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REACTIVE POWER COMPENSATION, SYSTEM AND VOLTAGE STABILITY OF AN INDUSTRIAL NETWORK WITH SHORT CIRCUIT LIMITING COUPLER

By

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Abstract

This thesis investigates Sasol Three (Secunda) system's needs for reactive power compensation under voltage and transient stability conditions. A short circuit limiting coupler is designed and the transient and voltage stability studies are performed with a short circuit limiting coupler (SLC) applied at the two 132 kV incoming supply lines from Eskom.

The simulations are based on solving ordinary loadflow cases augmented with dynamic models of the system elements. Motor loads were modelled in detail incorporating their dynamic characteristics. 75% of the Sasol Three system load constitute induction motors and 25 % is constant impedance and constant current load models. Power System Simulator (PSS/E) package was utilized in carrying out these studies.

The most impressive results is the way the Sasol Three System recovers in the range of milliseconds when subjected to severe disturbance with regard to voltage and transient stability. With a short circuit limiting coupler included at the two incoming supply lines, the system still recovers after being subjected to a disturbance.

In this project it is shown that there is no need to install reactive power compensation system on the Sasol Three System. This is because of the capabilities of the present system in regulating reactive power through the network during abnormal system conditions. It is also shown in this thesis that the Sasol Three network is transient and voltage stable when a short circuit limiting reactor is applied at the incoming lines from Eskom. The extent to which the network is transiently stable is also determined.

Preface

In the past, no special reactive power compensation devices were needed since loads were located close to the generators. As power systems grew and expanded, new demands were put on these systems. The need then arose to compensate the lines, using fixed capacitors, shunt reactors and synchronous condensers.

My mentor, Jozef Piorkowski, suggested that investigations be made into reactive power compensation needs of Sasol Three System during abnormal system conditions. He requested that a Short Circuit Limiting Coupler(SLC) be designed and stability of the system be evaluated with SLC at the incoming 132 kV lines from Eskom. I have been very interested in research and development of electric power system field. Contacts with Professor Silviu Darie of the Department of Electrical Engineering, University of Cape Town, have been developed. Therefore, the idea of Msc-project emerged during informal meetings with him. The objective of the study was identified.

Before studies on the Sasol network were carried out, literature on reactive power compensation, principles of fault level, system stability and voltage stability were reviewed.

During simulation process, some of the results on voltage stability were sent to Jozef Piorkowski. Suggestions were made regarding the topic which included some more work (see Appendix A).

The presentation of this thesis is simple and easy to follow. It consists of six chapters. Following the introductory remarks, chapter two begins by describing the theoretical concepts related to loadflow and fault level studies. Loadflow studies were performed to establish the initial steady state conditions prior fault level studies. Then, the chapter discusses the loadflow solution techniques followed by the description of the PSS/E package and Sasol Three network. Different types and sources of faults are also described. Finally, loadflow studies and fault level studies are performed on the Sasol Three network for the design of a short circuit limiting coupler that will reduce the fault level at 132 kV bus by 20%.

Chapter three reviews various compensation devices that are in use today. It then discusses the principal application of these devices in transmission and distribution systems. Reactive power control of the Sasol Three network is also discussed in this chapter. The need for additional reactive power compensation of Sasol Three network (e.g. using shunt capacitors or SVC) is evaluated.

Chapter four discusses transient stability of the system. It starts by providing theoretical concepts related to stability and then discusses various methods used to improve power system stability. Transient stability of the Sasol Three network is carried out in this chapter and the system is analysed. The need for reactive power compensation of the Sasol Three network during transient instabilities is evaluated.

Chapter five describes voltage stability. An introduction is given followed by the discussion of theoretical concepts related to voltage collapse. Then, description of voltage collapse mechanisms, equipment characteristics, analysis methods and sensitivities of voltage stability to system characteristics are provided. Prevention of voltage collapse is also described in this chapter. Voltage stability of the Sasol Three network is carried out in this chapter and the system is analysed. The need for reactive power compensation of the Sasol Three network during voltage instabilities is evaluated.

Chapter six closes the report by making conclusions and recommendations.

Acknowledgments

I would like to thank my supervisor, Professor Silviu Darie, for his support and guidance throughout the project.

Special thanks go to my mentor, Jozef Piorkowski of Sastech, for discussions and many excellent detailed comments. A warm acknowledgment go to my colleagues at Sastech and the University of Cape Town, for their interest in my work and have contributed to the results.

The gathering of system parameters and the layout of Sasol Three System have been carried out in Secunda. Krishna Govender has been extremely helpful.

Special thanks also go to Jens Birgersson , specialist in reactive power compensation (ABB), for his valuable ideas and information regarding reactive power compensation.

I would also like to thank Sasol for their financial assistance during my studies.

Finally, heartful thanks go to my family for their love and support.

Victor Shikoana

Contents

List of Illustrations

List of symbols and abbreviations

Q	*Reactive power*
V	*Voltage*
I, i	*current*
φ	*phase angle of voltage and current*
h	*harmonic number*
S	*Apparent power*
P	*Active Power*
Δv	*voltage drop across line*
R	*resistance*
X	*reactance*
$X'd, X'q$	*direct and quadrature axis transient reactance*
$X''d, X''q$	*direct and quadrature axis subtransient reactance*
$T'd0, T'q0$	*direct and quadrature axis transient time constant*
$T''d0, T''q0$	*direct and quadrature axis subtransient time constant*
$Sat._{facto}$	*generator saturation factor*
δ	*generator rotor angle*
$[Y]$	*network admittance matrix*
$[V]$	*vector of positive sequence voltages as the network nodes*
$[I]$	*vector of positive sequence currents flowing into network nodes*
j	*complex operator*
a	*voltage exponent for frequency dependent part of load*
b	*voltage exponent for non-frequency dependent part of load*
K_{sf}	*frequency sensitive coefficient of the load*

ABB	*Asea Brown Boveri (company)*
AVR	*Automatic Voltage Regulator*
EHV	*Extra High Voltage*
HVDC	*High Voltage Direct Current*
LCC	*Line Commutated Converter*

PFC	*Power Factor Correction*
SCC	*Self Commutated Converter*
SIL	*Surge Impedance Loading*
SLC	*Short Circuit Limiting Coupler*
SR	*Saturated Reactor*
SVC	*Static Var Compensator*
SVS	*Static Var System*
TCR	*Thyristor Controlled Reactor*
TCT	*Thyristor Controlled Transformer*
TSC	*Thyristor Switched Capacitor*
TSR	*Thyristor Switched Reactor*

Glossary

Compensation :	*effect of injecting recative power to boost voltages on system loading*
Compensation by sectioning:	*compensation achieved by dividing the line into shorter sections that are more or less independent of another*
Ferranti effect :	*The condition whereby the receiving end voltage is greater than the sending end voltage. Normally it happens when there is no load on the receving end*
Islanding conditions :	*separation of two electrical system during faults*
Line length compensation :	*compensation achieved by reducing the line reactance* (X_l) *using a series capacitor*
Modal analysis :	*computation of a small number of eigenvalues and the associated eigenvectors or a reduced Jacobian matrix which retains the Q-V relationships in the network and includes the appropriate characteristics of generators, loads, reactive power compensating devices and HVDC converters*
PSS/E :	*industrial grade package that handles loadflow, fault analysis, network equivalent construction and dynamic simulations of electrical power systems*

Surge impedance compensation :	*compensation achieved by modifying the surge impedance* (Z_0) *or surge impedance load* (P_0)
Surge impedance loading (SIL):	*A critical level of active power flow on a transmission line that results in the reactive power demanded by the line inductance just equal to the reactive power supplied by the line's capacitance. At SIL , the line compensate itself*
SVC :	*integrated system of static electrical components*
SVS :	*aggregation of SVC's and mechanically switched capacitors or reactors whose outputs are co-ordinated*

CHAPTER ONE

INTRODUCTION

Reactive power is present in every AC power system. Most loads absorb both active and reactive power. An electrical system can absorb or generate reactive power depending on whether the network loading is below or above the Surge Impedance Loading (SIL) [4]. Transmission and distribution of electric power involves reactive power losses due to series reactance of transformers, overhead lines and underground cables. Lines and cables generate reactive power due to their shunt capacitance. This reactive power generation is of significance at high system voltages.

During steady state conditions, reactive power generated must match the demand plus losses, otherwise the load voltage will change [4]. Excess reactive power means high voltages while a deficit in reactive power means low voltages. Reactive power balance influences active losses of the system, voltage stability and in some cases rotor angle stability of synchronous machines [4, 5]. The balance is also affected by generators and reactive power devices that produce or absorb reactive power.

In the past, no special reactive power compensation devices were needed since loads were located close to the generators. As power systems grew and expanded, new demands were put on these systems. For example, the need arose to compensate the lines, using fixed series capacitors, shunt reactors and synchronous condensers in order to stabilise the power transmission and make it more energy efficient. Larger and larger synchronous condensers were installed in transmission systems along with the development of more efficient and economic capacitors as a means of supplying reactive power. Shunt reactors and series capacitors became important compensation devices with the introduction of extra-high-voltage (EHV) lines in power systems. Recently, the thyristor controlled static var compensator has been the well established device in transmission systems as well as in high power industrial networks [9-24] for reactive power compensation.

In this thesis a short circuit limiting coupler (SLC) is designed and the need for reactive power compensation of the Sasol Three network is evaluated. Voltage and transient stability studies of the Sasol Three network are also carried out to determine the need for reactive power compensation of the network with the SLC.

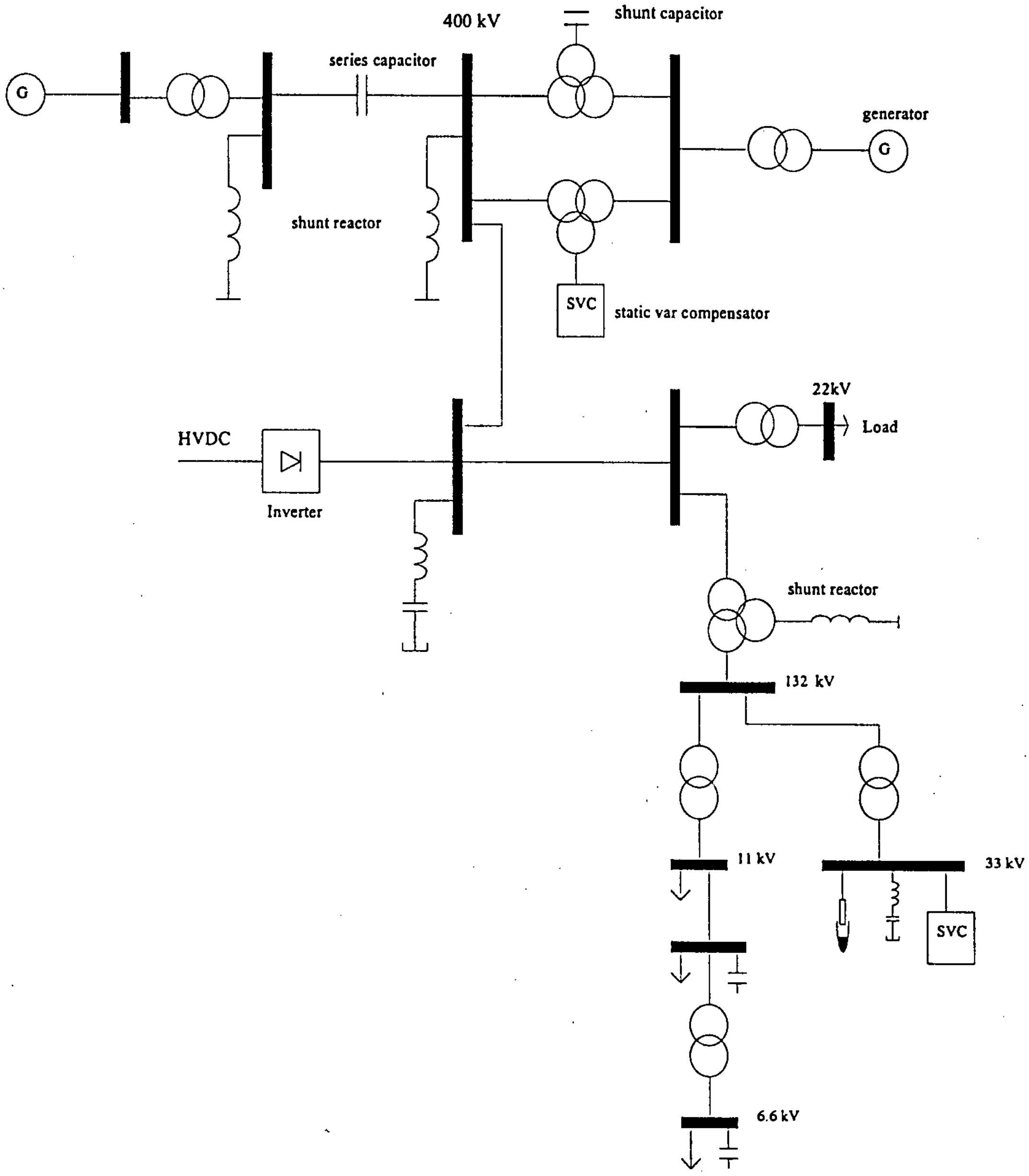

Figure 1.1 Typical industrial system illustrating possible locations of reactive power compensation devices

The sizes, locations and type of reactive compensation devices for a particular power system under study depends on the characteristics and performance requirements of that system. Figure 1.1 illustrates the location of different compensation devices on a typical power network [8].

1.1. Problem definition

Sasol Three experience increased fault level at the 132 kV bus due to the expansion of the Sasol Three network. Sasol intended to install a short circuit limiting system that will reduce the fault level at the 132 kV bus by 20%. It was required that the SLC be designed and the need for reactive power compensation of the Sasol Three network be investigated.

The performance of the network under voltage and transient stability (with the short circuit limiting reactors connected in the incoming lines) was carried out to determine the need for reactive power compensation of the Sasol three network under this conditions. If the network is transient or/ and voltage instable, a reactive power compensation system should be designed to improve the performance under voltage and transient stabilities of the system.

1.2. Objectives

The objectives of this thesis are:

- To design a short circuit limiting coupler that is capable of reducing the fault level at the 132kV bus by 20%.
- To evaluate the need for reactive power compensation of the Sasol Three network.
- Analyse transient stability of the Sasol Three network with SLC applied at the two 132 kV incomers from Eskom and evaluate the need for reactive power compensation.

- Evaluate the extent to which transient stability is attained.
- Analyse voltage stability of the Sasol Three network with SLC applied at the two 132 kV incomers from Eskom and evaluate the need for reactive power compensation of the system.
- Design a reactive power compensation system that will improve the performance of the Sasol Three network if it is transient or/and voltage instable.

1.3. Research effort

In an attempt to address the growing concerns of Sasol with regard to power system studies, previous studies have been performed on the Sasol Three system [1-3]. CTB Engineers [1] evaluated the configurations of the power supply to the plant from the Eskom system for reliability, stability and losses. Fluor [2] modelled the Eskom system as an equivalent machine connected to the SOL-substation[1]. Fluor analysed the system in both steady state and transient state. De Kock [3] performed the fault level and stability studies on both the Eskom and Sasol systems (i.e. Sasol Three and Sasol Two systems).

In this thesis , a short circuit limiting coupler is designed and the need for reactive power compensation of the Sasol Three network is evaluated. Transient and voltage stability studies are carried out (with SLC applied at the two 132 kV incomers to Sasol Three) and the system's need for reactive power compensation is investigated.

The thesis entails the study of the fault level to design a short circuit limiting coupler, reactive power compensation, transient stability and voltage stability of the Sasol Three Industrial network. The industrial grade software package, Power System Simulator for Engineers (PSS/E) Version 20, is utilised for computer simulations. The software runs on an Apollo work station.

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[1] SOL substation - Eskom 400kV/132kV substation that supply the Sasol power network. This substation is about 6.4 km away from Sasol Three.

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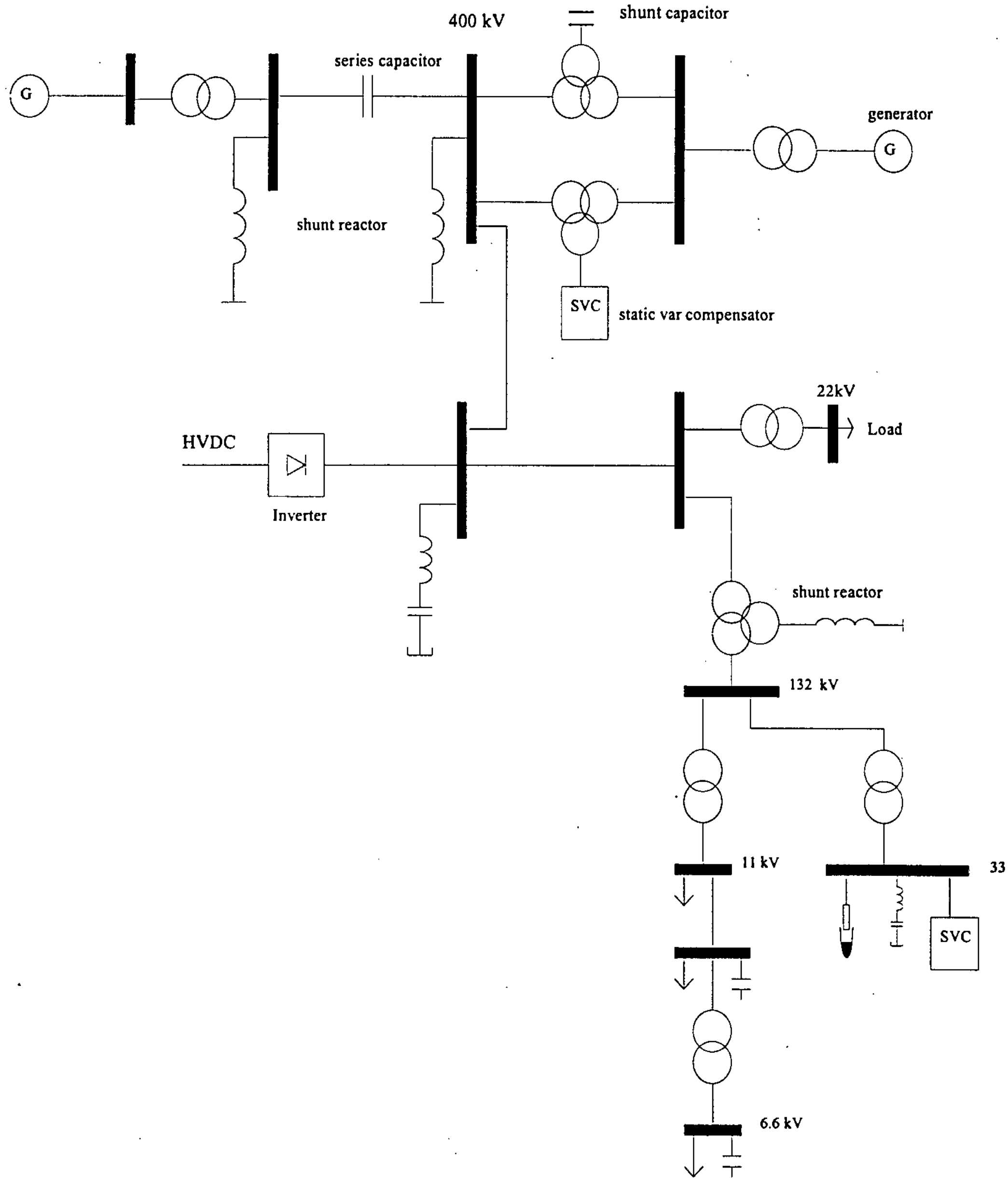

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1.4 Literature review

Before carrying out studies on the Sasol three network, literature on *fault studies*, *reactive power compensation*, *transient stability* and *voltage stability* were reviewed. Chapters 2 - 6 briefly discuss the relevant theoretical concepts related to fault studies, reactive power compensation, transient stability and voltage stability. Detailed theoretical descriptions of the abovementioned topics are covered in references [4,5,8, 25-33].

1.5 Research publications

Certain parts of this thesis have been presented at the Southern African Universities Post- graduate Electrical Engineering Symposium [6], and Southern African Universities Power Engineering Conference [7].

1.6 Report breakdown

The contents of this report consists of six chapters. Following the introductory statement, chapter two begins by describing the theoretical concepts related to loadflow and fault level studies. Loadflow studies were performed to establish the initial steady state conditions prior fault level studies. Then, the chapter discusses the loadflow solution techniques followed by the description of the PSS/E package. Different types and sources of faults are also described. Finally, loadflow studies and fault level studies are performed on the Sasol Three network for the design of a short circuit limiting coupler that will reduce the fault level at 132 kV bus by 20%.

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Chapter six closes the report by making conclusions and recommendations.

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CHAPTER TWO

LOADFLOW AND FAULT LEVEL STUDIES

2.1. Introduction

Loadflow studies are concerned with the determination and analysis of the steady state performance of the power system network [2-4]. Analysis of the loadflow solution ensures that the power system satisfy its performance criteria while incurring the most favorable investments and operating costs.

Fault analysis is concerned with the determination and analysis of short circuit currents of the power system [2-4]. Analysis of the fault levels in the system ensures that proper switching equipment, current path, protective devices and their trip settings are selected.

This section of the thesis serves as the basis to the next chapters. The chapter starts by describing the loadflow solution techniques followed by the description of the PSS/E package. Description of the Sasol Three network is also provided. Then the loadflow and fault level studies of the Sasol Three network are carried out. Finally, the design of a short circuit limiting coupler that reduces the fault current by 20 % is carried out.

2.2. Loadflow solution methods

Loadflow studies are performed to investigate active and reactive power flows in the branches of the network; bus voltages; optimum rating and tap range of the transformers; optimum system losses; load distribution of the system; the effect of injecting boost voltages on system loading (i.e. *reactive power compensation*); and the effect of temporary loss of generation and transmission networks.

The loadflow calculation is a network solution problem. The currents and voltages are described by the following equation :-

$$[I] = [Y] \cdot [V] \qquad (2.1)$$

where :

- $[I]$ = vector of total positive sequence currents flowing into the network nodes (buses).
- $[V]$ = vector of positive sequence voltages at the network nodes(buses).
- $[Y]$ = network admittance matrix of positive sequence.

Equation (2.1) is a linear algebraic equation with complex coefficients. If either the currents or voltages were known, the solution for the unknown quantities could be determined by the application of numerical solution methods for linear equations.

The terminal conditions at each bus are normally described in terms of active and reactive power (P and Q). The bus current I_i is related to these quantities as follows :

$$I_i = \frac{(P_i + jQ_i)^*}{V_i^*} \qquad (2.2)$$

where * designates the complex conjugate.
Substituting equation (2.2) into equation (2.1) yields the following non - linear equation:

$$\left[\frac{P - jQ}{V^*} \right] = [Y] \cdot [V] \qquad (2.3)$$

The above equation requires an iterative trial and error process for its solutions.

Iterative solution algorithms

The network equations are solved by a digital computer using an iterative calculation process. Endless collection of iterative schemes has been developed and reported [1, 2, 4,7-9]. Many of these are variations of one or the other of two basic techniques that are in widespread use by the industry today - *Gauss Seidel technique and Newton Raphson technique.*

In PSS/E[1], the user is allowed to choose from five different ac loadflow iteration schemes. These are :

(i) Gauss Seidel iteration.
(ii) Modified Gauss Seidel iteration suitable for series capacitors.
(iii) Fully Coupled Newton Raphson iteration.
(iv) Decoupled Newton Raphson iteration.
(v) Fixed Slope Decoupled Newton Raphson iteration.

In this thesis, the first and the third iteration schemes were used.

2.3. Description of the PSS/E package

PSS/E is a power system simulation package developed by the Power Technologies Incorporated, USA. The package allows simulations of power system networks to perform loadflow and dynamic analysis.

The software consist of programs which allow studies to be made on power system transmission and generation networks in both steady state and dynamic conditions.

PSS/E handles loadflow, fault analysis (balanced and unbalanced), network equivalent construction and dynamic simulations. The PSS/E software runs on the APOLLO workstation and PC's. It has a large library of different models (e.g. loads, generators, excitation system and induction motors) which can be used to analyse the system.

Power system networks up to 12000 buses, 3600 generating buses, 4000 generators, 24000 branches and 4800 transformers can be represented in this package.

The three programs incorporated in the PSS/E package are PSSLF4, PSSDS4 and PSSPLT. The PSSLF4 program was used to do the loadflow studies, fault analysis on the network, and to prepare input data for dynamic studies. The PSSDS4

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[1] industrial grade package that was used to study the performance of the Sasol Three system in Secunda

program was used to carry out the dynamic analysis of the network. The results of the dynamic simulation were then presented graphically using the PSSPLT program.

This program was used to investigate the performance of the Sasol Three system in Secunda.

2.4. Description of the Sasol Three network

Eskom supply power to Sasol Three network via two 132 kV overhead transmission lines. The source to the lines are two 500 MVA, 400/132 kV transformers operating in parallel. The 500 MVA transformers are located at the Eskom SOL substation which is 6.4 km from Sasol Three.

Sasol three network consists of a 400 MW load area and local generation that serve a major part of the load. The power generated in-house is 240 MW. Their output depends on the availability of steam. The balance is imported from Eskom. The average power factor of the Sasol Three network is 85% lagging. This is achieved by controlling the reactive power generated by the synchronous motors and generators.

In essence the Sasol Three network is a radial system that is fed from the 132 kV busbar (see Appendix B for the drawing), which is stepped down to 33kV where most of the distribution takes place in five 160 MVA substations. From there voltage is stepped down to 6.6 kV and 525V for use. In addition to this the oxygen plant has one 54 MVA transformer fed from the 132kV, that is stepped down to 11 kV and 6.6 kV to feed one oxygen train. Two 65 MVA, three winding transformers that step down to 11 kV and 6.6 kV are used to supply large synchronous and induction motors at the Linde Gas plant (see the drawing in Appendix B).

There is a complete listing of the Sasol Three network parameters in Appendix C.

2.5. Fault analysis

This section describes different types of faults and sources of short circuit currents that commonly occur in an electrical power system. Different components that limit the short circuit currents are also discussed in this section.

2.5.1. Types of faults

Faults in a particular power system may be *overload, overvoltage or short circuits*. In three phase system, the types of faults that may occur in practice are shown in Figure 2.1 and the most common of these is the short circuit of a single line to ground. Sometimes the path to earth contains a resistance as shown in figure 2.1(f).

The earth faults that may flow on a particular power system depend mainly on the earthing method used . For example, an ungrounded system will not experience earth current flowing through the system since there is no return path to ground, instead, overvoltages may appear from line to ground fault during normal switching of the system having line-ground fault.

An ungrounded system is in reality a "capacitively grounded system" by virtue of the distributed capacitance from the system conductors to ground. The critical network at Sasol Three is capacitively earthed and the system is prone to such problems of overvoltages which in many cases resulted in circuit breaker explosions. At the present moment the system is modified by providing earthing through zig-zag transformers.

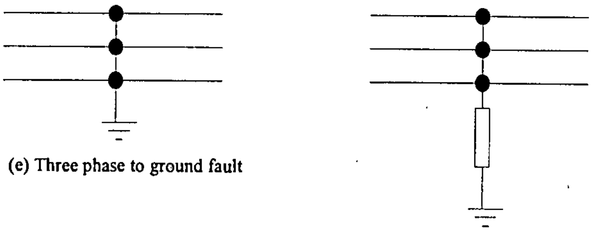
The short circuit faults can be divided into symmetrical and unsymmetrical. Symmetrical and unsymmetrical faults are covered in much more detail in references [1, 2, 10-12].

(a) Single line to ground fault
(solidly grounded)

(b) Line to line fault

(c) Double line to ground fault

(d) Three phase fault



(e) Three phase to ground fault

(f) Single line to ground fault
(grounded through an arcing resistor)

Figure 2.1 Types of faults on three phase system

2.5.2. Sources of short circuit currents

It is important to know the exact short circuit current magnitude in order to select proper protective device or design the short circuit limiting coupler. The magnitude of the currents depends on different sources that generate them, their reactances and on the system reactances up to the fault location.

Sources of short circuit currents are:-

1. Electric utility systems
2. Generators
3. Synchronous motors
4. Induction motors

Figure 2.2 illustrates the short circuit current flowing into the point of fault contributed by several possible sources including the utility system, plant generators and motors.

2.5.2.1. Electric utility systems

Remote generators of the electric utility system are a source of short circuit current usually delivered through a supply transformer. The current contribution to a fault in the remote plant appears to be merely a small increase in load current to the very large central generators, and this current contribution tends to remain constant[11].

2.5.2.2. Synchronous generators

Generators are driven by prime movers such as steam or gas turbine, engine etc. When a short circuit occurs, the generator continues to be driven by its prime mover thus producing voltage since field excitation is maintained by the generator rotating at normal speed.

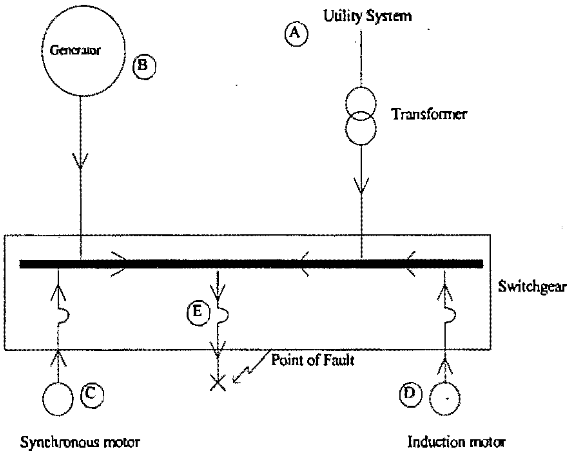


Figure 2.2 Sources of Short Circuit Current in Electrical networks

The generated voltage produce short circuit current of large amplitude that flows to the fault [12]. This current flow is limited by the reactance of the generator and the circuit between the generator and the point of the fault.

The reactance of the generator varies with time after the inception of a fault. Industrial Standards, IEEE Std.141-1986 [12] have established three specific names of this variable reactance called subtransient reactance, transient reactance and synchronous reactance. In South Africa the same standards are used.

X_d'' = Subtransient reactance which determines short circuit current immediately after fault inception.
Last for the first few cycles and in about 0.1 seconds increases to

X_d' = Transient reactance which lasts for about two seconds while increasing to the final value

X_d = Synchronous reactance which determines the current flow after steady state is reached.

Short circuit current decreases exponentially in time from an initial high value to a lower steady state level [11,12].

2.5.2.3. Synchronous motors

Synchronous motors behave similarly like synchronous generators. When a fault cause the system voltage to drop, the synchronous motor stops taking power from the system to rotate its load and starts slowing down.

Inertia of the load tends to prevent the motor from slowing down quickly. Inertia acts as the prime mover and with excitation maintained, the motor acts as generator supplying short circuit current for several cycles after the short circuit occurs[11,12].

The same designations are used for variable reactances of a synchronous motor as for a generator (i.e. X_d'', X_d' *and* X_d).

2.5.2.4. Induction motors

Induction motors contribute short circuit current because of the generator action produced by the inertia of the load and rotor driving the motor after the fault occurs. The field flux of induction motors is produced by induction from the stator and not from dc field winding. Induction motor contribution drops off quickly and dies out completely after a few cycles [11] since the flux decays rapidly.

No steady state fault current contribution hence induction motors are assigned only the subtransient value of reactance, X_d''. This value is nearly equal to the locked rotor reactance.

2.5.3. Short circuit current limiters

Electrical components that limit current during short circuits are transformer impedances, reactors, cables, buses, current limiting fuses, and any other network impedance. These devices may be used primarily to reduce short circuit current magnitude. With these devices, lower interrupting capacity breakers may be employed to save the total equipment costs. However, the expansion of power system increases the available short circuit current beyond the interrupting capacity.

By installing current limiting devices, short circuit requirements can be reduced to avoid replacing the breakers. Limiting fault current magnitude results in smaller bus voltage drop during short circuits which minimize its effect on the other part of the system.

Selection of current limiting reactors is based on the percentage reactance to be introduced into the system. This percentage reactance is the ratio of the voltage drop across the reactor to the voltage between line and neutral in 3 phase systems and between lines in single phase circuits.

To select a reactor properly, the type, frequency, kVA, voltage drop, current and percentage reactive drop of the reactor must be known as well as the kVA and voltage of the system. Reactor types include 3-phase and single phase, air-cooled. oil-immersed, etc.

The reactance/phase required to reduce an unacceptable fault current to the desired value is given by;

$$X_{(ohms)} = V_n^2 \times \left(\frac{1}{S_d} - \frac{1}{S_a}\right) \quad \text{...} (2.4)$$

where, V_n is the nominal voltage, in kV

S_d is the desired short circuit level, in MVA

S_a is the actual short circuit level, in MVA

The voltage drop across the reactor is,

$$V_{drop} = I_L \cdot X_{(ohms)} \quad (2.5)$$

where, I_L is the current flowing through the line

The power losses of the reactor are given by,

$$P_{losses} = 3I^2 R \quad (2.6)$$

where, R is the resistance of the reactor.

Since system stability is influenced by reactors, a balance must be found between system stability and the economical benefits of reactors.

2.6. Loadflow studies of Sasol Three network

The simplification of the Sasol Three network for the loadflow study is discussed and the summary of the information used is given.

For the Sasol Three network, the information was obtained from the Central Control Room of Sasol Three, the Fluor report and Distribution Engineers at Sasol Three. This information was added to the latest electrical drawings for use in this study. The loadflow figures reflect the load on the Sasol Three network under maximum demand conditions.

In Appendix B, there is drawings used in this investigation. The synchronous machines at Sasol Three produce adequate supply of reactive power to regulate the voltage at 2H4-SP-1 to 99.32% (see Appendix D). The high voltage cables were not explicitly modelled but rather lumped as an equivalent shunt capacitor on 2H4-SP-1 (i.e. bus 7630 in Appendix C). Sasol Three imported 263.4 + j114 MVA from Eskom at a power factor of 0.917. In May 1994 , 220 MW was imported and in this study it was increased to 263.4 MW. The reason being the expected increase in production due to a higher production of oxygen and steam (latest addition for oxygen train 7 supply).

Table 2.1 summarises the loadflow results of the five distribution stations and the power plant. Detailed summary of voltages and power flows of the whole Sasol Three network is provided in Appendix D.

Table 2.1 Loadflow results of five distribution stations and the power plant at Sasol Three

Line	Power flow (MVA)
IMPORT FROM ESKOM	
100 - 7630 (L1)	131.7 + j57.1
100 - 7630 (L2)	131.7 + 57.1
Total import	263.4 + j114.1
IN HOUSE GENERATION	
7640 - gen2	60 + j45
7641 - gen1	60 + j45
7650 - gen4	60 + j45
7651 - gen3	60 + j45
Total generation	240 +j 180
2GG-DS-1 POWER CONSUMPTION	
7630 - 7710	21.8 + j16.6
7630 - 7710	21.8 + j16.6
Total consumption	43.6 + j33.2
2EE-DS-1 POWER CONSUMPTION	
7630 - 7840	22.6 + j17.1
7630 - 7840	22.6 + j17.1
Total consumption	45.2 +j34.2
2JJ-DS-1 POWER CONSUMPTION	
7630 - 7940	22.4 + j16.3
7630 - 7940	22.4 + j16.3
Total consumption	44.8 + j32.6
2JJ-DS-2 POWER CONSUMPTION	
7630 - 8010	23.9 + j17.3
7630 - 8010	23.9 + j17.3
Total consumption	47.8 + j34.6
2JJ-DS-3 POWER CONSUMPTION	
7630 - 8060	24.8 + j21.6
7630 - 8060	24.8 + j21.6
Total consumption	49.6 + j43.2

2.7. Fault level studies of Sasol Three network

Complete fault level study was not the object of this analysis, but some results were generated as the spin-off for the loadflow and stability study (see Appendix D). At the request of Mr J. Piorkowski, of Sastech, the fault level at the 132 kV bus was obtained from the short circuit studies and then this value was reduced by 20 %[the reason being that the switchgear at 2H4-SP-1 (switchplant) is rated at 35kA and the calculated short circuit current is 31.45 which is close to the design limit of the circuit breakers due to increased loads at Sasol Three system. As a matter of fact, my mentor, J Piorkowski, requested that this value be reduced by 20 % to provide safety margin for the operation of our switchgear]. The SLC required for this reduction in fault level was then calculated. Losses and voltage drop across this SLC were also determined.

Selection of current limiting reactor

The three phase fault current at the132 kV bus (7630) is **31.45 kA.** (see Appendix D). The fault level at that bus is given by,

$$S_{132} = \sqrt{3}\; I_{sc} V_n$$

i.e.,

$$S_{132} = \sqrt{3} \times 31.45kA \times 132kV$$
$$= 7.19 \times 10^{3}\; MVA$$

To reduce this value by 20 %, the desired short circuit level is,

$$S_d = 0.8 \times S_{132}$$
$$= 5.752 \times 10^{3}\; MVA$$

Using equation (2.4), the reactance per phase required to reduce an unacceptable symmetrical power to a desired value can be found

$$X_{(ohms)} = (132)^2 \times \left(\frac{1}{5752} - \frac{1}{7190}\right)$$
$$= 0.6058\Omega$$

On 100 MVA base,
The reactance required for each line is actually 1.2116 Ω.

$$Z_{(base)} = \frac{132^2}{100}$$
$$= 174.24\Omega$$

Hence the p.u. reactance to be introduced in the incoming lines is,

$$X_{(p.u.)} = \frac{X_{(ohms)}}{Z_{(base)}}$$
$$= 0.00695$$

From table 2.1, the imported power from Eskom was found to be *263 + j114 MVA* (i.e. 287 MVA).
The load current is,

$$|I_L| = \frac{S}{\sqrt{3} \cdot |V|}$$
$$= \frac{287 \cdot 10^6}{\sqrt{3} \cdot 132 \cdot 10^3}$$
$$= 1255.34\,Amps$$

Using equation (2.5), the voltage drop across the SLC will be,

$$V_{(drop)} = 1255.34 \times 1.2116$$
$$= 1520 \quad Volts$$

The percentage voltage drop introduced by each reactor will be,

$$\%\ Voltage\ drop = \frac{V_{(drop)} \cdot \sqrt{3}}{V_n} \cdot 100\%$$
$$= \frac{1520 \cdot \sqrt{3}}{132 \cdot 10^3} \cdot 100\%$$
$$= 1.995\%$$

Rating of the SLC will be,

$$SLC_{(rating)} = \sqrt{3} \times 1255.34 \times \frac{1520}{1000} \ KVA$$
$$= 3.304 \ MVA$$

To calculate the power losses on the reactor, the effective resistance of the reactor (SLC) should be known. These value can be calculated from the reactance to resistance ratio if that is given on manufacturer's data.

For the X/R ratio of say 30[2],

$$R = 0.04\Omega$$

Using equation (2.6) ,power losses will be,

$$P_{(losses)} = 189.1 \ kW$$

% power losses will be,

$$\%P_{(losses)} = \frac{P_{(losses)}}{P_{(imported\ from\ Escom)}} \cdot 100$$
$$= \frac{189.1 \cdot 10^3}{263.4 \cdot 10^6} \cdot 100$$
$$= 0.0718$$

The table below summarises the rating of the reactor to be selected in order to reduce the fault level by 20 % :-

Reactance (ohms)	V_{drop}	% V_{drop}	Current	Circuit Voltage	KVA rating
1.2116	1520	1.995	1255.34	132000	3304

ABB was consulted to find out whether it is possible that SLC with the above specification could be designed and manufactured. The results of the discussions are summarised below :-

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[2] In practice the X/R ratio of a reactor will be larger than this value, which will yield lower power losses across the reactor. Even though the X/R ratio of 30 has been assumed for calculation of power losses, the results indicate that the losses are less than 1%.

Results of the consultation with ABB[3]

In 1995, Mr Jens Birgesson, of ABB Johannesburg was consulted to find out about the feasibility of designing and manufacturing the SLC with the parameters provided in the above table. Since Sasol Three network is supplied via two overhead lines from Eskom, the calculated reactance was for both lines connected in parallel. The actual reactance of each line is double as shown in table above. This is the value of reactance that was introduced on each line for simulations of the Sasol Three system. Mr Birgersson confirmed that such a reactor can be designed and manufactured with more specifications to be included (such as cooling method, winding material etc.).

ABB Powertech Transmission and Distribution (Johannesburg branch) was recently consulted and also confirmed in writing that there is no problem in manufacturing such a reactor. They also provided the standard X/R ratio of the reactor with the above parameters to be 89. With this value, the power losses will be about nine times lesser than the one calculated above. X/R ratio of 30 requires that a de-Q-ing ring be installed which will dramatically increase the losses across the reactor due to the resistive nature of the de-Q-ing ring. The feasibility of this factor of 30 was further determined through the help of Mr K Palbot, ABB, and a conclusion was reached by the manufacturers that the assumed X/R ratio of 30 was not possible for the type of reactor specified in this thesis, hence this value was used for calculating whether the losses across the reactor were acceptable or not.

The estimated cost for manufacture and installation of such reactors is R1 321 106.00 (excluding VAT). The cost of these reactors need to be evaluated against the cost of replacing the Circuit breakers (in the near future)due to high interrupting capacity that will be required for operating the breakers.

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[3] see Appendix D for the comments from ABB regarding the reactor specified in this section

2.8. Summary

The industrial package used to perform the loadflow and dynamic studies has been described. Different types of faults and sources of short circuit currents were also described in this chapter.

The Sasol Three system was studied and analysed. Various aspects were covered in the investigation :loadflow studies were performed, the fault level at the 132kV bus was calculated and a short circuit limiting reactor was selected for the reduction of the fault level at the 132 kV by 20 %.

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CHAPTER THREE

REACTIVE POWER COMPENSATION

3.1. Introduction

This chapter provides the necessary background and the theoretical foundation on reactive power compensation. Reactive power compensation devices are also presented in this chapter. These devices can be grouped into two categories, namely, *passive and active compensators.*

Passive compensators include shunt reactors, shunt capacitors and series capacitors. These devices may be permanently connected or switched in and out of the power system. They operate by modifying the inductance and capacitance of the system. Passive compensations are used only for *surge impedance compensation* and *line-length compensation* [1]. For example, shunt reactors are used to compensate for the effects of distributed line capacitance and shunt capacitors are used to augment the natural capacitance of the line under heavy loading.

Active compensators are shunt connected devices that have the property of maintaining constant voltage at their terminals [1]. They generate or absorb the required amount of reactive power in response to any small variation of voltage. The reactive power limits of the compensators limit the capability of this devices. Synchronous compensators and Static Var Compensators (SVC) provide active compensation. They may be applied for surge impedance compensation or *compensation by sectioning.*

Reactive power compensation is an important method for achieving reactive power balances in power systems. It contributes to the steady state voltage control, reduction of losses and avoid unnecessary thermal loading of primary components. Reactive power compensation is necessary for reduction of temporary overvoltages and improve stability in long transmission lines. Stability improvement includes both rotor angle stability and prevention of voltage collapse.

The need for compensation originate from the behaviour of voltage and reactive power on an uncompensated transmission system. This behaviour is influenced by the system impedance, variable active and reactive load characteristics as a function of supply voltage, and the loading on synchronous machines. Table 3.1 provides information concerning ways of defining system's need for reactive power compensation.

The structure of this chapter is as follows :

Description of reactive power compensation devices is given. Then the principal applications of these devices in distribution as well as transmission systems are discussed.

Furthermore, reactive power compensation in distribution system is discussed.
The main advantages associated with distribution system compensation are outlined and discussed. This advantages are;

- steady state reactive power supply and control.
- reduction of voltage fluctuations.
- reduction of voltage drop during large motor start.
- prevention of voltage collapse.
- balancing of unbalanced loads.

Finally, reactive power control of Sasol Three system is discussed and the need for reactive power compensation of the Sasol Three system is investigated.

Table 3.1 Parameters for characterising system's need

- **Magnitude of compensation**
  - MVAr of production capacity.
  - MVAr of absorption capacity.
- **Speed of response for adjustable compensation**
  - changes required in a number of cycles or seconds.
- **Period of need**
  - continuous need.
  - short time need for specific duration.
- **Frequency of adjustment**
  - twice daily to follow typical load cycle.
  - once every half cycle of power frequency to control voltage flicker.
  - once every half second to follow typical synchronizing power swings.
- **Location of compensation**
  - point of greatest voltage variation even if no load is there.
  - near variable industrial loads.
  - near mixed loads.
  - near HVDC converter station.
  - near generators.
- **Phase voltage control**
  - balanced control - same on all three phases.
  - individual phase voltage control.
- **Short circuit contribution by compensators**
  - desirable.
  - undesirable.
  - no preference.

3.2. Compensation devices

In this section, different compensation devices will be described. These devices can be divided into two groups, viz., series compensation devices and shunt compensation devices. Series compensation device is made up of series capacitor while shunt reactor, shunt capacitor, synchronous condenser make up the shunt compensation devices.

3.2.1. Series capacitors

Series capacitor is a reactance compensation device that influence the reactive power conditions of transmission systems. Series capacitors have been used successfully to enhance stability and loadability of the high voltage *transmission systems.*

The principle of counteracting the inductive voltage drop in the line by inserting proportional capacitive voltage has proven to be technically sound and improved the transmission performance of the line.

Compensation technique using series capacitors is characterised by the following attributes :

(a) Series capacitor decrease the phase angle separation between voltages at the line terminal and increase the angle margin. Furthermore, the maximum power transfer of the line is increased in proportion to the inverse of the resulting compensated line reactance, i.e.

$$P = \frac{E_1 E_2}{X}\sin(\delta) \qquad \text{.......... (3.1)}$$

Figure 3.1 illustrates how stability is improved using series capacitors.

(b) Series capacitor is self regulating as the generated reactive voltage is proportional to the square of the line current. This leads to the reactive power generation increasing with the load increase and limited by the maximum acceptable voltage.

