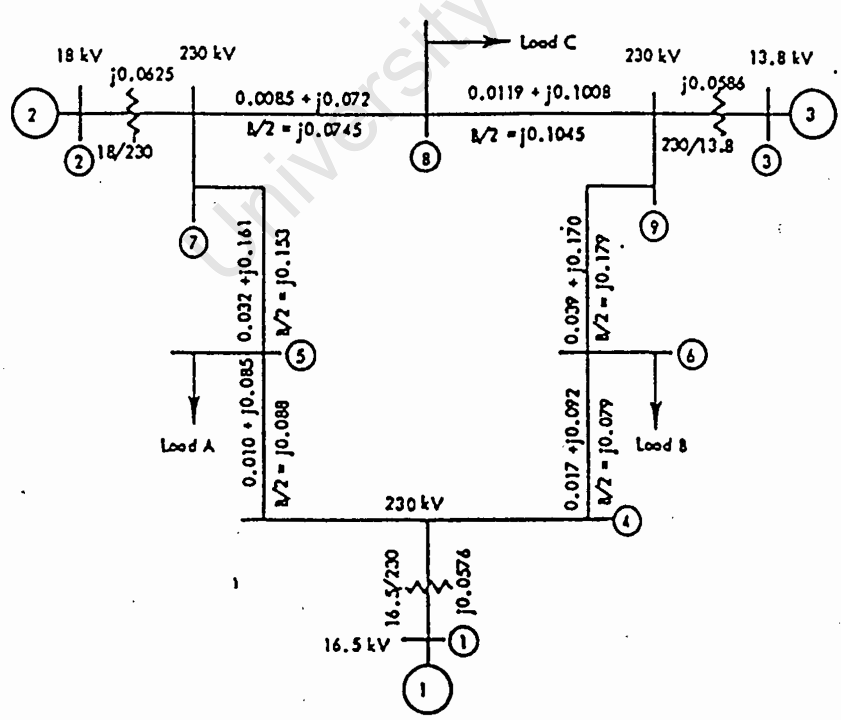


Figure A3.1: The nine-bus network

For each out-of-step blocking protection shown in Figure A3.2, the settings are the following:

$$\text{Zset-inner} = \text{Z3-set} \tag{A3.1}$$

$$\text{Zset-outer} = 1.3 * \text{Zset-inner} \tag{A3.2}$$

where

Zset-inner = inner-zone setting

Zset-outer = outer-zone setting

Z3-set = zone 3 setting of distance relay

Table A3.1 shows the zone 3 setting of the distance relay for each line in the nine-bus network, as calculated in Appendix 2. Table A3.2 lists the settings for the inner and outer zones for each out-of-step blocking relay in the nine-bus network. The settings were calculated by means of equations (A3.1) and (A3.2).

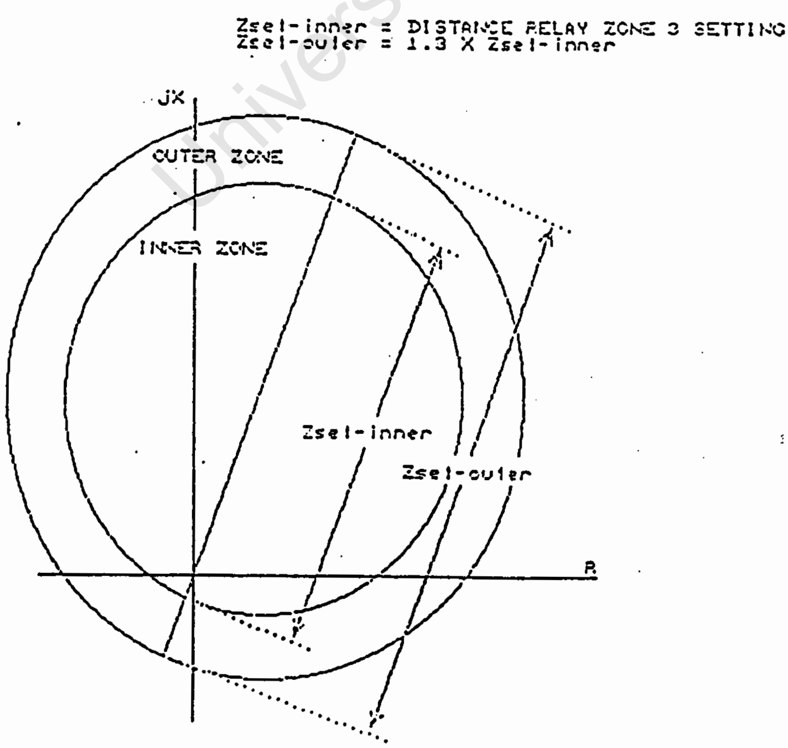


Figure A3.2 : Out-of-step protection characteristics

Table A3.1 : Zone 3 setting of distance relay for each line in the nine-bus network

RELAY LOCATION♣	DISTANCE RELAY ZONE 3 SETTING	RELAY LOCATION	DISTANCE RELAY ZONE 3 SETTING
4-5	0.32	5-4	0.23
4-6	0.34	6-4	0.23
5-7	0.31	7-5	0.33
6-9	0.36	9-6	0.35
7-8	0.20	8-7	0.29
9-8	0.23	8-9	0.35

♣ The number appearing first indicates the busbar at which the relay is located.

