THE UNIVERSITY OF ZAMBIA

SCHOOL OF ENGINEERING

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

DETERMINING THE TRANSIENT STABILITY MODELS FOR GENERATORS AT KARIBA NORTH BANK POWER STATION

BY

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" Report submitted in partial fulfilment of the requirements for the degree of Bachelor of engineering, University of Zambia."

13th July, 2001

TO MY FAMILY

for many years of patience and encouragement, especially my parents Pastor and Mrs Kanjelesa.

AKNOWLEDGEMENTS

In presenting this report, I wish to sincerely pay tribute to the following individuals: -

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PREFACE

To obtain the University of Zambia Bachelor of Engineering, one must do a final year project as a partial fulfilment. Such a project is supervised by a lecture from the same department.

This report has been submitted to give a report on the final year project entitled "Determining the transient stability models for generators at Kariba North Bank Power Station". This project was proposed and supervised by Dr L. D. Nyirenda, and was done at the University of Zambia in collaboration with Kariba North Bank Company.

Performing the power system transient stability is a very comprehensive task that requires knowledge of machine dynamic models, machine control unit models (such as Excitation and AVR, Governor and Turbine, and PSS), numerical computations and power equilibrium phenomena. Therefore, the report is concerned with synchronous generators, their associated theoretical models, system parameters, and their effect on the system transient stability.

The various aspects are treated in the order in which each develops naturally out of those preceding it. After a brief introductory discussion in chapter 1, which is intended to give a general idea of the study and concepts employed, chapter 2 gives the background theory , the literature review and chapter 3 presents the description of the system. Development of models is subsequently presented in chapter 4, which is followed by transient stability study presentation in chapter 5. Chapter 6 gives the discussion while chapter 7 presents conclusions and recommendations of the study. At the end of the study are the appendices, mainly consisting figures that could not be labelled for instance computer print outs.

The report is specially written to suit even a layman as well as technical. This has been put into place to facilitate any future work that may be undertaken in the same line as this project

LIST OF EQUATIONS

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LIST OF SYMBOLS AND ABBREVIATIONS

CB – Circuit Breaker

D – Damping factor

E –Machine (generator) internal EMF

Efld – Field voltage

Fe – System frequency

Fr – Rotor field MMF

G – Machine MVA base

Ge(s) – Transfer function corresponding to 'linearlized' feed forward part of excitation system

Gm(s) – Transfer function corresponding to 'Linearized' feed forward part of excitation system.

H – Machine inertia constant, at synchronous speed per MVA

If – Field current

Ifs – Field current corresponding to 100% terminal voltage air-gap line (no saturation)

If100 – Field current corresponding to 100% Vt on open circuit saturation curve

If120 – Field current corresponding to 120% Vt on open circuit saturation curve

Ka – Amplifier gain

Ke – Exciter gain

Kf – Field gain

K1,2,3,4,5,6 – Gain parameters, with K5 and 6 depending on system reactances and operating Conditions