When series compensation technique is used for controlling the power flow in the network, the following aspects may be noticed :

* Series capacitor is an efficient means of controlling the power flow in the line [11] at the line terminal buses. Figure 3.2 shows the phasor diagram for the series compensated line of figure 3.1.

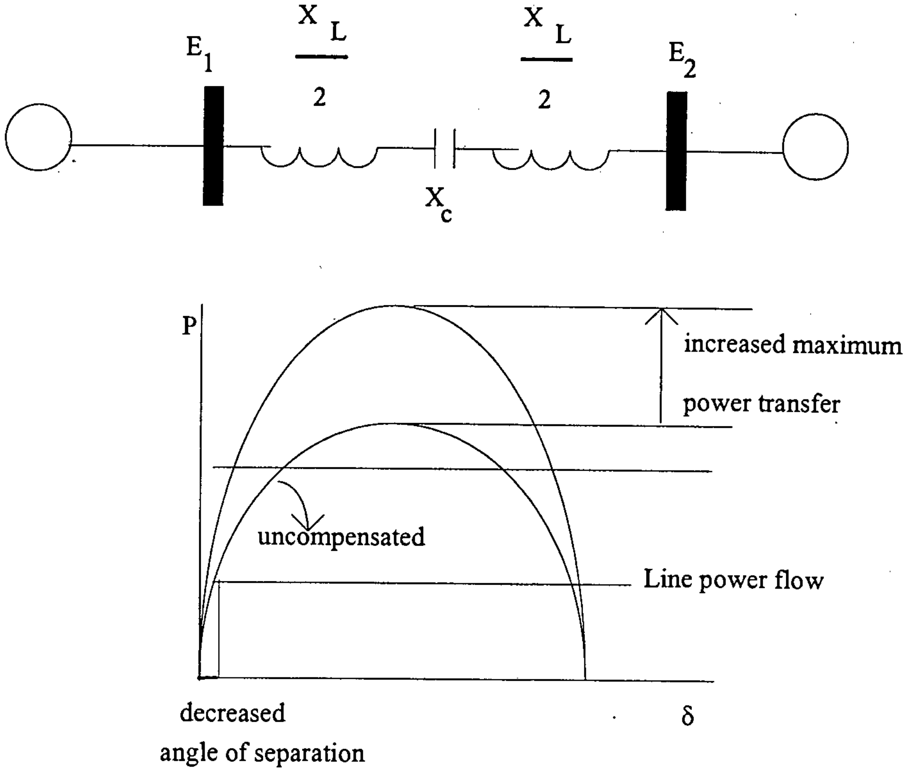


Figure 3.1 Stability improvement using series capacitors

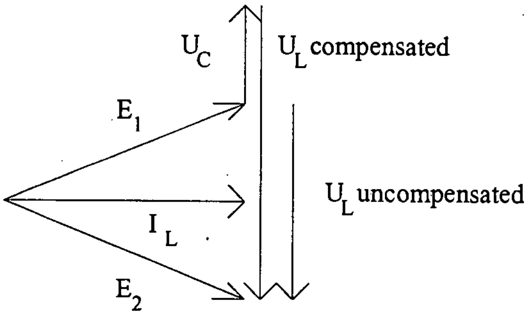


Figure 3.2 Phasor diagram of series compensated line

* A number of problems occur in transmission system as a result of the free-flow of power in uncontrolled network (e.g. low capacity usage of many lines due to uneven sharing of power between parallel lines while one critical facility is near its transfer capability) [10]. Inserting a voltage in series with the line has the advantage that the geographical location of the capacitor in the first

approximation does not have a significant influence of its performance from a power flow control standpoint.

* From figure 3.2, the voltage is in quadrature with the line current. In networks having sources with reasonably changes of degree of compensation, the line terminal voltages will be left unaffected.

Segmented capacitor

Most power system networks are used closer to their stability limits due to increase in power transmission systems. This led Power Industries to experience problems in making major additions to their networks.

Power industries have shown growing interest in controlling the power in their networks so as to improve the operating point of their system. This is achieved by using *segmented series capacitors.*

Detailed application background of this kind of power flow control is described in reference [12].

Problems associated with series capacitors

Application of series capacitors and problems associated with them are well documented in reference [8-11].

Some of the problems associated with their application are:

- Self excitation of large induction and synchronous motors during starting.
- Hunting of synchronous motors at light load, due to the high resistance to reactance (R/X) ratio of the feeder.
- Ferro resonance between transformers and series capacitors results in harmonic overvoltages.
- Limitation of level of compensation due to subsynchronous resonance.

Series capacitors are not widely used in today's distribution system because of the above problems and difficulties in protecting the capacitors from system fault currents.

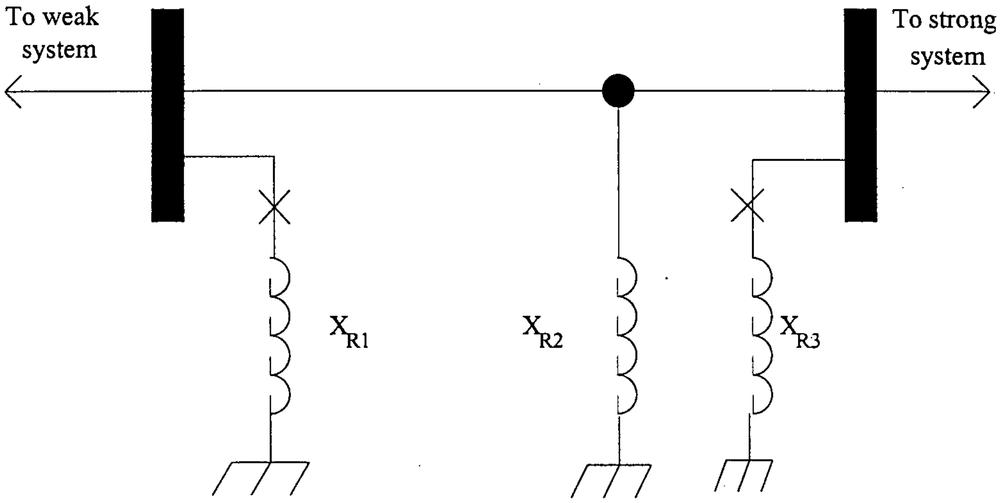
Most series capacitors are installed in 300 to 800 kV EHV transmission lines to increase transmission loading capability as determined by transient stability limits.

3.2.2. Shunt reactors

Shunt reactor is a reactor connected in shunt to a power system for absorbing reactive power.

Majority of shunt reactors are applied in conjunction with long EHV overhead lines. They are also applied in conjunction with HV and EHV underground cables in large urban areas.

Shunt reactors may be connected to the EHV bus as shown in figure 3.3 if used to maintain normal voltage under light load conditions [4]. They may also be connected to the tertiary windings of the adjacent transformers as shown in figure 3.4. During heavy loading, some of the reactor may have to be disconnected using circuit breakers(i.e. those that are mechanically switched).



X_{R1} , X_{R3} -- switchable bus connected reactor

X_{R2} -- permanently line connected reactor

Figure 3.3 Line and bus connected shunt reactors in EHV systems.

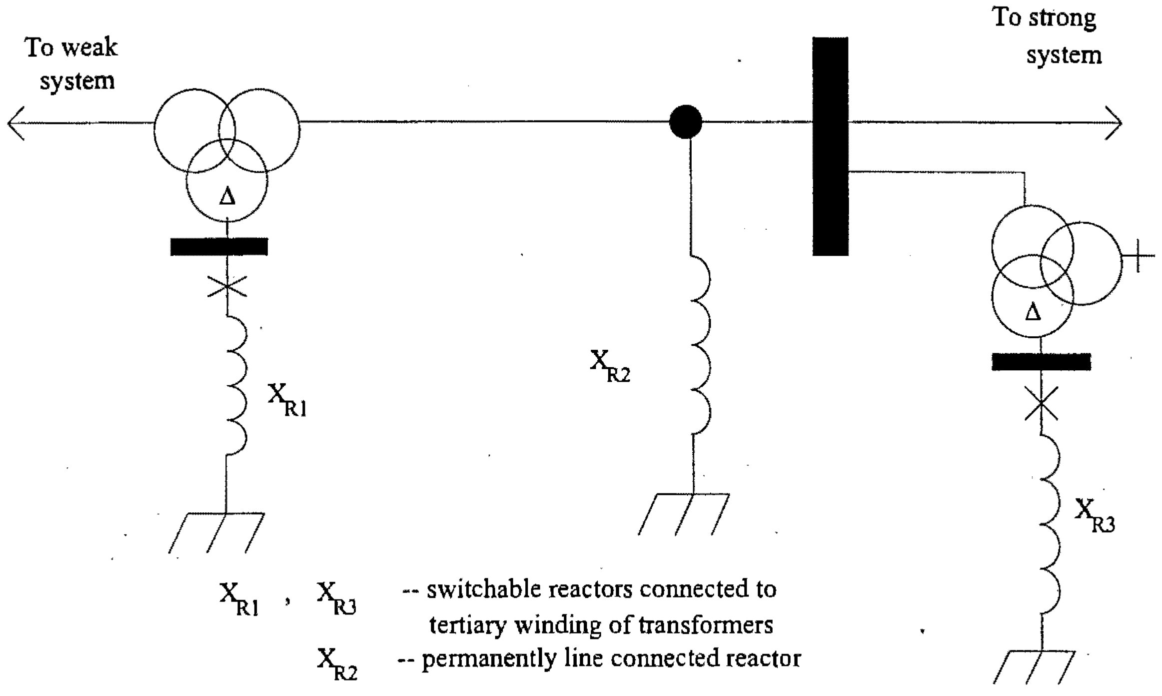


Figure 3.4 Line and transformer connected shunt reactors

Shunt reactors are similar in construction to transformers, but has a single winding (per phase) on an iron core with air gaps and immersed in oil .

3.2.3. Shunt Capacitors

A shunt capacitor is a single capacitor unit or a bank of capacitor units connected in shunt to a power system. They supply reactive power. The majority of shunt capacitors are applied within distribution systems of different types: industrial, urban and rural residences. Some capacitors are installed in transmission substations [3].

Shunt capacitors in use range in size from a single unit rated a few kVAr at low voltage up to a bank of units, rated hundreds of MVAr at EHV.

The principal advantages of shunt capacitor are their low cost and their flexibility of installation and operation. An unfavorable characteristic is that they provide least support during major outages and disturbances because their reactive power output is proportional to the square of the voltage.

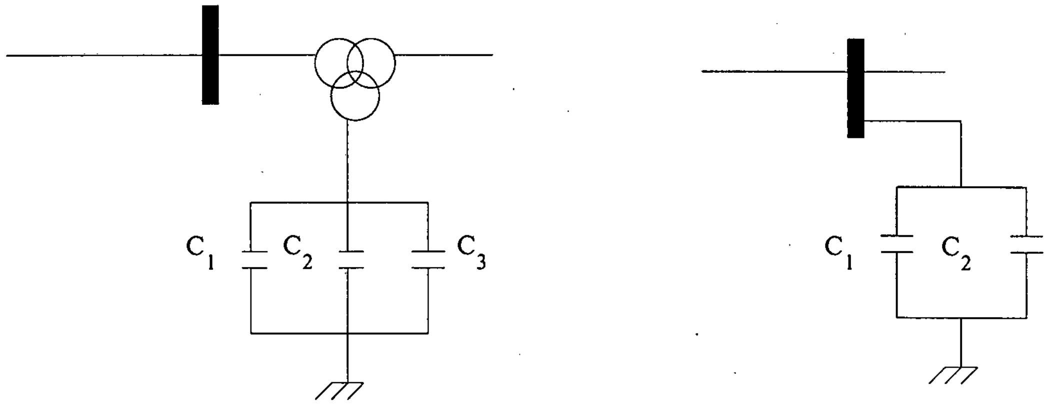
In distribution systems, shunt capacitors are used for power factor correction and feeder voltage control. Power factor correction is provided by means of fixed (permanently connected) and switched shunt capacitors at various voltage levels throughout the distribution systems.

Switched shunt capacitors are also installed at appropriate locations along the length of the feeder to ensure that voltages at all points remain within the allowable limits as the load changes.

In transmission systems, shunt capacitors are used to: -

- compensate the reactive power losses in transmission systems.
- ensure satisfactory voltage levels during heavy loading conditions.

Capacitor banks are connected directly to the high voltage bus or to the tertiary winding of the main transformer as shown in figure 3.5.



(a) Tertiary connected capacitor bank (b) HV capacitor bank

Figure 3.5 Capacitor bank connections

3.2.4. Synchronous compensators

A synchronous compensator is a synchronous machine running without a prime mover or a mechanical load.

Synchronous machines are used in transmission systems [13,14],

- at the receiving end of long transmissions.

- at HVDC inverter stations connected to weak systems.
- and in important substations.

Synchronous compensators are also installed in high power industrial networks[1]. They range in size from a few MVA up to hundreds of MVA. The rated voltage normally lies below 24 kV [3].

Synchronous compensators below 50 MVA are usually air cooled and above 50 MVA are hydrogen cooled. Modern synchronous compensators are equipped with a fast excitation system with a potential source rectifier exciter [3].

Synchronous compensators automatically adjust reactive power to maintain constant terminal voltage. This is achieved by the voltage regulator installed on synchronous machines. The reactive power production of synchronous compensators is not affected by the system voltage. They contribute to system short circuit capacity.

3.2.5. Static Var Compensators

A *static var compensator*(SVC) is an integrated system of static electrical components (e.g. capacitors, reactors, transformers and switches). These components are combined in such a manner to provide rapid, continuously controllable shunt reactive power compensation.

A *static var system* is an aggregation of SVCs and mechanically switched capacitors or reactors whose output are co-ordinated.

SVC has established itself as the state of the art concept for high performance reactive power compensation in transmission network. It is the latest developed means of reactive power compensation.

Since the early 1970s, ABB.[2] reported [30] more than 300 SVCs installed in distribution, industrial and transmission systems throughout the world. In most applications, the purpose of SVC is to provide voltage support for critical contingency situations in system operation [19-29]. Other applications include

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[1] e.g at the Sasol plant, three large synchronous machines are installed. They are rated at 37.3 MW, and two of 20.3 MW.

[2] Asea Brown Boveri company.

damping of power oscillations [21-24], voltage balancing [22,23,25], steady state voltage support and stabilization of voltage at fluctuating industrial loads [23-29]. For transmission system application, requirements on the SVC control range can be several hundred MVAr(e.g. the largest SVC on ABB. order was quoted at 650 MVAr or +325 MVAr to -325 MVAr). These larger SVC ratings are usually installed on EHV transmission systems.

The state of the art thyristor switch ratings extend only to about 34.5 kV hence coupling transformer is required. For smaller SVC ratings, a coupling transformer is unnecessary if a sufficiently rated transformer tertiary winding is available.

References [1, 4, 15-18] provide detailed description of the types, characteristics and selection of static var compensators.

Advantages of Static Var Compensators

- *Fast response time*

  Reactive power compensation of SVCs can be changed in 0.5 to 2 cycles of power frequency depending on the type of SVC [1]. In some cases, large voltage dips occurs during the first half second following a fault initiated system disturbance. The large voltage swings can be serious enough to threaten loss of large motor loads even if the system generators remain stable. The speed of response of a strategically located SVC can reduce these severe voltage swings provided the SVC is of appropriate capacitive rating. The high speed of response make the SVC superior to other forms of shunt compensation for preventing intolerable voltage swings.

- *Balanced three phase or individual phase control*

  Voltage swings due to repetitive fluctuating loads such as excavators, arc furnace etc., may require continuously acting voltage control. Switching on and off capacitors with mechanical switches is not practical for such loads. SVCs can be utilised to minimise the voltage swings on the system. SVCs can be cost effective in solving the problem of fluctuating loads if they are single phase or highly unbalanced three phase loads. SVC provide reactive power for compensation or control voltage differently in each phase depending on the type of SVC and how it is connected into the system. High speed and the ability to control each phase independently makes the SVC a device for solving flicker problems caused by arc furnaces [32]. However, economics of the alternatives will ultimately dictate the final choice.

- *Response to overvoltage and undervoltage*

  Another important advantage of an SVC that will be discussed, is their performance under conditions of very high or very low voltages.

  Sustained power frequency overvoltages can occur following major load rejections. These overvoltages can persist for a second or more if allowed to go uncorrected by additional reactive compensation means. SVC or switched reactor bank may be used to reduce these overvoltages.

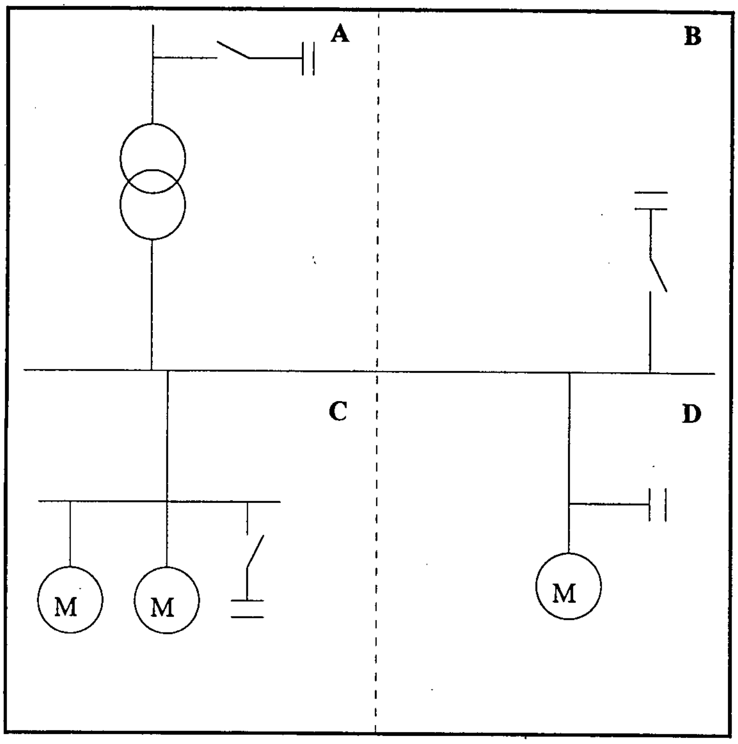
  Detailed discussions of these characteristics from the system point of view is carried out in reference [1].

3.3. Distribution system compensation

Distribution systems need reactive power to balance the reactive power consumed by the load and the net reactive power losses from the system. The required reactive power is supplied from one or more of the following sources :

- Transmission system
- Synchronous machines within distribution systems
- Shunt capacitors
- Static compensators

For long distribution systems, there is no universal applicable recommendation for the location and rating of shunt capacitors because of the large number of parameters involved and the many possible combinations of shunt capacitor equipment. Profitability evaluation of the above gains versus the capacitor costs has to be made, considering different constraints such as maximum size of switched banks with regard to voltage change, availability of space, etc. Figure 3.6 shows different capacitor locations.



A - central compensation on the high voltage side

B - central compensation on the low voltage side

C - group compensation

D - individual compensation

Figure 3.6 Industrial power factor correction capacitor locations

Distribution systems can be divided into urban, residential, rural and high-power industrial systems. The objectives of high power industrial system compensation will be considered most since this thesis is based on application of this compensation systems on Sasol Three network.

The objectives of distribution system compensation are :

- Steady-state voltage and reactive power control.
- Reduction of voltage fluctuations.
- Reduction of voltage drop during large motor starts.
- Prevent voltage collapse.
- Balancing of unbalanced loads.

Each of the above objectives will be briefly described below.

3.3.1. Steady state voltage and reactive power control

At Sasol three plant, the voltage is primarily controlled by means of on-load-tap changers of the step down transformer from the metering point and synchronous machines are used for reactive power generation .

Voltage can also be controlled by means of power factor correction devices. Power factor correction refers to the method of generating reactive power relatively close to the loads consuming it.

Power factor correction by means of fixed and switched shunt capacitors is extensively used in industrial distribution systems. The aim is one or more of the following, [7]:-

- To reduce power costs by avoiding low power factor penalty .
- To reduce active and reactive losses in distribution network.
- To release current capacity of transformers and cables.
- To increase the voltage level and, in cases of switched shunts, to improve the voltage regulation.

3.3.2. Reduction of voltage fluctuations.

Reactive power consumption fluctuations of unbalanced industrial loads (e.g. arc furnace) can be compensated by means of static compensators. Before the state of the art on static compensators, there were no good means for effective reduction of the rapid , unbalance voltage fluctuations.
Reference [32] describes the design of static var compensator for such loads.

In South Africa, Eskom encourages consumers with such loads to improve the power factor of their system by formulating tariffs so that it is worthwhile for such industrial customers to install reactive power compensation devices. For the Sasol system in Secunda, the tariff is based on a power factor of greater than 0.95 (i.e. Eskom agreed with Sasol that they will charge them using the so called *E-tariff system* if the power factor of Sasol is kept above 0.95).

3.3.3. Reduction of voltage drop during large motor starts

Starting of large induction motors in industries creates high inrush currents at low power factor thus causing voltage drop at motor terminal bus.

In the case where one or more large motors are installed in relation to the network short circuit capacity, these voltage drops may be objectional depending on their size and frequency of occurrence [3]. These voltage drops may disturb the performance of other loads in the other parts of the system.

One method of reducing the voltage drop due to large motor starting is to use a starting shunt capacitor which is disconnected during the running time. Static compensator may also be used in this regard.

3.3.4 Prevention of voltage collapse

Voltage collapse is defined as a severe voltage depression without inherent recovery. Voltages decrease to low voltages making the proper operation of the system impossible. This phenomenon may appear in both transmission and distribution systems.

It is a form of voltage instability caused by inadequate reactive power generation supplies. The process depends very much on the network configuration and the manner in which it is triggered.

It can usually be prevented by installing sufficient amounts of reactive power generation sources. In cases of conceivable slow voltage collapse, breaker switched capacitors can be used while in case of rapid voltage collapse, thyristor controlled static compensators can be used.

Detailed discussion of this phenomenon is provided in reference [17] and chapter 5 discusses the state of the art in voltage stability, voltage collapse mechanisms, characteristics of power system elements, analysis methods, sensitivities of voltage stability to system characteristics and methods used to prevent voltage collapse.

3.3.5 Balancing of unbalanced loads

Most AC power system are three phase and designed for balance operations. Unfortunately certain elements introduce unbalance in the electrical networks (such as thyristor switches, arc furnace , etc.). This unbalance operation creates components of current in wrong phase sequences (i.e. negative and zero sequence components). Such components have undesirable effects on the elements of the system (e.g. motors, generating units etc.).

Thyristor controlled static compensator with individual phase control is used to balance rapidly varying loads. The first static compensator in the world, using both TSC and TCR, was the Eskom compensator connected to the 132 kV system to balance the voltages [6].

3.4. Transmission system compensation

Transmission system reactive power control is of most importance under both normal conditions and major system disturbances. It is advantageous to operate the transmission part of the system with:

(a) fairly flat voltage profile to avoid unnecessary reactive power flows.
(b) relatively little supply of reactive power into the distribution systems.
(c) reactive power capacity reserves available for use during major disturbances and under generator, transformer or line outage conditions.

Reference [1,17,18,21] covers the theory of reactive power control of transmission systems in more detail.

3.5. Reactive power control of Sasol Three network

Sasol Three network consist of four generators that supply reactive power when overexcited. Due to interdependence between the system voltage and reactive power flow, the control of voltage and reactive power can be done in many ways. The voltage levels are regulated by tap changers of the step-up transformer while the reactive power balance is achieved by the excitation of the generators, or vice versa.

According to special agreement with Eskom, the reactive (MVAr) charge of the overall Sasol system[3] at the SOL substation is dropped if its power factor is kept above 0.95. In July 1994, the average power factor of Sasol Three System was 0.85 lagging (see Appendix E). This power factor is controlled by the 11/132 kV transformer tap changers with the generator output voltage kept constant at 11 kV by Automatic Voltage Regulators. This control is achieved because the 11 kV and 132 kV sides of the transformer are fixed thus any change in tap changer causes an internal reactive volt drop in the transformer.

Each of the four generators produces 40 MVAr of reactive power. In addition the oxygen plant air compressor motor produces 17 MVAr and the two methane compressor motors[4] produce 9.7 MVAr each (see Appendix E).

3.6. Application of Additional Reactive Power Compensation devices on the Sasol Three Network

Eskom supply tariff is based on 30 minute maximum demand (KVA) charge as well as a unit energy (KWh) charge (see Appendix E). It is the aim of this part of the thesis to investigate whether the provision of power factor correction capacitors could produce considerable annual savings for Sasol Three system.
This saving must of course be off set against the capital cost and loan charges for the purchase of such capacitors [37].

---

[3] Sasol system includes two mines, Sasol two and Sasol three.

[4] these motors are actually synchronous machines that absorb active power but produce reactive power due to excitation.

Calculations have been carried out to show the savings to be made using various degrees of power factor correction with different rates of interest and repayment time being considered.

In 1994, Sasol Three was billed on the E tariff at a unit charge of R52.50 and maximum demand charge of R 26150 per MVA. It is assumed that the interest charges are assessed at 10 % and 15 % with five year loan repayment period. The cost of capacitors is R4.00 per KVA.

Appendix F derives the general formulas based on total annual charges comprising the sum of demand charge and the cost of power factor correction equipments.

For Sasol Three System, the load active power is about 400 MW. The reactive power compensation required to correct the load to a power factor of between 0.95 and 1 is as shown in figure 3.7. The three graphs shown indicate different corrected power factor and the x-axis represent the present operating power factor.

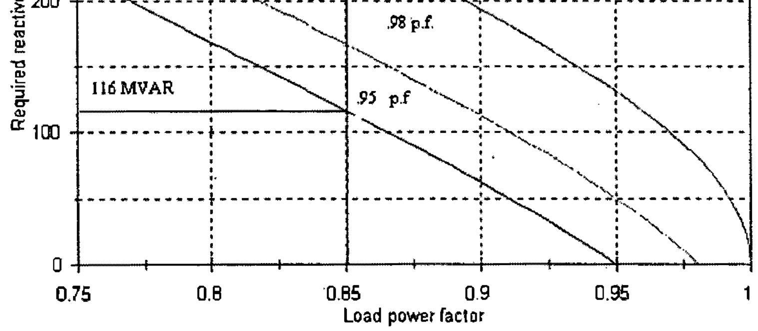


Figure 3.7 Power factor correction requirements for different load power factors

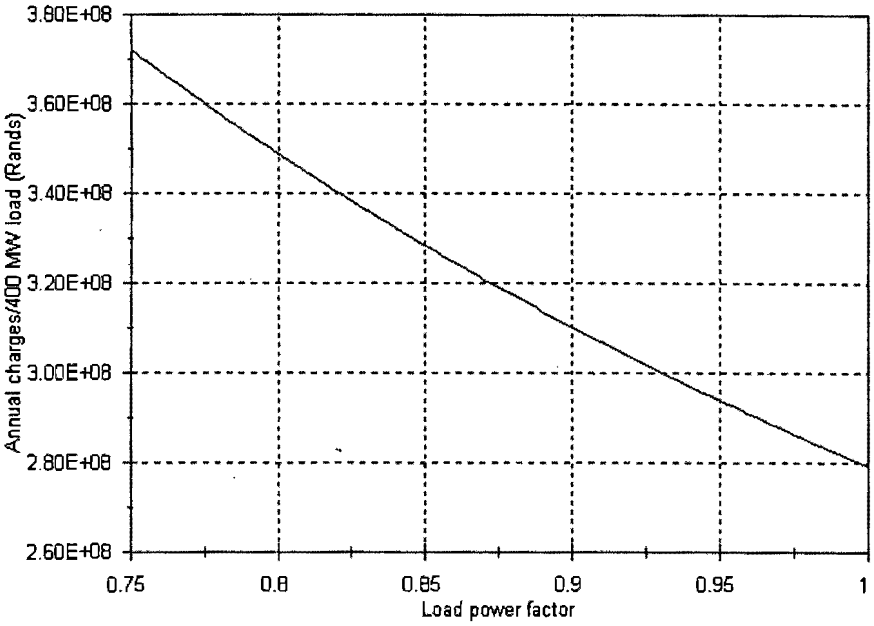


Figure 3.8 Cost of supplying 400 MW load at Sasol for different load power factors.

From figure 3.7, 116 MVAr is required to correct the 400 MW load operating at 0.85 p.f. to 0.95 p.f. To correct it to unity p.f., 250 MVAr is required. This shows the reactive power compensation required to correct 400 MW of load, at the factor of the abscissa axis to a compensated power factor of between 0.95 and unity, increases as the power factor is improved to a better value.

Figure 3.8 illustrates the annual charges for running the 400 MW load at the power factor of between 0.75 and 1. This graph is obtained by multiplying the annual charge/MVA with the total power per power factor (derivation of this formula is shown in Appendix F). From this graph, it is clear that the annual charge per 400 MW of load decreases with high power factor.

Figure 3.9 and 3.10 show the annual cost of maximum demand, annual cost of compensation equipment, total annual costs and annual savings with the installation of correction equipment for an interest charge of 10 % and 15 % respectively. Similarly, the equations derived in Appendix F were used to obtain these figures. From this graphs, it is clear that substantial savings can be realised by correcting to high power factor.

Disadvantages of applying capacitors or SVC's for distribution system

Disadvantages of applying SVC's or capacitors for power factor correction are well covered in [1], these are :-

- Shunt capacitors are fixed in value and are prone to switching transients.
- Thyristor controlled reactor (SVC type) generates harmonics and its performance is sensitive to location.
- Thyristor switched capacitor (SVC type) is prone to low frequency resonances with the system and its performance is also sensitive to location.

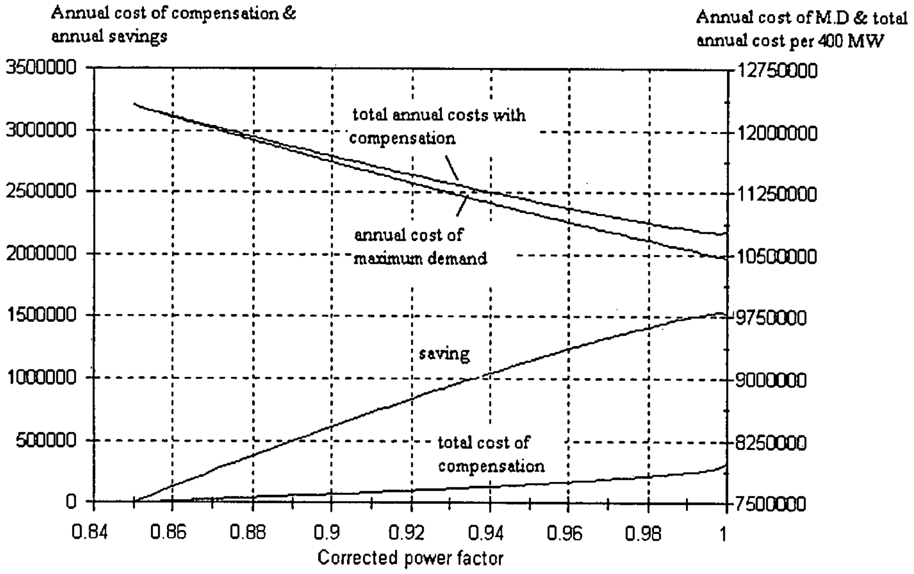


Figure 3.9 Annual savings with compensation equipment (10 % interest)

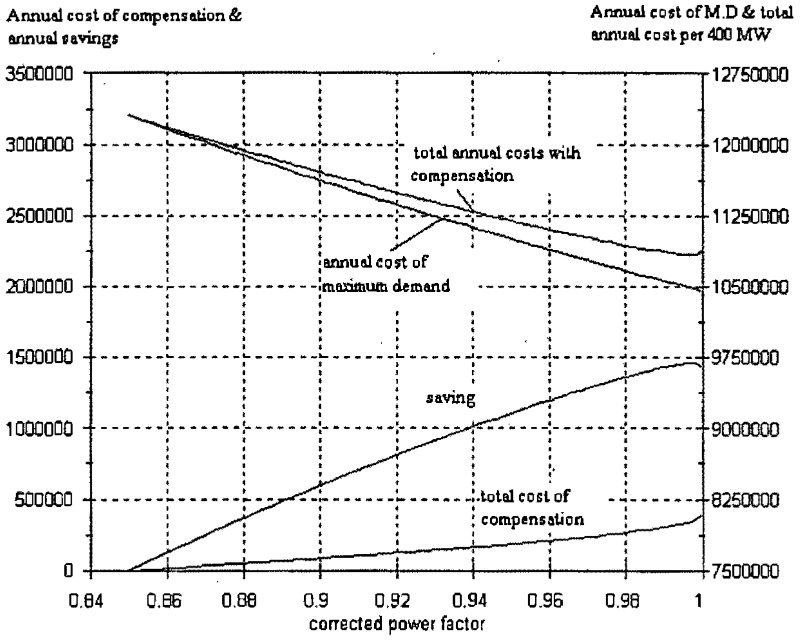


Figure 3.10 Annual savings with compensation equipment (15 % interest)

3.7 Summary

Reactive power compensation devices has been discussed in this chapter. Thyristor controlled static compensator has more advantages over synchronous condenser due to relatively lower operational costs.

By using reactive power compensation systems in distribution systems, the following aspect will be beneficial to industrial consumers :

- reactive power and voltage control will be achieved.
- reduction of voltage fluctuations.
- less cost of supply due to improved power factor.
- reduction of voltage drop during large motor start.

Reactive power control of the Sasol Three system has been discussed and it has been shown in this chapter that by improving the power factor at Sasol Three 132 kV busbar (2H4-SP-1) will save the company a considerable amount over some period. It is recommended that the power factor at the 132 kV busbar (2H4-SP-1) be improved to a high value - approaching unity by overexcitation of the generators to produce more reactive power. These could produce significant economies in costs.

There is no need to install additional reactive power compensation devices (such as SVC or switched capacitors) since the synchronous machines at Sasol can produce enough reactive power for power factor correction. More over, application of SVC's or capacitors may result in other adverse consequences on the network (e.g. harmonics, series resonant etc.).

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CHAPTER FOUR

TRANSIENT STABILITY

4.1. Introduction

System stability is a complex subject that challenged power system engineers for many years. *Steinmetz* [1] recognized the stability of power system as an important problem to system engineers. *Evans and Bergvall* [2] conducted the first laboratory tests on miniature system in 1924 and in 1926 [3-4], the first field tests on stability of a practical system were conducted.

This chapter provides an introduction to system stability concepts and modelling requirements. Different stability problems are outlined and their basic definitions are given. Furthermore, various methods used to improve system stability are discussed. Finally, transient stability of the Sasol Three network is analysed with the short circuit limiting reactor applied at the two 132 kV supply incomers. The reactive power requirements of the network during this condition is also evaluated. The extent to which transient stability of the network is attained is also determined.

4.2. Stability concepts and definitions

In power systems, stability refers to the ability of the system to move from one operating point to another stable operating point following a disturbance [2].
There are three types of stability problem: *Rotor angle stability, Voltage stability, Mid-term and Long-term stability*. These stability problems are closely related but for analysis purposes, they are studied separately. In this thesis, the first and second type of stability will be studied.

4.2.1. Rotor angle stability problem

Rotor angle stability is the ability of interconnected synchronous machines to remain in synchronism following a disturbance. The stability problem involves the study of the electromechanical oscillations in power systems.

Rotor angle stability is characterised by the following two categories :-

[a] Small-signal stability

It is defined as the ability of the power system to maintain synchronism under small disturbances. Small disturbances would include, among others, small variations in loads and generation.
Instability may result in two forms;

- Steady increase in rotor angle due to lack of sufficient synchronizing torque.
- Rotor oscillations of increasing amplitude due to lack of sufficient damping torque.

System response to small disturbances depends on number of factors including initial operating conditions, strength of the transmission system, and type of generator excitation control used.

[b] Transient stability

It is defined as the ability of the system to maintain synchronism when subjected to a severe transient disturbance. This chapter focuses on this category of angle stability that involves major disturbances such as loss of generation, line switching operations, faults and sudden load changes.

Stability depends on both the initial operating state of the system and the severity of the disturbance.

Dynamic stability has been used widely as a class of rotor angle stability. This term has been used to denote different aspects of the phenomenon by different authors. In North American Literature, it was used to denote small-signal stability in the presence of automatic control device which was different to classical steady state stability without automatic controls [6,7]. In French and German literature, the term has been used to denote transient stability. CIGRE and IEEE [8,9] recommended that this term should not be used to avoid confusion.

4.2.2. Voltage stability

Voltage stability is the ability of a power system to maintain steady state acceptable voltages at all the busses following a disturbance. It is characterised with lack of reactive power.

The problem is usually the voltage drop that occurs when active and reactive power flow through inductive reactances associated with transmission system [10-12]. Voltage stability will be discussed separately in chapter five.

4.2.3. Mid-term and Long-term stability

Mid-term and long-term stability are new types of stability problems in power systems. These types of stability were introduced to deal with problems associated with the dynamic response of power system to severe disturbances [13-18].

Severe disturbances result in large differences of voltage, frequency and power flows that may operate the actions of slow processes, controls and protections not modelled in conventional transient stability studies.

Long-term stability analysis assumes that inter-machine synchronizing power oscillations have damped out , the result being uniform system frequency [8,16-18]. The focus is on slower and longer duration phenomena that follows large system disturbances.

In *mid-term stability* studies, focus is on synchronizing power oscillations between machines including the effects of some of the slower phenomena and large voltage and frequency deviations [15,17].

Long-term and mid-term stability problems are associated with inadequacies in equipment responses, poor co-ordination of control and protection equipment, or insufficient active /reactive power reserves.

4.3. Power system models

To simulate a power system performance using digital computer, mathematical models of all system components are required. Detailed representation of these models determine the depth and complexity of the analysis. Reference [19] discusses modelling concepts for power system simulations in greater detail.

In system stability studies, the main system components that need accurate modelling are synchronous machine and their associated controls, loads and interconnecting networks. Transmission lines and transformers are usually modelled with their π-equivalent circuits, their fast electromagnetic transient are neglected.

4.3.1. Synchronous machine representation

Representation of generator models is very important when dealing with stability studies. This is because different generator models can lead to different transient stability results, thus leading to wrong conclusions from the viewpoint of system stability [11].

In PSS/E, there are four generator models that can be used. Each generator model use different parameters in direct and quadrature axis. Table 4.1 summarises the four generator models present in PSS/E [22]. At Sasol Three, non-salient pole generators are utilised. The generators have subtransient & transient reactances and includes saturation effects. From table 4.1, GENROU model is the most appropriate model that represent the generators at Sasol Three. Above all, this model is more detailed than the other two non-salient pole generator models in PSS/E.

Table 4.1 Generator models in PSS/E

Model	Xd	Xq	X'd	X'q	X"d	X"q	X_l	T'd0	T'q0	T"d0	T"q0	Sat factor
GENCLS			*									
GENTRA	*	*	*					*				*
GENROU	*	*	*	*	*	*	*	*	*	*	*	*
GENSAL	*	*	*		*	*	*	*		*	*	*

From the table;

X_d, X_q -direct and quadrature axis synchronous reactance
X'_d, X'_q -direct and quadrature axis transient reactance
X''_d, X''_q -direct and quadrature axis subtransient reactance
T'_{do}, T'_{qo} -direct and quadrature axis open circuit transient time
T''_{do}, T''_{qo} -direct and quadrature axis open circuit subtransient time
Sat. facto -saturation factor of the generator

GENCLS is the classical generator model represented by a constant internal voltage E' behind its direct axis transient reactance X'_d. This model assumes positive sequence conditions and the machine excitation is constant. Furthermore, the model neglects losses, saturation, saliency, field and damper windings.

GENTRA is the generator model that includes the field windings in the direct axis only. This model assumes that the saturation affects the direct axis reactance only. The mutual inductances vary as a function of the flux linkage E'_q, behind a transient reactance. Furthermore, the model neglects damper windings.

GENROU is the non-salient pole generator model that has two damper windings in the quadrature axis, a field and damper winding in the direct axis. This models assumes that the saturation affects both the direct and quadrature axis reactances. Furthermore, the mutual inductances vary as a function of the flux linkage behind the subtransient reactance.

GENSAL is the salient pole generator that has a field winding and a damper winding in the direct axis, a single damper winding in the quadrature axis. The model assumes that the saturation affects both the direct and quadrature axis reactances as in the previous model. Furthermore, the mutual inductances vary as a function of the flux linkage behind the subtransient reactance.

Detailed implementation of generator model for transient stability studies is provided in reference [20].

4.3.2. Excitation system representation

All synchronous machines have a voltage control unit or excitation system to control the generator output or terminal voltage. The excitation system controls the generated emf and therefore controls the generator output voltage, power factor and the current magnitude.

There are different types of excitation system models that are present in PSS/E. Sasol Three generators make use of the IEEE Type I excitation system (figure 4.1 illustrates this model). The other types of excitation systems (i.e in PSS/E) are not relevant to the model of Sasol Three system because;

- The source used for the excitation system stabilizing feedback differ.
- In some cases, the voltage regulator's source of supply is the generator or auxilliary bus voltage. As a result , the regulator output limits are proportional to the terminal voltage (VT).

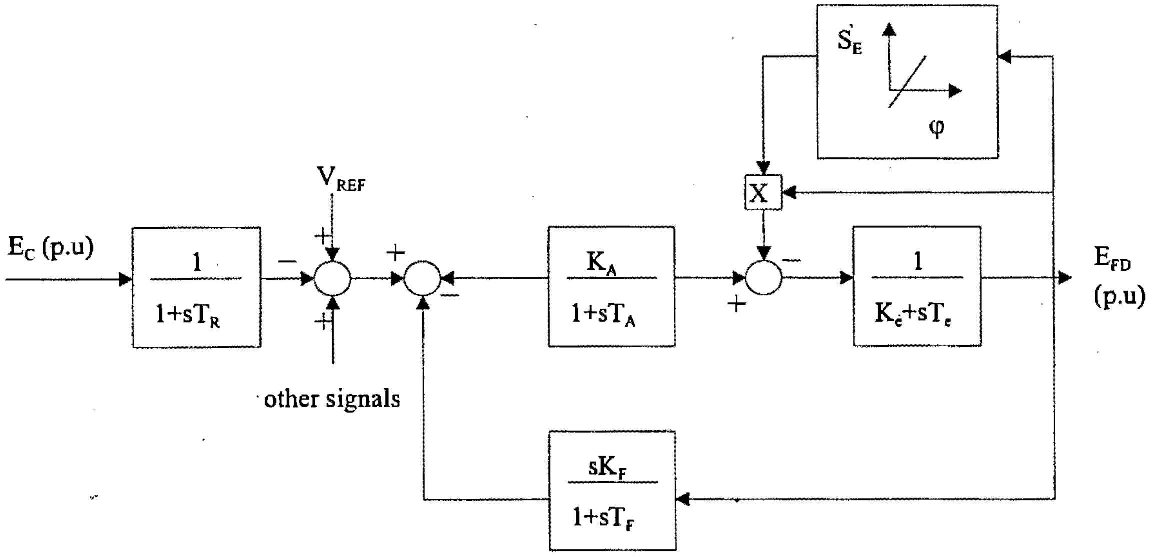

Figure 4.1 IEEE Type I excitation system[22]

For this model, the generator terminal voltage is first filtered by a first order system before it is taken as the input to the AVR. This filter has a time constant of T_R, which is usually very small and often approximated as zero in some studies. Furthermore, the effect of saturation in the exciter is taken into account by the saturation function, i.e.

$$S_{FD} = f(E_{FD}) \quad \text{(4.1)}$$

References [21,22] provide detailed descriptions of the different types of excitation systems.

4.3.3. Load representation

Load characteristics have an important influence on stability. Modelling of loads is complicated because typical load bus represented in stability studies is composed of a large number of devices (e.g. refrigerators, heaters, compressor motors, furnaces etc.). Load composition changes depending on many factors including *time, weather conditions and state of the economy.*

It is impractical to represent individual loads as there are millions of such loads in the total load supplied by the power system. Load representation is based on considerable amount of simplification in power system studies.

This section of the thesis discuss the two different types of loads (i.e. static loads and dynamic loads). For static loads, different loads will be outlined and discussed. For dynamic loads, emphasis is on aggregation of induction motor loads.

Static loads

Static loads can be expressed by polynomials or some algebraic functions like exponentials. This kind of loads are either voltage dependent, frequency dependent or both.

There are four ways of representing power system loads. These are *constant power representation, constant admittance representation, constant current representation , and voltage and frequency sensitive load representation.*

Constant power representation

Active and reactive power are assumed to remain constant during and after the disturbance. The equation expressing this representation can be written as ,

$$S = V \cdot I^{*} = P + jQ \qquad (4.2)$$

This representation is suitable for steady state calculations under the assumption that the load voltage is kept constant by LTC transformers or by reactive power compensation system.

Constant admittance representation

Complex power is directly proportional to the square of the voltage so that the impedance is constant. The equation expressing this representation can be written as,

$$Y = \frac{S^{*}}{|V|^{2}} \qquad (4.3)$$

where Y represents the equivalent shunt admittance of the load.

Frequency and voltage sensitive representation

The load varies with changing voltage and frequency. The general equation that express this kind of load representation can be written as , [11]

$$\frac{S}{S_0} = A\left(\frac{V}{V_0}\right)^{a}\left(1 + K_{sf}\,\Delta f\right) + B\left(\frac{V}{V_0}\right)^{b} \qquad (4.4)$$

where,

$S_0 = P_0 + jQ_0$, initial bus active and reactive power
V_0, initial bus voltage magnitude
a , voltage exponent for frequency dependent part of the load
b , voltage exponent for non-frequency dependent part of the load
K_{sf}, frequency sensitive coefficient of the load

Δf , frequency variation
A and B are constants

Constant current representation

Complex power is directly proportional to the voltage so that the current is kept constant. The equation expressing this representation can be written as,

$$I = \frac{S^*}{V^*} \qquad (4.5)$$

where I is the load current. When the voltage deviation is very small, the constant current load model gives very good results.