Detection of an out-of-step condition is achieved by monitoring the rate of the change in measured impedance, using a timer. A timer setting above a predetermined set value is interpreted as an out-of-step condition. The timer setting is determined by the swing frequencies of the system during out-of-step conditions.

Table A3.2 : Settings for the inner and outer zones

RELAY LOCATION♣	INNER ZONE SETTING = ZONE 3 SETTING IN TABLE A3.1	OUTER ZONE SETTING = 1.3 * INNER ZONE SETTING
4-5	0.32	0.42
4-6	0.34	0.44
5-7	0.31	0.40
6-9	0.36	0.47
7-8	0.22	0.29
9-8	0.23	0.30
5-4	0.23	0.30
6-4	0.23	0.30
7-5	0.33	0.43
9-6	0.35	0.46
8-7	0.29	0.38
8-9	0.35	0.46

♣ The number appearing first indicates the busbar at which the relay is located.

See Figure A3.3. To determine the timer setting **T**, the frequency of the measured impedance through zone 2 is calculated. With reference to Figure A3.3, the following equations are used:

$$T=\frac{\alpha_1-45°}{360°}\cdot\frac{1}{S} \tag{A3.3}$$

$$\alpha_1=\arctan\left(\frac{Zset-outer}{Zset-inner}\right) \tag{A3.4}$$

where

Zset-inner	= inner-zone setting
Zset-outer	= outer-zone setting
T	= timer setting
S	= maximum swing frequency obtained from stability studies.
$\alpha 1$	= angle defined in Figure A3.3

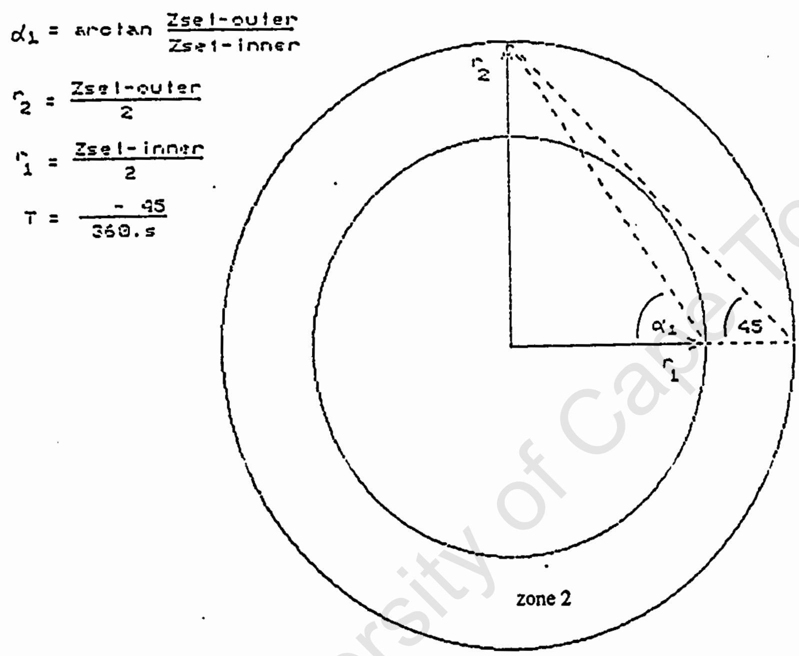


Figure A3.3 : Determining the timer setting T

This research included stability studies (refer to Chapter 5). The maximum swing frequency obtained was 2.41 Hz. For the purpose of setting the out-of-step blocking protection, a maximum swing frequency **S** = 2.41 Hz was used. The timer settings for every out-of-step blocking relay are listed in Table A3.4.

Table A3.4: Timer settings for out-of-step blocking protection

—RELAY LOCATION♣	α_1=arctan$(\frac{Zset-outer}{Zset-inner})$ (degrees)	$T=\frac{\alpha_1-45°}{360°}\cdot\frac{1}{S}$ S = 2.41 Hz (seconds)
4-6	52.4	8.53
4-5	52.4	8.53
6-9	52.4	8.53
5-7	52.4	8.53
7-8	52.4	8.53
9-8	52.4	8.53
6-4	52.4	8.53
5-4	52.4	8.53
9-6	52.4	8.53
7-5	52.4	8.53
8-7	52.4	8.53
8-9	52.4	8.53

♣ The number appearing first indicates the busbar at which the relay is located.

The setting data listed in Tables A3.2, A3.3 and A3.4, supplemented by a data sheet provided by the PSS/E, were used to represent the relay in the Working Case. The data sheet for **CIRCOS** can be seen in Figure A3.4. The data sheet was completed to represent the out-of-step blocking protection located at bus 4 on line 4-6.