Lf – Field winding inductance

M – Inertia constant, given by GH/180f [

N – Rotor speed

P – Number of poles

Pc – Power command

Pe – Output electrical power

Pm – Input mechanical power

Pp – Per-phase electrical power

Rf – Field winding resistance

Se(Efd) – p.u saturation function

Sbreak - % Vt at saturation break point

Ta – Amplifier time constant

Tdo' – Flux decay time constant

Te – Exciter time constant

Tem – Electromagnetic torque

Tf – Time constant

Tg – Governor time constant

Tm – Mechanical torque

Tt – Turbine time constant

Ve – Excitation voltage

Vf – Input field terminal voltage

Vinfinite – Voltage at the infinite bus

Vr – Regulator voltage

Vref – Exciter reference voltage

Vt – Machine terminal voltage

x – Fault location

X – Relative linear displacement of links

Xd – Direct-axis reactance

Xq – Quadrature-axis reactance

Xt – Transfer reactance

Φair – Air-gap flux

θ - Angle

Δ - Incremental function

∞ - Infinite

ϕ - Phase

δ - Power/rotor/ angle

ω - Rotor angular speed

USA – United States of America

PSS – Power System Stabilizer

ETAP – Electrical Transient Analyser Program

KNBPS – Kariba North Bank Power Station

KGPS – Kafue Gorge Power Station

KSPS – Kariba South Power Station

E – Machine (generator) Internal EMF

EMF – Electromotive Force

MMF – Magnetomotive force

p.u – Per unit

mach – machine

syst – system

RATIONALE

Power system are designed to operate continuously without interruption over the whole operating range. However, due to disturbances that occur on these systems, the system experiences interruptions which are undesirable in any power system operation.

Kariba North Bank power station being one of the major power producers in the country, contributes so much to the country's economy such that jeopardising its stable operations by these disturbances would have an adverse effect on both the power station and the county as a whole.

It is therefore essential that a stability study be undertaken on this power system, to assess the power station's stability and come up with methods of enhancing and improving its stability. This is the question the project is seeking to address.

SUMMARY

Electrical energy is an essential ingredient for the industry and all-round development of a country. It is transmitted, from its sources to far located places of utilization, by large interconnected power systems within which synchronous machines operate.

For efficiency, reliability and in order to meet the demands and expectations of the end user, these power systems must operate continuously without interruption. However, in practice, these power systems are subjected to a number of disturbances of which the most severe is a large and sudden one having a remote possibility that an initial disturbance may lead to a regional blackout, hence presenting us with a ***transient stability problem***. The USA Great North east regional blackout of 1965 is such an example.

Stability of a power system is therefore its ability to retain stable operation during normal and abnormal conditions. Stability considerations have been recognised as an essential part of power system planning and operation for a long time. With interconnected systems continually growing in size and extending over vast geographical regions, it is becoming increasingly more difficult to maintain synchronism between various parts of a power system and planning for future expansion .

Kariba North Bank Power Station (KNBPS) the second largest 600MW hydro-electric power plant and first Independent Power Producer (IPP) in Zambian, since its commissioning, has played a vital role in the country's development by continued supply and exportation of great amount of electrical energy. Besides, it has great influence on the area oscillations because of its large units. There is therefore inevitable need to determine conditions, which provide indication for transient stability assessment for the Kariba North Power Station generators.

To assist the engineer in power system planning especially the operations personnel, digital computers and highly developed computer programs, such as power flow, stability programs, etc are used.

CHAPTER ONE

INTRODUCTION

Electrical energy is an essential ingredient for the industry and all-round development of a country. It is a converted form of energy because it can be generated centrally in bulk, transmitted over long distances, and can easily and efficiently be adapted for domestic and industrial purposes.

Conventionally, electrical energy is obtained by conversion from fossil fuels, nuclear and hydro sources, whose energy is first converted into mechanical form and then to electrical form through the generators. This electrical form can either be alternating current (AC) or direct current (DC) system.

AC system has more advantages over DC in terms of cost and technological reasons. These days, three-phase AC system is being exclusively used for generation, transmission and distribution of power. The machine, which converts three-phase power from mechanical power, is called an alternator or a synchronous generator. Generally, these synchronous
generators are used in a power system where they are in parallel with many other synchronous generators forming an interconnected power system.

In order for the interconnected power system to be efficient and reliable, the main requirement is that it must operate continuously without interruption; meaning that the generators must generate and deliver power continuously over the whole operating time.

However, in practice, these power systems are subjected to a number of disturbances some of which are small and slow while others are large and sudden. Therefore, ***stability*** of a power system is its ability to retain or maintain normal or stable operation after being subjected to some form of a disturbance. Conversely, instability means a condition denoting loss of synchronism or falling out of step. For every power system having a number of synchronous machines operating in parallel, stability denotes a condition in which various synchronous machines remain in synchronism or in step, having the same running speed.

Accordingly, power system stability problems are classified into three basic types: - Steady state, dynamic and transient stability problems.