From the above discussions, it is very important to model static load accurately in power system. The stability limit decrease when the load is modelled as constant power [44] for loads that are remote from generating units, and the limit increase for load near generating units. Hence, for accurate load modelling, the type and location of the load should be taken into consideration.

Dynamic loads

Dynamic loads vary considerably with changes in voltage and frequency. Frequency deviation is caused by an imbalance between the electrical output of the generators and the power demand by the loads. The deviation changes the active and reactive power taken by the load, and the active and reactive power losses. This changes the voltage at the load bus .

Studies [45-47,49] have shown that proper modelling of loads plays an important role in the overall dynamic response of power system. Since induction motors constitutes a large portion of industrial power system loads, it is necessary that its model is accurately represented in dynamic and transient stability studies.

Techniques for simulating the response of individual motor to power system disturbance are well known [45-49] and have been implemented in transient stability programs. However, load at a particular bus may include many types of induction motors, each with different dynamic characteristics and different steady state operating conditions.

Figure 4.2 shows the model of a single cage induction motor. The parameters of this dynamic load model can be determined using the induction motor (IMD) program in PSS/E.

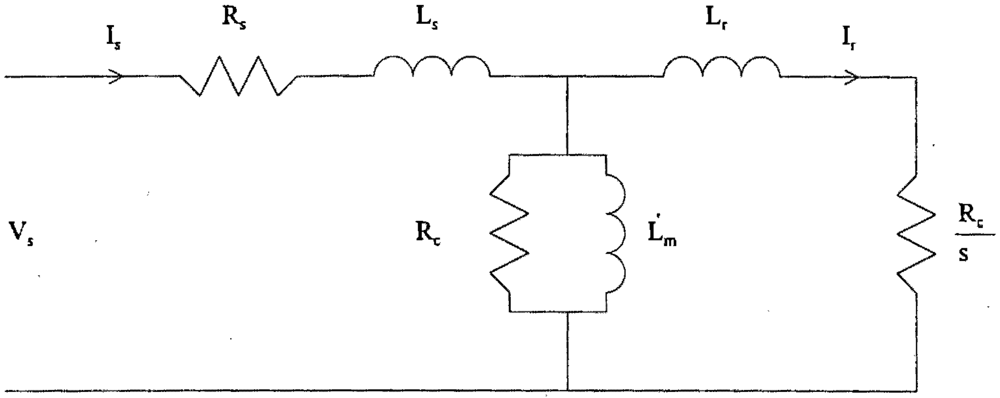

Figure 4.2 Representation of the single cage induction motor

Literature review

Brereton et al [47] developed a third order model for induction motors. They used various methods of representing induction motor loads on power system stability studies, and simulated the electrical transients of the rotor circuits by a voltage behind a transient reactance.

Iliceto and Capasso [50] used the method of reference [47] in their analysis. They investigated the influence of rotor time constants and rotor inertia constants on dynamic characteristics of power system loads, and calculated the parameters of the aggregate motor as the weighted average of the individual motor parameters according to their kVA[1] ratings.

Abdel Hakim and Berg [49] suggested an aggregation method for induction motors based on steady state performance. The motor circuits are connected in parallel and then reduced to a single equivalent circuit representing the individual motors.

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[1] rated power of the motor

Recently, *de Kock* in his Ph.D. Thesis [51] applied the output error method to determine the equivalent parameter values for a group of induction motors. His results support Illiceto / Capasso [50] theory regarding the equivalent transient time constants.

4.4. Analysis methods

At present the most practically available method of transient stability analysis is the time domain simulations in which the non-linear differential equations are solved by using step by step numerical integration techniques.

References [21,23-25] describe this method in more detail.

4.5. Methods of improving system stability

The preceding sections described the aspects of various categories of power system stability, modelling requirements and analysis methods. This section describes methods used for enhancing transient stability.

♦ High speed fault clearing

The quicker the fault is cleared, the less disturbance it causes because the amount of kinetic energy gained by generators during faults is directly proportional to fault duration.

Reference [26] describes the application of one cycle circuit breaker for enhancing transient stability following a large disturbance.

♦ Regulated shunt compensation

Shunt compensation can improve system stability by increasing the flow of synchronising power among generators (i.e. synchronous compensators and SVC's).

Synchronous compensator

Synchronous compensator can be utilised to stabilise the voltage in the system during system oscillations, by means of pure voltage control. Reference [58] provides the application of a 345MVA synchronous compensator used to provide voltage control and helps maintaining transient stability during disturbances at Dumont substation.

Static Var Compensator

Static var compensators can be utilised to improve the stability of transmission system as demonstrated in references [52, 57].

♦ Dynamic braking [27-30]

Dynamic braking uses the concepts of applying artificial load during a transient disturbance to increase the electrical power output of generators hence reducing rotor acceleration.

Reference [30] provides reports of braking resistor applications in Japan, China, Russia and Australia. Braking resistors have been applied only to hydraulic generating stations that can be temporarily separated from load areas. When a separation occurs, the braking resistor is inserted into the generation area for a second or two, preventing or slowing acceleration in the generation area. Shelton et al [29] describe a 1.4 GW braking resistor.

◆ Single pole switching

Single pole switching uses separate operating mechanisms on each phase. Only the faulted phase is tripped followed by fast reclosure within 0.5 to 1.5 seconds. For three phase faults, all three phases are tripped.

Single pole switching is attractive for situations where a single major line connects two systems. The problems associated with this method of improving stability are;

- secondary arc extinction.
- fatigue duty on turbine-generator shafts and turbine blades.
- thermal duty on nearby generators due to negative -sequence currents.

Detailed description of the above problems related to single pole switching are covered in references [31-34].

Single pole switching with regard to Sasol Three network

Historic background

During the design phase of Sasol two project, prior to the start of construction , considerable attention was paid to the need for an assured power supply to the plant and to the stability of the power system network.

To assure continuity of supply it was decided that at least a dual feed from Eskom was necessary as in the initial conceptual design. A plant with a base running load of 740 MVA was envisaged without any in plant generation capacity. Management's overall intent being that all electric power necessary would be drawn from the Eskom system.

The power system network design thus proceeded on the assumption that it would be prudent to provide three parallel incoming 132 kV feeders from Eskom system. the source of this power being by step-down transformation from the Eskom 400 kV grid at a substation located in close proximity to the Sasol two side. It was recognised that the plant would be geographically situated in an area of the country subject to an extremely high lightning incidence level, and the Eskom overhead transmission lines would be subject to outages resulting from both direct lightning strikes and induced surges. Some consideration was given to the use of auto-reclosure schemes on Eskom transmission line feeder breakers particularly on their 400 kV network (Eskom have in fact within recent years introduced single phase auto reclosure practice in their 400kV network).

Eskom faced with meeting a base load power demand of 750 MVA dictated that they were only willing to provide a bulk supply at a voltage of 132 kV. As the detailed plant design firmed up and the quantity of coal fines (resulting from the stock piling of coal and coal handling methods employed) became known, project management was forced into the introduction of additional boiler plant to get rid of the fines and this in turn led to the introduction of in-plant power generation.

The magnitude of the plant load also forced the design of the in-plant power reticulation onto a 132 kV underground cable feeder basis and the use of an intermediate 33 kV distribution system for supply of power to individual process plant units. From an electrical design point view it was also anticipated that the shear size of the plant being built and the nature of the process would result in excessive atmospheric pollution. This motivated the use of indoor 132 kV SF_6 insulated switchgear (GIS) in the main 132 kV distribution substation. The switchgear selected for use in this substation was of Siemens design with all the equipment housed in three phase enclosures (other manufacturers offered phase segregated switchgear but this was considerably larger in size and more expensive at the time).

Final outcome

When finally purchased, the 132 kV switchplant layout consisted of tripple bus bar system with 3 tie breakers in a delta busbar configuration with only two incoming 132 kV feed from Eskom and with four incoming feeders from inplant generators. As each of the Eskom incoming feeders was sized to meet the full Sasol Two power demand (after discounting the inplant generation capacity). The loss of either Eskom feeders does not limit production under normal plant operating conditions.

No further consideration was then given to the use of single phase auto reclosure on the 132 kV Eskom incoming feeder lines, probably because the Siemens three pole SF_6 circuit breaker did not have this design feature or if the circuit breakers with single phase reclosure mechanisms were available, their cost was prohibitive. At any rate the probability of simultaneous failure of both Eskom incoming feeders was considered to be remote. (Subsequent experience proved this to be too optimistic - several years ago a veld fire resulted in simultaneous outage of both lines). The two 132 kV Eskom feeder lines are however comparatively short (roughly 7 km in route length), their exposure to veld fires is thus limited particularly if the veld grass in the line servitude is routinely cut.

The Sasol Three power network was an exact copy of the Sasol Two with some design improvements, thus single pole switching was not considered during the design phase of this network too due to the reasons mentioned in this section. Above all it is not economically feasible to consider single phase switching now because that will require new 132 kV single phase breakers and more physical space will be required to house this equipments which is a limiting factor at 2H4-SP-1 substation.

♦ Reduction of transmission system reactance

Reduction of reactances of various elements of the transmission system improves transient stability by increasing synchronising power transfers. Network reactances can be reduced by;

(a) using transformers with lower leakage reactances.

(b) series capacitor compensation of transmission lines.

Series capacitors has been used successfully to enhance the stability and loadability of the high voltage transmission networks [35,36].

Chapter three described how series capacitors increase the stability of the system.

♦ Independent pole operation of circuit breakers

Independent pole operation refers to the use of separate mechanisms for each phase circuit breaker so that each phase is closed and opened independently. This method of enhancing stability is advantageously applied where system design criteria include three phase fault compounded by breaker failure.

Reference [21] describes this methodology in more detail.

♦ Fast responding , high gain exciters

Modern machine excitation systems with fast thyristor controls and high amplifier gains (to overcome generator saturation) can rapidly increase generator field excitation after sensing low terminal voltage during faults. The effect is to rapidly increase internal machine voltages during faults, thereby increasing generator output power during fault and post-fault [37].

♦ Fast valving

Fast valving is applicable to thermal units to assist in maintaining transient stability of the system.

For faults near generators, the electrical power is reduced and the fast valving action acts to balance the mechanical and electrical power by providing reduced acceleration and longer critical clearing times.

References [38-41] provide the basic concepts and effects of fast valving.

♦ Reactor switching

Shunt reactors near generators provide a simple means of improving transient stability. The reactor is normally connected to the system and switched out following a fault. This improves stability.

Reference [21] provides detailed description and application of reactor switching for enhancing transient stability.

♦ Controlled system separation and load shedding

Controlled system separation is applicable to interconnected system. Part of the system is separated to prevent a major disturbance from propagating into the rest of the system.

In some cases, it is necessary to shed loads in order to balance generation and load in the separated systems.

References [42,43] describe the application of load shedding to maintain transient stability in power systems.

4.6. Transient Stability of the Sasol Three network

This study comprises of dynamic elements models and the actual simulations of the Sasol three network. The results of the simulations for the recovery of the system after line and bus faults are presented. Only the most important results will be shown in the text. More results are shown in the Appendices.

The Sasol Three generator models includes subtransient, transient and saturation effects. From PSS/E package, *GENROU* was used to carry out transient stability studies because it is much more detailed than the other two non salient pole generator models and the faults that are simulated are closer to the generator buses. The exciters are of IEEE Type 1 (see figure 4.1) and the governor system consists of speed governors and single stage non-reheat high pressure steam turbines. The synchronous motors are modelled in the same way as the generators except that they absorb active power. The exciters of the synchronous motors are of static type (i.e. IEEE Type 1S [22, 54]). The synchronous motors at Sasol Three do not have governors. Inertia constants of the synchronous motors were obtained from reference [55].

For motors larger than 2 MW, a double rotor cage model with subtransient, transient and saturation effects was used. For smaller motors, a static load model was used by lumping all the individual motors connected to the respective bus.

Reference [56] provides a complete list of all the dynamic models and parameters used in this study.

The simulations involves disturbances in the form of three phase faults at the 132kV busbar at Sasol Three (2H4-SP-1). This busbar faults are cleared by the bus zone protection scheme which initiates the tripping of all the breakers connected to the busbar. The faults are cleared after 5 cycles.

The PSS/E dynamic analysis program (PSSDS4) allows the whole Sasol Three network operating point to move if a disturbance is applied to the network. Initially the Sasol Three network start at the steady state operating point determined by the loadflow and thereafter the network operating point change as the frequency of the network changes which moves the reference angle of the network. The actual movement of the Sasol Three network is shown in Appendices G to I.

4.6.1. Simulation One

This simulation involve a 3 phase fault at bus number 7630. This is done to determine the stability of the system before SLC is applied on the two 132 kV incomers to the Sasol Three network. The fault was cleared after 5 cycles.

The relative rotor angles of the synchronous machines and the bus voltages affected by the event are presented in figure 4.3a and b.

From figure 4.3a, it is very clear that the effect of the fault on synchronous machines is fairly small. Generator excitation system help to stabilise the generators within 1.4 seconds after the fault. Generators are within their stability limits. Synchronous motors are also within their stability limits and their load helps to dampen the oscillations as shown in the figure.

From figure 4.3b, the voltage at bus number 7630 dropped to zero, recovered to 0.752 p.u. in 5 cycles and to 0.905 p.u. in 12.5 cycles after the fault was cleared (this is highlighted on figure 4.3b).

Figure 4.3c shows the response of the motor slips due to the event. The motor slips dips immediately after the fault and then recovers within 35 cycles.

The stability of the 35 MW synchronous motor is illustrated in figure 4.3d. The diagram shows the phase plot of the motor relative angle/speed relationship following the fault. After the fault is cleared, the trajectory of the angle and speed of the motor circles inward and return to the pre-disturbed operating point.

The speed of the generators increases during the fault and after the fault it recovers to its predisturbance value. For the synchronous motor, the speed drops during the fault and then recovers after the fault is cleared (see Appendix G).

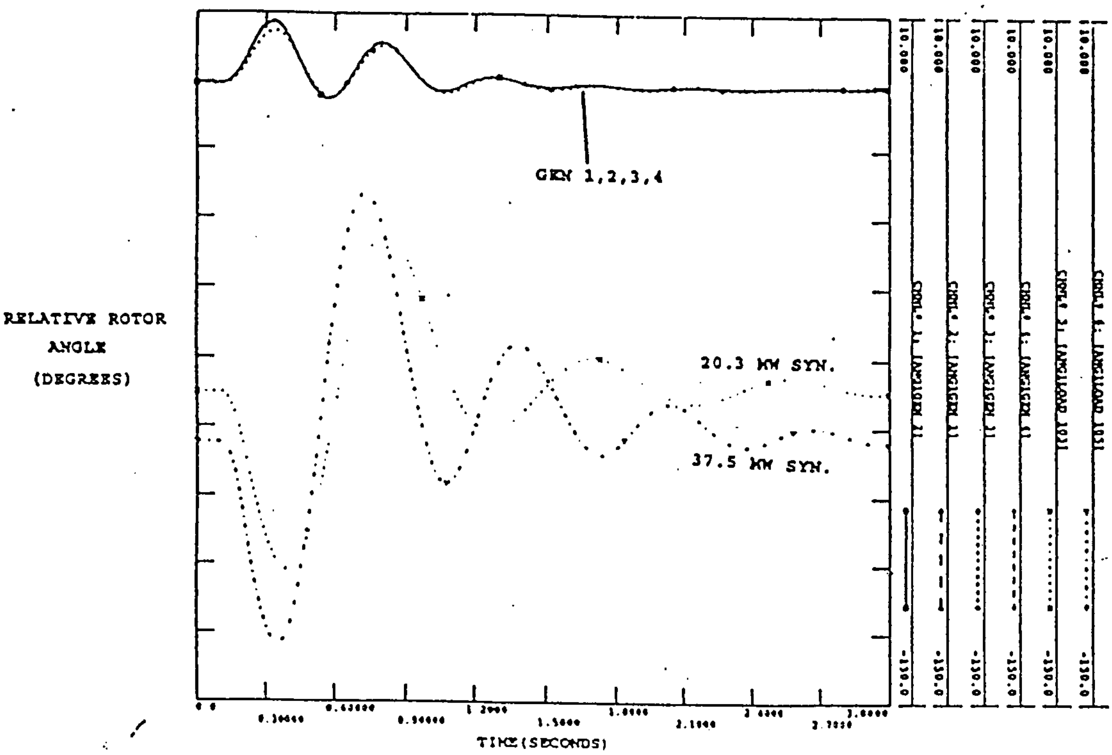

Figure 4.3a The relative rotor oscillations of Sasol Three synchronous machines after a fault at bus number 7630

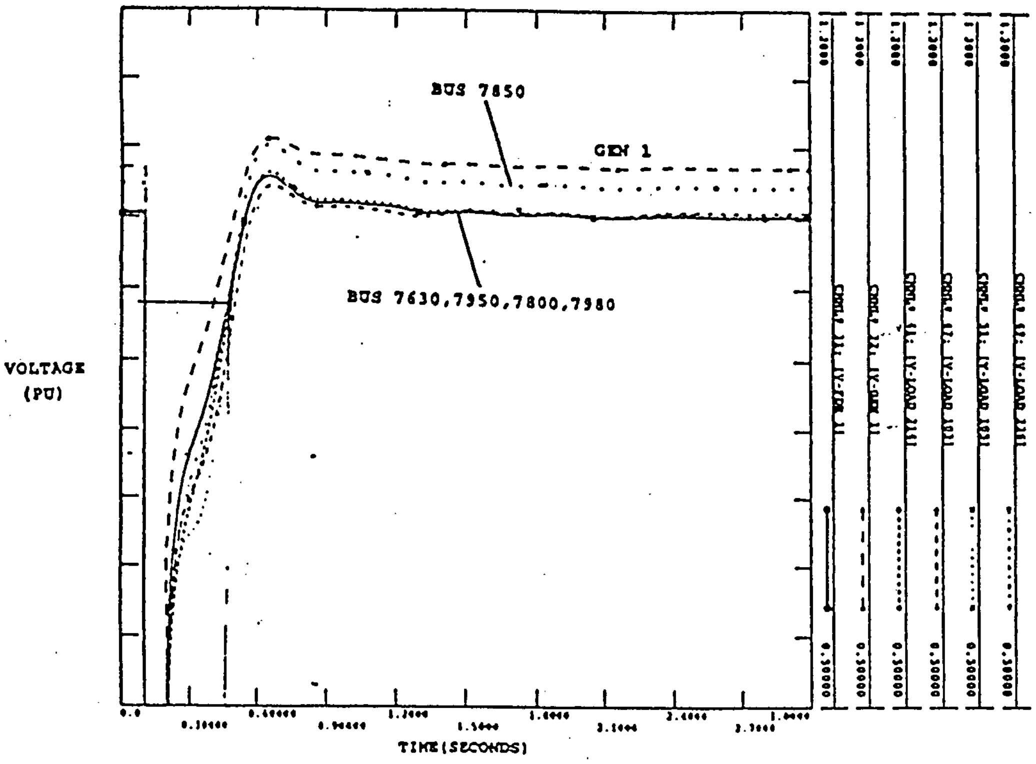

Figure 4.3b Recovery of the 11, 33 and 132 kV voltages at Sasol Three after a fault at bus number 7630

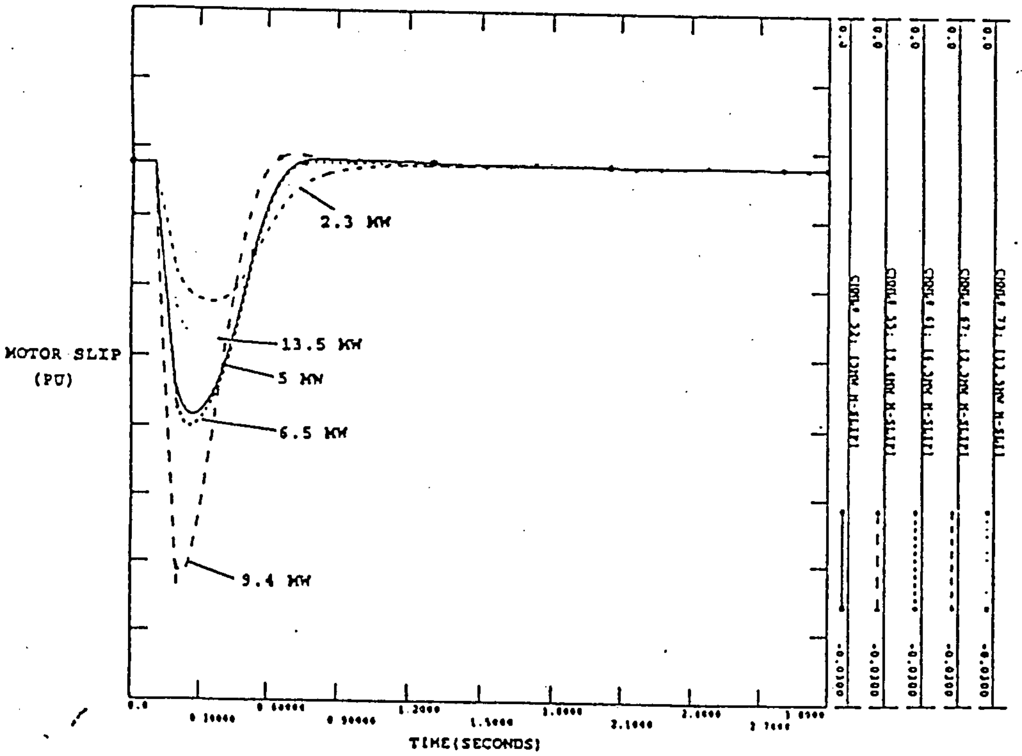

Figure 4.3c Slip response of the large induction machines of Sasol Three after a fault at bus number 7630

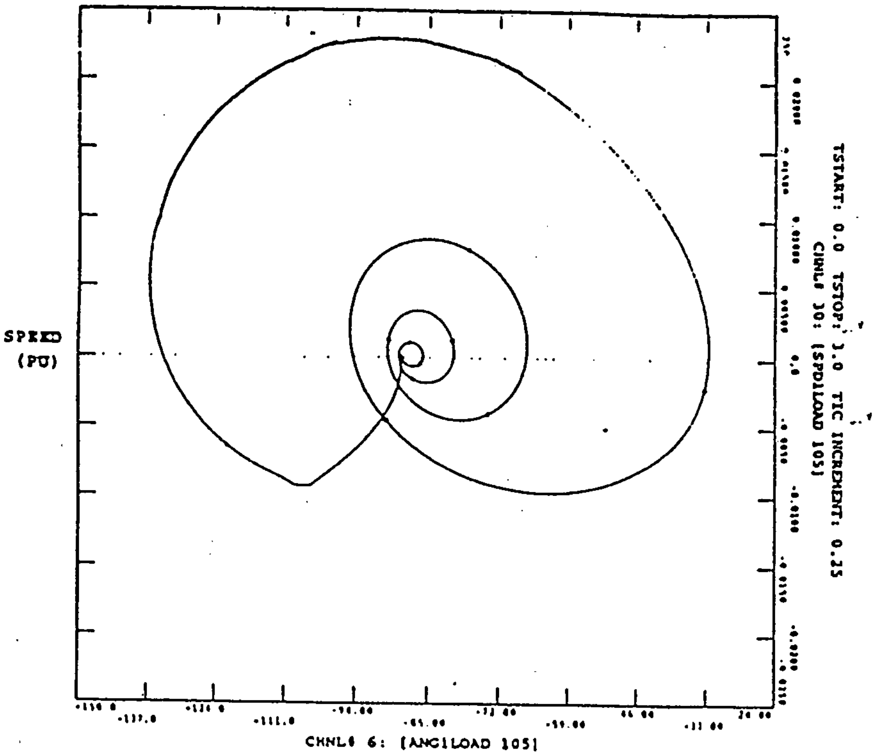

Figure 4.3d Angle/speed trajectory of the 37.5 MW synchronous motor after a fault at bus number 7630

4.6.2 Simulation Two

In this simulation a 3 phase fault is applied at the 132 kV busbar (bus 7630) of Sasol Three network. The fault was cleared after 5 cycles. The system was simulated with SLC applied at the two 132kV incomers to Sasol Three. The simulation is similar to simulation one.

The relative rotor angle of the synchronous machines affected by the event are presented in figure 4.4a and b. The simulation time was extended to five seconds in order to evaluate the stability of the system over a long simulation time (it was not clear about the system stability when the simulation time was three seconds).

From figure 4.4a, the first swing of the machine following the fault is similar to that without SLC. This is because of the increased impedance from the supply due to the reactance of the SLC being relatively small.

Figure 4.4b shows the response of the 20 MW synchronous motor angle following the fault. Figure 4.4c shows the phase plots of the 37.5 MW synchronous motor angle/speed trajectories following the fault.

The long duration fault is not assessed with and without SLC because of the capabilities of the Sasol Three generator excitation systems in stabilising the system following a disturbance. Above all, the impedance of the SLC is relatively small compared to the system impedance.

From these results, it can be concluded that the Sasol Three System is stable. Additional results are shown in Appendix H.

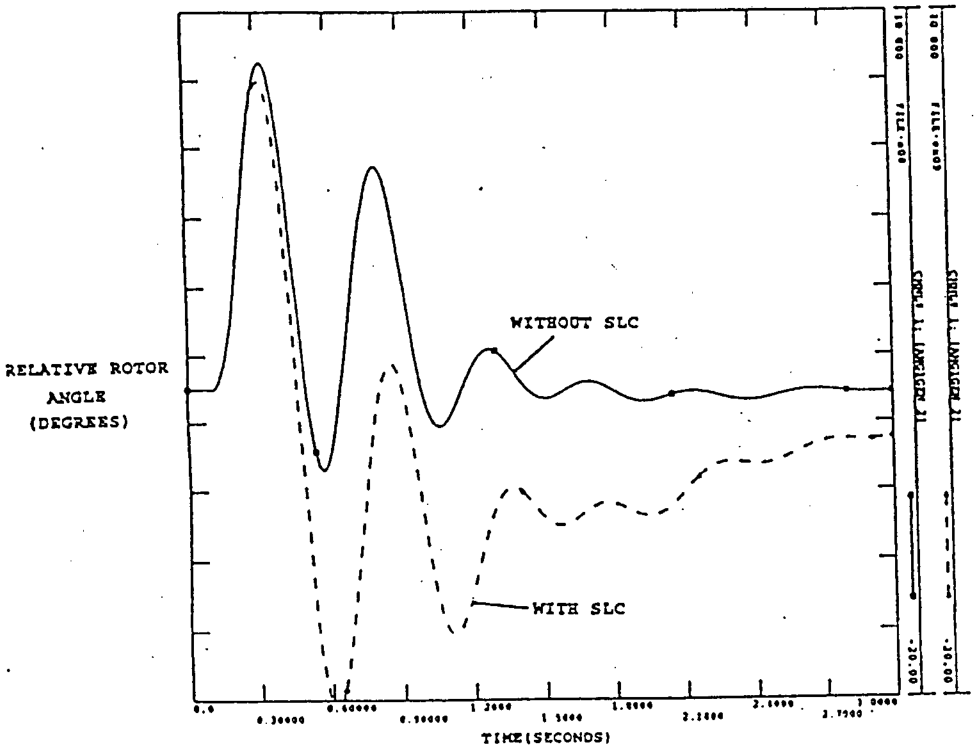

Figure 4.4a Relative rotor oscillations of generators after a fault at bus number 7630 (with SLC)

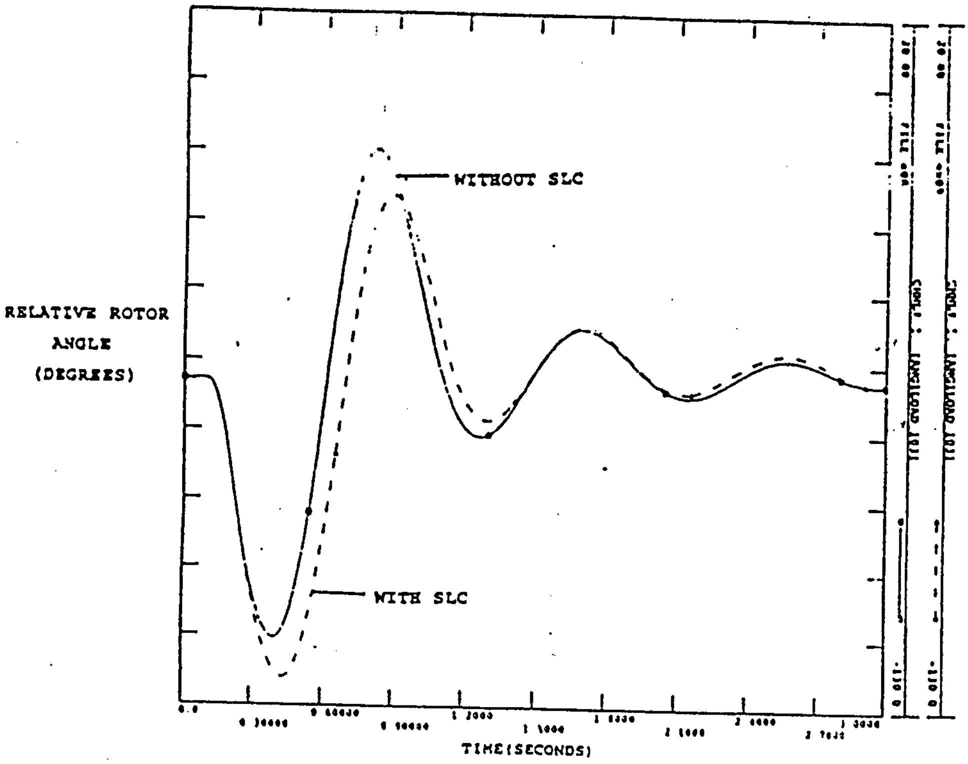

Figure 4.4b Relative rotor oscillations of 20.3 MW synchronous motor after a fault at bus number 7630 (with SLC),

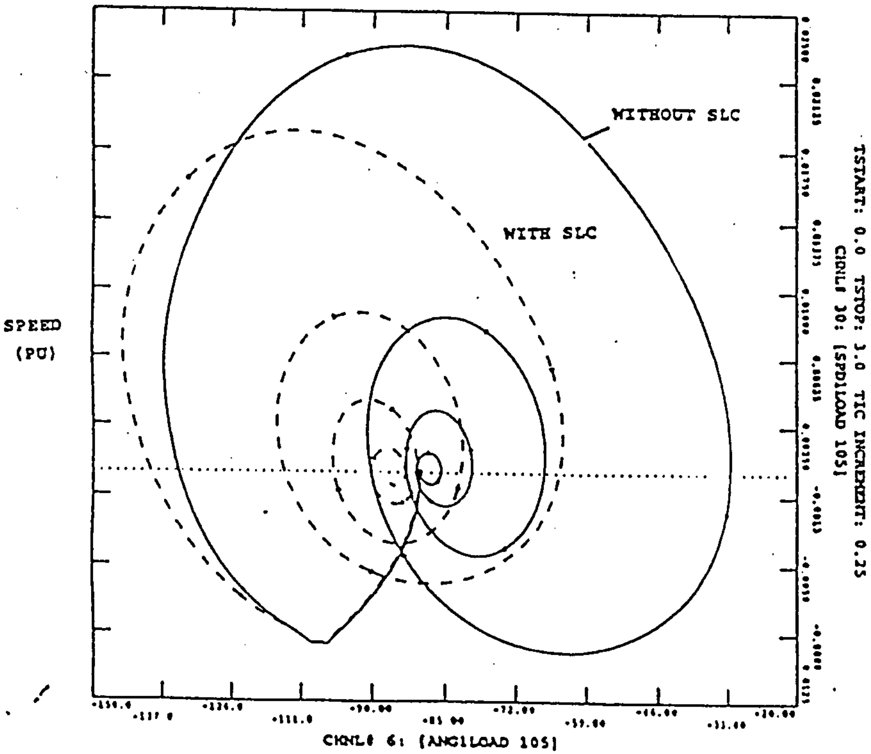

Figure 4.4c Angle/speed trajectory of the 37.5 MW synchronous motor after the fault at bus number 7630 (with SLC)

4.6.3. Simulation Three

This simulation evaluates the extent to which stability can be achieved on the Sasol Three System. This simulation is the same as simulation two except that the duration of the fault was extended to determine the stability limit. This was done by increasing the time which the fault stayed on the system, while the stability of the synchronous machines of the system were checked.

When the fault was allowed to persist for 15 cycles, generator rotor angles were stably operating within their limits (figure 4.5a). The relative rotor angle settles down at a new operating point.

Figure 4.5b shows the response of the 20 MW synchronous machine. The motor has lost synchronism with the rest of the system. This results can be demonstrated further by observing the transient angle/speed trajectories of the 37.5 MW synchronous motor over three seconds (see figure 4.5c).

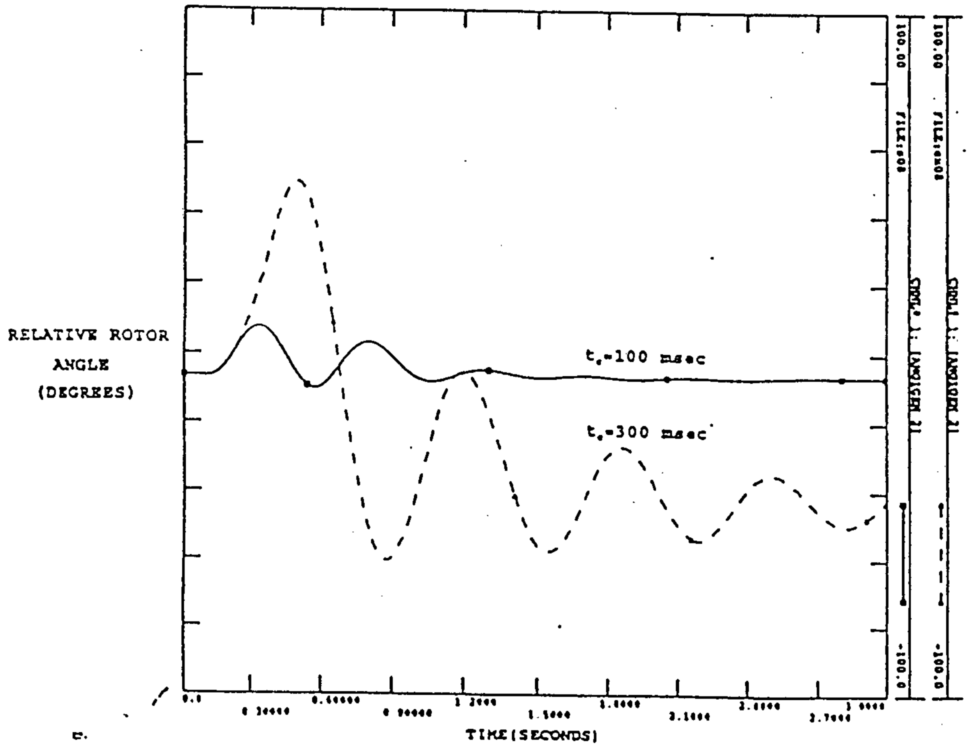

Figure 4.5a Relative rotor oscillations of Gen. 1 after the fault at bus 7630 (increased fault clearing time)

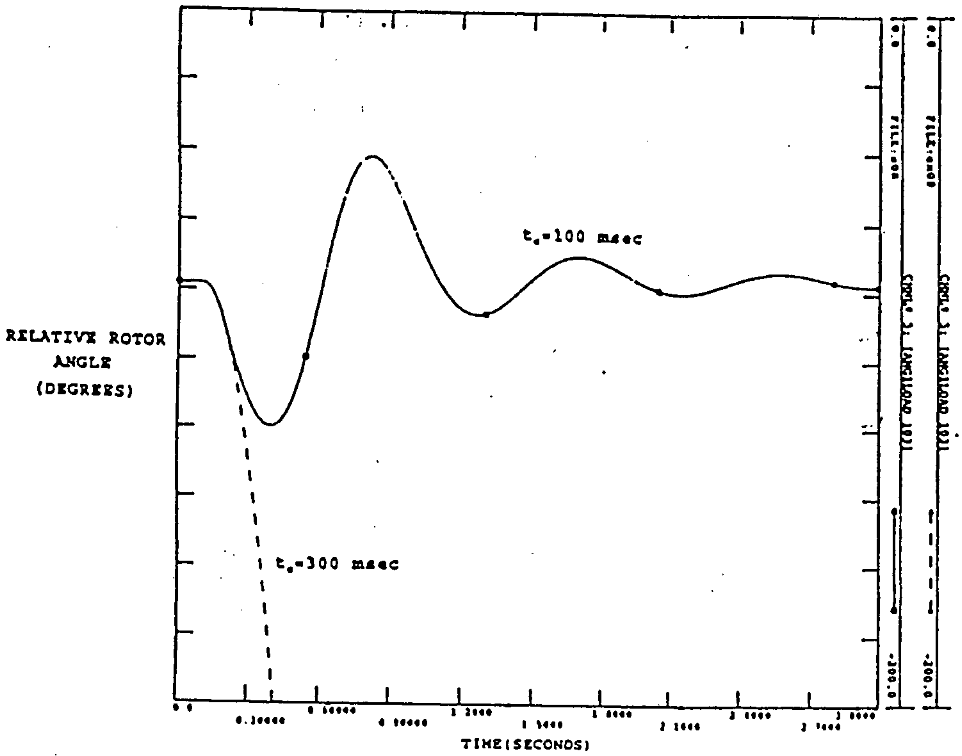

Figure 4.5b Relative rotor oscillations of 20.3 MW sync. motor after a fault at bus 7630 (increased fault clearing time),

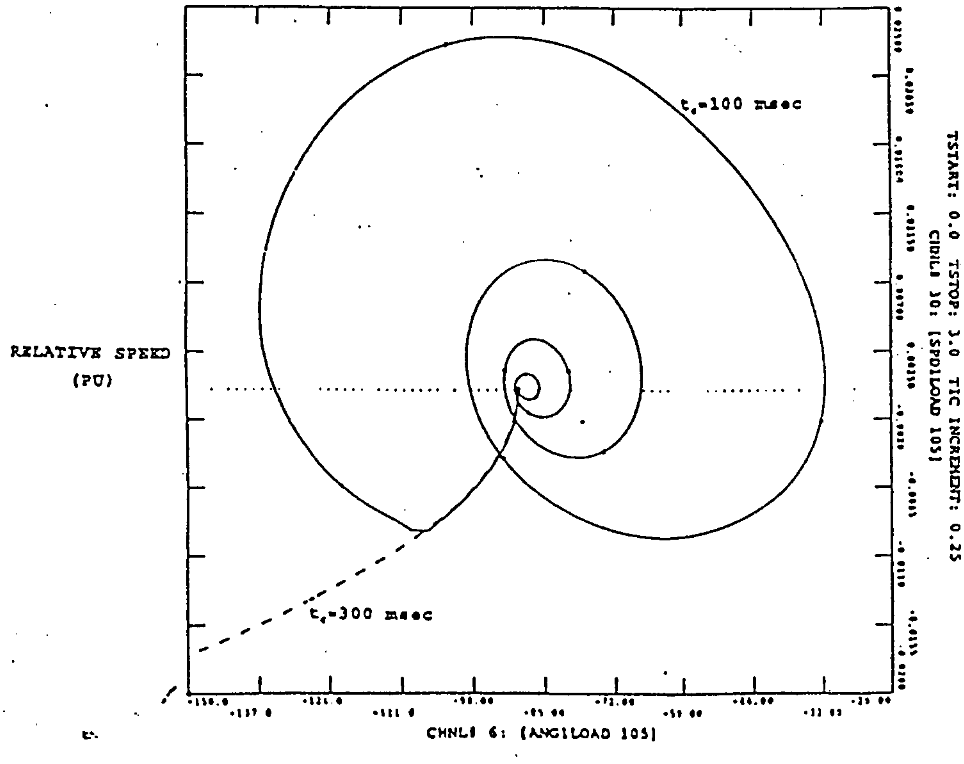

Figure 4.5c Angle/speed trajectory of the 37.5 MW synchronous motor after a fault at bus 7630 (increased fault clearing time)

From figure 4.5c, it is very clear that both the speed and the rotor angle of the 20.3 MW synchronous motor decreases until it reaches the pull-out torque. After the pull-out torque is reached, the motor losses synchronism with the rest of the system. More results are shown in Appendix I.

4.6.4. Discussions on Transient Stability and Reactive Power Requirements of the Sasol Three Network

In these studies, the "worst" case of having a disturbance on the 132 kV main busbar (2H4-SP-1) was taken into account although such severe disturbance may not occur very often. It is the worst case since by loosing the Eskom supply, the whole Sasol Three plant has to be shutdown. This case also indicates the boundary condition of the Sasol Three network.

The purpose of the simulations was not to cover all the worst case conditions where generators island and some of the loads shed from the network, but to give an indication of how the system reacts when a short circuit limiting coupler is applied on the two incomers to Sasol Three network. In the case where the disturbance is on the generator bus, that generator will be tripped and isolated from the rest of the network. Following this disturbance is an increase power imported from Eskom.

Considering the results of the simulations, it is significant to see that the Sasol Three network is quite stable for faults occuring on the 132 kV busbar (2H4-SP-1) and cleared in less than 300 msec. The recovery of the Sasol three system is quite rapid even if no load or generator is dropped. If the fault lasts for 300 msec or longer, the synchronous motors at the Linde and Oxygen plants become unstable. This is the result of the voltage depression on the 132 kV busbar that hampers the recovery of the synchronous motors which are dependent on the electrical power to recover.

From the results of the simulations and the comments made above, it is not necessary to apply additional reactive power compensation devices since the generators at the Sasol Three network have adequate capacity to supply reactive power for system recovery.

4.7. Summary

In this chapter, transient stability of the Sasol Three network was studied and analysed. The short circuit limiting reactance designed to limit the fault level at the 132 kV busbar was applied and the system investigated for transient stability.

Various aspects were covered in the investigation :-
- reactive power compensation need during transient instability condition
- the extent to which transient stability of the whole network is attained

This reflects how the system would perform (with short circuit limiting reactors applied) under load condition for a severe disturbance at the 132 kV busbar and still remain stable.

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CHAPTER FIVE

VOLTAGE STABILITY

5.1. Introduction

The existing and continuing trend towards heavier line loadings has resulted in an increased need for reactive power management. This raised the possibilities of voltage instability and collapse. Concerns for voltage instability and collapse are prompting utilities to better understand the phenomenon so as to devise effective, efficient and economic solutions to the problem.
Recently, voltage collapse played a part in several major system incidents throughout the world [2-4]. The latest major disturbances occurred in January 1987 in France, and in Tokyo area in July 1987. It was also the case in Florida in May 1985 and Utah (USA) in July 1985. This type of failures and many others justify the attention which must be paid to analysing this phenomenon, studying methods, and means which could possibly be introduced to reduce risk of occurrence.

The problem of reactive power and voltage control (i.e. maintaining an acceptable system voltage profile by providing adequate reactive supports at appropriate locations so as to meet system reactive power demand efficiently), is well understood and reported extensively in the literature [10-11]. It is not appreciated that maintaining a good voltage profile guarantee voltage stability, and that voltage instability need not be associated with low voltages, although frequently it is [5].

In this chapter, the state of the art in voltage stability, voltage collapse mechanisms, characteristics of power system elements, analysis methods, and sensitivities of voltage stability to system characteristics are discussed. Application of reactive power compensation devices to prevent voltage collapse is also analysed. Voltage stability of the Sasol Three network is analysed with the short circuit limiting reactor applied at the two 132 kV incomer feeders to Sasol Three. Reactive power requirements of the network during this condition is evaluated.

5.2. Fundamental concepts

Voltage instability and voltage collapse are often used interchangeably. Voltage instability or collapse is normally caused by large disturbances, including large load increases [2]. The degree of stability is assessed by observing the eigenvalues of the system, linearized around an operating point.

Power system voltage stability is a subset of overall power system stability [2]. Voltage stability is also called *load stability*. The following definitions are based on reference [2] and are in the spirit of references [7-9]. They are closely related to definitions for stability of general linearised and nonlinear dynamic systems.

- **Small disturbance voltage stability definition**

A power system at a given operating state is small-disturbance voltage stable if, following any small disturbance, voltages near loads are identical or close to the pre-disturbance values.
(Small disturbance voltage stability correspond to a related linearised dynamic model with eigenvalues having negative real part. For analysis , discontinuous models for tap changers may have to be replaced with equivalent continuous model.)

- **Voltage stability definition**

A power system at a given operating state and subject to a given disturbance is voltage stable if, voltages near loads approach post-disturbance equilibrium values. The disturbed state is within the region of attraction of the stable post-disturbance equilibrium.

Voltage collapse definition

A power system at a given operating state and subject to a given disturbance undergoes voltage collapse if post-disturbance equilibrium voltages are below acceptable limits. Voltage collapse may occur on certain parts of the system (partial) or on the whole network (total blackout).

Voltage instability is the absence of voltage stability. It is characterised by a progressive voltage fall (or rise) at a particular bus. It may spread out in the network causing a complete system voltage collapse. Voltage collapse is attributed to the inability of a power system to meet a certain load demand of reactive power.

Figure 5.1 illustrates the relationship between voltage and megawatt loading on a heavily loaded transmission line. As the load increases, voltage declines until it falls outside the acceptable range. Further increase in load produce precipitous voltage decline until the steady state stability limit is reached. Any attempt to operate beyond this point can result in loss of system stability (i.e. *synchronism*), system separation (i.e. *islanding*) and a wide spread voltage collapse.

5.3. Mechanism of voltage collapse

Voltage collapse involves a large disturbance or a large load increase on a heavily stressed power system. The network reactive power consumption increases as the power system is weakened.