CIRCOS

Double Circle Or Lens Out-Of-Step Tripping Or Blocking Relay

CALL CIRCOS (I,J,K,IFL) from CONET

Uses ICONs starting with # ________ I,

and CONs starting with # ________ J,

and VARs starting with # ________ K.

ICON (IFL) is the permissive flag of a relay being supervised by CIRCOS # ________ IFL

ICONs	#	Value	Description	
I		/	Ref # (Max Of 9)	
I+1		−/	Type +1 Double Circle Tripping Type -1 Double Circle Blocking Type +2 Lens Type Tripping Type -2 Lens Type Blocking	
I+2		/	Operation Mode 0 - Monitor 1 - Monitor And Operate	
I+3		/	Resolution (Time Steps)	
I+4		4	From Bus #	Monitored Line,
I+5		6	To Bus #	Relay Is At
I+6		/	Circuit ID	'From' Bus End
I+7		0	From Bus #	First
I+8		0	To Bus #	Transfer
I+9		0	Circuit ID	Trip
I+10		0	From Bus #	Second
I+11		0	To Bus #	Transfer
I+12		0	Circuit ID	Trip
I+13		0	From Bus #	Third
I+14		0	To Bus #	Transfer
I+15		0	Circuit ID	Trip
I+16		X	Permissive Flag For Self Trip*	
I+17		X	Permissive Flag For Transfer Trip*	

VARs	#	Description
K		Apparent R
K+1		Apparent X
K+2		Current
K+3		VARs Required For
K+4		Internal Program
K+5		Logic

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CIRCOS

Double Circle Or Lens Out-Of-Step Tripping Or Blocking Relay

(Continued)

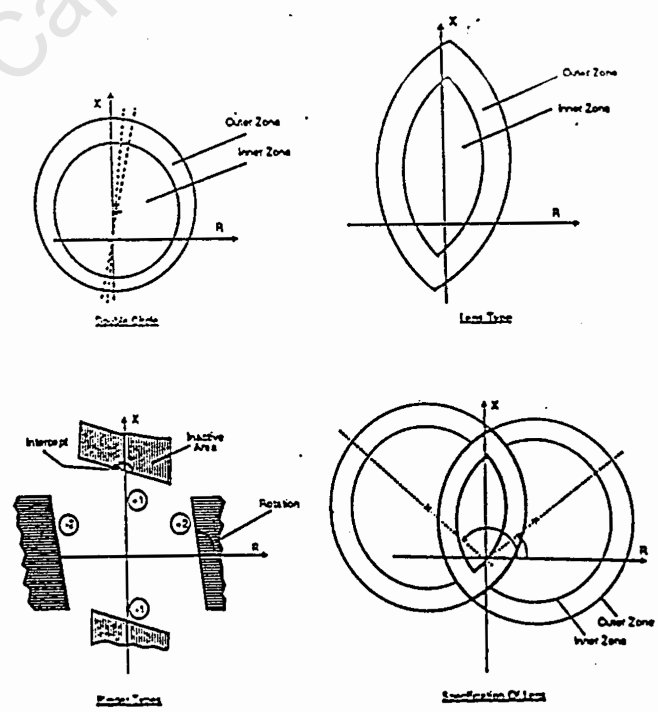

Figure A3.4: CIRCOS data sheet with data representing the relay at bus 4 on line 4-6 in the Working Case (taken from the PSS/E Program Operational Manual, Volume II, PTI, Appendix VII)

CIRCOS

Double Circle Or Lens Out-Of-Step Tripping Or Blocking Relay

(Continued)

ICONs	#	Value	Description
I+18 . . I+27		X	ICONs Required For Internal Program Logic

*Normally set to 1 in user input if tripping is desired. Value 0 prevents trip.

CONs	#	Value	Description
J		0.43	Inter-Zone Travel Time (Cycles)
J+1		0.32	Zone 1 (Inner Zone) Diameter (p.u.)
J+2		80	Center Line Angle (Degrees)
J+3		0.15	Center Line Distance (p.u.)
J+4		0.44	Zone 2 (Outer Zone) Diameter
J+5		80	Center Line Angle (Degrees)
J+6		0.15	Center Line Distance (p.u.)
J+7		0	Threshold Current (p.u.)
J+8		0.1	Self Trip Breaker Time (Cycles)
J+9		0	Transfer Trip Breaker And Delay Time
J+10		0	1st Blinder Type (±1 or ±2)
J+11		0	1st Blinder Intercept (p.u.)
J+12		0	1st Blinder Rotation (Degrees)
J+13		0	2nd Blinder Type
J+14		0	2nd Blinder Intercept (p.u.)
J+15		0	2nd Blinder Rotation (Degrees)

0, 'CIRCOS', first 16 ICONs, CON list /

Figure A3.4 (cont.): CIRCOS data sheet with data representing the relay at bus 4 on line 4-6 in the Working Case (taken from the PSS/E Program Operational Manual, Volume II, PTI, Appendix VII)

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