(1) **Steady-state stability** is basically concerned with determination of upper limit of machine loadings before losing synchronism, provided the loading is increased gradually.

(2) **Dynamic instability,** which is more probable than steady-state instability is caused by small disturbances continually occurring in a power system (variations in loadings, changes in turbine speed, etc.). These are small enough not to cause a system to loose synchronism, but do excite the system into a state of natural oscillations, a problem solved by damping.

(3) Following a sudden disturbance on a power system rotor speeds, rotor relative angular differences and power transfer undergo fast changes whose magnitude depend upon the severity of a disturbance. For a large disturbance, changes in angular differences may be so large as to cause the machines to fall out of step. This instability is known as **transient instability** and it is a fast phenomena occurring within 1 second.

There is a large range of disturbances, which may occur on a power system, but a three-phase balanced fault (a short circuit) on a heavily loaded line, which require opening of the line to clear a fault, is usually of greatest concern. This is so because it is the most severe type of disturbance a power system can be subjected to.

The successful stable operation of the power system depends on that of the generators. This is because synchronous generators play a decisive role in power system stability, since for every disturbance, they must adjust their relative rotor angles to meet the conditions of power imposed on the system.

The project is therefore aimed at determining models for conditions that provide indication for KNBPS generator transient stability assessment.

1.1 PROJECT PROBLEM STATEMENT

The large interconnected systems in which synchronous generators work, must operate continuously without interruption over the whole operating time for efficiency, reliability and in order to meet end user demands and expectations.

If machine stability is jeopardised by sudden load changes or changes by sudden short-circuits, we are faced with the most severe condition a power system can be subjected to, the transient stability problem.

Since the main requirement is that the machines go on operating even under such extreme conditions, there is inevitable need to determine conditions, which provide indication for system transient stability assessment. Since system generators play a decisive role in power system operation and stability, their transient stability assessment implies the assessment for the system within which they operate.

1.2 RATIONALE

The purpose of undertaking this project is to determine the ability of the KNB Power Station network to withstand major faults without the generators connected to the network losing synchronism, and therefore coming up with transient stability models for the generators at this power station.

The models obtained can widely be utilised in future expansion of the respective power company, and mostly in the enhancement and / or improvement of the power station transient stability. With this in place, during operation, the station continues to run even under severe conditions hence reducing interruption of service to customers and safeguarding equipment. This is cost effective in that equipment is preserved from permanent severe damage and consequently not disrupting the business operations.

1.3 PROJECT AIM

To determine the transient stability models for generators at Kariba North Bank Power Station.

1.4 OBJECTIVES

- To determine the circuit and mathematical models for synchronous generators
- To develop s-plane control models for the generator prime-mover/governor-turbine and excitation/automatic voltage control systems.
- To perform a sample study on the ETAP software.
- To model the KNPS system network into ETAP and assess the transient stability for the generators at the Power Station.

1.5 SCOPE OF WORK DONE

KNBPS is a 600MW power generating plant with four (4) salient-pole synchronous generators connected, in parallel, to the National grid. The grid subsequently connects the power station to other power stations in the SAPP region. Therefore, the scope of this project was with respect to the following:

- Review of literature on salient-pole synchronous generators and their control systems, the Excitation and Governor systems, significant to the study.
- System network size of four (4) synchronous generators connected to a common bus-bar as shown in figure of appendix 1, was considered.
- A balanced three-phase solidly grounded (short-circuit) fault at different bus-bars, within the system network was connected.

1.6 METHODOLOGY

The project work was done as follows:

- Familiarisation of the KNB Power Station system operation and network configuration relevant to the study was done through the Industrial training program at KNBPS.
- Review of literature within the scope of the study. For the purpose of understanding synchronous machine operation and ways of modelling its performance.
- A sample study using the ETAP computer software was then carried, so as to get acquainted to its operation.
- Presentation and subsequently data collection was done at the power station.
- The system models were developed using the data collected and typical data for non-available information, with respect to IEEE and ANSI standards.
- The power station system network was then modelled into the ETAP program, using the developed models.
- Finally, the system generators transient stability simulation and assessment was carried out as regard to variation of system parameters.