Voltage collapse dynamics range in time from a fraction of a second to tens of minutes. Time response charts have been used to capture the chronological events leading to instability [13,14]. Figure 5.2 shows the classification of voltage stability into transient and longer-term time frames.

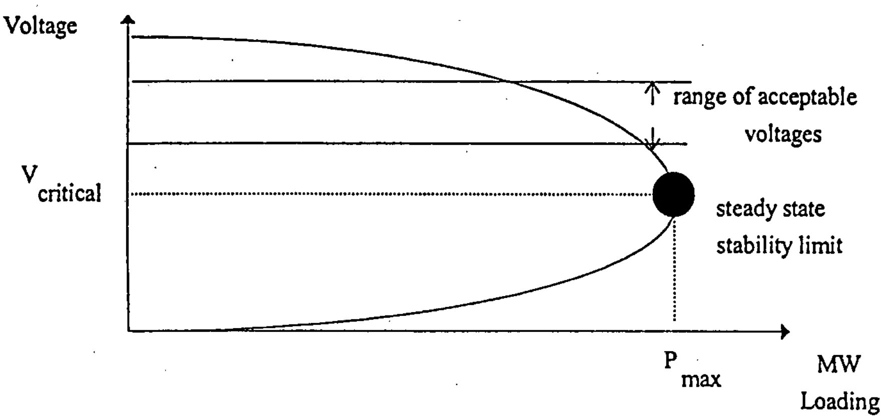

Figure 5.1 Conventional P-V graph for Voltage Stability

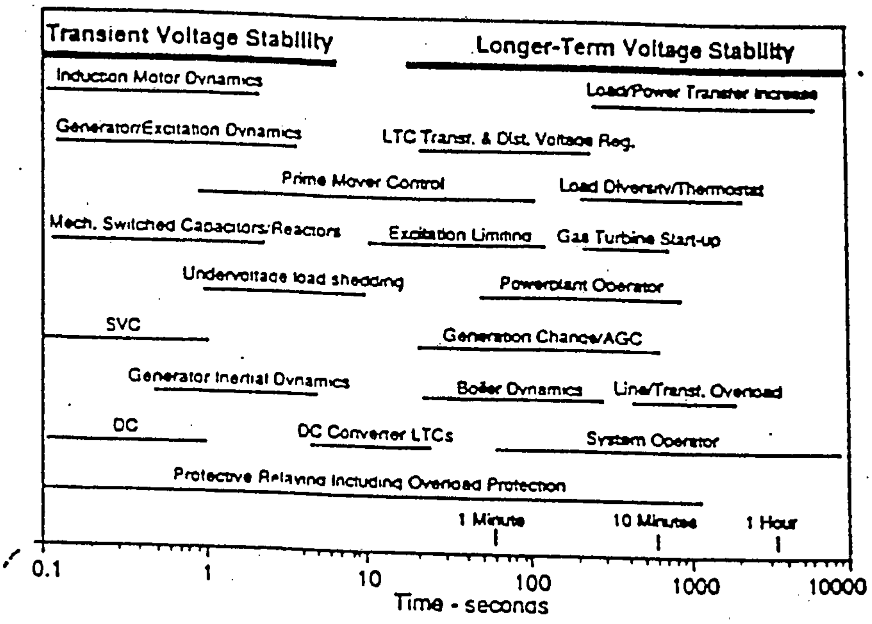

Figure 5.2 Voltage stability phenomenon and response time, [2]

5.3.1. Transient voltage stability

The response time is zero to about ten seconds[1]. The problem of rotor angle stability and voltage stability are dependent of each other. It is difficult to single out specific network problems as voltage stability problems or rotor angle stability problems.

Major mechanism of transient voltage instability is due to induction motors. For severe voltage dips, the reactive power demand of induction motors increases,

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[1] Same time frame as for transient rotor angle stability.

contributing to voltage collapse. Motors have difficulty in reaccelerating following short circuit because of greatly weakened supply network.

Transient voltage stability may involve HVDC links[2].The dynamics of reactive power consumed by an inverter and its shunt compensation, contribute to voltage instability. Constant power control, constant extinction angle control methods restore inverter terminal reactive power demand in a short time thus causing voltage collapse.

5.3.2. Longer-term voltage stability

The response time is tens of seconds to tens of minutes. Mechanisms of longer-term voltage stability involves restoration of the load by the load tap changing (LTC) transformers and distribution voltage regulators which regulate voltage near loads.

Longer-term voltage stability involves current limiters at generators too (see figure 5.2). Generator field and armature windings have time overload capability of some tens of seconds or few minutes. Field current is controlled by overexcitation limiters. When the current at particular generator is limited, the required reactive power must be supplied from generators further away, leading to cascading of current limiters [5]. Generation and transmission system cannot support the loads and reactive losses efficiently and effectively, hence the voltage declines rapidly. Partial or complete voltage collapse follows.

5.4. Characteristics of power system elements

This section of the thesis describes the characteristics of transmission networks, generators and loads. Emphasis is on describing equipment characteristics affecting voltage stability.

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[2] Particularly, inverter terminals located in a load area of low short circuit capacity.

5.4.1. Transmission networks

The most important characteristics of transmission systems are the relationship between transmitted power (P_r), receiving end voltage (V_r), and the reactive power injection. Figure 5.3 illustrates the characteristics of the simple radial system.

There is maximum value of active power that can be transmitted through a transmission system from a constant voltage source. The conditions corresponding to maximum power are the limits of satisfactory operation [15].

For a load demand higher than the maximum power, the system would be *unstable.* The voltage may progressively decrease depending on the *load-voltage characteristics.* For constant admittance load characteristics, the system become stable at a voltage level that is lower than normal.

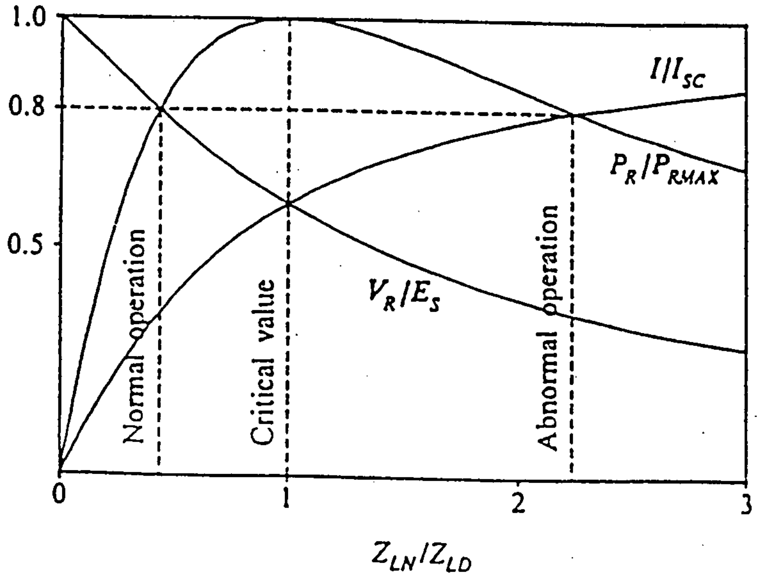


Figure 5.3 Characteristics of simple radial system

From figure 5.3;

Z_{LN} is line impedance in ohms,
Z_{LD} is load impedance in ohms,
I_{SC} is short circuit current in kA.
E_S is sending end voltage in kV.

For a load supplied by a transformer with LTC, the tap-changer action will try to raise the load voltage [5]. This reduce the effective load impedance and lowers the voltage at load further leading to voltage instability.

Classical methods of illustrating this phenomenon is shown in figure 5.1. Such characteristics represent the basic properties of transmission systems with predominantly inductive reactance elements.

Certain aspects of voltage stability can be shown using Q-V relationship. The curve shows the sensitivity and variations of bus voltages with respect to reactive power injections or absorptions.

Principal causes of voltage instability are [2]:-

- Transmission system loading being too high.
- Voltage sources being too far from load centres.
- Low source voltages.
- Insufficient load reactive compensation.

Transmission system P-V and Q-V characteristics illustrate the basic phenomenon associated with voltage instability. Methods of analysing voltage stability will be discussed in section 5.5.

5.4.2. Generators

AVRs are the most important means of voltage control in power system. Under normal conditions, the terminal voltages of generators are maintained constant.

During low-system voltages, the reactive power demand may exceed the field current limits [15]. The terminal voltage is no longer maintained constant due to reactive power output limits.

Generator field current is automatically limited by an overexcitation limiter. Figure 5.4 shows a typical overexcitation limiter model for modern excitation systems, [12]. Reference [2]. provide good explanation of this overexcitaion limiter.

When the generator hits its field current limit, the bus voltage can no longer be maintained [15], hence the operating condition of the system changes.

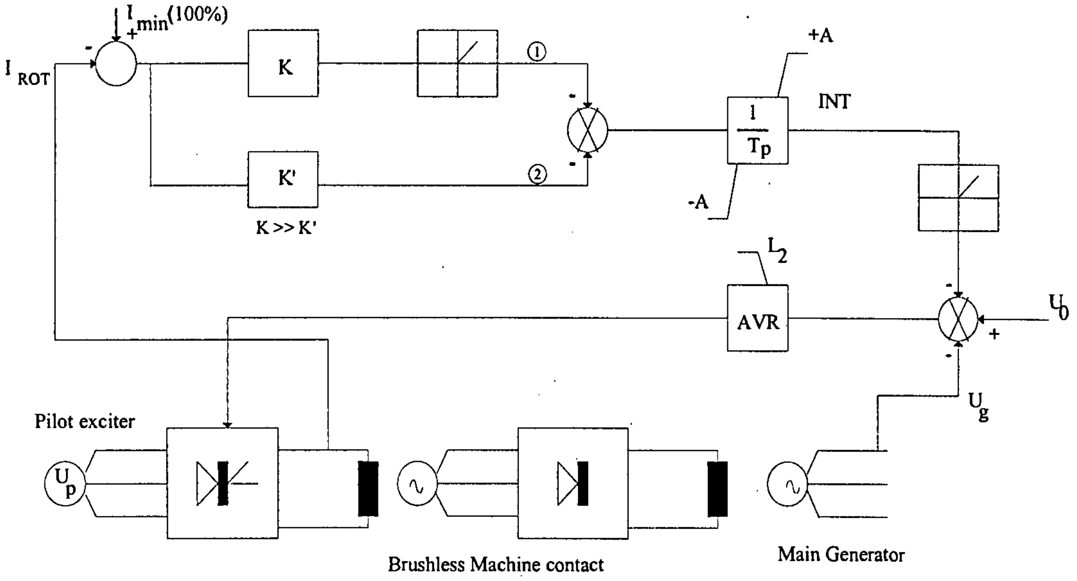
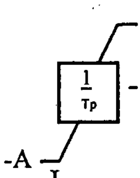


Figure 5.4 Typical model of an overexcitation limiter, [2,12]

where,

U_p - pilot exciter voltage.
AVR - automatic voltage regulator.
U_g - generator terminal voltage.
U_0 - reference voltage.
I_{min} - minimum setpoint current (i.e typically set to 105 % of rated field current).



- integrator with non windup limits.

I_{rot} - Field current.
L_2 - Upper limit of the AVR.
A,-A - Upper & lower limits of the integrator.
K,K' - Gain of the transfer functions.

6.4.3. Loads

Voltage stability depends on the load characteristics of the system. In order to analyse stability of the voltage, it is necessary to understand load characteristics of the system and be able to model them [2].

The modelling of different load types is discussed in the previous chapter. Reference [24] provides detailed discussions on load types and modelling.

Active and reactive load components that are voltage sensitive, interact with transmission characteristics by changing the power flow through the system [23]. System voltages settles down at points determined by the composite characteristics of the loads and transmission system.

Below 0.85 p.u. of the nominal voltage, some induction motors may stall and draw high reactive current [2]. This causes the voltage to drop further which may lead to voltage collapse if the problem still persists.

For accurate voltage stability analysis, representation of the network must include the effects of distribution transformer tap-changer action and capacitors. Representation of load characteristics should take into account the effects of thermostats and other load regulation devices [14] depending on the scope of the study. In industrial systems, motors and capacitors need to be represented explicitly.

Effect of voltage to real and reactive power demand of the motor

At Sasol, most of the loads are induction motors (i.e. pumps blowers, fans and compressors account for more than half of the motors that are in use). It is therefore important to discuss how the real and reactive power demand of this load varies with the voltage.

Under steady state condition, the real power demanded by motors is fairly independent of voltage until the point of stalling. The reactive power of the motor is more sensitive to voltage levels of the system. As the voltage drops, the reactive power will first decrease, and then increase as the voltage drops further. References [10, 23] provides detailed description of the characteristics of voltage to active & reactive power demanded by motors.

5.5. Analysis methods

Voltage stability analysis involves the examination of two aspects, viz., voltage proximity indicator and mechanism of voltage instability.

Most voltage stability problems are analysed using *static methods* because of the slow response of system dynamics influencing voltage stability [2]. Static analysis method provide insight into the nature of the problem and identifies the key contributing factors.

Dynamic analysis method is useful for detailed study of specific voltage collapse situations, coordination of protection and controls, and testing of remedial measures. Dynamic simulations examine whether and how the steady state equilibrium point will be reached. These two analysis methods complement each other.

5.5.1. Static analysis

Stability is determined by computing the V-P and the Q-V curves. These curves are generated by the execution of power flow programs using conventional system models.

Q-V Sensitivity

The sensitivity of the reactive power to voltage at a particular bus is given by the slope of the Q-V curve at any given operating point.

i.e.,

$$\left(\frac{dQ}{dV}\right)_i = \frac{(\textit{change in reactive power at the operating point } i)}{(\textit{change in voltage at the operating point } i)}$$

Positive Q-V sensitivity is indicative of stable operation. The smaller the sensitivity, the more stable the system. As system stability decreases, the magnitude of the sensitivity increases, becoming infinite at the stability limit. Conversely, negative Q-V sensitivity is indicative of unstable operation.

Because of the non-linear nature of the Q-V relationships, the magnitude of the sensitivities for different system conditions do not provide direct measure of relative degree of stability. Hence, sensitivity analysis provides useful information about vulnerability of the parts of the power system with respect to voltage instability [15]. Reference [25] describe the practical application of an approach based on Q-V sensitivity.

Eigenvalue Analysis

Transient voltage stability can be analysed by assessing the eigenvalues of the system. Instability is detected by the presence of a positive real eigenvalue [15].

Transient state analysis

It is the analysis of voltage stability following an outage or during load growth. " Snapshots" in time present the system condition along the transient trajectories. Voltage stability is investigated using modal analysis [15].

Voltage collapse Proximity

Proximity to voltage collapse is determined by the P-V curves. Load is increased in steps until the system becomes unstable or the power flow fails to converge.

Modal analysis applied at particular operating points, provide information regarding areas that are prone to instability.

References [17-19] provide detailed description of determining the point of collapse and proximity to voltage instability.

5.5.2. Dynamic analysis

Stability is determined by time domain simulations of the system using numerical methods and power flow analysis methods [15].

Detailed dynamic models of the system components (generating units and controls, motors, SVC's etc.) are used.

5.6. Sensitivities of voltage stability to system characteristics

Accurate load modeling of equipment is necessary for the assessment of system voltage collapse. Some equipments may have significant impacts on system voltage stability. The effect of load modeling on voltage stability is covered in reference [16]. It is shown in reference [16] that the load that maintains constant power characteristics is the most *sensitive load* from the voltage stability point of view.

Voltage stability is also affected by overexcitation limiter. Sometimes voltage instability and collapse do not occur when generators are modeled with current limiters[3].

Line drop compensation or generator secondary voltage regulation improve voltage stability significantly [15].

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[3] i.e In practice voltage collapse do occur even though the system generators are modelled with current limiters, e.g. Voltage Collapse of the three lightly-loaded 500kV lines at South Florida (17 May 1985) which resulted in total blackout within a few seconds.Transient stability simulation indicated the system should have recovered and load modelling deficiencies (including modelling of power plant auxiliaries) were suspected [2].

5.7. Prevention of voltage collapse

This section of the thesis describes various methods that can be utilised to prevent the occurence of voltage collapse.

5.7.1. Utilisation of reactive power compensating devices

Chapter 3 described different reactive compensating devices that are in use. This section considers those devices that are capable of improving voltage stability of the system.

Proper selection of compensation schemes should ensure adequate stability margin. Selection of the type, size, rating and location of these devices is based on detailed study of the system condition for which the system is required to operate satisfactorily. Design criteria based on maximum allowable voltage drop following a contingency is not satisfactorily from voltage stability point of view [15]. The stability margin should be based on MW and MVAr distances to instability. Thus it is important to recognize voltage control areas and weak transmission boundaries for proper selection of such schemes.

Shunt capacitors

Shunt capacitors are the most inexpensive means of providing reactive power reserves and voltage support at the receiving end of the transmission system. However, this device have a number of inherent limitations from voltage stability and control point of view.

It has been shown in references [26, 27] that shunt capacitors can be used to prevent voltage instability even though beyond certain level of compensation, stable operation is unattainable with shunt capacitors.

Static var systems

Static var system regulates up to its maximum capacitive output. There is no voltage control or instability problems within the regulating range. When the limit is reached, the SVS become a simple capacitor.

Reference [26] provides simulation of voltage instability of a 132 kV system. Application of an SVC (operating in capacitive reactive power range) prevented voltage instability from occurring. However, the possibility of (i.e. any power system equipped with SVC) this leading to voltage instability must be recognised. For example, with the 2nd generator outage, not adequate reactive power will be reserved to prevent the voltage to become unstable unless the reactive power range of the SVC is designed for the absolute worst case with one or two generators operating.

Synchronous condenser

Synchronous condenser supply reactive power to relatively low voltages and contribute to the stable voltage performance.
Recently, synchronous condensers are not considered due to their relatively high capital, operating costs, losses, slow response time and rotor inertial oscillations following disturbances. These synchronous devices has been ruled out since the introduction of static var compensators in late seventies [6].

Reference [10] provides detailed description of the reactive power compensation and dynamic performance of such devices on a power system network. Most application of synchronous condensers are associated with HVDC installations. Reference 28 provide the description of three synchronous condensers that are installed at the Nelson River project inverter station.

Series capacitors

Reactive power supplied by series capacitor is proportional to the square of the line current and does not depend on voltages. This is a favourable effect on voltage stability.

Series capacitors improves both voltage regulation and stability since it reduces both the characteristic impedance and the electrical length of the line.

Detailed description of the practical application of such devices is provided in reference [10].

5.7.2. Control of reactive power supply

Load compensation of generators AVR contributes to the stability of the voltage at the buses [10, 15].

French and Italian utilities developed so called *secondary voltage control schemes* for controlling the network voltages and generator reactive power outputs from central points [20,21]. Tokyo Electric Power Company has an adaptive control of reactive power supply [22].

5.7.3. Undervoltage load shedding

Undervoltage load shedding is defined as the instant when a disturbance occurs in a system and the voltage drops to a certain pre-selected level for a certain pre-selected time period, then selected loads may be shed.

The intention is to ensure that the voltage recovers to normal levels when the load is dropped. The characteristics and locations of loads to be shed are more important for voltage problems.

According to reference [23], load shedding schemes should be designed so as to ensure that they do not misoperate for conditions other than true approach to voltage instability.

5.8. Voltage stability of the Sasol Three network

This study comprises of the actual simulation of voltage instability. The results of the simulations for the recovery of the system after line and generator outages are presented. The dynamic models of the system components are used.

The most important results will be shown in the text. More results are shown in Appendix J. The system is also simulated with generators modelled without their excitation systems.

The simulations involve disturbances in the form of line (Eskom incoming line) and generator fault. The line fault is cleared by opening both the Eskom breaker upstream and the Sasol 132 kV breaker downstream, thus isolating the fault from the system. The generator fault is cleared by tripping the affected generator hence isolating it from the network.

5.8.1. Simulation One

This simulation involves tripping out of one incoming transmission line at t=0.1 seconds followed by a generator outage at t=10 seconds. The simulation time is extended to 20 seconds for evaluating the system performance due to the events.

The response of selected busbar voltages is shown in figure 5.5a. From figure 5.5a, it is clear that the system voltages decrease slightly when the transmission line (*L1*) is opened. The voltages remain constant until generator (*gen 1*) was tripped. Following *gen 1* trip, the system stabilised at a voltage lower than the prefault voltage.

Figure 5.5b shows the active and reactive power response of *gen 1* to the events From this figure, the reactive power of generator one increases immediately after the line fault occurred and then remain constant. This increase in generator reactive power is due to the increase in reactive power demand of the load. When this generator is tripped out, the generated active and reactive power output becomes zero as shown in the figure.

Figure 5.5c present the results of the motor active powers. From the active power plots of the motors (figure 5.5c), the faults results in the motor power dips which last for some few milliseconds and then recovers to the original powers. For more results see Appendix J.

From the above results, it can be concluded that the Sasol Three System recovers to stable voltages when severe faults are considered on the system. The 132 kV bus voltage does not decline (i.e no sign of voltage collapse on the system). This is because of the co-generators capabilities of controlling the reactive power and voltages throughout the Sasol Three system.

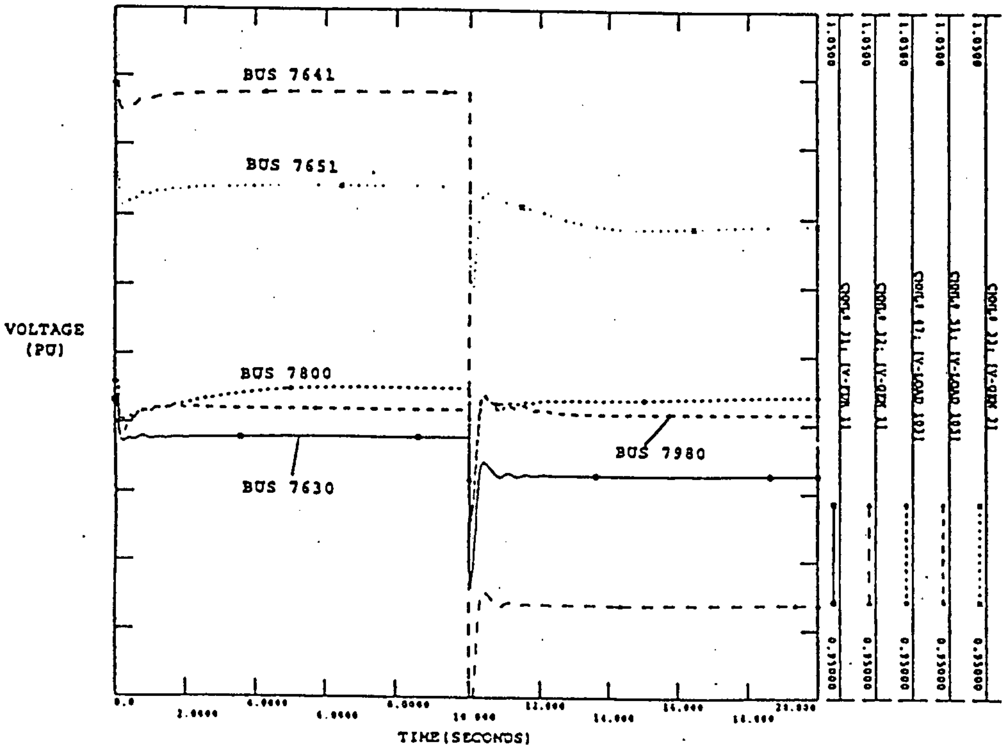

Figure 5.5a Recovery of the 11 and 132 kV voltages at Sasol Three after a line L1 and generator (gen 1) fault [Voltage stability studies]

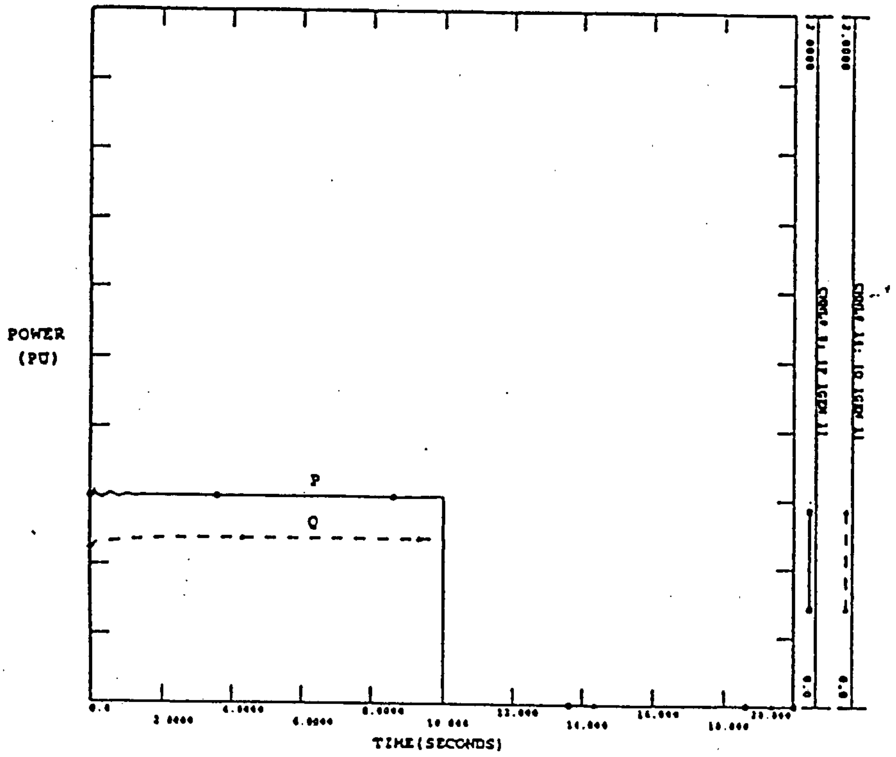

Figure 5.5b Active and reactive power plots of gen 1 after a line L1 and generator (gen 1) faults (Voltage stability studies)

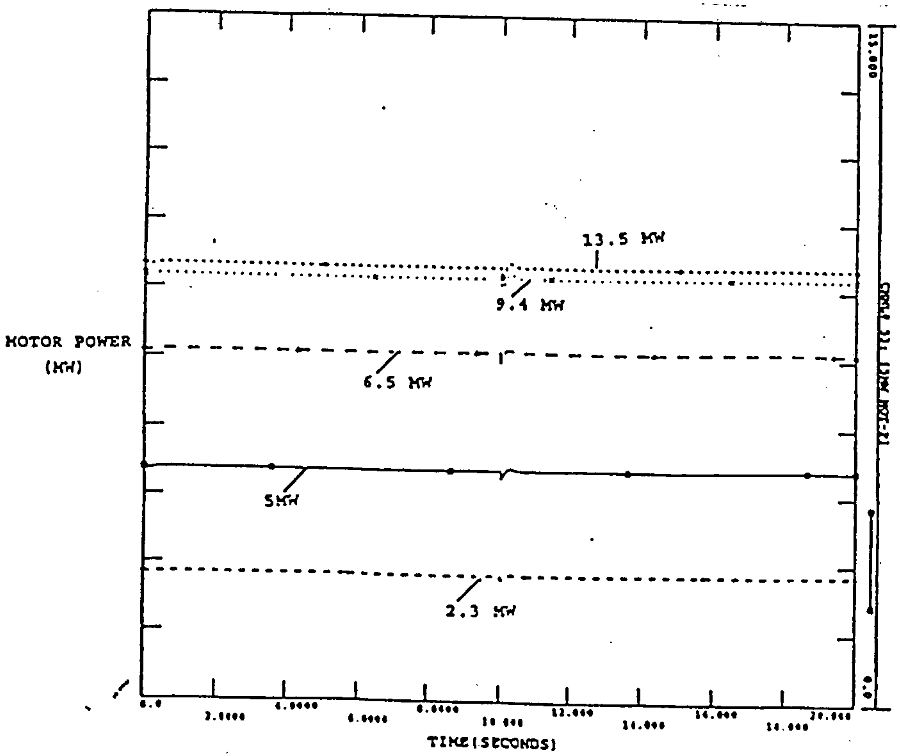

Figure 5.5c Active power plots of induction motors following line L1 and generator (gen 1) faults (voltage stability studies)

5.8.2. Simulation Two

This simulation evaluates the extent to which the Sasol Three System is voltage stable. The generators were modelled without their excitation system. This condition simulate the state where generators have reached their stability limits thus incapable of controlling their output voltages.

Figure 5.6 shows the response of the selected bus voltages to the line and generator outages. The voltage collapse after 32 seconds.

This scenario presents very little practical application since the time taken for voltage to collapse is very long.

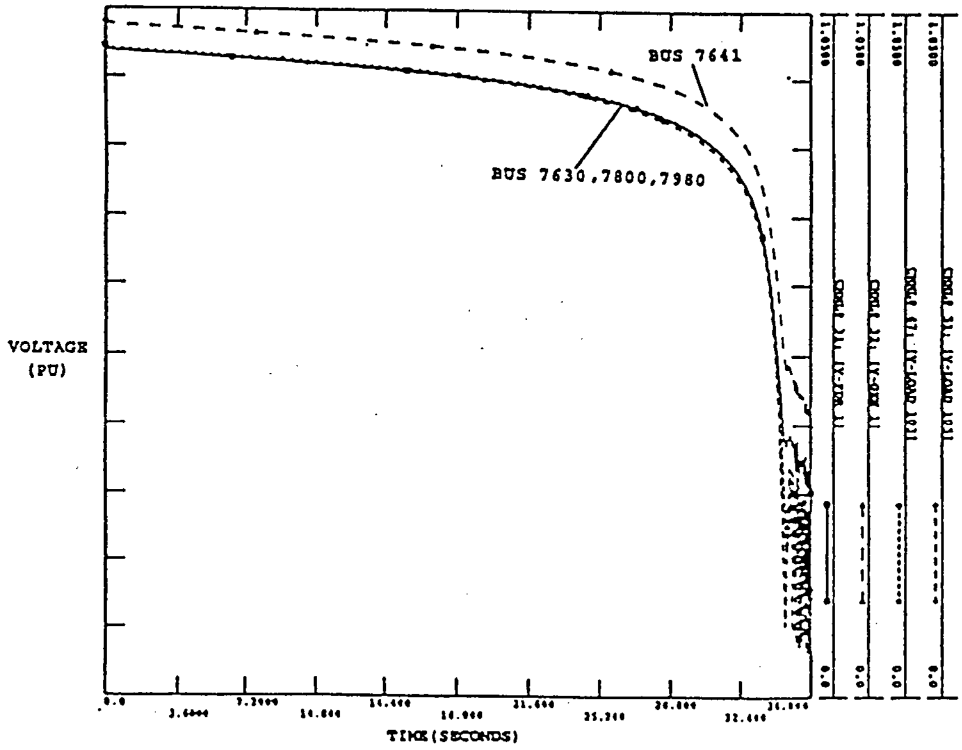

Figure 5.6 Response of bus selected voltages at Sasol Three following a line and generator outage (no excitation system)

5.8.3. Discussions on Transient Stability and Reactive Power Requirements of the Sasol Three Network

In this studies, the “worst “case of having a fault on one of Eskom line and generator fault was considered, even though it is very rare that such conditions may occur simultaneously. This indicates the boundary condition of the Sasol three network as far as voltage stability is concerned.

Some important facts emerged from the voltage stability studies of the Sasol Three network and are essential in understanding how the network operates. It is significant to see how strong the network is when one of the Eskom incoming lines experience a fault. The voltage at the 132 kV bus drop immediately after line outage and stays at that value. Since voltage instability is characterised by a decline in bus voltage at the affected busbar, this form of instability does not happen on the 132 kV busbar of Sasol Three network. Even when one of Sasol generators becomes faulty, the system recovers to save operating limits. This demonstrates capabilities of the generators to produce enough reactive power when one of Eskom lines is faulty and one of Sasol Three generators trips.

From this results, it is significant that the Sasol Three network doesn’t require additional reactive power compensation source during Eskom line outage and generator outage. The network is quite stable for such severe disturbance.

5.9 Summary

Voltage stability studies of the Sasol Three network were carried out. The network was analyzed with the short circuit limiting reactors applied at the two 132 kV Eskom incomers.

This reflects how the system performs under maximum load conditions for various disturbances and remain voltage stable.

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CHAPTER SIX

CONCLUSIONS AND SCOPE FOR FUTURE WORK

6.1. General

The purpose of this study was to design a short circuit limiting coupler that will reduce the fault level at the 132 kV busbar by 20 %; determine the reactive power compensation need of the Sasol Three network; analyze the performance of the system (with SLC) under voltage and transient stability; and finally determine the need for reactive power compensation of the network under voltage and transient stability conditions.

In this respect, the short circuit limiting reactor was designed to limit the short circuit level at the 132 kV bus by 20 % and then the transient stability of the Sasol Three System was evaluated with this device applied. This study showed that for a 3 phase fault, at the 132 kV bus, cleared in less than 15 cycles, the Sasol Three System was able to recover and the synchronous machines stayed stable.

With respect to voltage stability, it has been shown that the co-generators at Sasol Three plant are capable of controlling the 132 kV bus voltage when one of Eskom supply line is open circuited and one of the generators is out of service. Thus the 132 kV bus voltage does not decline due to such event ensuring voltage stability.

The Sasol Three System produces enough reactive power to recover the plant under voltage and transient instability conditions. Hence there is no need for reactive power reserves to improve stability of the Sasol Three network.

6.2. Chapter summaries and conclusions

Chapter one introduced the thesis by defining the problem related to insufficient reactive power at the load ends of the power system. The objectives of this thesis are also outlined.

Chapter two discusses the following :-

- Theoretical concepts related to loadflow and fault level studies.
- The industrial grade package used to perform the loadflow and dynamic studies is also discussed.
- The Sasol Three network.

Loadflow studies and short circuit studies of the Sasol Three network were performed and a short circuit limiting reactor was selected.

Chapter three covered the subject of reactive power compensation and the associated devices. Reactive power control of the Sasol Three system has been discussed and it has been shown in this chapter that by improving the power factor at Sasol Three 132 kV busbar (2H4-SP-1) will save the company a considerable amount over some period.

There is no need to install additional reactive power compensation devices (such as SVC or switched capacitors) since the synchronous machines at Sasol can produce enough reactive power for power factor correction. More over, application of SVC's or capacitors may result in other adverse consequences on the network (e.g. harmonics, series resonant etc.).

In Chapter four, transient stability of the Sasol Three network was studied and analyzed. The short circuit limiting reactance designed to limit the fault level at the 132 kV busbar was applied and the system investigated for transient stability.

Various aspects were covered in the investigation :-

- reactive power compensation need during transient instability condition.
- the extent to which transient stability of the whole network is attained.

This reflects how the system would perform (with short circuit limiting reactors applied) under load condition for a severe disturbance at the 132 kV busbar and still remain stable.

Chapter five carried out voltage stability studies of the Sasol Three network. The network was analyzed with the short circuit limiting reactors applied at the two 132 kV Eskom incomers. The results reflects how the system performs under maximum load conditions for various disturbances and still remain voltage stable.

6.3. Scope for future work

The research reported in this thesis was entirely based on simulations without any measurements. To validate the results of this studies, measurements need to be made on the Sasol Three System elements especially with regard to the system loads. This should form the core for future investigation. The development of SCADA[1] systems and powerful computer based instrumentation could be used for measurement of various parameters in the Sasol Three network.

Specific load models has been presumed, it would be better if more detailed models are used (i.e. models which take load consumption variations with variations in the supply voltage into account). The value of such studies varies very much of course depending on the actual behaviour of the load. However, the presumed load models used in the study were adequate for the transient and voltage stability studies carried out in this thesis.

For power factor correction, the optimum power factor equipment to be provided need to be determined. The marginal rates of return of capital will also need to be considered when approaching the optimum value.

---

[1] SCADA - Supervisory Control and Data Acquisition.

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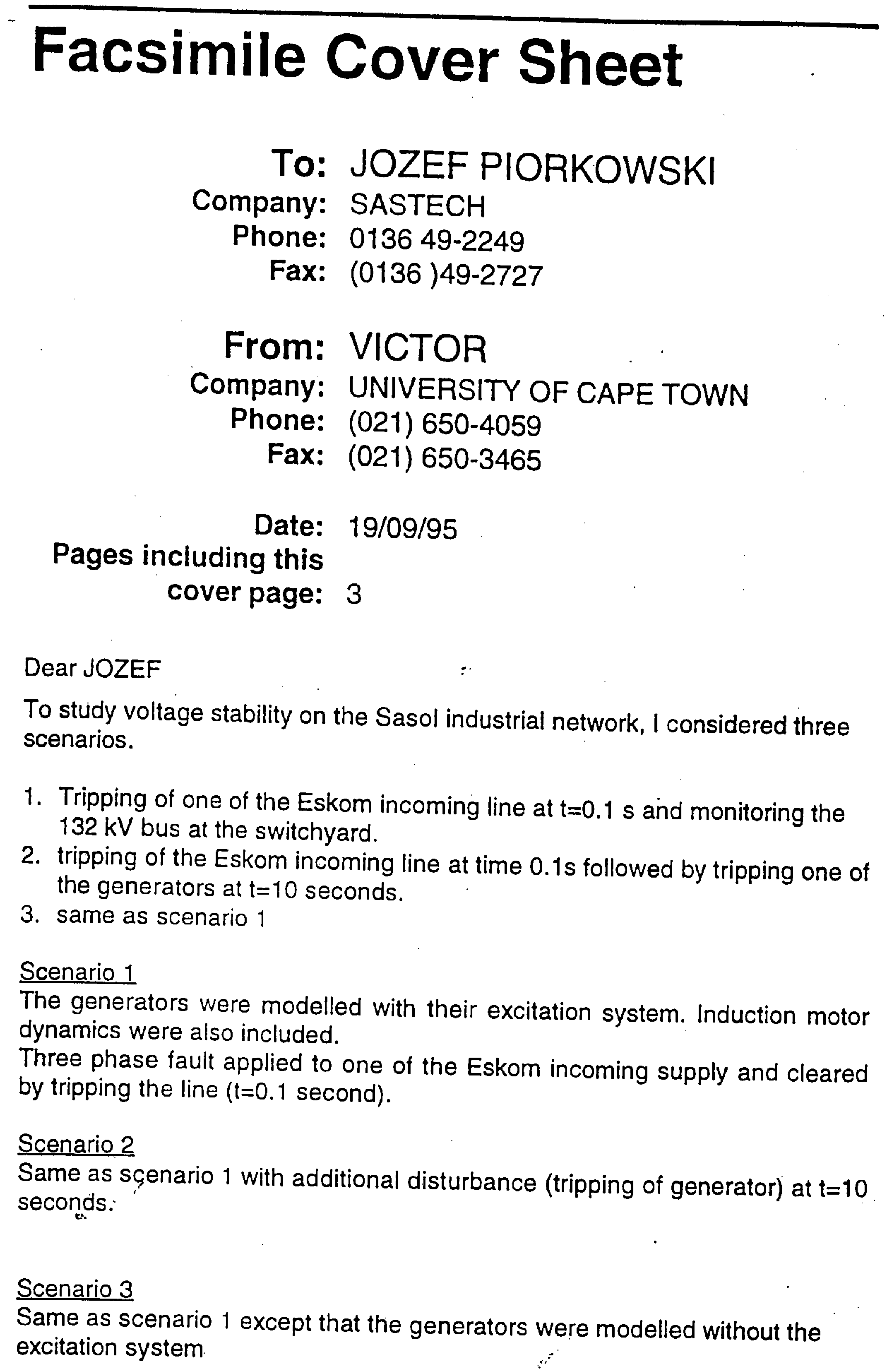
APPENDIX A

The appendix consist of the copy of the original fax that was sent to Mr. Jozef Piorkowski together with the reply. It is the results of the simulations that were carried out on the Sasol Three System. Suggestion have been made to carry out the design of short circuit limiting coupler and evaluate the stability of the system with SLC connected in the incoming lines.



Facsimile Cover Sheet

To: JOZEF PIORKOWSKI
Company: SASTECH
Phone: 0136 49-2249
Fax: (0136)49-2727

From: VICTOR
Company: UNIVERSITY OF CAPE TOWN
Phone: (021) 650-4059
Fax: (021) 650-3465

Date: 19/09/95
Pages including this cover page: 3

Dear JOZEF

To study voltage stability on the Sasol industrial network, I considered three scenarios.

1. Tripping of one of the Eskom incoming line at t=0.1 s and monitoring the 132 kV bus at the switchyard.
2. tripping of the Eskom incoming line at time 0.1s followed by tripping one of the generators at t=10 seconds.
3. same as scenario 1

Scenario 1

The generators were modelled with their excitation system. Induction motor dynamics were also included.
Three phase fault applied to one of the Eskom incoming supply and cleared by tripping the line (t=0.1 second).

Scenario 2

Same as scenario 1 with additional disturbance (tripping of generator) at t=10 seconds.

Scenario 3

Same as scenario 1 except that the generators were modelled without the excitation system

RESULTS (page 3)

Fig 1 shows the results of scenario 1. There is no sign of voltage instability for this case. The network seems to be voltage stable after line outage at t=0.1 second.

Fig 2 shows the results of scenario 2. It is also voltage stable.

Fig 3 shows the results of scenario 3. Voltage collapse at about 33 seconds after the fault.

Comments

My objective is to demonstrate that reactive power compensation devices can be used to prevent or improve voltage collapse, scenario 1 and 2 does not require such devices. This scenarios represent the actual Sasol network elements modelled explicitly.

In scenario three the generators are not modelled in details, which means that this is not the true reflection of the Sasol industrial network. Nevertheless, this case does provide necessity for reactive power compensation.

PROBLEMS

Since my thesis objectives are to improve voltage and system stability on the Sasol network (with all components modelled in detail); and from results of scenario 1 and 2 above there is no sign of voltage instability or rotor angle instability; should I actually carry out this studies using scenario 3[1] and comment that the Sasol network is actually voltage stable (with scenario 3 , reactive power compensator will be used to improve stability and illustrated by simulations)?
If not, then what should I do ?

I would appreciate if you could reply this as soon as you possibly can .

BEST REGARDS

VICTOR

---

[1] This scenario can be thought of as the instant when the generators have reached their excitation limits. hence the generator can no longer control its voltage or the voltage at the remote bus.

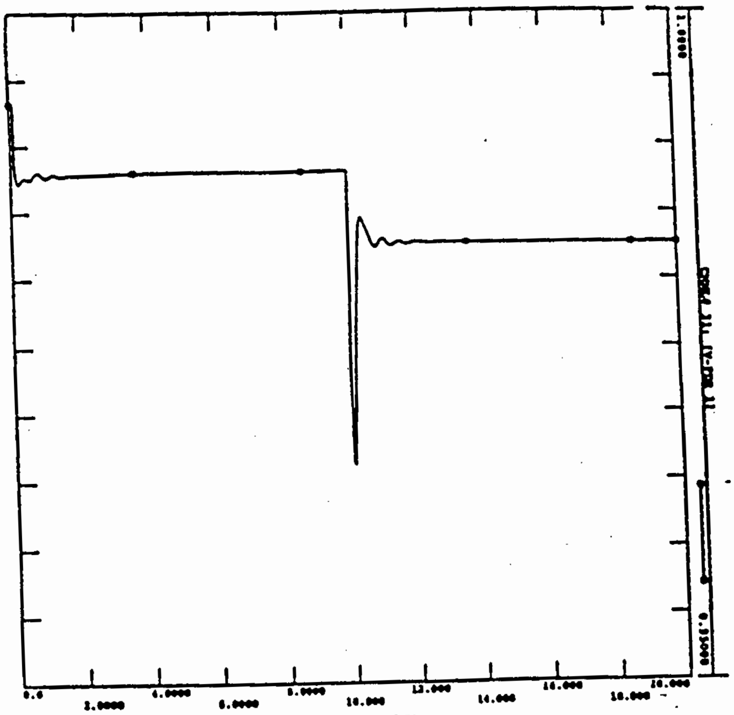
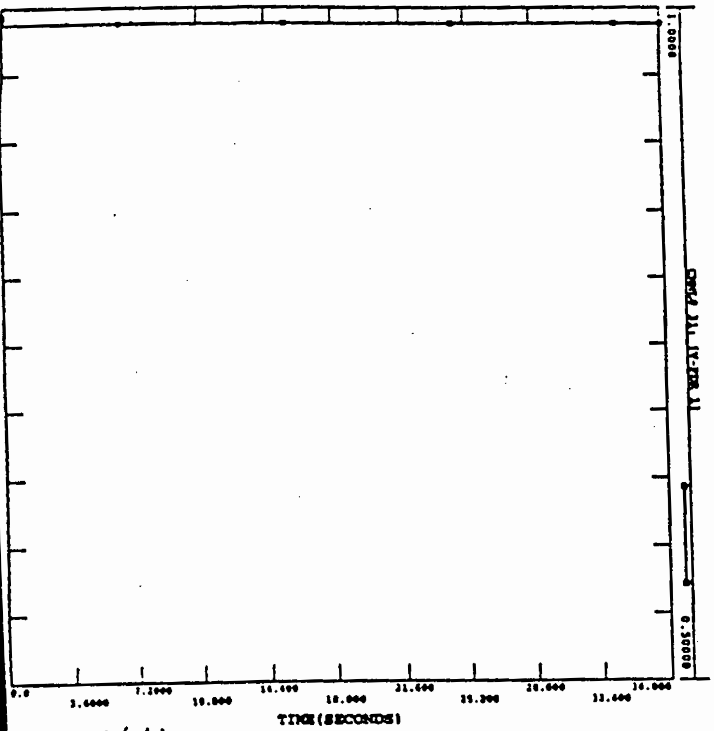
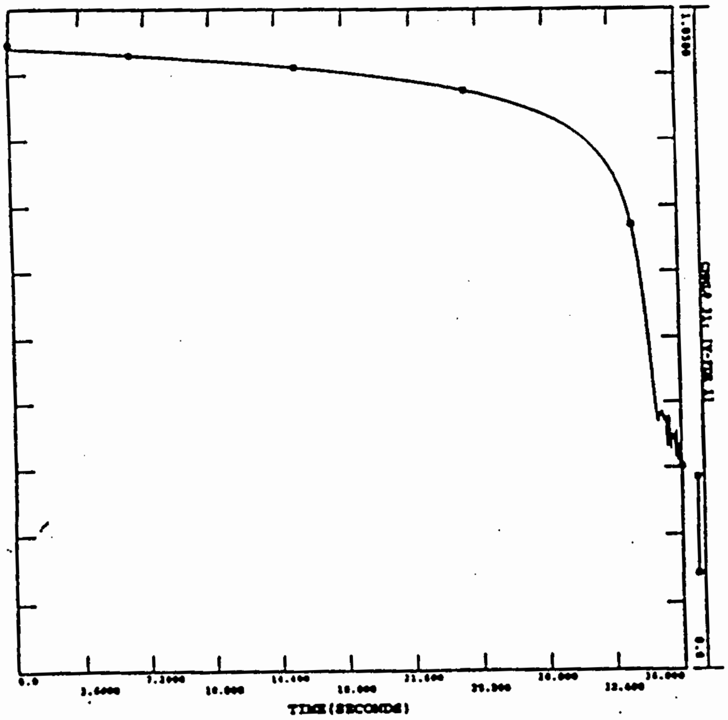


Fig2. 132KV bus Voltage Response fr
tripping line followed by tripping on
of the generators.