1.7 ASSUMPTIONS

The following assumptions were considered in the study:

- The National grid (the switchyard bus-bar) was considered an infinite bus (since many power generating stations are connected to it).
- Power station buses between generators and transformer input terminals were assumed to have negligible losses.
- The Excitation and Power Station loads were assumed static loads, considering only excitation and station transformer rated loadings with power factors assumed
- Typical models and data for the excitation and governor systems, and any other missing information were assumed with respect to IEEE and ANSI standards.

1.8 ORGANISATION OF THE REPORT

The various aspects of this are treated in the order in which each develops naturally out of those preceding it. After a brief introductory discussion in chapter 1, which is intended to give a general idea of the study and concepts employed, chapter 2 gives the background theory, the literature review and chapter 3 presents the description of the system. Development of models is subsequently presented in chapter 4, which is followed by transient stability study presentation in chapter 5. Chapter 6 gives the discussion while chapter 7 presents conclusions and recommendations of the study. At the end of the study are the appendices, mainly consisting figures that could not be labelled for instance computer printouts.

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CHAPTER TWO

BACKGROUND THEORY

Interconnected power system stability is its ability to remain in electromechanical equilibrium during normal or abnormal conditions, while instability denotes loss of synchronism or falling out of step.

Power system stability problems are classified into three basic types; *Steady-state:-* concerned with determination of upper limit of gradual machine loading before losing synchronism, *Dynamic:-* which is more probable than the former is concerned with small disturbances continually occurring in a system, and *Transient instability:-* the most probable, is concerned with maintenance of synchronism between generators following a severe disturbance.

2.1 TRANSIENT STABILITY

A transient instability problem is the most severe problem a power system can be subjected to. It is a fast phenomena occurring within 1second, and is caused by large and sudden disturbances.

Transient stability is affected by the type and location of a fault, so that its analysis requires consideration of these two factors.

2.1.1 Stability limits

There are two types of stability limit for a power system, namely steady-state stability limit and transient stability limit.

❖ ***Steady-State Stability Limit***

The steady-state stability is defined as the stability of a system under conditions of gradual or small changes in the system. This stability can be either found by

the load flow calculation for a steady-state operation, or determined by a transient stability study if there are system changes or disturbances involved. The system is said to be steady-state stable if, following any small and/or gradual disturbances, all synchronous machines reach their steady-state operating condition identical or close to the pre-disturbance operating conditions. The steady-state stability limit for any synchronous machine is when its rotor angle is less than 90 degrees.

❖ ***Transient Stability Limit***

Transient or dynamic stability is defined as the stability of a system during and after sudden changes or disturbances in the system, such as short-circuits, loss of generators, sudden changes in load, line tripping, or any other similar impact. The system is said to be transient stable if following a severe disturbance, all synchronous machines reach their steady-state operating condition without prolonged loss of synchronism or going out of step with other machines.

2.1.2 Causes of Instability Problems

The major causes to industrial power system instability problems include, but are not limited to:

- Short-circuits
- Loss of a tie connection to a utility system
- Loss of a portion of in-plant co-generation (generator rejection)
- Starting a motor that is large relative to the system generating capacity
- Switching operations of lines, capacitors, etc.
- Impact loading (motors and static loads)
- A sudden large step change of load or generation

2.1.3 Consequences of Instability Problems

Due to these causes, the consequences of power system instability problems usually are very severe and can range from permanent damage on equipment and shutting down processes, all the way to causing a whole area power outage. Some typical consequences are listed below:

- Area-wide blackout
- Interruption of loads
- Low-voltage conditions
- Damage to equipment
- Relay and protective device malfunctions

Due to these causes, changes in relative rotor angular differences may be so large as to cause machines fall out of step.

Of most concern, which is the most severe cause, is a short circuit (a balanced three-phase fault) on a loaded line (Modern power system analysis, "Nagrath and Kothari", page 406). To remove the fault, relays detect the short-circuit and cause circuit breakers to open at both ends of the line. The line is de-energised and air deionises, re-establishing its insulating properties (because the air insulation had broken down) hence fault "clears". These circuit breakers are set to re-close automatically after a present time interval, re-establishing the original circuit. This sequence of events (called a fault sequence) constitutes a "shock" to the power system and is accompanied by a transient.

The key question of transient stability is therefore: After such a transient period, will the system return or "lock" back into a steady-state condition, maintaining synchronism? If it does then it is transient stable, while if it does not it is unstable and system may break into disconnected subsystems or "islands" which may in-turn experience further instability.

In what has been called the "Great blackout of 1965", an improper action of a protective relay initiated a sequence of events that caused a cascade of circuit breaker openings (or trippings). These broke the interconnected Northeast power system into several parts. Eventually, 30million people were affected, service was interrupted for up to 17½ hours and a generator in New York city was severely damaged. Most power interruptions of this nature are fatal and so a transient stability problem is an important one.

Essentially, one hundred percent (100%) of the world's bulk electric power is being produced in three-phase (3-) synchronous generators. Therefore, large ac power networks operating at constant frequency, for instance 50/60 Hz, rely most exclusively on these machines for the provision of electrical energy.

As the synchronous generator, or alternator, dominates the operating features of a power system and, most importantly, also incorporates the major control functions of the system, these machines play a decisive role in the stable operation of system within which they are operating ("Electric Energy systems theory; an introduction", Olle.I. Algerd, page 68).

Power system stability is sometimes referred to as synchronous machine rotor angle stability because of their rotating parts (rotor), during and after disturbances their rotor angles will oscillate to cause power flow oscillations in the system. Depending on level of these oscillations, the electromechanical equilibrium in the system could be destroyed and the instability could occur.

Performing the power system transient stability is a very comprehensive task that requires knowledge of machine dynamic, and control unit models (such as Excitation system and Automatic Voltage Regulator, governor and turbine systems and power system stabilizers), numerical computations and power system electromechanical equilibrium phenomena.

2.2 MODELS

To understand and control complex systems, qualitative mathematical models should be obtained and used to analyse the relationship between system variables. A model is a representation of specifications or description of the

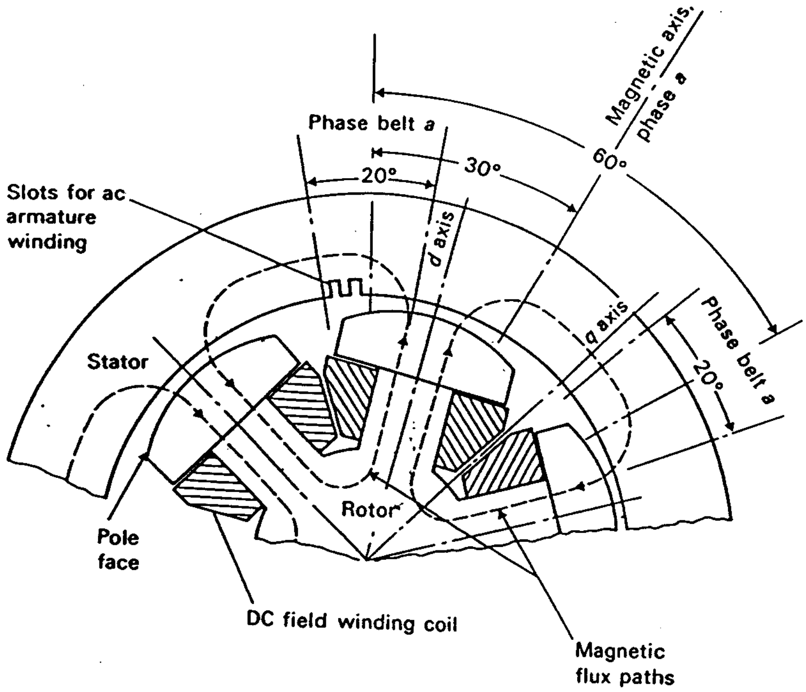

Figure 2.1: Design details of the three-phase salient-pole hydro-generator

system configuration and its components, in a form amenable to analysis, design and evaluation (Feedback and control systems, "J. Distefano, A. Stubberud and I. Willians", page 4).