TUE SEP 12, 1995

ig 1. Voltage Response of 132KVBus at Sasol
Three when one of the two incoming lines
is tripped.



TUE SEP 12, 19

Fig3. 132 KV Bus Response when one
of the two incoming lines is tripped.

TELEFAKS / TELEFAX

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UNIVERSITY OF CAPETOWN

Faks / Fax : (021) 650 3465

Bladsye / Pages : 1

Datum / Date : 1995-09-20

Verw. / Ref. : EE/JP6/950042.JP/hjs

REPLY TO YOUR FAX DATED 19/09/1995

Dear Victor

I would suggest that you don't carry out your studies using Scenario 3. The time taken for the voltage to collapse is very long and this scenario presents very little practical application.

I would like you to do a short circuit study on 132 kV bus at Sasol Three. Following this, you should design a short circuit limiting coupler (SLC) for application on 132 kV incoming lines, to achieve a reduction of 20 % in the fault level on the 132 kV busbars.

You should also evaluate the system stability with the short circuit current limiting reactors connected in the incoming lines.

I hope that the above information solves your problems.

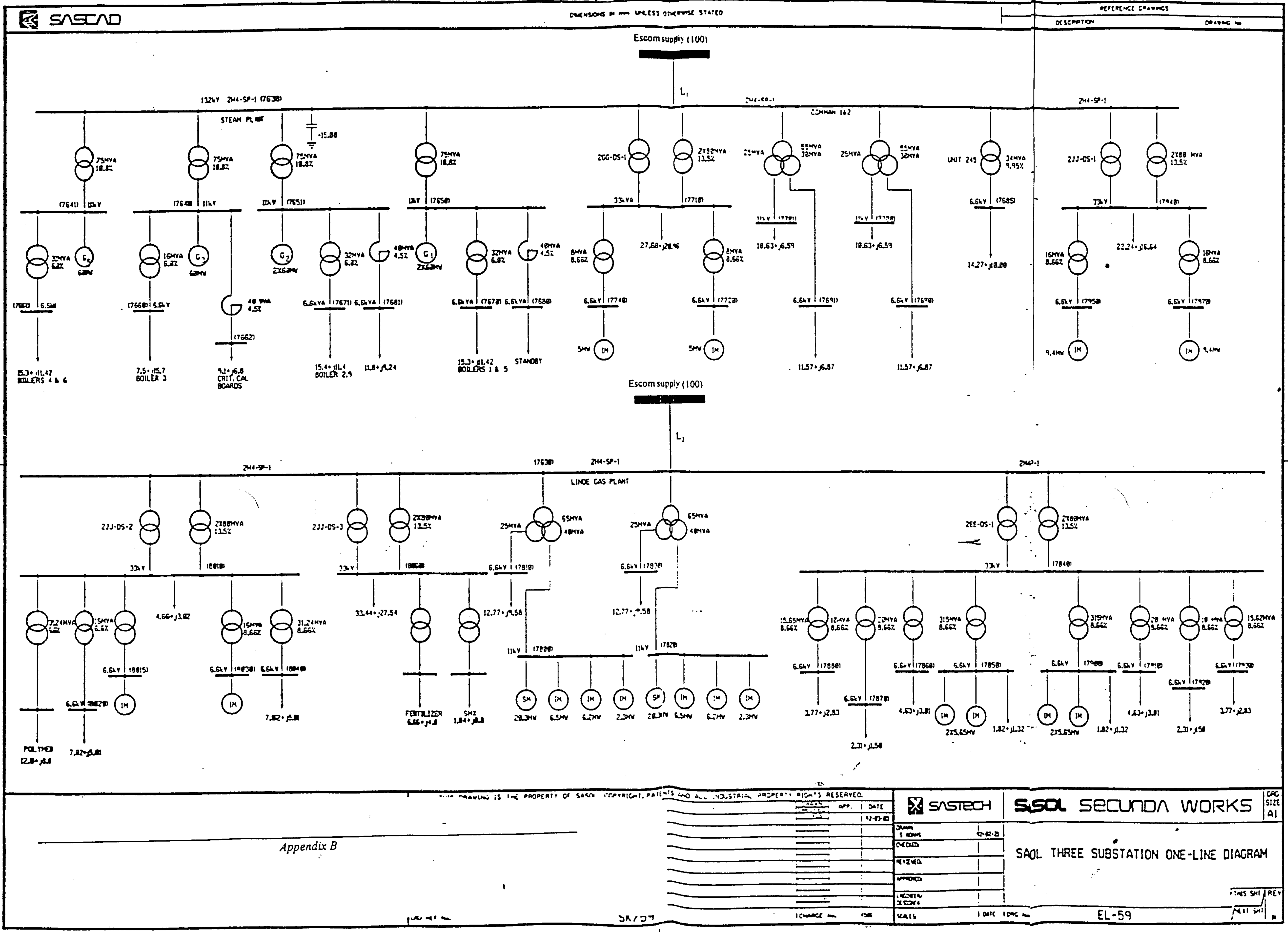
Best Regards

Signed

J PIORKOWSKI
Principal Engineer
Electrical Engineering

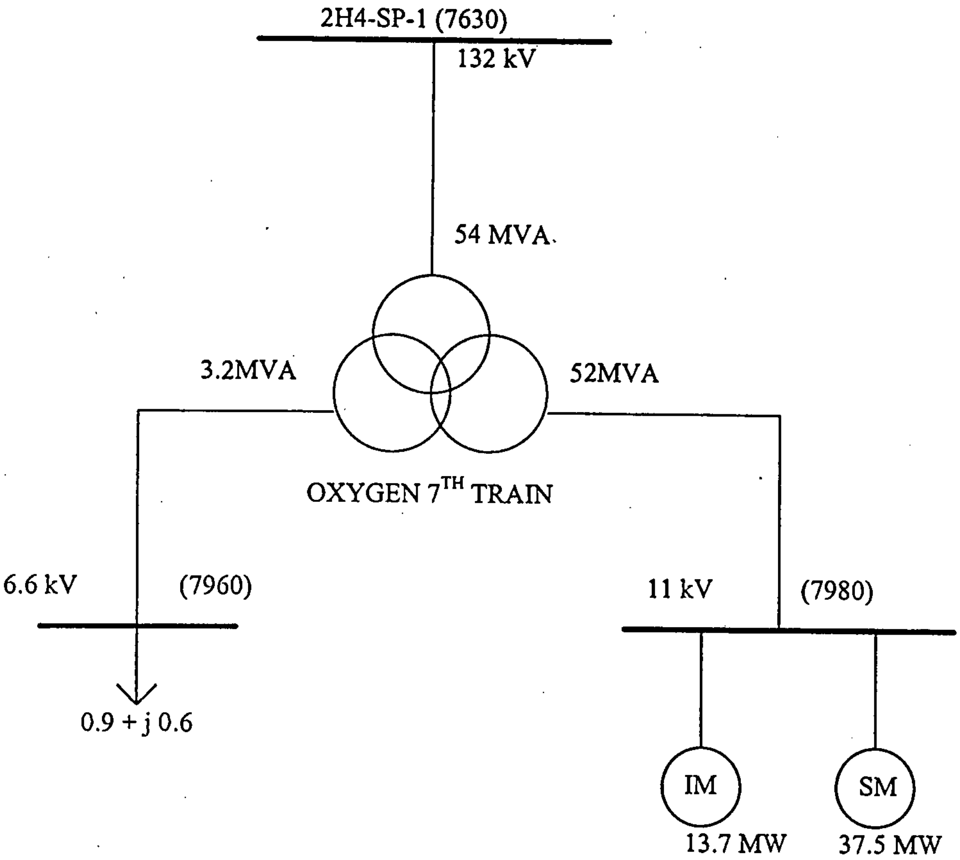
APPENDIX B

The one line diagram of Sasol Three network. This diagram was provided by Sastech Engineering at Secunda. It consists of Sasol Three distribution station one line diagram (B1) and the extensions made on the system (B2).


SASCAD
DIMENSIONS IN mm UNLESS OTHERWISE STATED
REFERENCE DRAWINGS
DESCRIPTION
DRAWING No
Escom supply (100)
L1
132kV 2H4-SP-1 (7638)
STEAM PLANT
-15.88
2H4-SP-1
COMMAN 1&2
2H4-SP-1
75MVA 18.8%
(7641) 11kV
(7648) 11kV
11kV (7651)
11kV (7650)
32MVA 6.8%
G4
63MW
16MVA 6.8%
G3
63MW
48 MVA 4.5%
G2
2X63MW
G1
2X63MW
48MVA 4.5%
(7660) 6.5kV
(7668) 6.6kV
(7662)
6.6kVA (7671)
6.6kVA (7681)
6.6kVA (7678)
6.6kVA (7686)
15.3+j11.42 BOILERS 4 & 6
7.5+j15.7 BOILER 3
9.1+j6.8 CRIT. CAL BOARDS
15.4+j11.4 BOILER 2.9
11.8+j9.24
15.3+j11.42 BOILERS 1 & 5
STANDBY
2GG-DS-1
2X92MVA 13.5%
33kVA
(7718)
8MVA 8.66%
27.68+j20.96
2MVA 8.66%
6.6kV (7740)
6.6kV (7720)
5MW
IM
25MVA
55MVA 32MVA
11kV (7781)
11kV (7779)
18.63+j6.59
6.6kV (7691)
6.6kV (7698)
11.57+j6.87
UNIT 245
34MVA 9.95%
6.6kV (7685)
14.27+j10.88
2JJ-DS-1
2X88 MVA 13.5%
33kV
(7948)
16MVA 8.66%
22.24+j16.64
6.6kV (7958)
6.6kV (7978)
9.4MW
Escom supply (100)
L2
2H4-SP-1
(7630)
2H4-SP-1
LINDE GAS PLANT
2HP-1
2JJ-DS-2
2X88MVA 13.5%
33kV
(8818)
7.24MVA 5.6%
15MVA 6.6%
4.66+j3.82
15MVA 8.66%
31.24MVA 8.66%
6.6kV (8815)
6.6kV (8838)
6.6kV (8848)
6.6kV (8828)
POLYMER 12.8+j8.8
7.82+j5.81
7.82+j5.81
2JJ-DS-3
2X88MVA 13.5%
33kV
33.44+j27.54
FERTILIZER 6.66+j4.8
SMX 1.84+j8.8
25MVA
55MVA 48MVA
65MVA 48MVA
6.6kV (7818)
6.6kV (7830)
12.77+j9.58
11kV (7828)
11kV (7820)
SM
28.3MW
6.5MW
6.2MW
2.3MW
2EE-DS-1
2X88MVA 13.5%
33kV
(7848)
15.65MVA 8.66%
12MVA 8.66%
20MVA 9.66%
315MVA 8.66%
20 MVA 9.66%
18 MVA 8.66%
15.62MVA 8.66%
6.6kV (7888)
6.6kV (7878)
6.6kV (7868)
6.6kV (7858)
6.6kV (7988)
6.6kV (7918)
6.6kV (7928)
6.6kV (7938)
3.77+j2.83
2.31+j1.58
4.63+j3.81
2X5.65MW
1.82+j1.32
DM
THIS DRAWING IS THE PROPERTY OF SASOL. COPYRIGHT, PATENTS AND ALL INDUSTRIAL PROPERTY RIGHTS RESERVED.
APP.
DATE
92-03-03
DRAWN
S ADAMS
92-02-21
CHECKED
REVIEWED
APPROVED
ENGINEER
DESIGNER
CHANGE No
SCALE
DATE
DWG No
SASTECH
SASOL SECUNDA WORKS
DRG SIZE A1
SAOL THREE SUBSTATION ONE-LINE DIAGRAM
EL-59
THIS SHT
NEXT SHT
REV
SK/59

Appendix B

32 Extensions made on the Sasol Three system



APPENDIX C

A summary of the network parameters of the Sasol Three system as it existed in June 1994.

(i) Busbar data (bus type 1=load bus, type 2= generator bus and bus type 3 = slack bus).

Bus No	Type	Bus load		Bus shunt		Voltage	Angle
		MW	MVAr	MW	MVAr		
100	3	0.0	0.0	0.0	0.0	1	0°0
7630	1	0.0	0.0	0.0	15.8		
7640	-2	0.0	0.0	0.0	0.0		
7641	-2	0.0	0.0	0.0	0.0		
7650	-2	0.0	0.0	0.0	0.0		
7651	-2	0.0	0.0	0.0	0.0		
7660	1	7.5	5.7	0.0	0.0		
7661	1	15.3	11.4	0.0	0.0		
7662	1	9.1	6.8	0.0	0.0		
7670	1	15.3	11.4	0.0	0.0		
7671	1	15.4	11.4	0.0	0.0		
7680	1	0.0	0.0	0.0	0.0		
7681	1	11.8	9.2	0.0	0.0		
7685	1	14.3	10.0	0.0	0.0		
7689	1	0.0	0.0	0.0	0.0		
7690	1	11.6	6.9	0.0	0.0		
7691	1	11.6	6.9	0.0	0.0		
7699	1	0.0	0.0	0.0	0.0		
7700	1	10.6	6.6	0.0	0.0		
7701	1	10.6	6.6	0.0	0.0		
7710	1	34.6	26.2	0.0	0.0		
7720	1	4.5	2.0	0.0	0.0		
7740	1	4.5	2.0	0.0	0.0		
7799	1	0.0	0.0	0.0	0.0		
7800	-2	0.0	0.0	0.0	0.0		
7801	1	5.8	2.7	0.0	0.0		
7802	1	5.5	2.9	0.0	0.0		
7803	1	2.0	0.8	0.0	0.0		
7810	1	12.8	9.6	0.0	0.0		
7819	1	0.0	0.0	0.0	0.0		
7820	-2	0.0	0.0	0.0	0.0		
7821	1	5.8	2.7	0.0	0.0		
7822	1	5.5	2.9	0.0	0.0		
7823	1	2.0	0.8	0.0	0.0		
7830	1	12.8	9.6	0.0	0.0		
7840	1	0.0	0.0	0.0	0.0		
7850	1	6.8	4.5	0.0	0.0		
7851	1	5.0	3.2	0.0	0.0		
7860	1	4.6	3.0	0.0	0.0		
7870	1	2.3	1.5	0.0	0.0		
7880	1	3.8	2.8	0.0	0.0		
7900	1	6.8	4.5	0.0	0.0		
7901	1	5.0	3.2	0.0	0.0		
7910	1	4.6	3.0	0.0	0.0		
7920	1	2.3	1.5	0.0	0.0		
7930	1	3.8	2.8	0.0	0.0		
7940	1	27.8	20.8	0.0	0.0		
7950	1	8.5	4.2	0.0	0.0		
7960	1	0.9	0.6	0.0	0.0		
7970	1	8.5	4.2	0.0	0.0		
7979	1	0.0	0.0	0.0	0.0		
7980	-2	0.0	0.0	0.0	0.0		
7981	1	13.7	9.2	0.0	0.0		
8009	1	12.0	8.0	0.0	0.0		
8010	1	4.7	3.0	0.0	0.0		
8015	1	8.5	4.2	0.0	0.0		
8020	1	7.0	5.0	0.0	0.0		
8030	1	8.5	4.2	0.0	0.0		
8040	1	7.0	5.0	0.0	0.0		
8060	1	41.8	34.8	0.0	0.0		
8061	1	6.7	4.0	0.0	0.0		
8062	1	1.0	0.8	0.0	0.0		

(ii) Generator plant data

Bus No.	Unit	Power generated		MVAr limits		V	MVA	X"
		MW	MVAr	Q_{min}	Q_{max}	(pu)	base	(pu)
100	1	263.4	114.1	0.0	0.0	1.0000	500	0.2100
7640	1	60.0	45.0	40.0	45.0	1.0000	75	0.1400
7641	1	60.0	45.0	40.0	45.0	1.0000	75	0.1400
7650	1	60.0	45.0	40.0	45.0	1.0000	75	0.1400
7651	1	60.0	45.0	40.0	45.0	1.0000	75	0.1400
7800	1	-18.0	9.8	-6.7	9.8	0.9980	23	0.1400
7820	1	-18.0	9.8	-6.7	9.8	0.9980	23	0.1400
7980	1	-35.3	17.0	-5.3	17.0	0.9980	40	0.1400

(iii) Line and transformer data

From bus	To bus	Crt no.	Branch impedance			Branch rating
			R	X	B	
100*	7630	1	0.0011	0.0095	0.0000	100
100*	7630	2	0.0011	0.0095	0.0000	100
7630*	7640	1	0.0047	0.1440	0.0000	75
7630*	7641	1	0.0047	0.1440	0.0000	75
7630*	7650	1	0.0047	0.1440	0.0000	75
7630*	7651	1	0.0047	0.1440	0.0000	75
7630*	7685	1	0.0000	0.2927	0.0000	34
7630*	7689	1	0.0005	-0.0187	0.0000	55
7630*	7699	1	0.0005	-0.0187	0.0000	55
7630*	7710	1	0.0044	0.1688	0.0000	80
7630*	7710	2	0.0044	0.1688	0.0000	80
7630*	7799	1	0.0043	-0.0159	0.0000	65
7630*	7819	1	0.0043	-0.0159	0.0000	65
7630*	7840	1	0.0044	0.1688	0.0000	80
7630*	7840	2	0.0044	0.1688	0.0000	80
7630*	7940	1	0.0044	0.1688	0.0000	80
7630*	7940	2	0.0044	0.1688	0.0000	80
7630*	7979	1	0.0001	-0.0296	0.0000	54
7630*	8010	1	0.0044	0.1688	0.0000	80
7630*	8010	2	0.0044	0.1688	0.0000	80
7630*	8060	1	0.0044	0.1688	0.0000	80
7630*	8060	2	0.0044	0.1688	0.0000	80
7640*	7660	1	0.0000	0.3750	0.0000	16
7640*	7662	1	0.0000	0.1125	0.0000	40
7641*	7661	1	0.0000	0.1875	0.0000	32
7650*	7670	1	0.0000	0.1875	0.0000	32
7650*	7680	1	0.0000	0.1125	0.0000	40
7651*	7671	1	0.0000	0.3750	0.0000	16
7651*	7681	1	0.0000	0.1125	0.0000	40
7689*	7690	1	0.0017	0.1976	0.0000	30
7689*	7700	1	0.0020	0.2569	0.0000	25
7691	7699*	1	0.0017	0.1976	0.0000	30
7699*	7701	1	0.0020	0.2569	0.0000	25
7710*	7720	1	0.0000	1.0825	0.0000	8
7710*	7740	1	0.0000	1.0825	0.0000	8
7799*	7800	1	0.0063	0.2174	0.0000	40
7799*	7810	1	0.0065	0.1672	0.0000	25
7800*	7801	1	0.0000	0.0000	0.0000	100
7800*	7802	1	0.0000	0.0000	0.0000	100
7800*	7803	1	0.0000	0.0000	0.0000	100
7819*	7820	1	0.0063	0.2174	0.0000	40
7819*	7830	1	0.0065	0.1672	0.0000	25
7820*	7821	1	0.0000	0.0000	0.0000	100
7820*	7822	1	0.0000	0.0000	0.0000	100
7820*	7823	1	0.0000	0.0000	0.0000	100
7840*	7850	1	0.0000	0.2749	0.0000	32
7840*	7860	1	0.0000	0.4330	0.0000	20
7840*	7870	1	0.0000	0.8660	0.0000	10
7840*	7880	1	0.0000	0.5544	0.0000	16
7840*	7900	1	0.0000	0.2749	0.0000	32
7840*	7910	1	0.0000	0.4330	0.0000	20
7840*	7920	1	0.0000	0.8660	0.0000	10
7840*	7930	1	0.0000	0.5544	0.0000	16
7850*	7851	1	0.0000	0.0000	0.0000	100
7900*	7901	1	0.0000	0.0000	0.0000	100
7940*	7950	1	0.0000	0.5412	0.0000	16
7940*	7970	1	0.0000	0.5412	0.0000	16
7960	7979*	1	0.0000	0.3778	0.0000	3
7979*	7980	1	0.0000	0.2574	0.0000	52

7980*	7981	1	0.0000	0.0000	0.0000	100
8009	8010*	1	0.0000	0.5412	0.0000	16
8010*	8015	1	0.0000	0.5412	0.0000	16
8010*	8020	1	0.0000	0.2772	0.0000	31
8010*	8030	1	0.0000	0.5412	0.0000	16
8010*	8040	1	0.0000	0.2772	0.0000	31
8060*	8061	1	0.0000	0.4330	0.0000	20
8060*	8062	1	0.0000	0.2772	0.0000	31

(iv) Transformer adjustment data

From bus	To bus	Crt no.	Tap side	High tap	Low tap	High V	Low V	Tap increm.
7630	7640	1	7630	1.1000	0.9000	1.0200	1.0000	0.01250
7630	7641	1	7630	1.1000	0.9000	1.0200	1.0000	0.01250
7630	7650	1	7630	1.1000	0.9000	1.0200	1.0000	0.01250
7630	7651	1	7630	1.1000	0.9000	1.0200	1.0000	0.01250
7630	7685	1	7685	1.0500	0.8500	1.0200	1.0000	0.01250
7630	7710	1	7710	1.0500	0.8500	1.0200	1.0000	0.01250
7630	7710	2	7710	1.0500	0.8500	1.0200	1.0000	0.01250
7630	7840	1	7840	1.0500	0.8500	1.0200	1.0000	0.01250
7630	7840	2	7840	1.0500	0.8500	1.0200	1.0000	0.01250
7630	7940	1	7940	1.0500	0.8500	1.0200	1.0000	0.01250
7630	7940	2	7940	1.0500	0.8500	1.0200	1.0000	0.01250
7630	8010	1	8010	1.0500	0.8500	1.0200	1.0000	0.01250
7630	8010	2	8010	1.0500	0.8500	1.0200	1.0000	0.01250
7630	8060	1	8060	1.0500	0.8500	1.0200	1.0000	0.01250
7630	8060	2	8060	1.0500	0.8500	1.0200	1.0000	0.01250
7640	7660	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
7641	7661	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
7650	7670	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
7651	7671	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
7689	7690	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
7689	7700	1	7700	1.0500	0.8500	1.0200	1.0000	0.01250
7691	7699	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
7699	7701	1	7701	1.0500	0.8500	1.0200	1.0000	0.01250
7710	7720	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
7710	7740	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
7799	7800	1	7800	1.0500	0.8500	1.0200	1.0000	0.01250
7799	7810	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
7819	7820	1	7820	1.0500	0.8500	1.0200	1.0000	0.01250
7819	7830	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
7840	7850	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
7840	7860	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
7840	7870	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
7840	7880	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
7840	7900	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
7840	7910	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
7840	7920	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
7840	7930	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
7940	7950	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
7940	7970	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
7960	7979	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
7979	7980	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
8009	8010	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
8010	8015	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
8010	8020	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
8010	8030	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
8010	8040	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
8060	8061	1	0	1.5000	0.5100	1.5000	0.5100	0.00625
8060	8062	1	0	1.5000	0.5100	1.5000	0.5100	0.00625

APPENDIX D

A summary of the load flow and short circuit results of Sasol Three system as it existed in June 1994.

(i) Tabulated results of the Sasol Three system

Bus No.	Voltage	Angle	Bus load		Power generated	
			MW	MVArs	MW	MVArs
100	1.0000	0.0	0.0	0.0	263	114
7630	0.9932	-0.7	0.0	0.0	0.0	0.0
7640	1.0379	2.7	0.0	0.0	60	45
7641	1.0390	2.8	0.0	0.0	60	45
7650	1.0390	2.8	0.0	0.0	60	45
7651	1.0255	1.9	0.0	0.0	60	45
7660	1.0165	1.2	7.5	5.7	0.0	0.0
7661	1.0176	1.3	15.3	11.4	0.0	0.0
7662	1.0304	2.2	9.1	6.8	0.0	0.0
7670	1.0176	1.3	15.3	11.4	0.0	0.0
7671	0.9801	-1.4	15.4	11.4	0.0	0.0
7680	1.0390	2.8	0.0	0.0	0.0	0.0
7681	1.0152	1.2	11.8	9.2	0.0	0.0
7685	1.0159	-2.9	14.3	10.0	0.0	0.0
7689	0.9957	-0.4	0.0	0.0	0.0	0.0
7690	1.0346	-1.6	11.6	6.9	0.0	0.0
7691	1.0346	-1.6	11.6	6.9	0.0	0.0
7699	0.9957	-0.4	0.0	0.0	0.0	0.0
7700	1.0173	-1.9	10.6	6.6	0.0	0.0
7701	1.0173	-1.9	10.6	6.6	0.0	0.0
7710	1.0184	-2.6	34.6	26.2	0.0	0.0
7720	0.9951	-5.4	4.5	2.0	0.0	0.0
7740	0.9951	-5.4	4.5	2.0	0.0	0.0
7799	0.9927	-0.3	0.0	0.0	0.0	0.0
7800	0.9958	-4.2	0.0	0.0	-18	10
7801	0.9958	-4.2	5.8	2.7	0.0	0.0
7802	0.9958	-4.2	5.5	2.9	0.0	0.0
7803	0.9958	-4.2	2.0	0.8	0.0	0.0
7810	0.9752	-1.5	12.8	9.6	0.0	0.0
7819	0.9927	-0.3	0.0	0.0	0.0	0.0
7820	0.9958	-4.2	0.0	0.0	-18	10
7821	0.9958	-4.2	5.8	2.7	0.0	0.0
7822	0.9958	-4.2	5.5	2.9	0.0	0.0
7823	0.9958	-4.2	2.0	0.8	0.0	0.0
7830	0.9752	-1.5	12.8	9.6	0.0	0.0
7840	1.0175	-2.7	0.0	0.0	0.0	0.0
7850	1.0224	-4.4	6.8	4.5	0.0	0.0
7851	1.0224	-4.4	5.0	3.2	0.0	0.0
7860	1.0308	-3.8	4.6	3.0	0.0	0.0
7870	1.0308	-3.8	2.3	1.5	0.0	0.0
7880	1.0281	-3.8	3.8	2.8	0.0	0.0
7900	1.0224	-4.4	6.8	4.5	0.0	0.0
7901	1.0224	-4.4	5.0	3.2	0.0	0.0
7910	1.0308	-3.8	4.6	3.0	0.0	0.0
7920	1.0308	-3.8	2.3	1.5	0.0	0.0
7930	1.0281	-3.8	3.8	2.8	0.0	0.0
7940	1.0189	-2.7	27.8	20.8	0.0	0.0
7950	0.9951	-5.3	8.5	4.2	0.0	0.0
7960	0.9905	0.0	0.9	0.6	0.0	0.0
7970	0.9951	-5.3	8.5	4.2	0.0	0.0
7979	0.9928	0.2	0.0	0.0	0.0	0.0
7980	0.9925	-7.3	0.0	0.0	0.0	0.0
7981	0.9925	-7.3	13.7	9.2	-35	17
8009	0.9704	-6.6	12.0	8.0	0.0	0.0
8010	1.0172	-2.8	4.7	3.0	0.0	0.0
8015	0.9934	-5.4	8.5	4.2	0.0	0.0
8020	1.0296	-3.9	7.0	5.0	0.0	0.0
8030	0.9934	-5.4	8.5	4.2	0.0	0.0
8040	1.0296	-3.9	7.0	5.0	0.0	0.0
8060	1.0103	-2.9	41.8	34.8	0.0	0.0
8061	1.0188	-4.5	6.7	4.0	0.0	0.0
8062	1.0341	-3.1	1.0	0.8	0.0	0.0

(ii) PSS/E results of the Sasol Three system

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1      PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS/E
TYPICAL INDUSTRIAL PLANT ELECTRICAL SYSTEM ( SASOL THREE)                  RATING
BASE CASE LOAD FLOW                                                          SET A

BUS    100 SWING BU 132 AREA CKT     MW      MVAR      MVA  %I 1.0000PU   0.00  100
 GENERATION             1          263.4    114.1H   287.0  57 132.00KV
 TO  7630 FDR 1      132   1   1    131.7     57.1    143.5 144
 TO  7630 FDR 1      132   1   2    131.7     57.1    143.5 144

BUS  7630 FDR 1      132 AREA CKT     MW      MVAR      MVA  %I 0.9932PU  -0.69 7630
                        1                                        131.10KV
 TO SHUNT                            0.0     -15.6     15.6
 TO    100 SWING BU 132   1   1   -131.5     -55.1    142.5 144
 TO    100 SWING BU 132   1   2   -131.5     -55.1    142.5 144
 TO  7640 GEN 2    11.0   1   1    -43.3     -28.2     51.6  69 1.0000LK
 TO  7641 GEN 1    11.0   1   1    -44.6     -28.8     53.1  71 1.0000LK
 TO  7650 GEN 4    11.0   1   1    -44.6     -28.8     53.1  71 1.0000LK
 TO  7651 GEN 3    11.0   1   1    -32.7     -20.5     38.6  52 1.0000LK
 TO  7685 LOAD 2006.60   1   1     14.3      10.9     17.9  53 0.9500LK
 TO  7689 FDR B           1   1     22.2      14.0     26.3  48
 TO  7699 FDR A           1   1     22.2      14.1     26.3  48
 TO  7710 LOAD 1  33.0    1   1     21.8      16.6     27.4  34 0.9500LK
 TO  7710 LOAD 1  33.0    1   2     21.8      16.6     27.4  34 0.9500LK
 TO  7799 FDR C           1   1     44.2       8.4     45.0  70
 TO  7819 FDR D           1   1     44.2       8.4     45.0  70
 TO  7840 FDR 100 33.0    1   1     22.6      17.1     28.3  36 0.9500LK
 TO  7840 FDR 100 33.0    1   2     22.6      17.1     28.3  36 0.9500LK
 TO  7940 LOAD 2  33.0    1   1     22.4      16.3     27.7  35 0.9500LK
 TO  7940 LOAD 2  33.0    1   2     22.4      16.3     27.7  35 0.9500LK
 TO  7979 FDR E           1   1     49.9      -1.5     49.9  93
 TO  8010 LOAD 3  33.0    1   1     23.9      17.3     29.5  37 0.9500LK
 TO  8010 LOAD 3  33.0    1   2     23.9      17.3     29.5  37 0.9500LK
 TO  8060 LOAD 4  33.0    1   1     24.8      21.6     32.9  41 0.9500LK
 TO  8060 LOAD 4  33.0    1   2     24.8      21.6     32.9  41 0.9500LK

BUS  7640 GEN 2    11.0 AREA CKT     MW      MVAR      MVA  %I 1.0379PU   2.71 7640
 GENERATION             1           60.0     45.0H     75.0 100 11.417KV
 TO  7630 FDR 1      132   1   1     43.4     32.0      53.9  69 1.0000UN
 TO  7660 LOAD 2056.60   1   1      7.5      6.0       9.6  58 1.0000LK
 TO  7662 LOAD 10211.0   1   1      9.1      6.9      11.4  28

BUS  7641 GEN 1    11.0 AREA CKT     MW      MVAR      MVA  %I 1.0390PU   2.81 7641
 GENERATION             1           60.0     45.0H     75.0 100 11.429KV
 TO  7630 FDR 1      132   1   1     44.7     32.9      55.5  71 1.0000UN
 TO  7661 LOAD 2046.60   1   1     15.3     12.1      19.5  59 1.0000LK

BUS  7650 GEN 4    11.0 AREA CKT     MW      MVAR      MVA  %I 1.0390PU   2.81 7650
 GENERATION             1           60.0     45.0H     75.0 100 11.429KV
 TO  7630 FDR 1      132   1   1     44.7     32.9      55.5  71 1.0000UN
 TO  7670 LOAD 2086.60   1   1     15.3     12.1      19.5  59 1.0000LK
 TO  7680 LOAD 2096.60   1   1      0.0      0.0       0.0   0

BUS  7651 GEN 3    11.0 AREA CKT     MW      MVAR      MVA  %I 1.0255PU   1.91 7651
 GENERATION             1           60.0     45.0H     75.0 100 11.281KV
 TO  7630 FDR 1      132   1   1     32.8     22.7      39.9  52 1.0000UN
 TO  7671 LOAD 2066.60   1   1     15.4     12.9      20.1 122 1.0000LK
 TO  7681 LOAD 2076.60   1   1     11.8      9.5      15.1  37

BUS  7660 LOAD 2056.60 AREA CKT      MW      MVAR      MVA  %I 1.0165PU   1.18 7660
                        1                                        6.709KV
 TO LOAD-PQ                           7.5      5.7       9.4
 TO  7640 GEN 2    11.0   1   1     -7.5     -5.7       9.4  58 1.0000UN

BUS  7661 LOAD 2046.60 AREA CKT      MW      MVAR      MVA  %I 1.0176PU   1.25 7661
                        1                                        6.716KV
 TO LOAD-PQ                          15.3     11.4      19.1
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 TO  7641 GEN 1    11.0   1  1   -15.3   -11.4     19.1  59 1.0000UN

BUS  7662 LOAD 10211.0 AREA CKT    MW     MVAR      MVA  %I 1.0304PU   2.16 7662
                          1                                 11.334KV
 TO LOAD-PQ                         9.1     6.8     11.4
 TO  7640 GEN 2    11.0   1  1     -9.1    -6.8     11.4  28

BUS  7670 LOAD 2086.60 AREA CKT    MW     MVAR      MVA  %I 1.0176PU   1.25 7670
                          1                                  6.716KV
 TO LOAD-PQ                        15.3    11.4     19.1
 TO  7650 GEN 4    11.0   1  1    -15.3   -11.4     19.1  59 1.0000UN

BUS  7671 LOAD 2066.60 AREA CKT    MW     MVAR      MVA  %I 0.9801PU  -1.38 7671
                          1                                  6.469KV
 TO LOAD-PQ                        15.4    11.4     19.2
 TO  7651 GEN 3    11.0   1  1    -15.4   -11.4     19.2 122 1.0000UN

BUS  7680 LOAD 2096.60 AREA CKT    MW     MVAR      MVA  %I 1.0390PU   2.81 7680
                          1                                  6.857KV
 TO  7650 GEN 4    11.0   1  1      0.0     0.0      0.0   0

BUS  7681 LOAD 2076.60 AREA CKT    MW     MVAR      MVA  %I 1.0152PU   1.18 7681
                          1                                  6.700KV
 TO LOAD-PQ                        11.8     9.2     15.0
 TO  7651 GEN 3    11.0   1  1    -11.8    -9.2     15.0  37

BUS  7685 LOAD 2006.60 AREA CKT    MW     MVAR      MVA  %I 1.0159PU  -2.94 7685
                          1                                  6.705KV
 TO LOAD-PQ                        14.3    10.0     17.4
 TO  7630 FDR 1     132   1  1    -14.3   -10.0     17.4  50 0.9500UN

BUS  7689 FDR B        AREA CKT    MW     MVAR      MVA  %I 0.9957PU  -0.44 7689
                          1                                       KV
 TO  7630 FDR 1     132   1  1    -22.2   -14.2     26.3  48
 TO  7690 LOAD 2136.60    1  1     11.6     7.2     13.6  46 0.9500LK
 TO  7700 LOAD 10111.0    1  1     10.6     7.0     12.7  51 0.9625LK

BUS  7690 LOAD 2136.60 AREA CKT    MW     MVAR      MVA  %I 1.0346PU  -1.64 7690
                          1                                  6.829KV
 TO LOAD-PQ                        11.6     6.9     13.5
 TO  7689 FDR B           1  1    -11.6    -6.9     13.5  43 0.9500UN

BUS  7691 LOAD 2126.60 AREA CKT    MW     MVAR      MVA  %I 1.0346PU  -1.64 7691
                          1                                  6.828KV
 TO LOAD-PQ                        11.6     6.9     13.5
 TO  7699 FDR A           1  1    -11.6    -6.9     13.5  43 0.9500UN

BUS  7699 FDR A        AREA CKT    MW     MVAR      MVA  %I 0.9957PU  -0.44 7699
                          1                                       KV
 TO  7630 FDR 1     132   1  1    -22.2   -14.2     26.3  48
 TO  7691 LOAD 2126.60    1  1     11.6     7.2     13.6  46 0.9500LK
 TO  7701 LOAD 10011.0    1  1     10.6     7.0     12.7  51 0.9625LK

BUS  7700 LOAD 10111.0 AREA CKT    MW     MVAR      MVA  %I 1.0173PU  -1.92 7700
                          1                                 11.191KV
 TO LOAD-PQ                        10.6     6.6     12.5
 TO  7689 FDR B           1  1    -10.6    -6.6     12.5  49 0.9625UN

BUS  7701 LOAD 10011.0 AREA CKT    MW     MVAR      MVA  %I 1.0173PU  -1.92 7701
                          1                                 11.191KV
 TO LOAD-PQ                        10.6     6.6     12.5
 TO  7699 FDR A           1  1    -10.6    -6.6     12.5  49 0.9625UN

BUS  7710 LOAD 1   33.0 AREA CKT    MW     MVAR      MVA  %I 1.0184PU  -2.63 7710
                          1                                 33.608KV
 TO LOAD-PQ                        34.6    26.2     43.4
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  TO  7630 FDR 1      132   1  1    -21.8    -15.4     26.7  33 0.9500UN
  TO  7630 FDR 1      132   1  2    -21.8    -15.4     26.7  33 0.9500UN
  TO  7720 LOAD 2116.60     1  1      4.5      2.3      5.1  62 1.0000LK
  TO  7740 LOAD 2106.60     1  1      4.5      2.3      5.1  62 1.0000LK

 BUS  7720 LOAD 2116.60 AREA CKT     MW     MVAR      MVA  %I 0.9951PU  -5.38 7720
                         1                                     6.568KV
  TO LOAD-PQ                          4.5      2.0      4.9
  TO  7710 LOAD 1  33.0     1  1     -4.5     -2.0      4.9  62 1.0000UN

 BUS  7740 LOAD 2106.60 AREA CKT     MW     MVAR      MVA  %I 0.9951PU  -5.38 7740
                         1                                     6.568KV
  TO LOAD-PQ                          4.5      2.0      4.9
  TO  7710 LOAD 1  33.0     1  1     -4.5     -2.0      4.9  62 1.0000UN

 BUS  7799 FDR C        AREA CKT     MW     MVAR      MVA  %I 0.9927PU  -0.26 7799
                         1                                          KV
  TO  7630 FDR 1      132   1  1    -44.1     -8.8     45.0  70
  TO  7800 LOAD 10311.0     1  1     31.4     -1.3     31.4  79 1.0000LK
  TO  7810 LOAD 2016.60     1  1     12.8     10.0     16.3  65 1.0000LK

 BUS  7800 LOAD 10311.0 AREA CKT     MW     MVAR      MVA  %I 0.9958PU  -4.22 7800
  GENERATION             1          -18.0      9.8H    20.5  89 10.954KV
  TO  7799 FDR C            1  1    -31.3      3.4     31.5  79 1.0000UN
  TO  7801 I LOAD 111.0     1  1      5.8      2.7      6.4   6
  TO  7802 I LOAD 211.0     1  1      5.5      2.9      6.2   6
  TO  7803 I LOAD 311.0     1  1      2.0      0.8      2.2   2

 BUS  7801 I LOAD 111.0 AREA CKT     MW     MVAR      MVA  %I 0.9958PU  -4.22 7801
                         1                                     10.954KV
  TO LOAD-PQ                          5.8      2.7      6.4
  TO  7800 LOAD 10311.0     1  1     -5.8     -2.7      6.4   6

 BUS  7802 I LOAD 211.0 AREA CKT     MW     MVAR      MVA  %I 0.9958PU  -4.22 7802
                         1                                     10.954KV
  TO LOAD-PQ                          5.5      2.9      6.2
  TO  7800 LOAD 10311.0     1  1     -5.5     -2.9      6.2   6

 BUS  7803 I LOAD 311.0 AREA CKT     MW     MVAR      MVA  %I 0.9958PU  -4.22 7803
                         1                                     10.954KV
  TO LOAD-PQ                          2.0      0.8      2.2
  TO  7800 LOAD 10311.0     1  1     -2.0     -0.8      2.2   2

 BUS  7810 LOAD 2016.60 AREA CKT     MW     MVAR      MVA  %I 0.9752PU  -1.48 7810
                         1                                     6.436KV
  TO LOAD-PQ                         12.8      9.6     16.0
  TO  7799 FDR C            1  1    -12.8     -9.6     16.0  65 1.0000UN

 BUS  7819 FDR D        AREA CKT     MW     MVAR      MVA  %I 0.9927PU  -0.26 7819
                         1                                          KV
  TO  7630 FDR 1      132   1  1    -44.1     -8.8     45.0  70
  TO  7820 LOAD 10411.0     1  1     31.4     -1.3     31.4  79 1.0000LK
  TO  7830 LOAD 2026.60     1  1     12.8     10.0     16.3  65 1.0000LK

 BUS  7820 LOAD 10411.0 AREA CKT     MW     MVAR      MVA  %I 0.9958PU  -4.22 7820
  GENERATION             1          -18.0      9.8H    20.5  89 10.954KV
  TO  7819 FDR D            1  1    -31.3      3.4     31.5  79 1.0000UN
  TO  7821 I LOAD 411.0     1  1      5.8      2.7      6.4   6
  TO  7822 I LOAD 511.0     1  1      5.5      2.9      6.2   6
  TO  7823 I LOAD 611.0     1  1      2.0      0.8      2.2   2

 BUS  7821 I LOAD 411.0 AREA CKT     MW     MVAR      MVA  %I 0.9958PU  -4.22 7821
                         1                                     10.954KV
  TO LOAD-PQ                          5.8      2.7      6.4
  TO  7820 LOAD 10411.0     1  1     -5.8     -2.7      6.4   6
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BUS  7822 I LOAD 511.0 AREA CKT     MW       MVAR      MVA  %I 0.9958PU  -4.22 7822
                          1                                     10.954KV
 TO LOAD-PQ                        5.5       2.9      6.2
 TO  7820 LOAD 10411.0    1   1   -5.5      -2.9      6.2   6

BUS  7823 I LOAD 611.0 AREA CKT     MW       MVAR      MVA  %I 0.9958PU  -4.22 7823
                          1                                     10.954KV
 TO LOAD-PQ                        2.0       0.8      2.2
 TO  7820 LOAD 10411.0    1   1   -2.0      -0.8      2.2   2

BUS  7830 LOAD 2026.60 AREA CKT     MW       MVAR      MVA  %I 0.9752PU  -1.48 7830
                          1                                      6.436KV
 TO LOAD-PQ                       12.8       9.6     16.0
 TO  7819 FDR D           1   1  -12.8      -9.6     16.0  65 1.0000UN

BUS  7840 FDR 100 33.0 AREA CKT     MW       MVAR      MVA  %I 1.0175PU  -2.70 7840
                          1                                     33.578KV
 TO  7630 FDR 1      132  1   1  -22.5     -15.9     27.6  34 0.9500UN
 TO  7630 FDR 1      132  1   2  -22.5     -15.9     27.6  34 0.9500UN
 TO  7850 LOAD 2266.60    1   1   11.8       8.2     14.4  45 0.9750LK
 TO  7860 LOAD 2256.60    1   1    4.6       3.1      5.6  27 0.9750LK
 TO  7870 LOAD 2246.60    1   1    2.3       1.6      2.8  27 0.9750LK
 TO  7880 LOAD 2236.60    1   1    3.8       2.9      4.8  30 0.9750LK
 TO  7900 LOAD 2306.60    1   1   11.8       8.2     14.4  45 0.9750LK
 TO  7910 LOAD 2296.60    1   1    4.6       3.1      5.6  27 0.9750LK
 TO  7920 LOAD 2286.60    1   1    2.3       1.6      2.8  27 0.9750LK
 TO  7930 LOAD 2276.60    1   1    3.8       2.9      4.8  30 0.9750LK

BUS  7850 LOAD 2266.60 AREA CKT     MW       MVAR      MVA  %I 1.0224PU  -4.44 7850
                          1                                      6.748KV
 TO LOAD-PQ                        6.8       4.5      8.2
 TO  7840 FDR 100 33.0    1   1  -11.8      -7.7     14.1  44 0.9750UN
 TO  7851 I LOAD 76.60    1   1    5.0       3.2      5.9   6

BUS  7851 I LOAD 76.60 AREA CKT     MW       MVAR      MVA  %I 1.0224PU  -4.44 7851
                          1                                      6.748KV
 TO LOAD-PQ                        5.0       3.2      5.9
 TO  7850 LOAD 2266.60    1   1   -5.0      -3.2      5.9   6

BUS  7860 LOAD 2256.60 AREA CKT     MW       MVAR      MVA  %I 1.0308PU  -3.76 7860
                          1                                      6.803KV
 TO LOAD-PQ                        4.6       3.0      5.5
 TO  7840 FDR 100 33.0    1   1   -4.6      -3.0      5.5  27 0.9750UN

BUS  7870 LOAD 2246.60 AREA CKT     MW       MVAR      MVA  %I 1.0308PU  -3.76 7870
                          1                                      6.803KV
 TO LOAD-PQ                        2.3       1.5      2.8
 TO  7840 FDR 100 33.0    1   1   -2.3      -1.5      2.8  27 0.9750UN

BUS  7880 LOAD 2236.60 AREA CKT     MW       MVAR      MVA  %I 1.0281PU  -3.81 7880
                          1                                      6.786KV
 TO LOAD-PQ                        3.8       2.8      4.7
 TO  7840 FDR 100 33.0    1   1   -3.8      -2.8      4.7  29 0.9750UN

BUS  7900 LOAD 2306.60 AREA CKT     MW       MVAR      MVA  %I 1.0224PU  -4.44 7900
                          1                                      6.748KV
 TO LOAD-PQ                        6.8       4.5      8.2
 TO  7840 FDR 100 33.0    1   1  -11.8      -7.7     14.1  44 0.9750UN
 TO  7901 I LOAD 86.60    1   1    5.0       3.2      5.9   6

BUS  7901 I LOAD 86.60 AREA CKT     MW       MVAR      MVA  %I 1.0224PU  -4.44 7901
                          1                                      6.748KV
 TO LOAD-PQ                        5.0       3.2      5.9
 TO  7900 LOAD 2306.60    1   1   -5.0      -3.2      5.9   6

BUS  7910 LOAD 2296.60 AREA CKT     MW       MVAR      MVA  %I 1.0308PU  -3.76 7910
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                         1                                    6.803KV
 TO LOAD-PQ                         4.6      3.0      5.5
 TO  7840 FDR 100 33.0   1  1      -4.6     -3.0      5.5 27 0.9750UN

BUS  7920 LOAD 2286.60 AREA CKT      MW     MVAR      MVA %I 1.0308PU  -3.76 7920
                         1                                    6.803KV
 TO LOAD-PQ                         2.3      1.5      2.8
 TO  7840 FDR 100 33.0   1  1      -2.3     -1.5      2.8 27 0.9750UN

BUS  7930 LOAD 2276.60 AREA CKT      MW     MVAR      MVA %I 1.0281PU  -3.81 7930
                         1                                    6.786KV
 TO LOAD-PQ                         3.8      2.8      4.7
 TO  7840 FDR 100 33.0   1  1      -3.8     -2.8      4.7 29 0.9750UN

BUS  7940 LOAD 2  33.0 AREA CKT      MW     MVAR      MVA %I 1.0189PU  -2.68 7940
                         1                                   33.624KV
 TO LOAD-PQ                        27.8     20.8     34.7
 TO  7630 FDR 1    132   1  1     -22.4    -15.1     27.0 33 0.9500UN
 TO  7630 FDR 1    132   1  2     -22.4    -15.1     27.0 33 0.9500UN
 TO  7950 LOAD 2146.60   1  1       8.5      4.7      9.7 59 1.0000LK
 TO  7970 LOAD 2156.60   1  1       8.5      4.7      9.7 59 1.0000LK

BUS  7950 LOAD 2146.60 AREA CKT      MW     MVAR      MVA %I 0.9951PU  -5.28 7950
                         1                                    6.568KV
 TO LOAD-PQ                         8.5      4.2      9.5
 TO  7940 LOAD 2  33.0   1  1      -8.5     -4.2      9.5 59 1.0000UN

BUS  7960 LOAD 2036.60 AREA CKT      MW     MVAR      MVA %I 0.9905PU  -0.02 7960
                         1                                    6.537KV
 TO LOAD-PQ                         0.9      0.6      1.1
 TO  7979 FDR E          1  1      -0.9     -0.6      1.1 34 1.0000UN

BUS  7970 LOAD 2156.60 AREA CKT      MW     MVAR      MVA %I 0.9951PU  -5.28 7970
                         1                                    6.568KV
 TO LOAD-PQ                         8.5      4.2      9.5
 TO  7940 LOAD 2  33.0   1  1      -8.5     -4.2      9.5 59 1.0000UN

BUS  7979 FDR E        AREA CKT      MW     MVAR      MVA %I 0.9928PU   0.17 7979
                         1                                         KV
 TO  7630 FDR 1    132   1  1     -49.9      0.8     49.9 93
 TO  7960 LOAD 2036.60   1  1       0.9      0.6      1.1 34 1.0000LK
 TO  7980 LOAD 10511.0   1  1      49.0     -1.4     49.0 95 1.0125LK

BUS  7980 LOAD 10511.0 AREA CKT      MW     MVAR      MVA %I 0.9925PU  -7.27 7980
 GENERATION              1        -35.3    17.0H     39.2 98 10.918KV
 TO  7979 FDR E          1  1     -49.0      7.8     49.6 96 1.0125UN
 TO  7981 I LOAD 911.0   1  1      13.7      9.2     16.5 17

BUS  7981 I LOAD 911.0 AREA CKT      MW     MVAR      MVA %I 0.9925PU  -7.27 7981
                         1                                   10.918KV
 TO LOAD-PQ                        13.7      9.2     16.5
 TO  7980 LOAD 10511.0   1  1     -13.7     -9.2     16.5 17

BUS  8009 LOAD 2166.60 AREA CKT      MW     MVAR      MVA %I 0.9704PU  -6.59 8009
                         1                                    6.404KV
 TO LOAD-PQ                        12.0      8.0     14.4
 TO  8010 LOAD 3  33.0   1  1     -12.0     -8.0     14.4 93 1.0000UN

BUS  8010 LOAD 3  33.0 AREA CKT      MW     MVAR      MVA %I 1.0172PU  -2.82 8010
                         1                                   33.568KV
 TO LOAD-PQ                         4.7      3.0      5.6
 TO  7630 FDR 1    132   1  1     -23.8    -16.0     28.7 35 0.9500UN
 TO  7630 FDR 1    132   1  2     -23.8    -16.0     28.7 35 0.9500UN
 TO  8009 LOAD 2166.60   1  1      12.0      9.2     15.1 93 1.0000LK
 TO  8015 LOAD 2186.60   1  1       8.5      4.7      9.7 60 1.0000LK
 TO  8020 LOAD 2176.60   1  1       7.0      5.2      8.7 28 0.9750LK
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 TO  8030 LOAD 2196.60    1  1      8.5      4.7       9.7  60 1.0000LK
 TO  8040 LOAD 2206.60    1  1      7.0      5.2       8.7  28 0.9750LK

BUS  8015 LOAD 2186.60 AREA CKT     MW      MVAR       MVA  %I 0.9934PU  -5.43 8015
                          1                                     6.556KV
 TO LOAD-PQ                         8.5      4.2       9.5
 TO  8010 LOAD 3  33.0    1  1     -8.5     -4.2       9.5  60 1.0000UN

BUS  8020 LOAD 2176.60 AREA CKT     MW      MVAR       MVA  %I 1.0296PU  -3.85 8020
                          1                                     6.796KV
 TO LOAD-PQ                         7.0      5.0       8.6
 TO  8010 LOAD 3  33.0    1  1     -7.0     -5.0       8.6  27 0.9750UN

BUS  8030 LOAD 2196.60 AREA CKT     MW      MVAR       MVA  %I 0.9934PU  -5.43 8030
                          1                                     6.556KV
 TO LOAD-PQ                         8.5      4.2       9.5
 TO  8010 LOAD 3  33.0    1  1     -8.5     -4.2       9.5  60 1.0000UN

BUS  8040 LOAD 2206.60 AREA CKT     MW      MVAR       MVA  %I 1.0296PU  -3.85 8040
                          1                                     6.796KV
 TO LOAD-PQ                         7.0      5.0       8.6
 TO  8010 LOAD 3  33.0    1  1     -7.0     -5.0       8.6  27 0.9750UN

BUS  8060 LOAD 4  33.0 AREA CKT     MW      MVAR       MVA  %I 1.0103PU  -2.90 8060
                          1                                    33.341KV
 TO LOAD-PQ                        41.8     34.8      54.4
 TO  7630 FDR 1    132    1  1    -24.7    -19.9      31.8  39 0.9500UN
 TO  7630 FDR 1    132    1  2    -24.7    -19.9      31.8  39 0.9500UN
 TO  8061 LOAD 2216.60    1  1      6.7      4.3       7.9  39 0.9750LK
 TO  8062 LOAD 2226.60    1  1      1.0      0.8       1.3   4 0.9750LK

BUS  8061 LOAD 2216.60 AREA CKT     MW      MVAR       MVA  %I 1.0188PU  -4.47 8061
                          1                                     6.724KV
 TO LOAD-PQ                         6.7      4.0       7.8
 TO  8060 LOAD 4  33.0    1  1     -6.7     -4.0       7.8  38 0.9750UN

BUS  8062 LOAD 2226.60 AREA CKT     MW      MVAR       MVA  %I 1.0341PU  -3.06 8062
                          1                                     6.825KV
 TO LOAD-PQ                         1.0      0.8       1.3
 TO  8060 LOAD 4  33.0    1  1     -1.0     -0.8       1.3   4 0.9750UN
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(iii) Short Circuit results of the Sasol Three Network

Three-phase fault at bus: (7630) , Nominal kV = 132.000 Prefault Voltage = 100.00 % of nominal bus kV
Voltage factor (C): 1.10 , Base kV = 132.000 = 100.00 % of base kV

Contribution		Voltage (%) & Initial Symmetrical Current (rms)				
From Bus ID	To Bus ID	% V From Bus	kA Real	kA Imaginary	X/R Ratio	kA Magnitude
(7630)	Total	0.00	1.605	-31.414	19.6	31.455
(100)	(7630)	23.82	0.694	-11.966	19.6	11.986
(100)	(7630)	23.82	0.694	-11.966	17.3	11.986
(7641)	(7630)	42.19	0.039	-1.377	35.1	1.378
(7710)	(7630)	0.00	0.000	0.000	999.9	0.000
(7685)	(7630)	0.00	0.000	0.000	999.9	0.000
(7640)	(7630)	42.19	0.039	-1.377	35.1	1.378
(7651)	(7630)	42.19	0.039	-1.377	35.1	1.378
(7650)	(7630)	42.19	0.039	-1.377	35.1	1.378
(7710)	(7630)	0.00	0.000	0.000	999.9	0.000
(7940)	(7630)	0.00	0.000	0.000	999.9	0.000
(7940)	(7630)	0.00	0.000	0.000	999.9	0.000
(8010)	(7630)	0.00	0.000	0.000	999.9	0.000
(8010)	(7630)	0.00	0.000	0.000	999.9	0.000
(8060)	(7630)	0.00	0.000	0.000	999.9	0.000
(8060)	(7630)	0.00	0.000	0.000	999.9	0.000
(7840)	(7630)	0.00	0.000	0.000	999.9	0.000
(7840)	(7630)	0.00	0.000	0.000	999.9	0.000
(7701)	(7630)	0.00	0.000	0.000	999.9	0.000
(7691)	(7630)	0.00	0.000	0.000	999.9	0.000
(7700)	(7630)	0.00	0.000	0.000	999.9	0.000
(7690)	(7630)	0.00	0.000	0.000	999.9	0.000
(7800)	(7630)	17.97	0.024	-0.545	23.1	0.546
(7810)	(7630)	1.17	-0.006	-0.026	4.4	0.026
(7820)	(7630)	18.24	0.024	-0.554	23.0	0.554
(7830)	(7630)	1.19	-0.006	-0.026	4.4	0.027
(7980)	(7630)	31.19	0.034	-0.786	23.4	0.787
(7960)	(7630)	2.04	-0.008	-0.037	4.4	0.038

Peak Value = 88.968 kA (Method B)
Symm. Breaking = 31.023 kA rms (No decay of non-terminal faulted ind. motors)
Steady State = 34.030 kA rms (Maximum value)
d.c. component = 37.890 kA (86.36% of Ib at tmin =0.01 sec.)
Asymm. Breaking = 40.991 kA rms

S. C. SUMMARY REPORT

Etap PowerStation 1.4.1

Study Case: Sasol Three Network

Three-Phase Fault Currents: (Prefault Voltage = Bus Nominal Voltage)

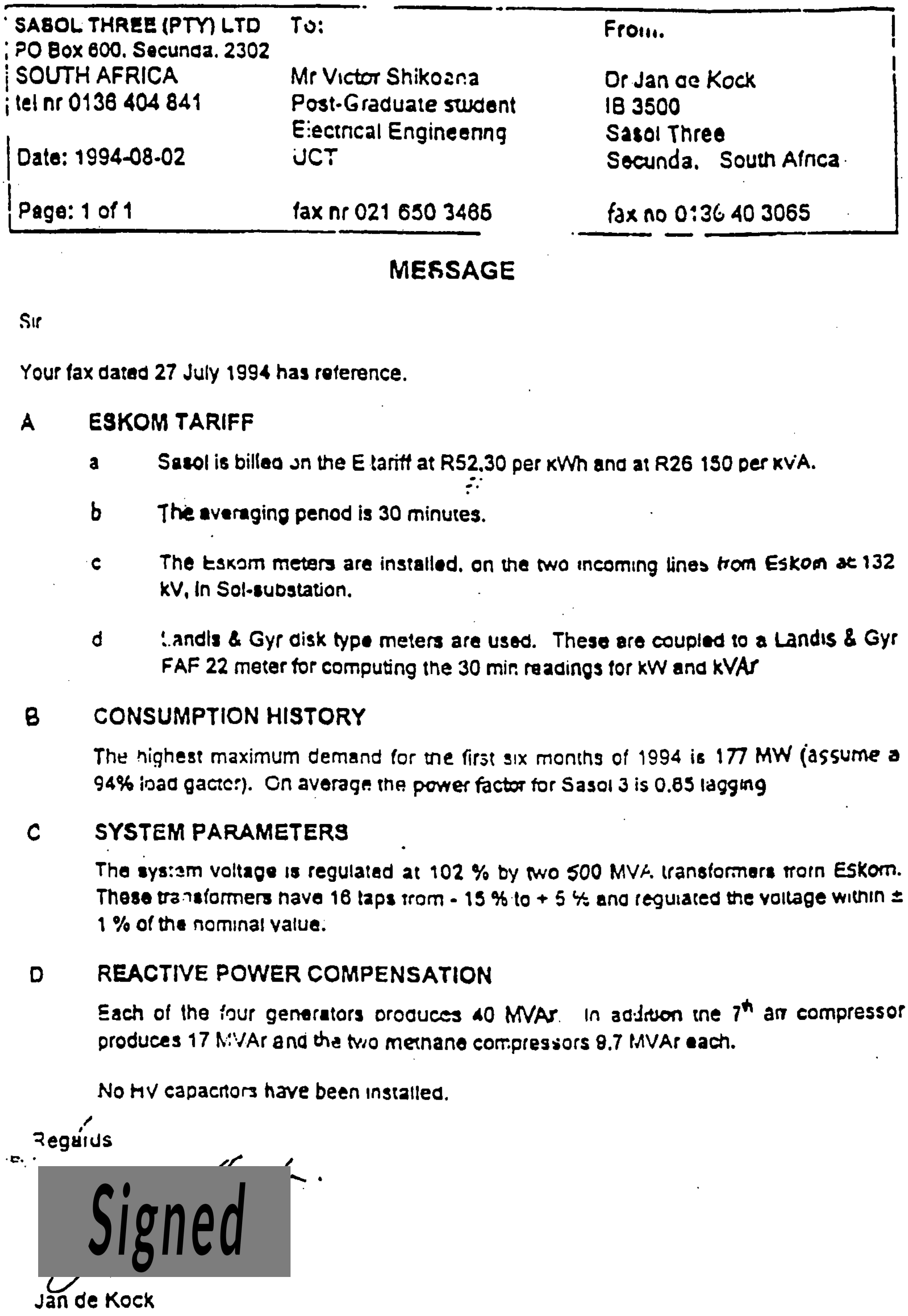
Bus Information		Device Information			* Device Capacity (kA)		Short Circuit Current				
ID	kV	ID	Type	TD (sec)	Making	Breaking	I"k(kA)	Ip(kA)	Ib(kA)	Ik(kA)	Idc(%)
(7630)	132.00	(7630)	Bus				31.46	88.97	31.02	34.03	86.36

Where;
Ib Includes decays from non-terminal faulted induction motors
Ik Is the maximum steady state fault current
Idc is based on X/R from Method C and Ib as specified above

* Indicates buses with short-circuit values exceeding the device ratings.

APPENDIX E

This appendix consist of the information on reactive power compensation of Sasol Three System and the ABB fax regarding the design and manufacture of short circuity limiting reactors. The Escom tariff structure is also given. The information was obtained from Dr. Jan de Kock of Sasol Three, Secunda.



SASOL THREE (PTY) LTD **PO Box 600, Secunda. 2302** SOUTH AFRICA tel nr 0136 404 841	To:	From.
	Mr Victor Shikoana Post-Graduate student Electrical Engineering UCT	Dr Jan de Kock IB 3500 **Sasol Three** **Secunda.** South Africa
Date: 1994-08-02		
Page: 1 of 1	fax nr 021 650 3465	fax no 0136 40 3065

MESSAGE

Sir

Your fax dated 27 July 1994 has reference.

A ESKOM TARIFF

a Sasol is billed on the E tariff at R52.30 per kWh and at R26 150 per kVA.

b The averaging period is 30 minutes.

c The Eskom meters are installed, on the two incoming lines from Eskom at 132 kV, in Sol-substation.

d Landis & Gyr disk type meters are used. These are coupled to a Landis & Gyr FAF 22 meter for computing the 30 min readings for kW and kVAr

B CONSUMPTION HISTORY

The highest maximum demand for the first six months of 1994 is 177 MW (assume a 94% load gactor). On average the power factor for Sasol 3 is 0.85 lagging

C SYSTEM PARAMETERS

The system voltage is regulated at 102 % by two 500 MVA transformers from Eskom. These transformers have 16 taps from - 15 % to + 5 % and regulated the voltage within ± 1 % of the nominal value.

D REACTIVE POWER COMPENSATION

Each of the four generators produces 40 MVAr. In addition the 7th air compressor produces 17 MVAr and the two methane compressors 9.7 MVAr each.

No HV capacitors have been installed.

Regards

Signed

Jan de Kock

ABB Powertech Transmission & Distribution (Pty) Ltd
Reg Nr 65/02429/07
Reactive Power Compensation Division

To : SASOL Secunda
Attention : Victor Shikoana
Fax number : (017) 619 ~~2570~~ 2727
From : Kevin Talbot
Department : RPC
Date : 16 March, 1998
Subject : Budget for 132 kV Current limiting reactors
Pages : 1

Dear Victor

Thank you for your enquiry for installing 132 kV current limiting reactors. Firstly, to manufacture a reactor as requested would not be a problem. However, in order to reduce the fault level by 20% with two incomers, each reactor must have double the impedance of that when one incomer is assumed. This will result in the reactors having the following characteristics:

2 Sets	3 phase current limiting reactors	
-	rated system voltage (kV)	132
-	system highest voltage (kV)	145
-	BIL (kV, peak)	650
-	rated inductance (mH)	3.86
-	rated frequency (Hz)	50
-	rated cont currents (A)	1250
-	rated short time currents thermal (kA, rms/1s)	22 kA for 1s
-	cooling method	AN
-	winding material	aluminium
-	Q-factor natural	89

In order to achieve an X/R ratio of 30, a dc 'Q' ring would have to be installed which would dramatically increase the losses and is hence not desirable. The feasibility of a Q-factor of 30 is still being determined and will be confirmed as soon as possible.

A cost estimate for the manufacture and installation of these reactors is R 1 321 106.00 excl VAT. Should the above be of interest to yourselves, we would provide a fully detailed offer against which an order could be placed.

Yours faithfully

Signed

Kevin Talbot

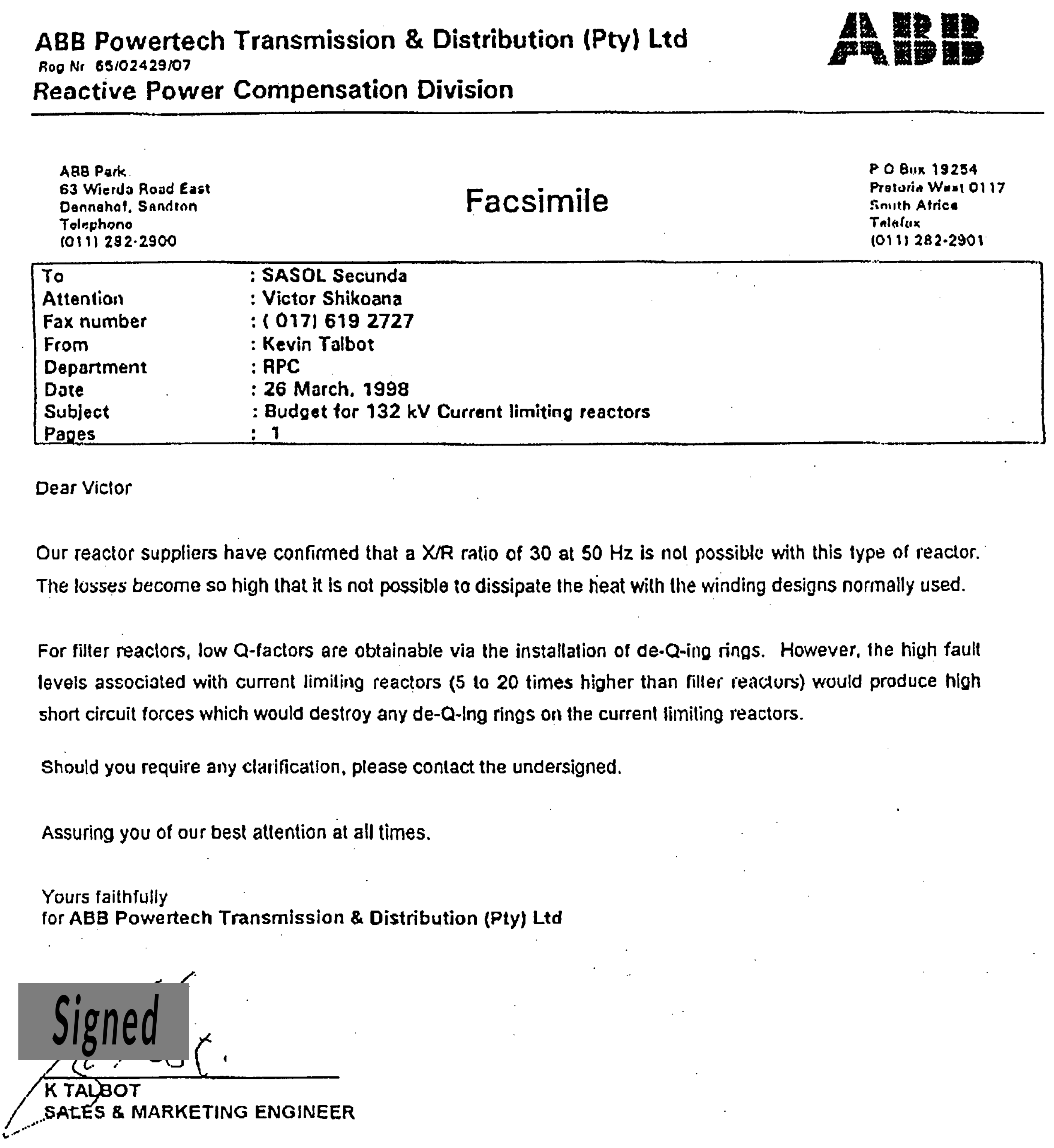


ABB Powertech Transmission & Distribution (Pty) Ltd
Reg Nr 65/02429/07
Reactive Power Compensation Division

ABB Park
63 Wierda Road East
Dennehof, Sandton
Telephone
(011) 282-2900

P O Box 19254
Pretoria West 0117
South Africa
Telefax
(011) 282-2901

Facsimile

To	: SASOL Secunda
Attention	: Victor Shikoana
Fax number	: (017) 619 2727
From	: Kevin Talbot
Department	: RPC
Date	: 26 March, 1998
Subject	: Budget for 132 kV Current limiting reactors
Pages	: 1

Dear Victor

Our reactor suppliers have confirmed that a X/R ratio of 30 at 50 Hz is not possible with this type of reactor. The losses become so high that it is not possible to dissipate the heat with the winding designs normally used.

For filter reactors, low Q-factors are obtainable via the installation of de-Q-ing rings. However, the high fault levels associated with current limiting reactors (5 to 20 times higher than filter reactors) would produce high short circuit forces which would destroy any de-Q-ing rings on the current limiting reactors.

Should you require any clarification, please contact the undersigned.

Assuring you of our best attention at all times.

Yours faithfully
for ABB Powertech Transmission & Distribution (Pty) Ltd

Signed

K TALBOT
SALES & MARKETING ENGINEER

Appendix F

Consider the following diagram;

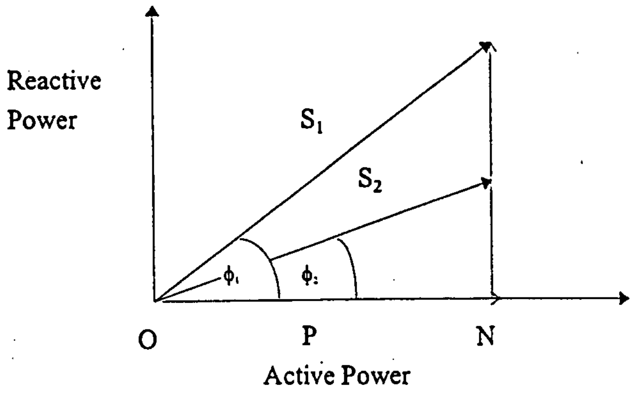


Figure J1.1 Power factor improvement diagram

For a given power P,

$$\text{at } \cos\phi_1,\ S_1 = OT = \frac{P}{\cos\phi_1}$$

$$\text{at } \cos\phi_2,\ S_2 = OR = \frac{P}{\cos\phi_2}$$

For annual charge A per MVA,

$$\text{Then the charge at } \cos\phi_1 = \frac{AP}{\cos\phi_1}$$

$$\text{and charge at charge at } \cos\phi_2 = \frac{AP}{\cos\phi_1}$$

$\therefore$ Saving $= AP\left(\frac{1}{\cos\phi_1} - \frac{1}{\cos\phi_2}\right)$ due to compensation.

MVAr compensation required to raise the power factor from $\cos\phi_1$ to $\cos\phi_2$ is

$$Qc = TR = P(\tan\phi_1 - \tan\phi_2)$$

Let the annual charge of compensating devices and associated controls be K per MVA

Then the total annual costs of compensating devices is,

$$= KP(\tan\phi_1 - \tan\phi_2)$$

∴ total annual charge in correcting from cos ϕ_1 to cos ϕ_2 is equal to

[annual charge of MVA Maximum Demand at cos ϕ_2] + [annual charge of compensating devices]

$$= \frac{AP}{\cos\phi_2} + KP(\tan\phi_1 - \tan\phi_2)$$

And annual saving for an infeed of P MW is given by,

$$= AP\left(\frac{1}{\cos\phi_1} - \frac{1}{\cos\phi_2}\right) - KP(\tan\phi_1 - \tan\phi_2)$$

APPENDIX G

In simulation one, a three phase fault was applied at bus 7630 for 100 msec.

Figure g1.1 shows the response of the absolute rotor angles of synchronous machine. The rotor angles increases immediately after the fault. The generator angles increase to about 120 degrees. The synchronous motor angles increase to about 35 degrees. It is worth noting that the rotor angles of the generators increases by the same amount until the maximum is reached and stay constant at this value. This results shows that the synchronous machines remain stable after the three phase fault at bus 7630.

Figure g1.2 shows how the 20.3 MW synchronous machine angle relates to rotor speed after event. The angle and the speed of the machine decreases immediately after the fault and then encircles inward towards the prefault values. This indicates that the motor remains stable with the rest of the power system

The response of the power flows, speed of synchronous machines, induction motors can be seen in the following graphs.

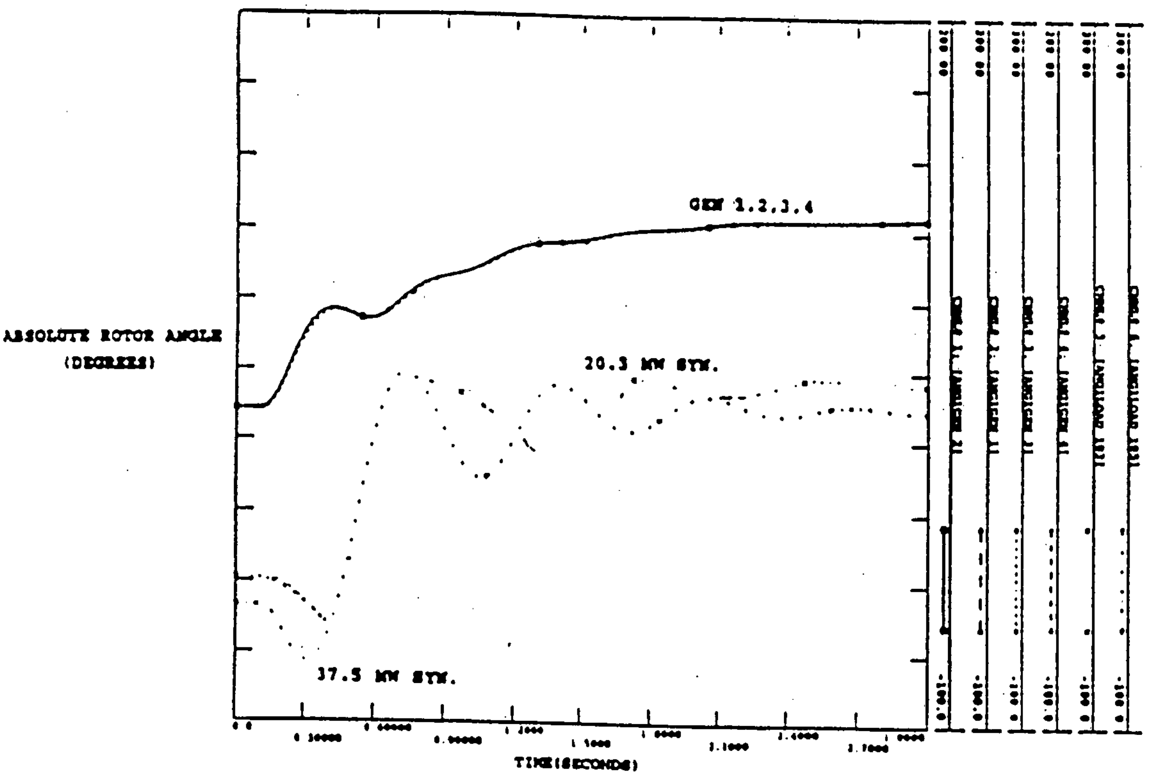


Figure *g*1.1 Absolute rotor angle response of synchronous machines after three phase fault at bus 7630

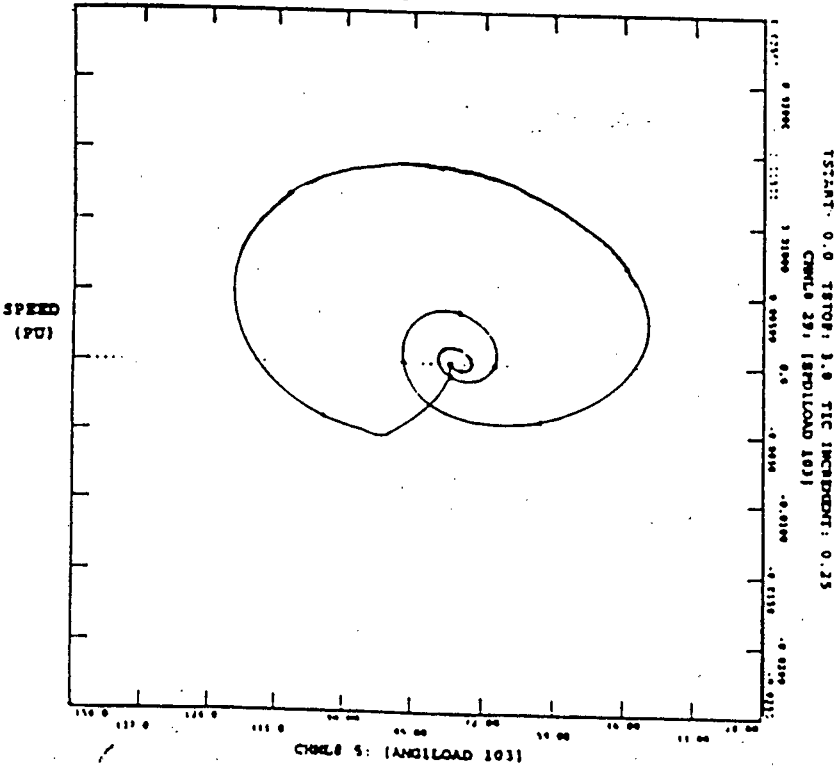


Figure *g*1.2 Angle/ speed trajectory of the 20.3 MW synchronous motor after three phase fault at bus 7630

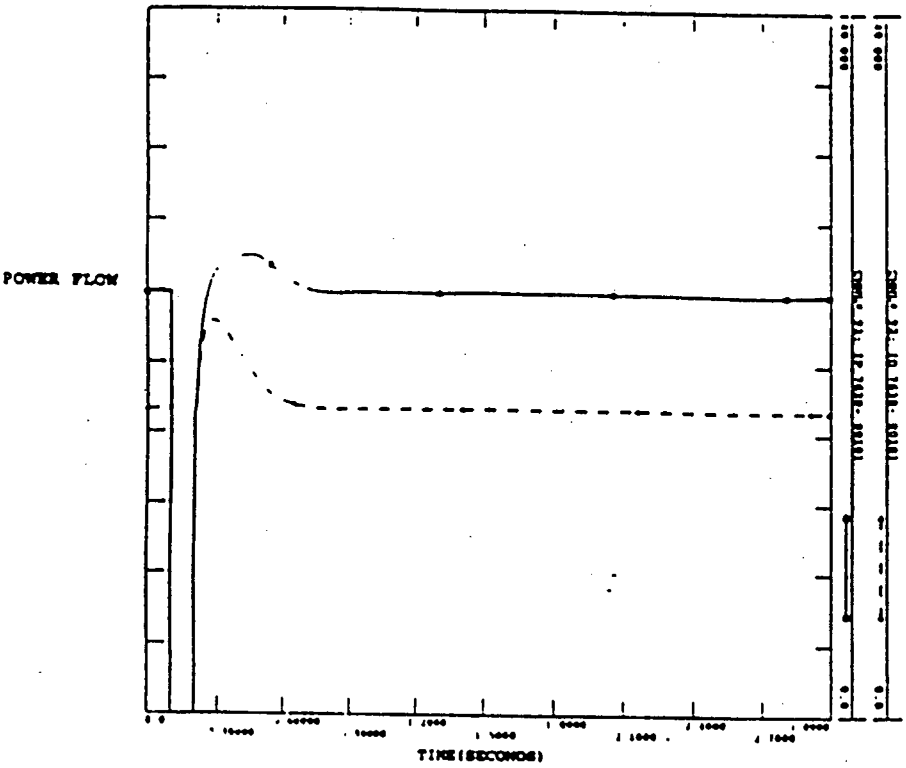


Figure *g*1.3 Response of the power flow to 2JJ-DS-2 after three phase fault at bus 7630

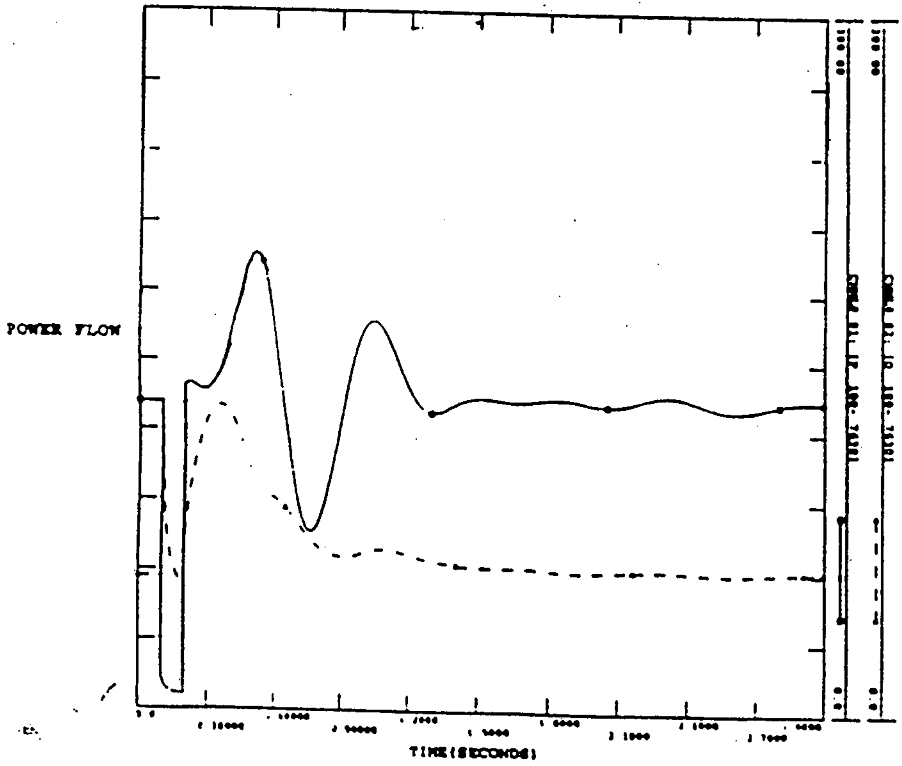


Figure *g*1.4 Response of the power imported from Escom after three phase fault at bus 7630

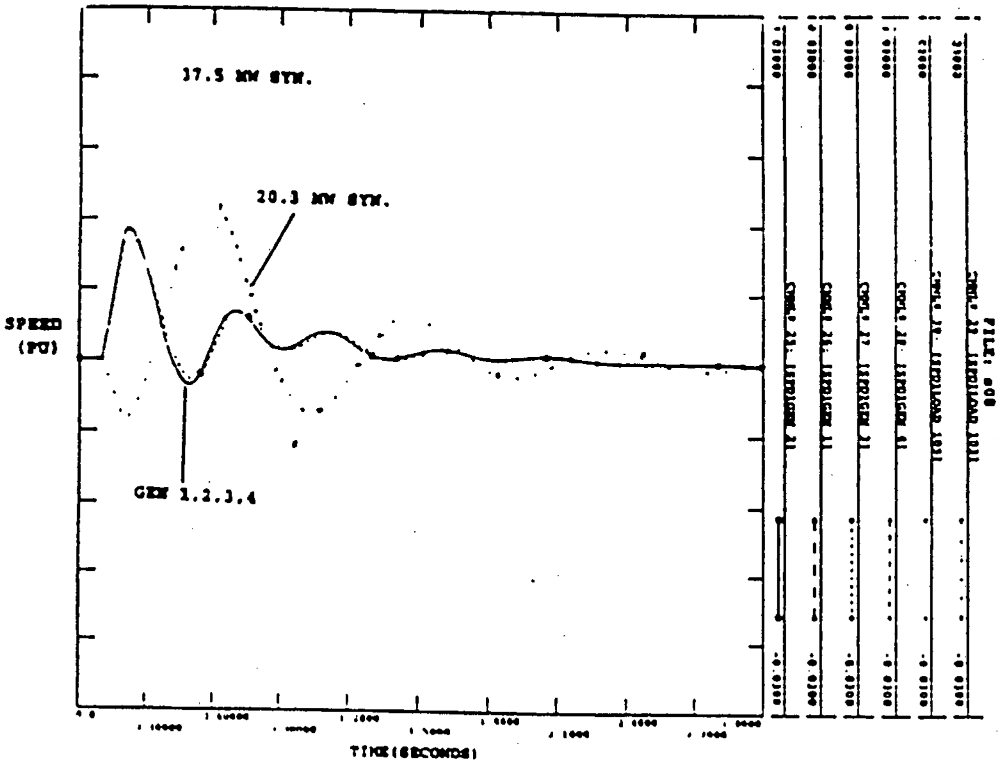


Figure g1.5 Speed response of synchronous machines after three phase fault at bus 7630

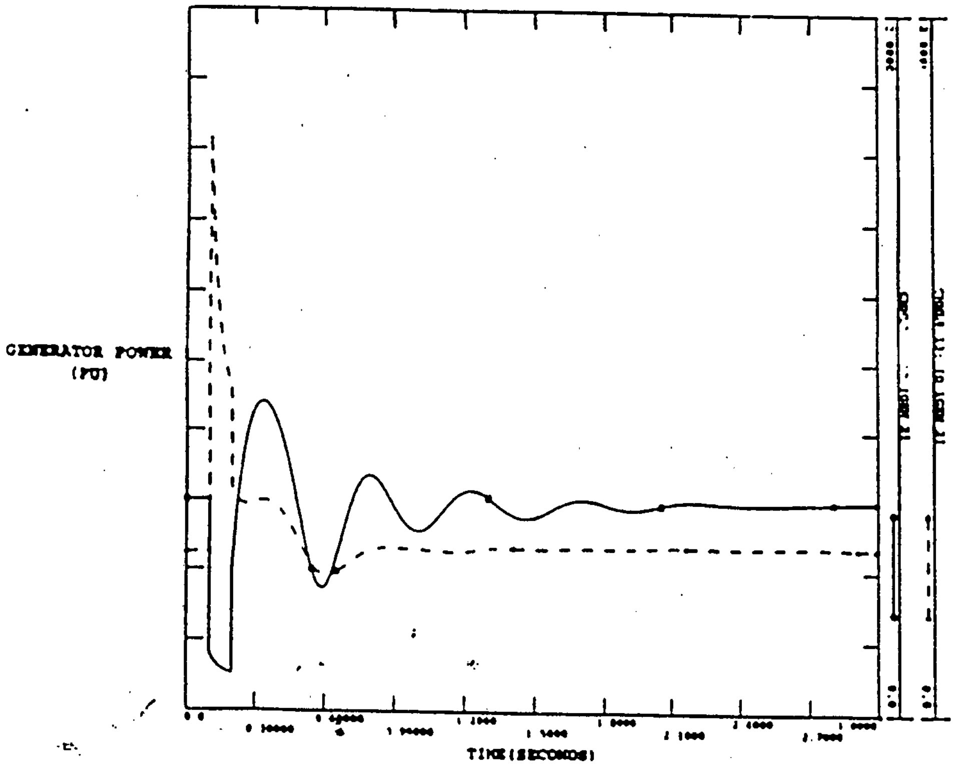


Figure g1.6 Generator 2 power response after three phase fault at bus 7630

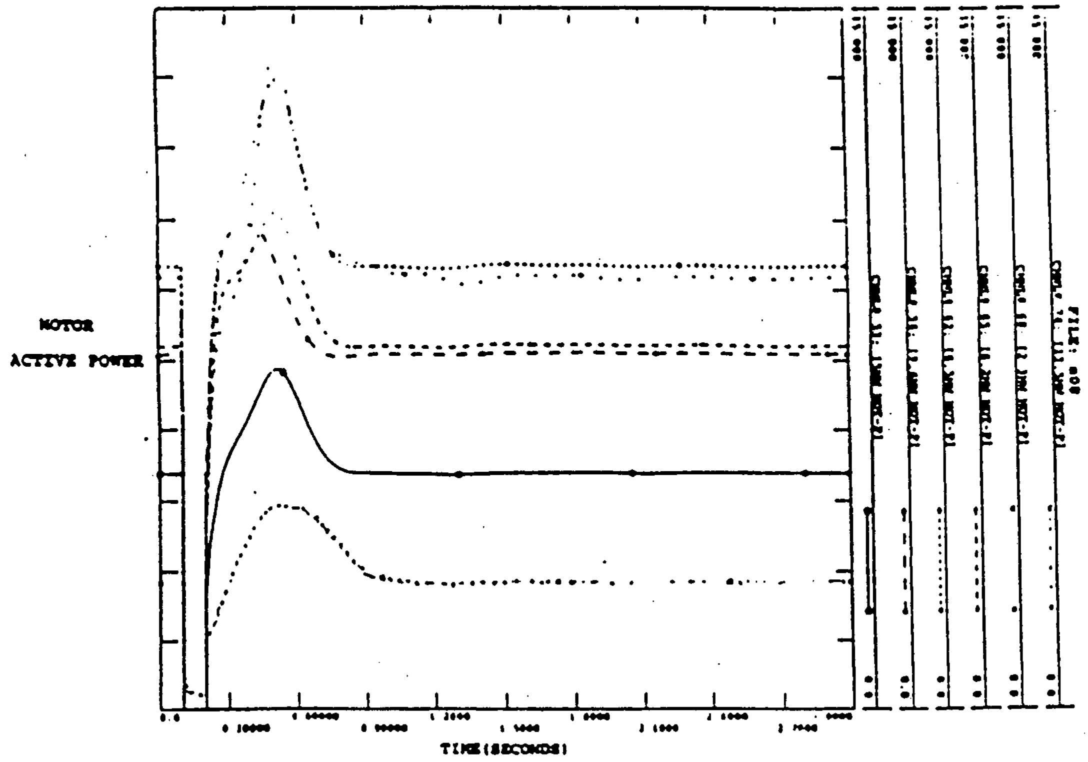


Figure g1.7 Motor active power response after three phase fault at bus 7630

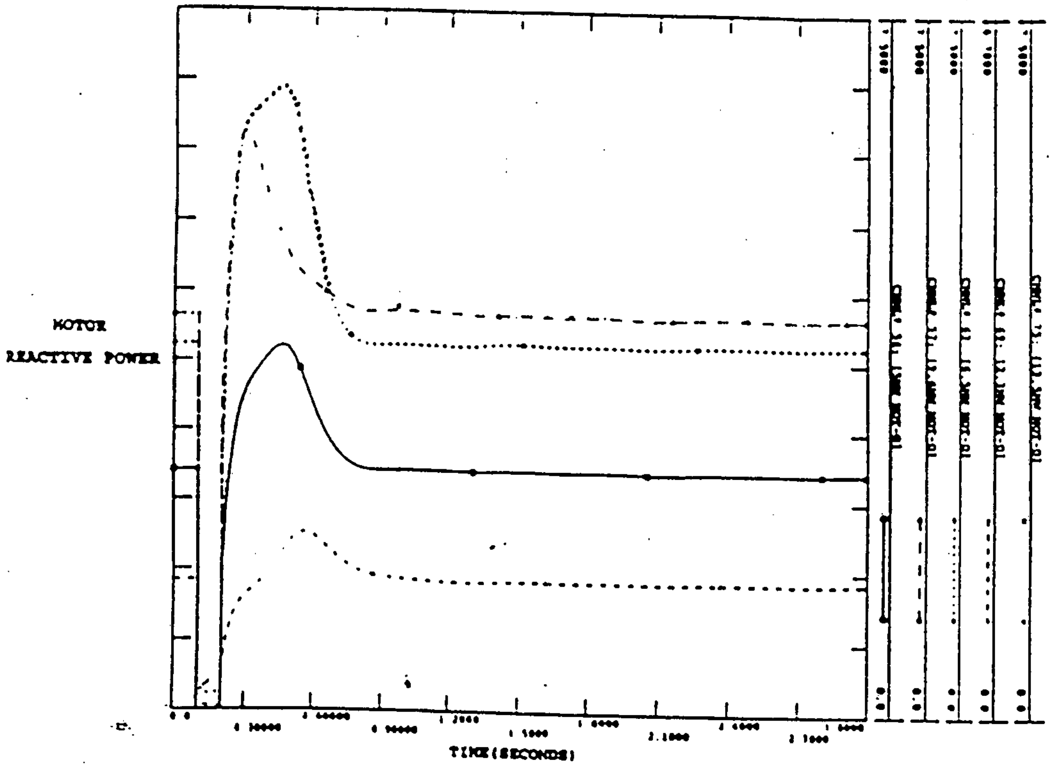


Figure g1.8 Motor reactive power response after three phase fault at bus 7630

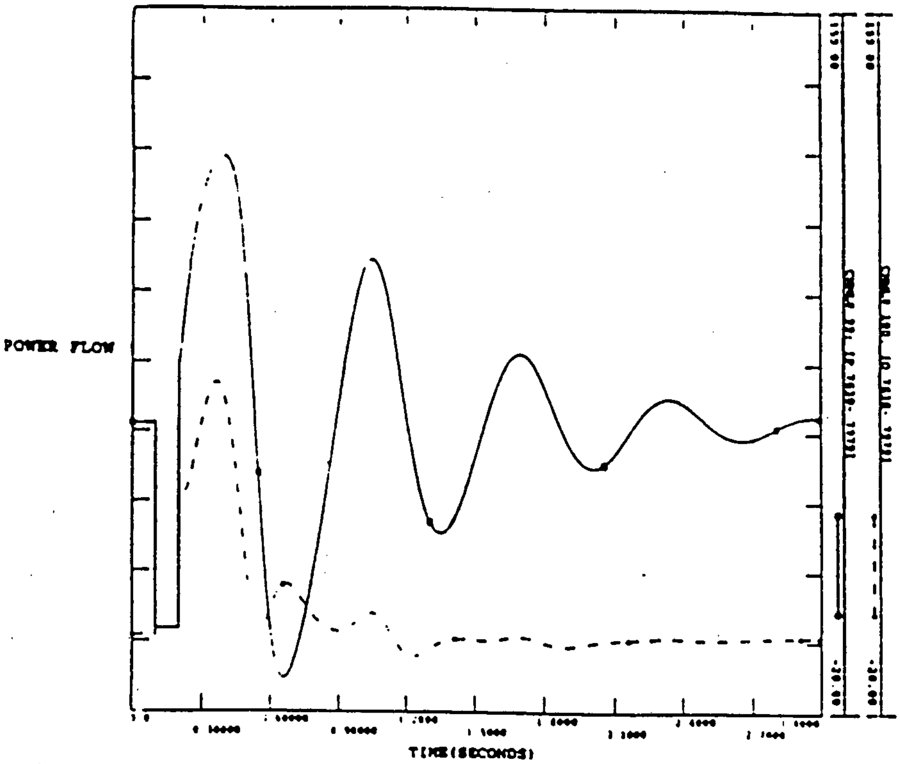


Figure g1.9 Response of the power flow to the 37.5 MW synchronous motor after three phase fault at bus 7630

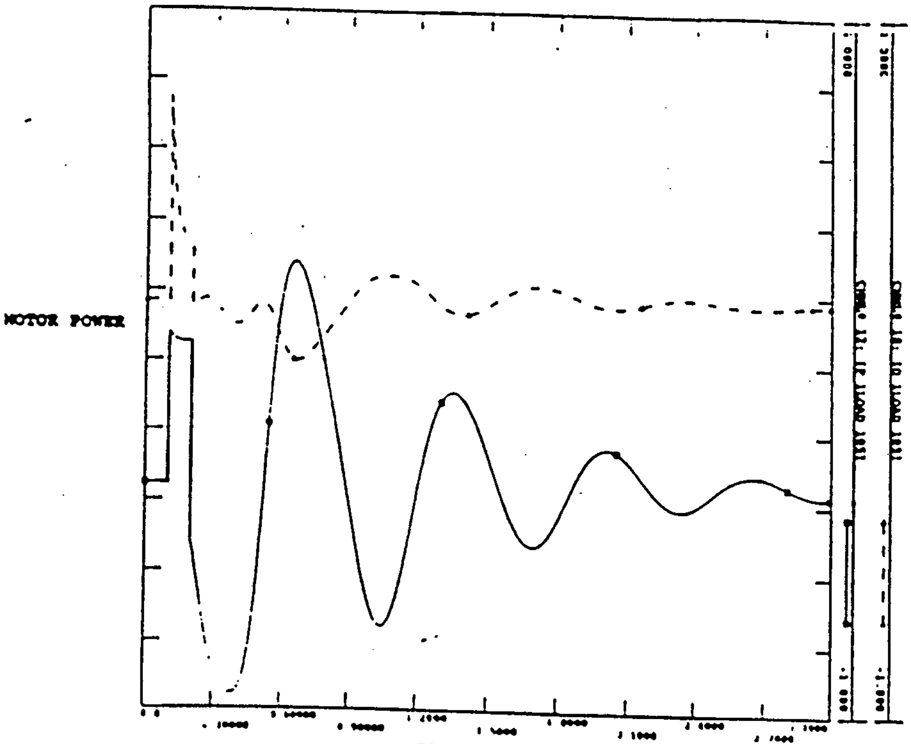


Figure g1.10 Synchronous motor (37.5 MW) power response after three phase fault at bus 7630

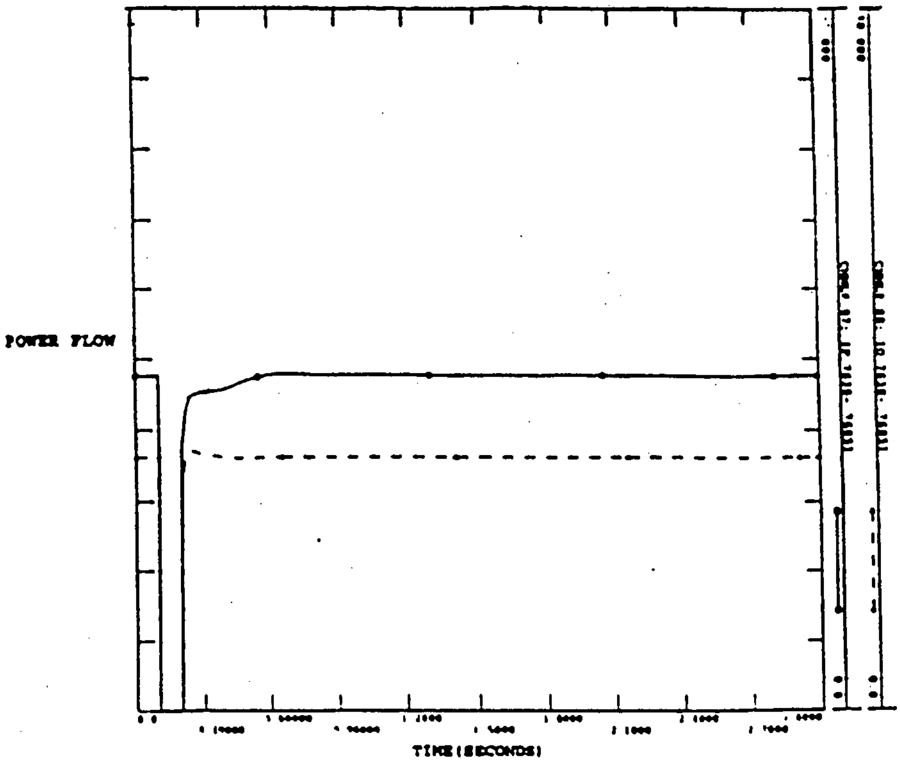


Figure g1.11 Response of the power flow to unit 245 after three phase fault at bus 7630

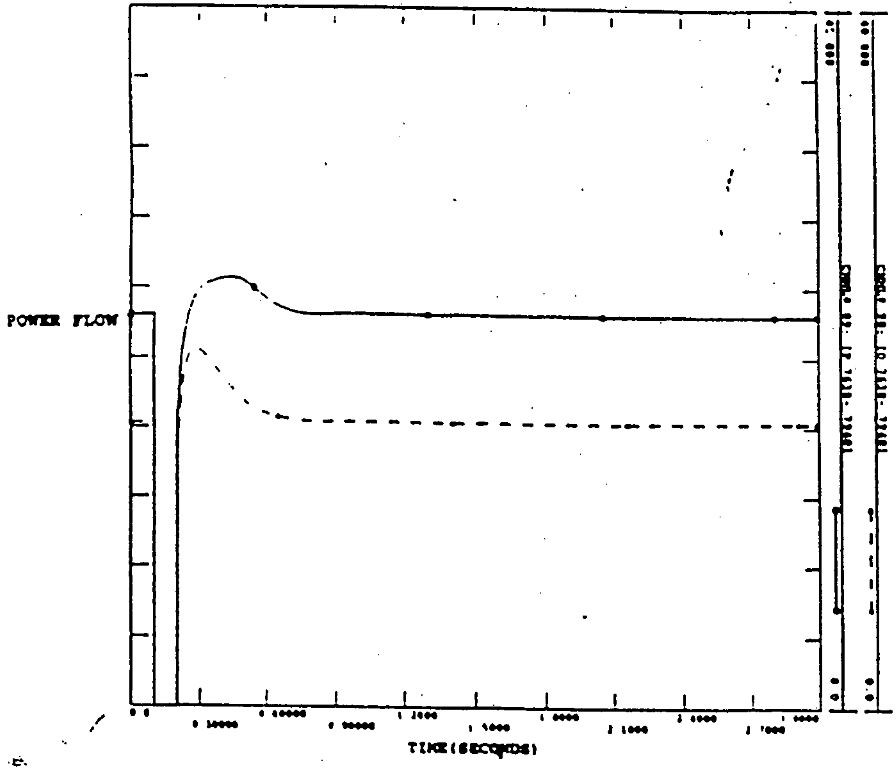


Figure g1.12 Response of the power flow to 2JJ-DS-1 after three phase fault at bus 7630

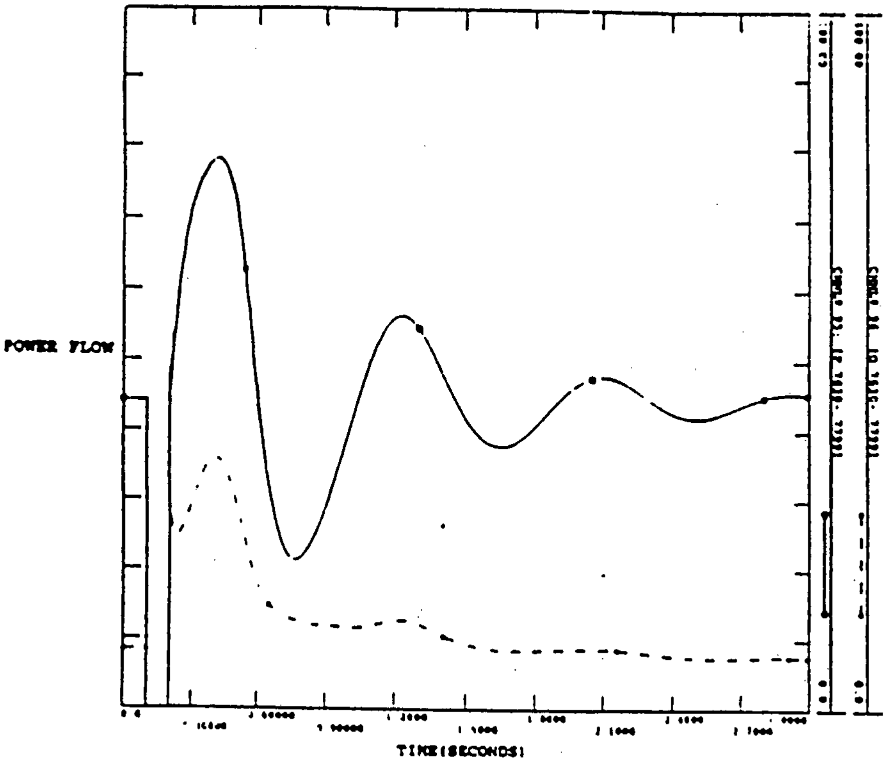


Figure g1.13 Response of the power flow to gassification plant after three phase fault at bus 7630

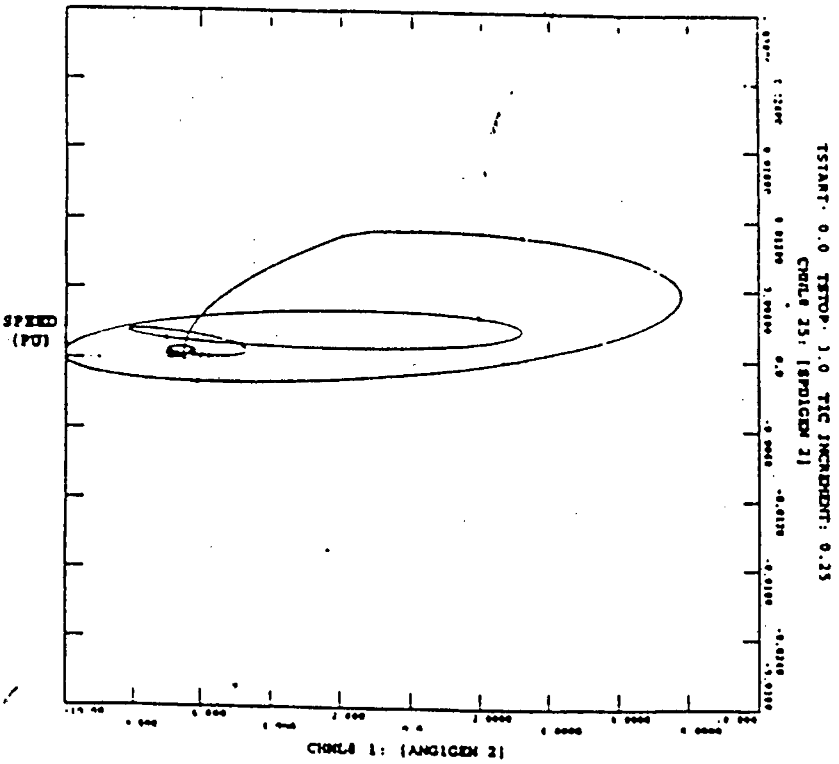


Figure g1.14 Angle/ speed trajectory generator 2 after three phase fault at bus 7630

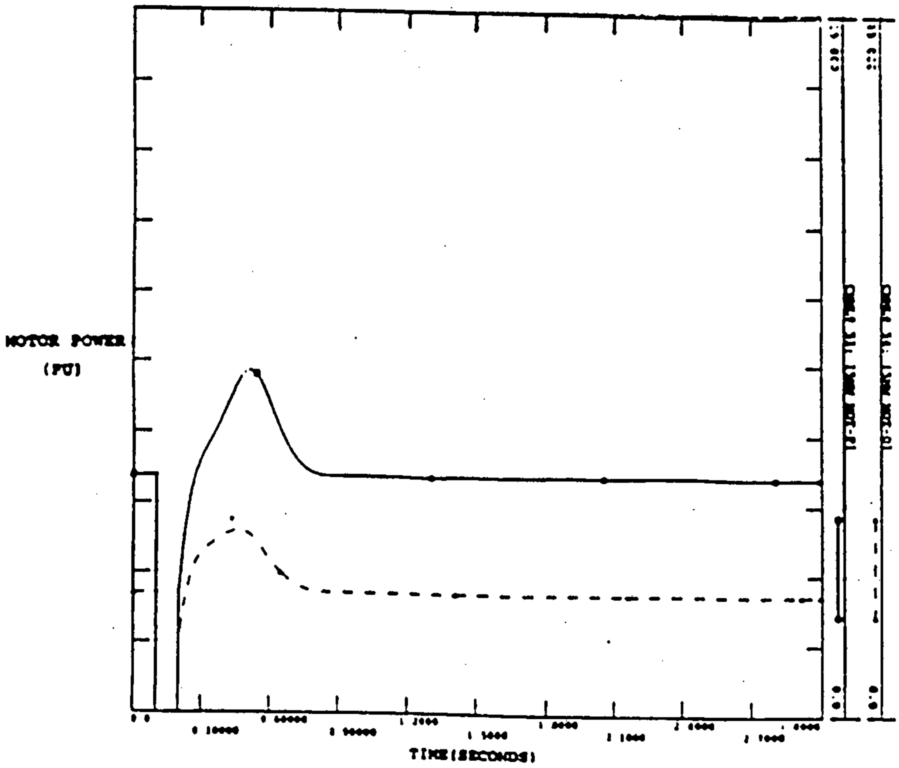


Figure *g*1.15 Power response of the 5 MW induction motor after three phase fault at bus 7630

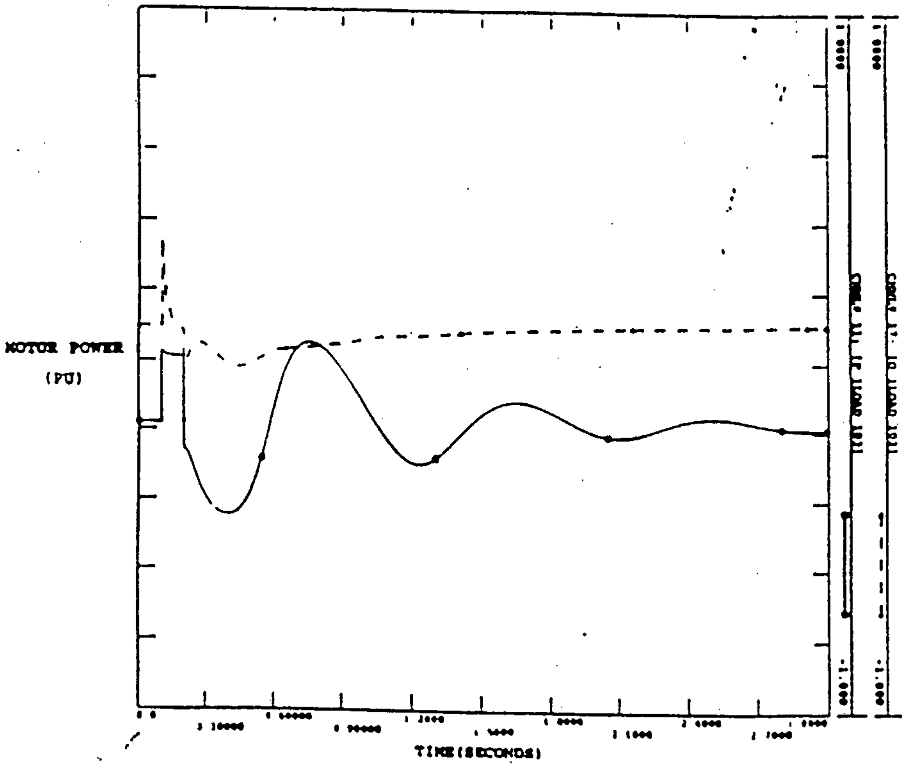


Figure *g*1.16 Power response of the 20.3 MW synchronous motor after three phase fault at bus 7630

APPENDIX H

In simulation two, a short circuit limiting coupler was inserted at the Escom incoming lines and a 3 phase fault was applied at bus 7630. The response of the system can be seen in the following graphs.

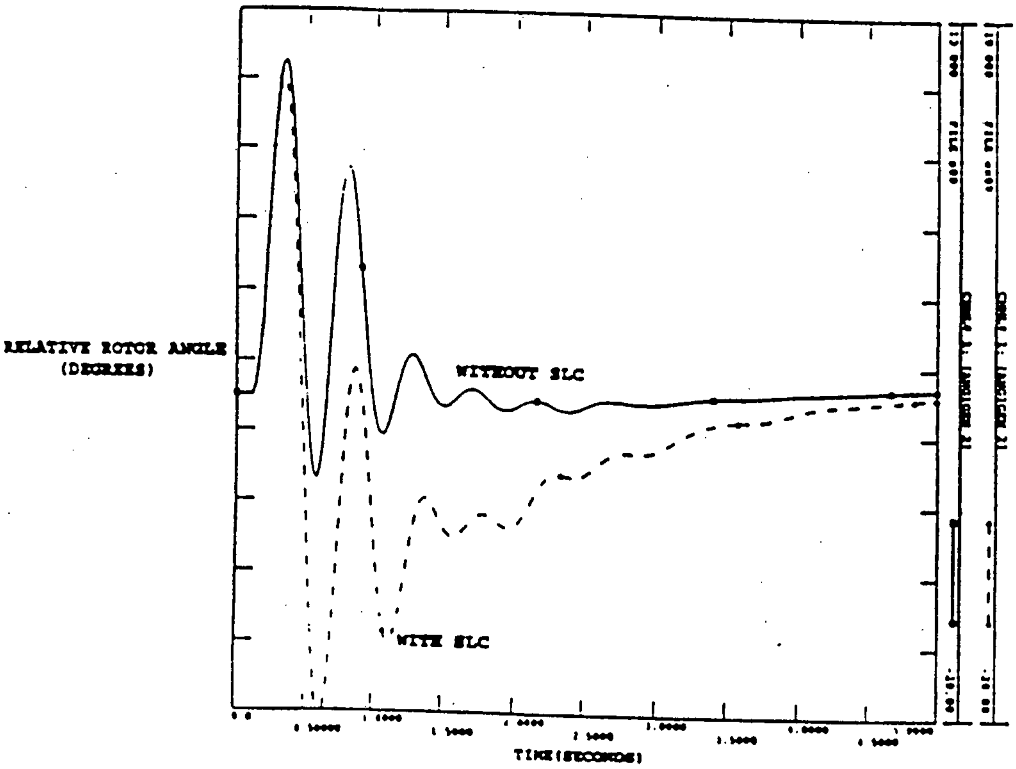


Figure *h*1.1 Relative rotor oscillations of generator 2 after three phase fault at bus 7630

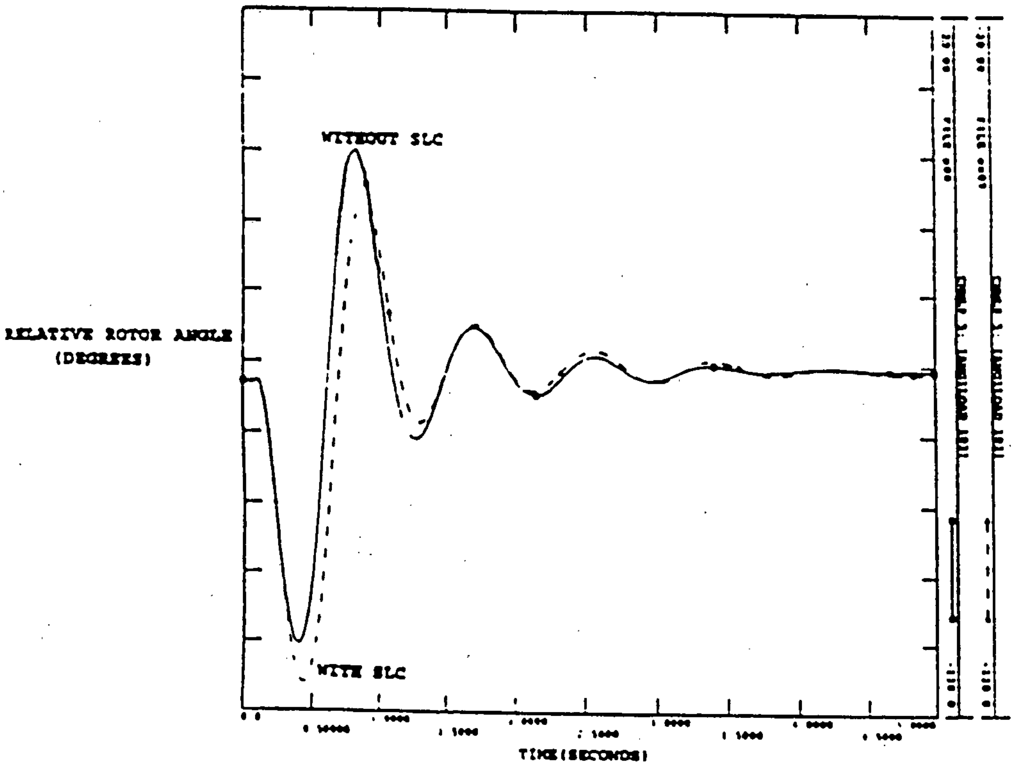


Figure *h*1.2 Relative rotor oscillations of 20.3 MW synchronous motor after three phase fault at bus 7630

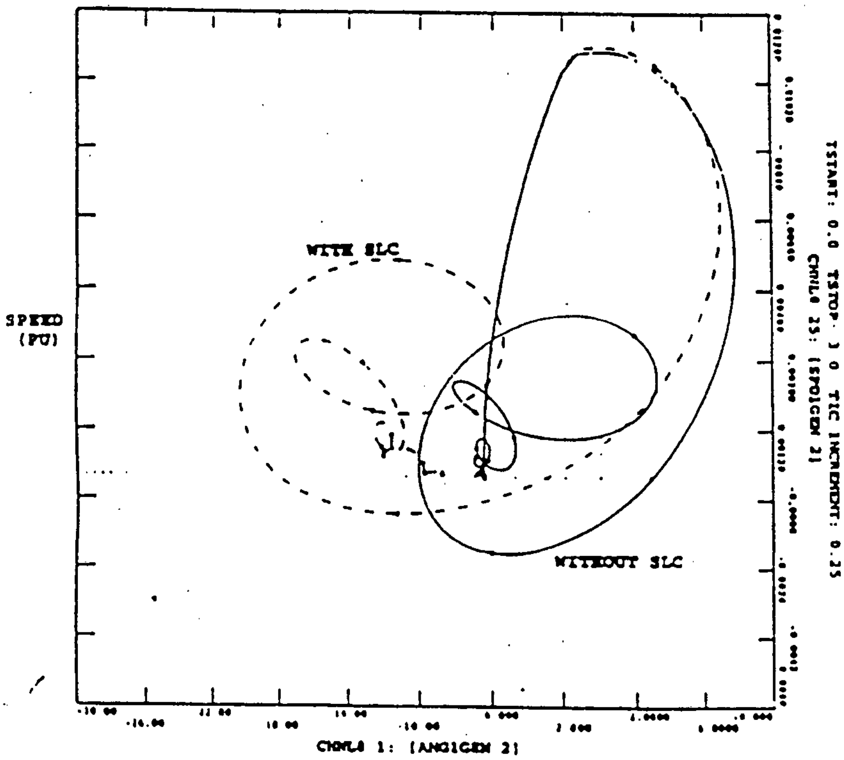


Figure *h*1.3 Angle/ speed trajectory of generator 2 after three phase fault at bus 7630

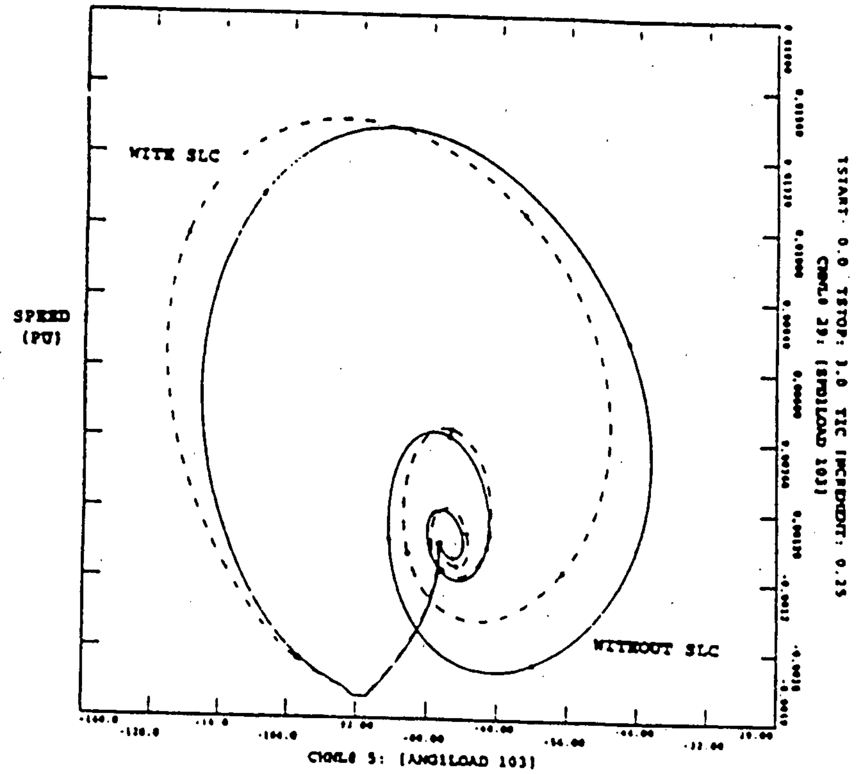


Figure *h*1.4 Angle/ speed trajectory of 20.3 MW synchronous motor after three phase fault at bus 7630

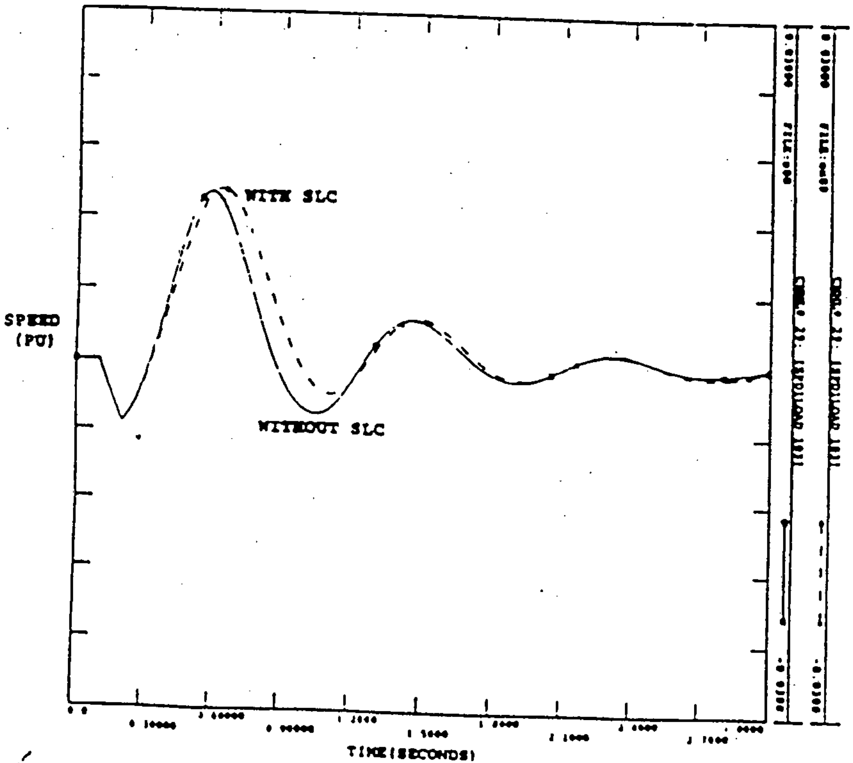


Figure *h*1.5 Relative speed response of 20.3 MW induction motor after three phase fault at bus 7630

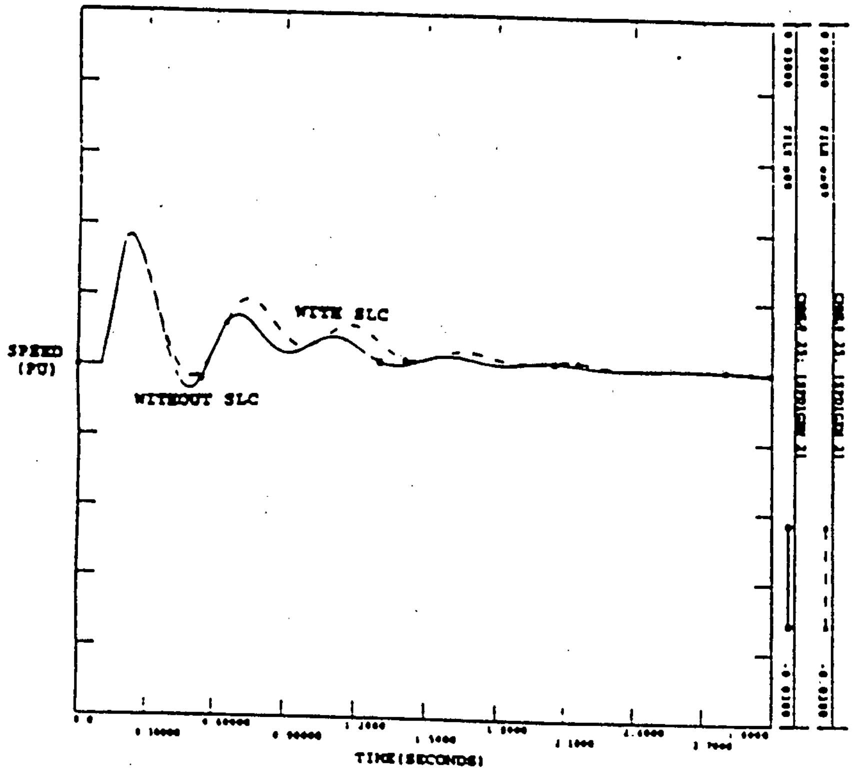


Figure *h***1.6** Relative speed response of generator 2 after three phase fault at bus 7630

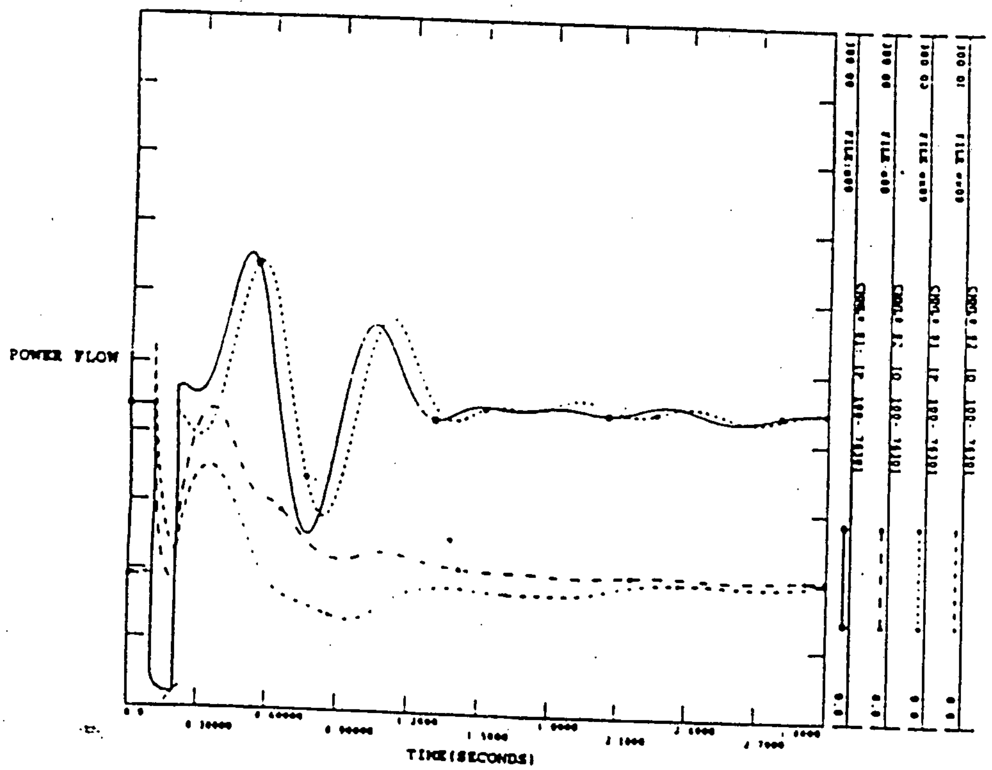


Figure *h***1.7** Response of the power imported from Escom after three phase fault at bus 7630

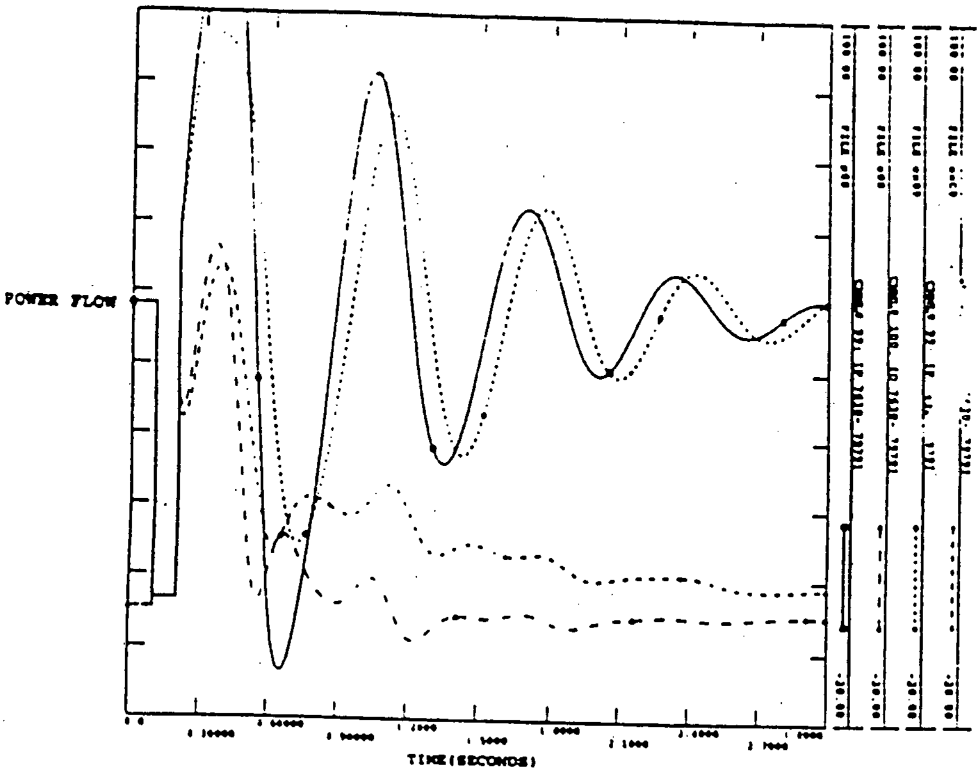


Figure *h*1.8 Response of the power to the 37.5 MW synchronous motor after three phase fault at bus 7630

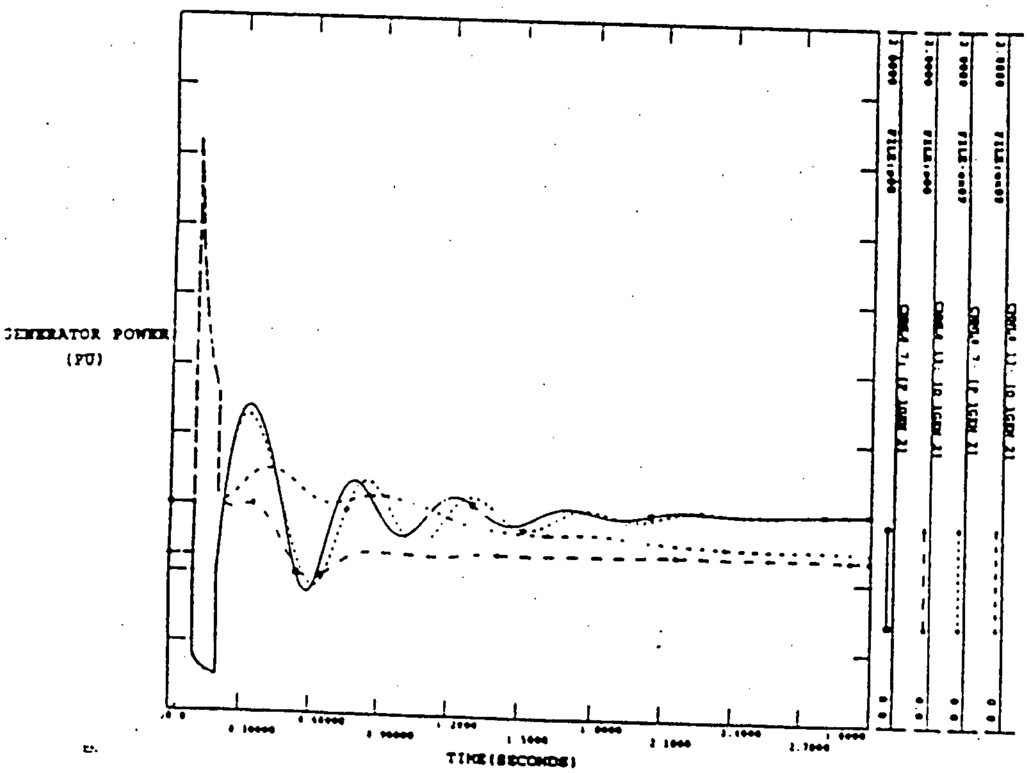


Figure *h*1.9 Power response of generator 2 after three phase fault at bus 7630

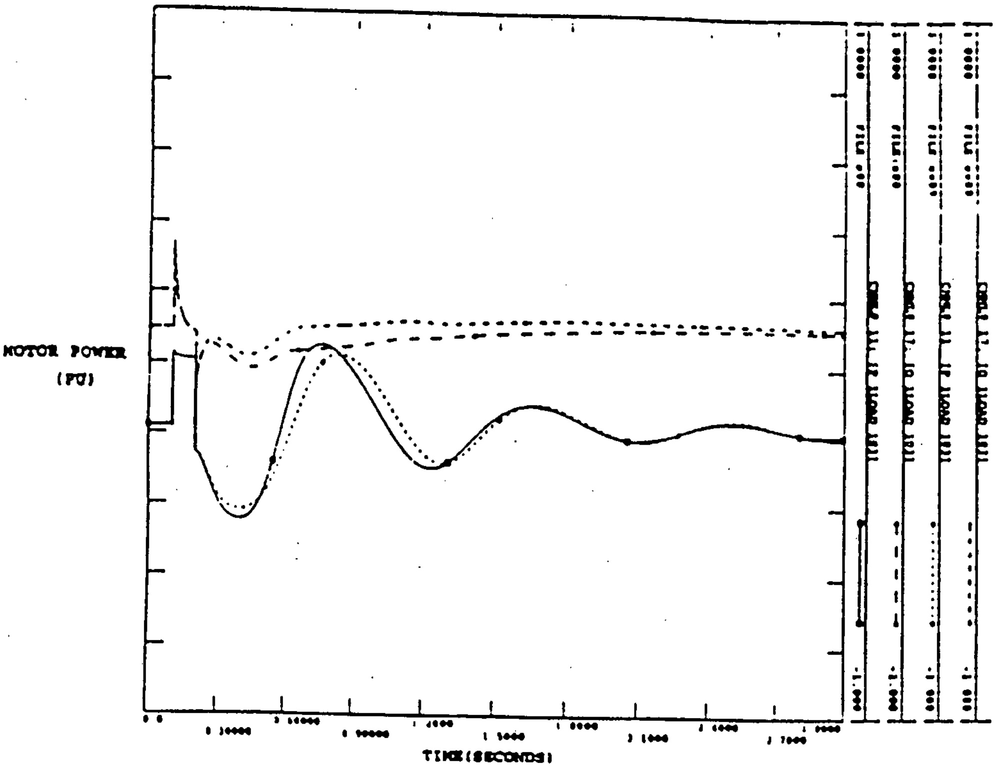


Figure *h*1.10 Power response of the 20.3 MW synchronous motor after three phase fault at bus 7630

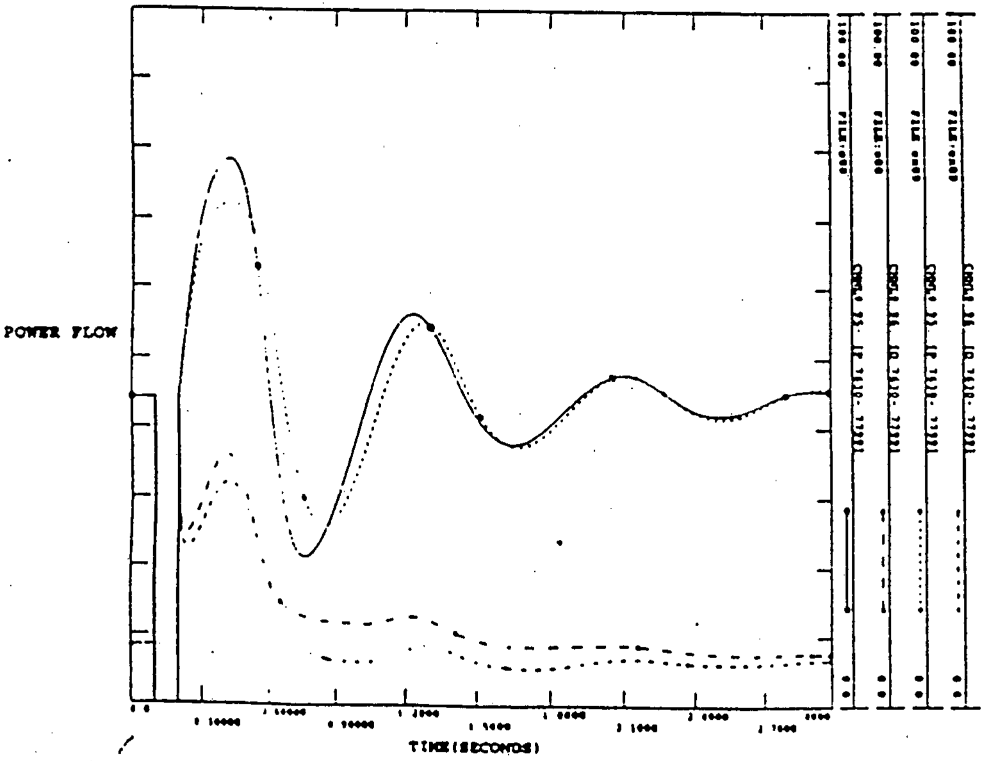


Figure *h*1.11 Response of the power flow to the gassification plant after three phase fault at bus 7630

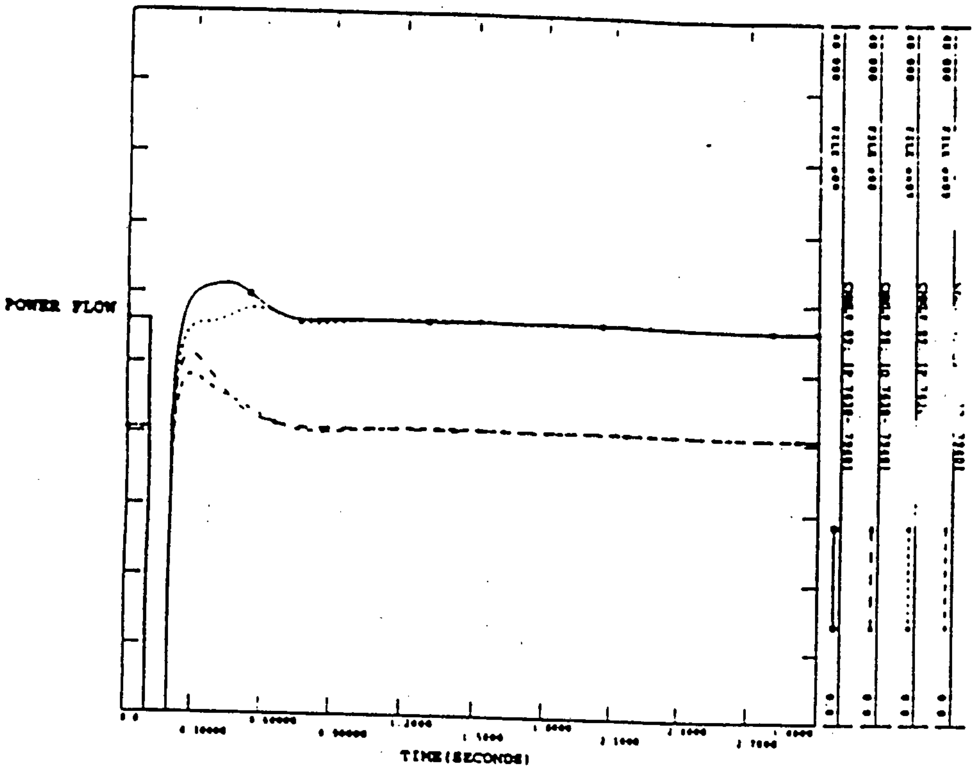


Figure *h*1.12 Response of the power flow to 2JJ-DS-1 after three phase fault at bus 7630

APPENDIX I

In simulation three, a 3 phase fault was applied at bus 7630 for 300 msec.

Figure *i*1.1 shows the speed response of generator one after the event. From this figure, it is clear that the relative speed of generator one with respect to the swing bus oscillates much more than when the fault clearing time is decreased . From this figure, it is not quite clear that the system is stable or not.

Figure *i*1.2 shows the relative speed response of 20.3 MW synchronous motor after the event. The relative speed of the motor increases until the pull out torque is reached where the motor becomes unstable to the rest of the power system. The instability of this motor can easily be shown by figure *k*1.5. This figure shows the angle to speed relationship of the motor. The trajectory shows the pulling out of the motor after the fault was applied.

The response of the power flows, generator power are also provided.

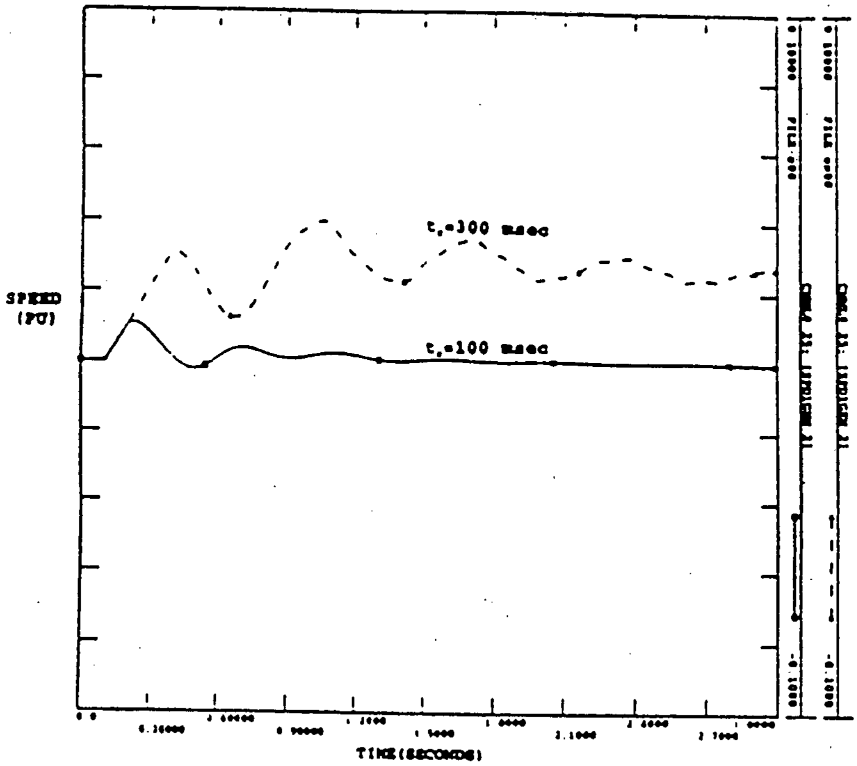


Figure *i*1.1 Relative speed response of generator 2 after three phase fault at bus 7630

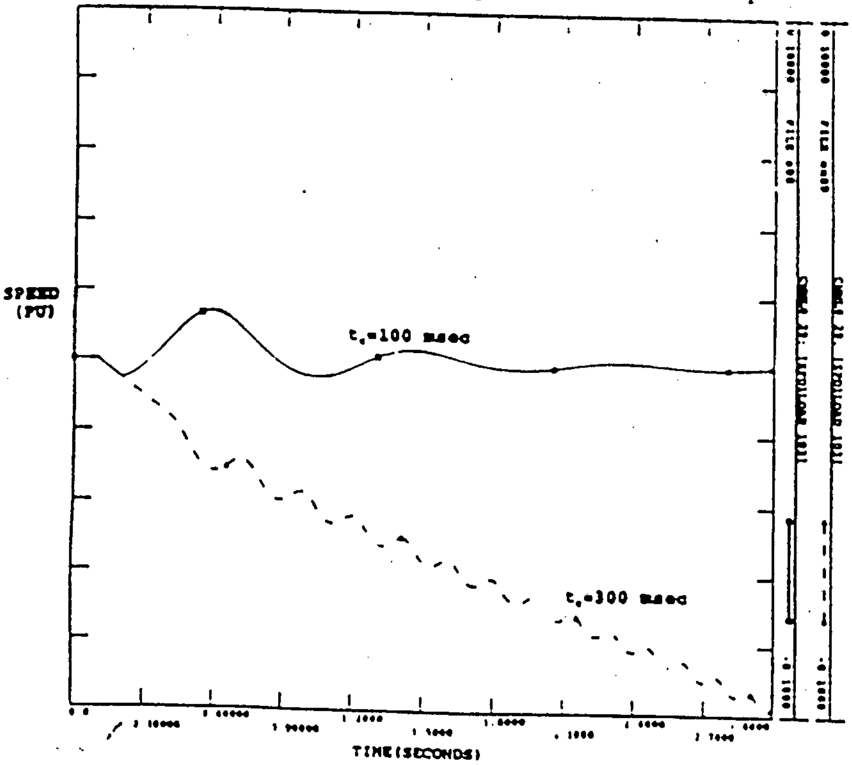


Figure *i*1.2 Relative speed response of 20.3 MW synchronous motor after three phase fault at bus 7630

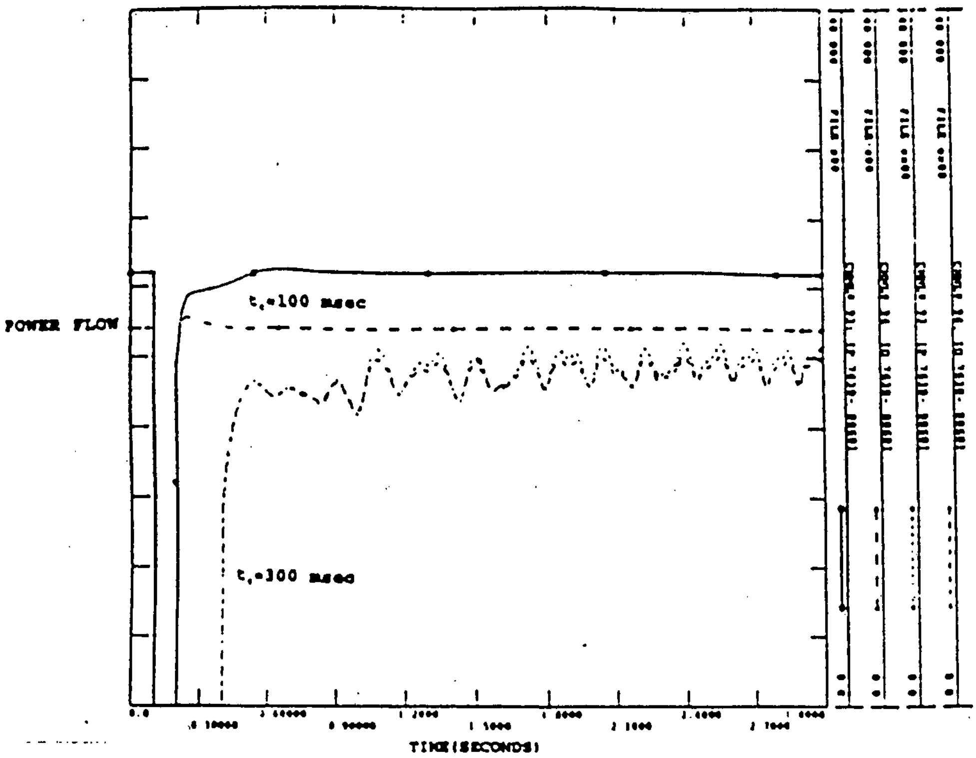


Figure *i*1.3 Response of the power to 2JJ-DS-3 after three phase fault at bus 7630

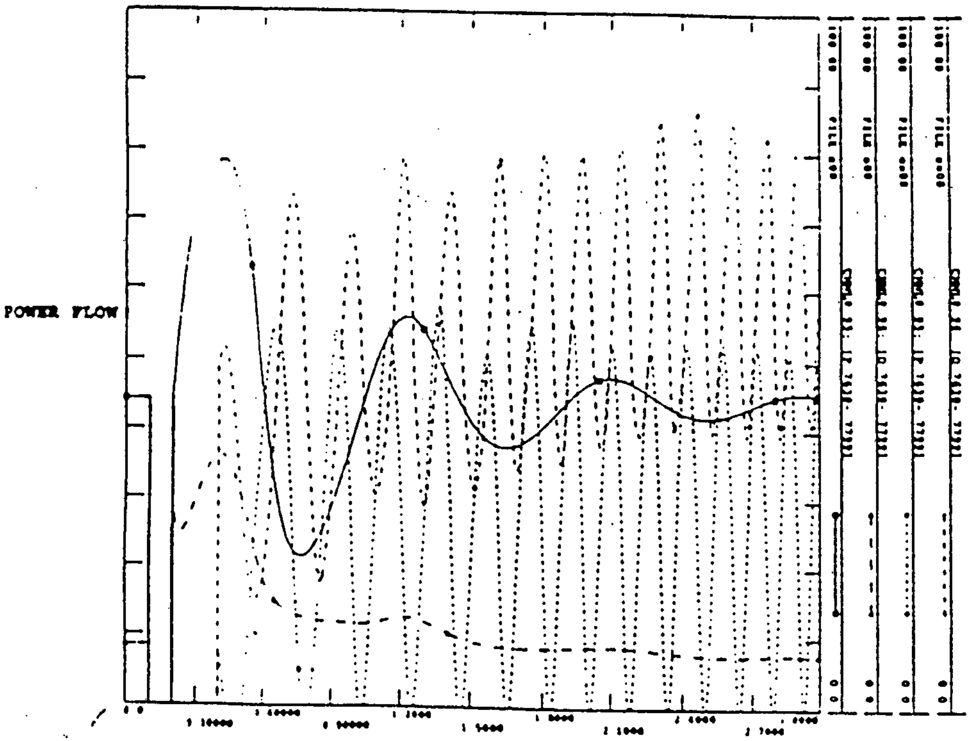


Figure *i*1.4 Response of the power to the gassification plant fter three phase fault at bus 7630

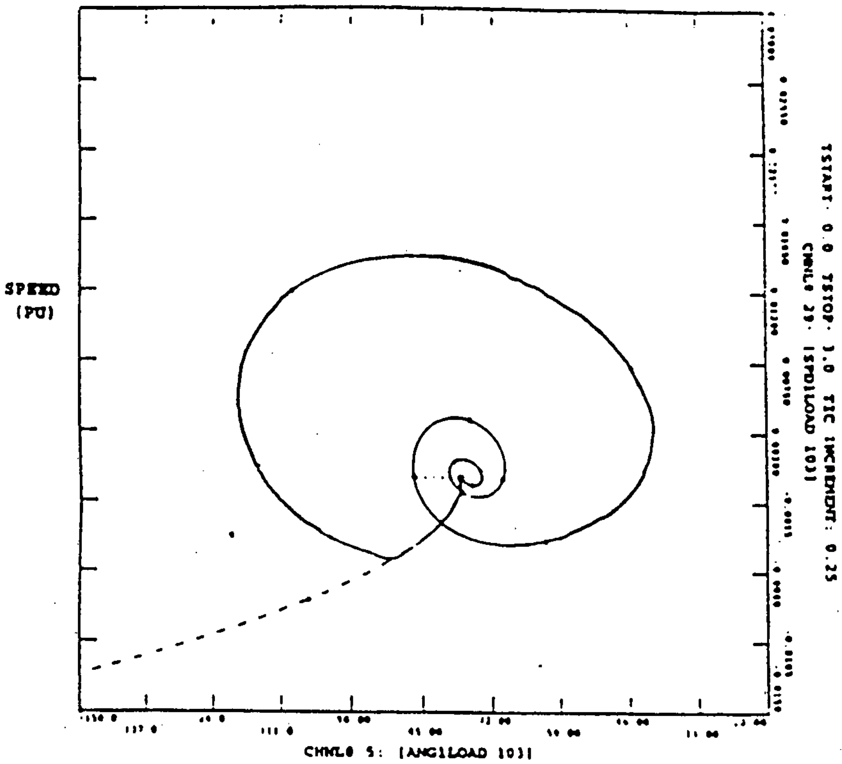


Figure *i*1.5 Angle/ speed trajectory of 20.3 synchronous motor after three phase fault at bus 7630

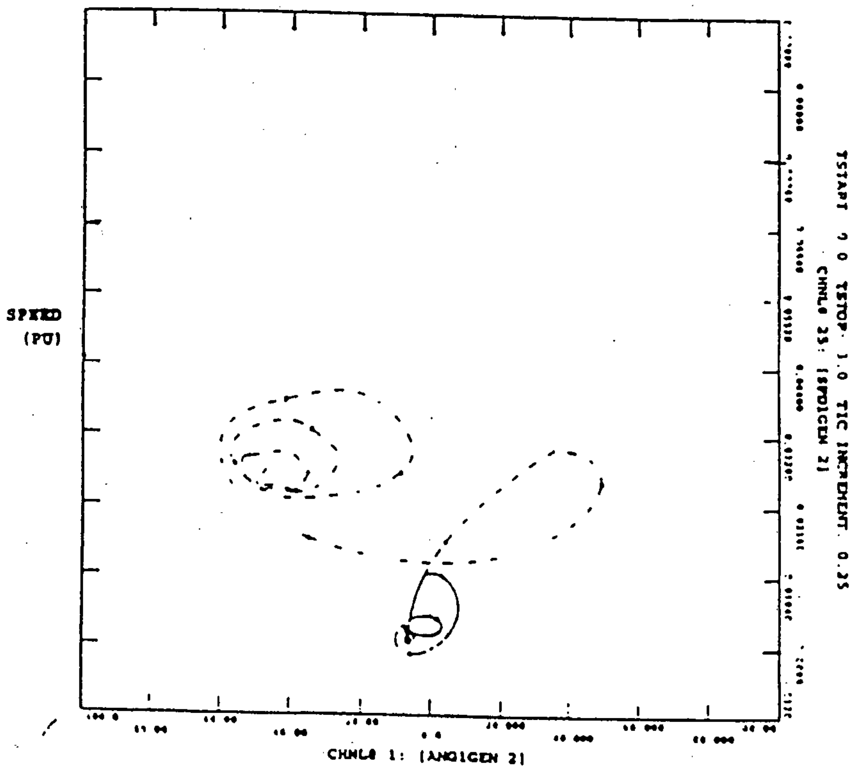


Figure *i*1.6 Angle/ speed trajectory of generator 2 after three phase fault at bus 7630

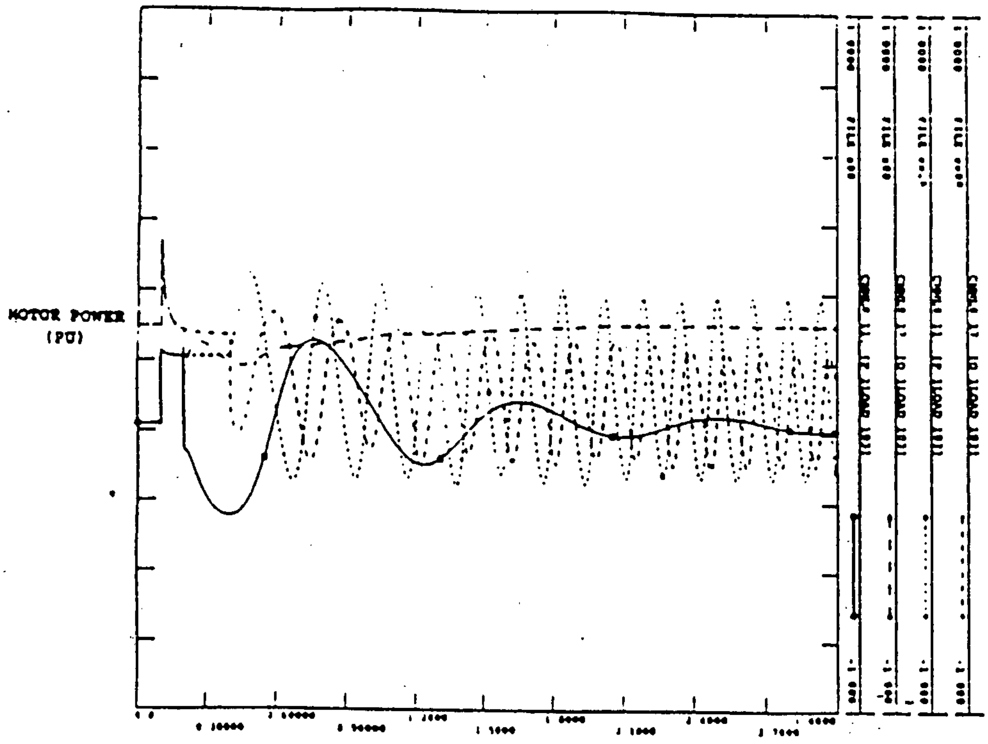


Figure *i*1.7 Response of the power to the 20.3 MW synchronous motor after three phase fault at bus 7630

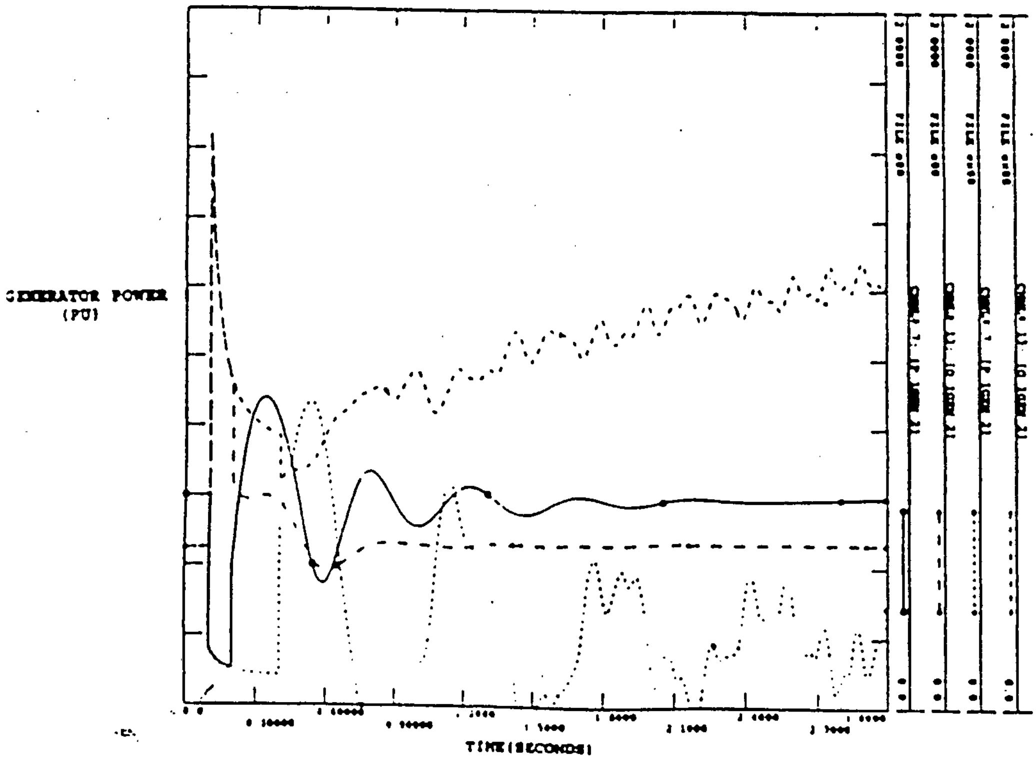


Figure *i*1.8 Power response of generator 2 after three phase fault at bus 7630

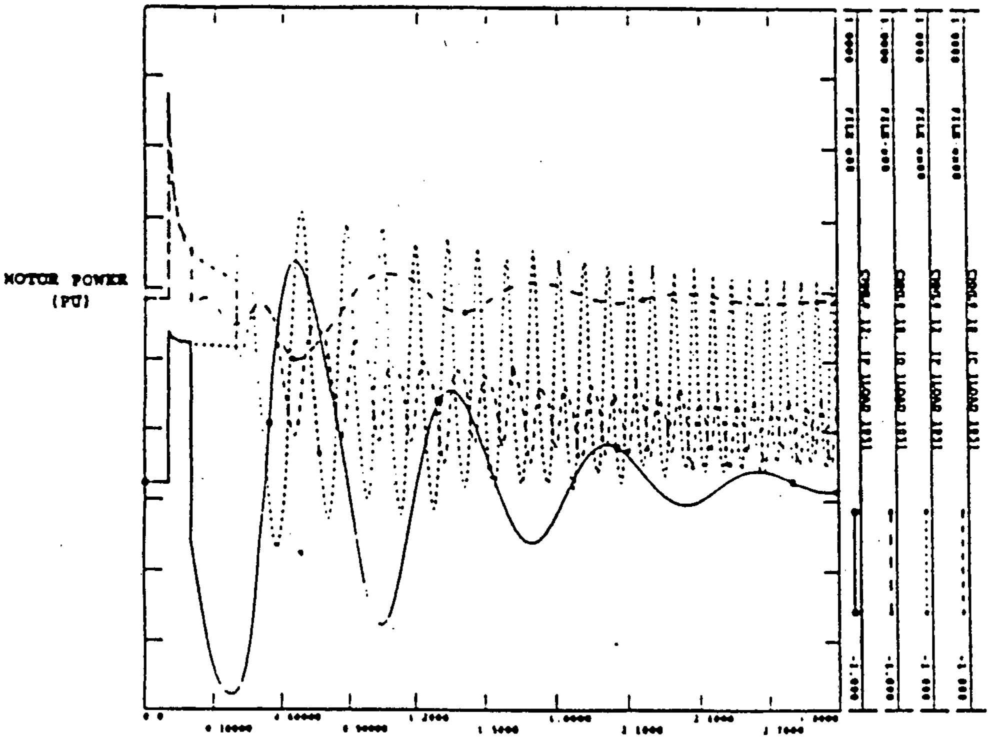


Figure *i*1.9 Power response of the 37.5 MW synchronous motor after three phase fault at bus 7630

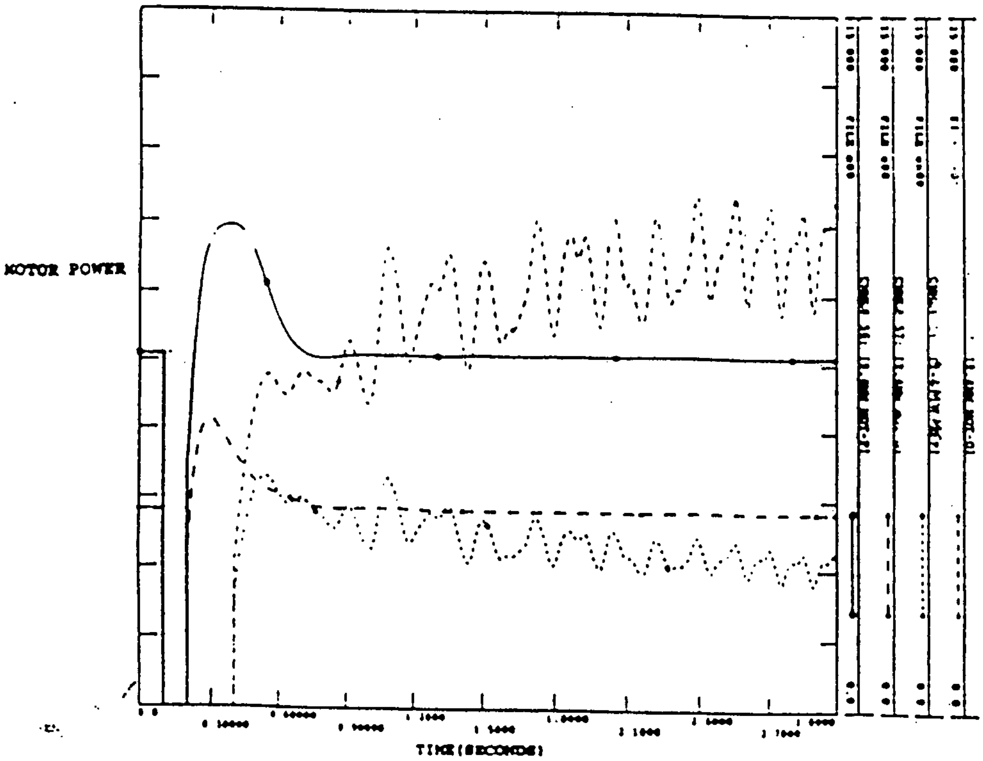


Figure *i*1.10 Power response of 9.4 MW induction motor after three phase fault at bus 7630

APPENDIX J

In simulation four, one of the Escom incoming transmission line is opened at t=100 msec followed by a generator outage at t = 10 sec. The response of the system can be seen in the following graphs.

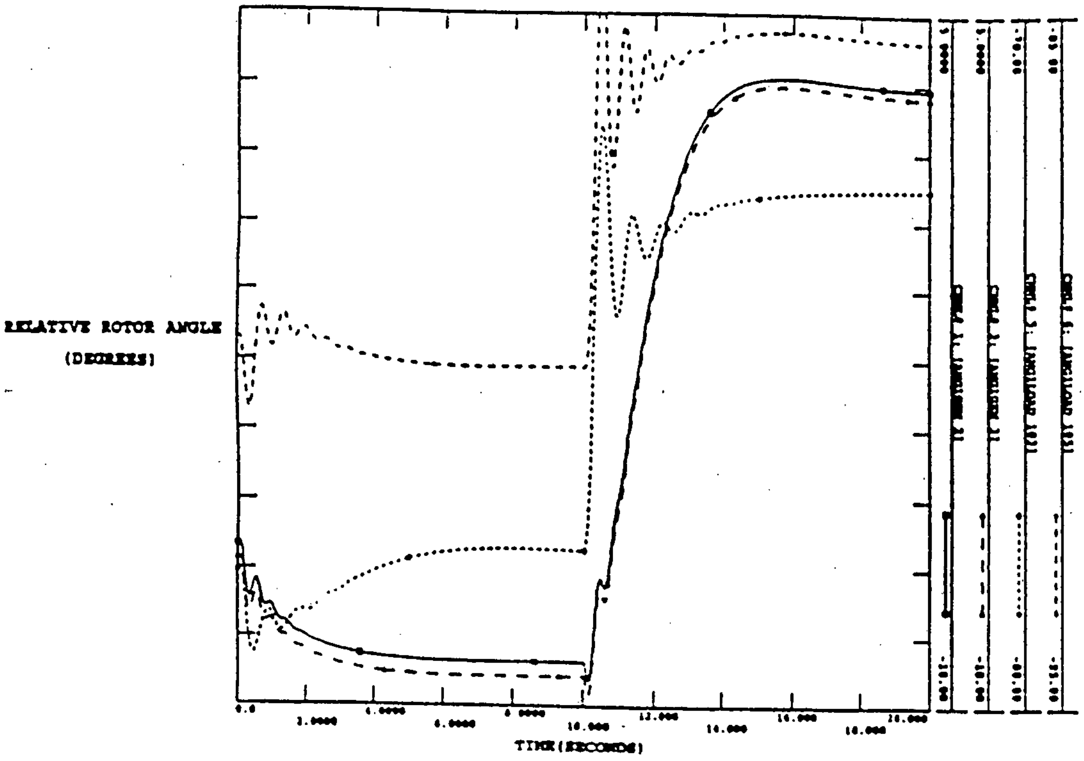


Figure j1.1 Relative angular response of synchronous machines to the event

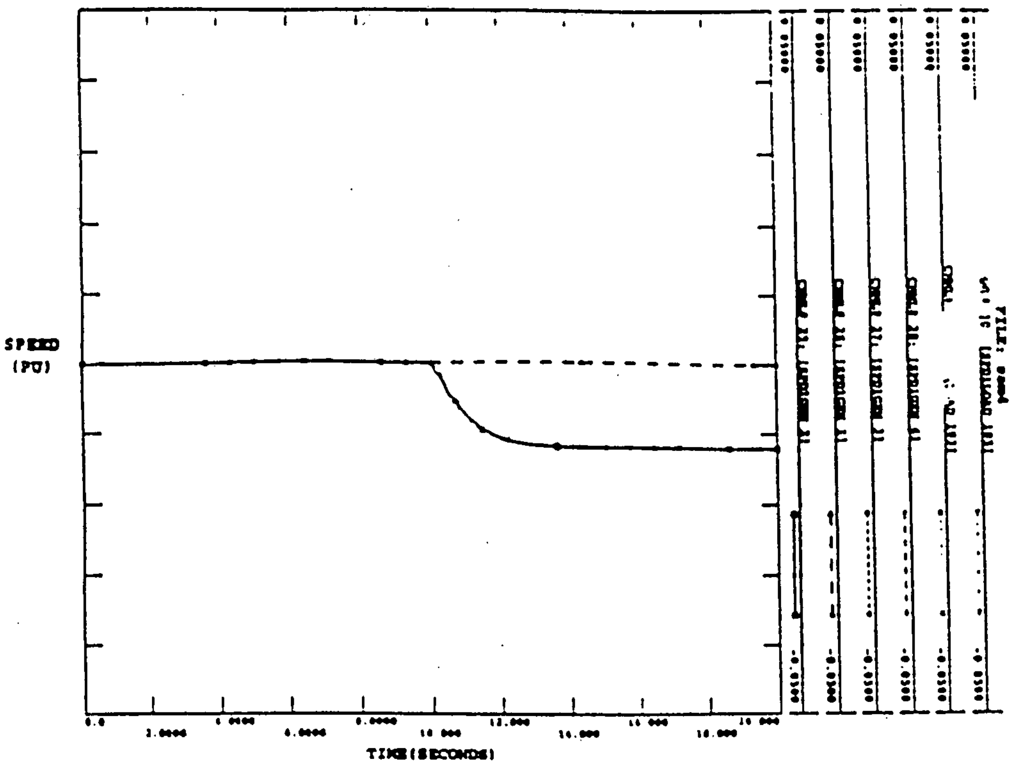


Figure *j*1.2 Relative speed response of synchronous machines to the events

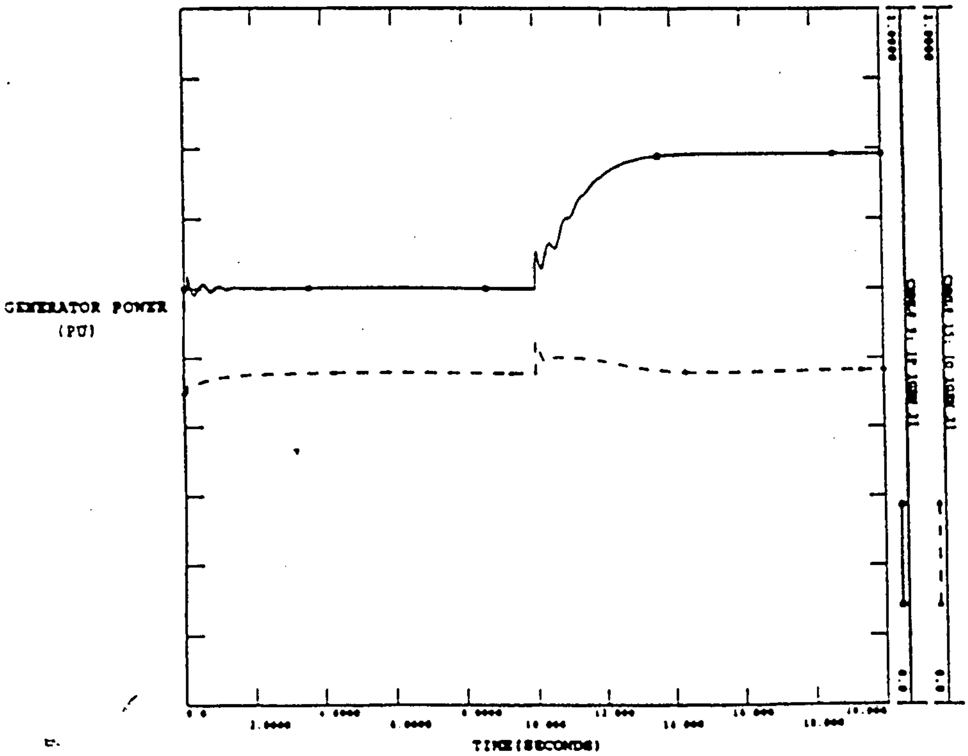


Figure *j*1.3 Response of the power of generator 3 to the event

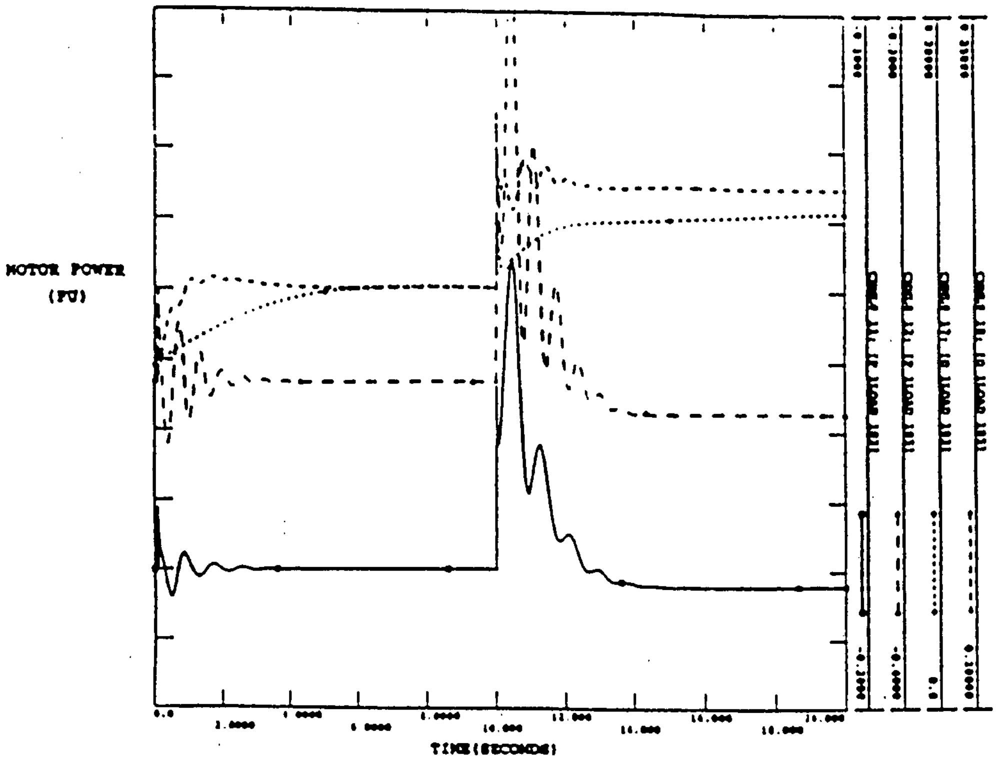


Figure *j*1.4 Response of synchronous motor power to the events

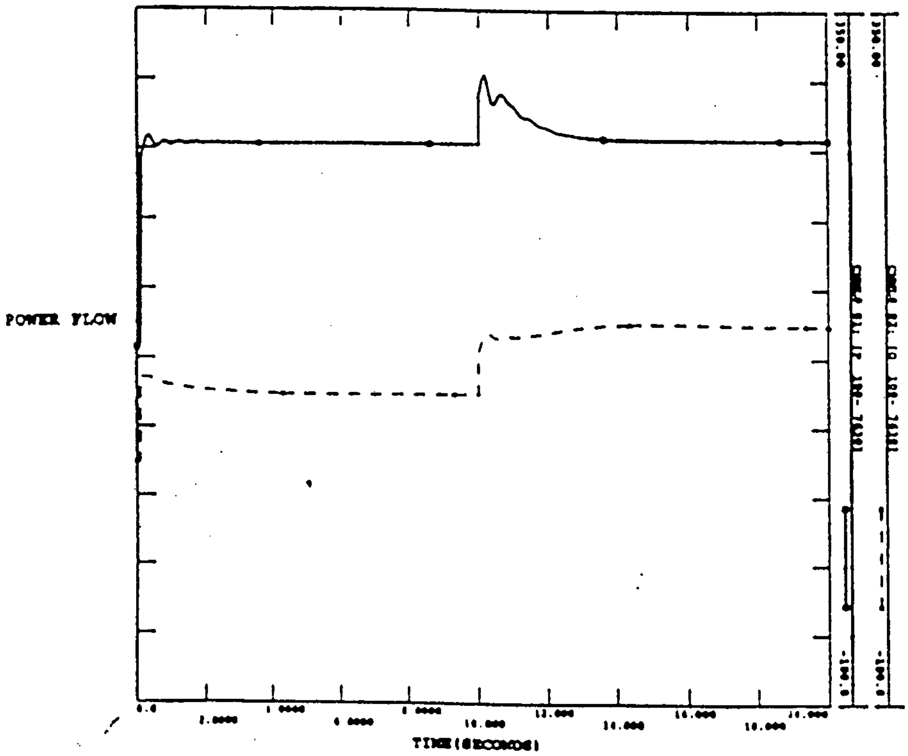


Figure *j*1.5 Response of the power imported from Escom

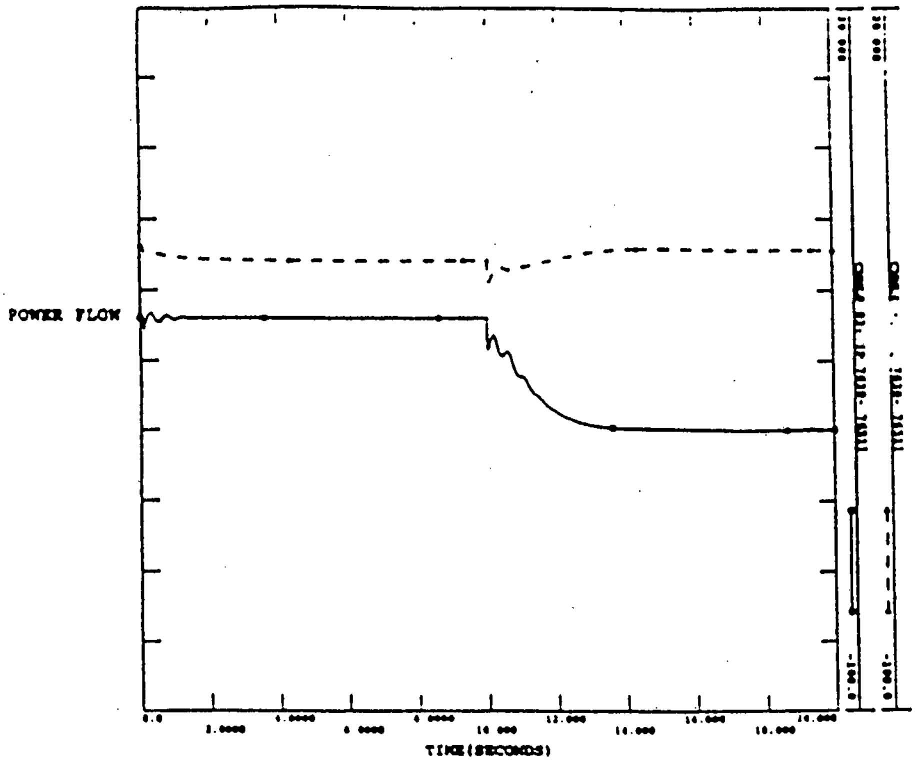


Figure j1.6 Power flow from generator three

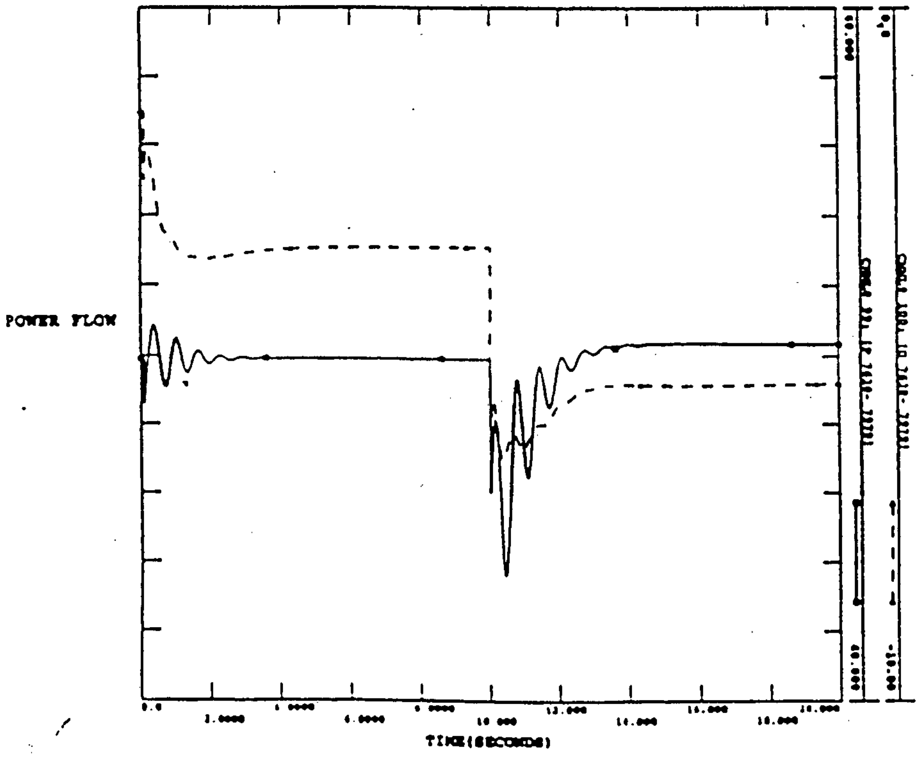


Figure j1.7 Response of the power to the 37.5 MW synchronous motor