2.2.1 **Synchronous generators**

A synchronous generator is a synchronous machine, which is used to convert mechanical power to 3-ph ac electrical power. This machine with its many windings , some of which are in motion relative to others, constitute a rather complex device, whose analysis can be reduced to formulae.

2.2.1.1 Basic design features

Usually, turbo (steam-turbine driven) and hydro (water-turbine driven) generators are used. Two-pole design is usually used for high-speed steam turbine prime movers, which are most common in developed countries. Generator rotor and turbine are directly coupled on a single shaft in horizontal arrangement.

When slower primers for instance Hydro- turbines, must be used, a higher number of poles is required and rotor is normally designed with salient poles. Figure 2.1 shows the design of six-pole machine. The field winding is on the rotor and, rotors or 'runners', are typically slow and tend to have very large diameter and relatively small axial length. The turbine-generator shaft is normally vertical, with turbine placed below generator. In addition to field windings and amarture windings, which are placed on the stator, all synchronous machines are provided with rotor damper windings, consisting of short-circuited cages quite similar to the 'squirrel-cage' induction motor windings. For salient –pole machines, these are placed on pole surfaces. Damper windings are idle during normal balanced operation but go automatically into operation during transients.

Magnetic flux in rotor, under normal condition, is constant whereas in stator it will fluctuate with time. Rotor iron is therefore solid while that of the stator is laminated to reduce eddy currents. The solid iron provides current paths and does, in reality, act as a separate damper winding during transient conditions.

2.2.1.2 Operation (Induction of stator EMFs)

The rotor windings are supplied by a dc source, for constant rotor magnetic flux. When a dc field current (If) flows in the rotor field windings, a magneto-motive force (mmf) is set up, which causes formation of rotor-based field flux. In a salient-pole generator the mmf produced is not uniform and pole faces are tapered, resulting in a maximum flux density along the direct-axis (d-axis, centre of pole) diminishing to zero in the quadrature-axis (q-axis, between poles).

The rotor is coupled to the prime mover, which gives it mechanical rotational power. The rotor hence spins at a constant synchronous speed 'n' , and stator conductors experience a travelling 'flux wave' in travelling constant flux wave of rotor. When a magnetic flux of density B cuts a perpendicular conductor at a relative speed (s), an electro-magnetic force (emf.) 'E' is induced in the conductor, whose instantaneous magnitude is given by the formula

$$E = Bs \quad [v/m] \qquad 2.1$$

This emf will follow the distribution of mmf flux distribution. The stator will experience an emf wave or 'E' wave of same speed as flux wave.

The two waves consist of p/2 (with p =number of poles) full cycles around the full peripheral . Thus if rotor speed is n (rev/min), each stator conductor will experience an ac emf of frequency;

$$F = (p/2)(n/60) = pn/120 \quad [Hz] \qquad 2.2$$

Due to a number of poles on stator, electrical degrees of stator emf differ from rotor mechanical degrees θm, in that when rotor turns one mechanical degree stator emf completes p/2 electrical degrees θe. This gives a relation $\theta m = (p/2)\theta e$.

Three-phase synchronous generator have three stator phase windings displaced 120deg from each other. The emf induced in stator windings makes a stator current to flow in each conductor hence in each phase.

When a load is connected current flow creates a rotating flux mmf, which reacts, with rotor mmf and this results in a flux wave called armature reaction wave. The two-flux wave adds up vectorily, to a resulting emf E (in the air gap). E is called open circuit generator terminal voltage because it can be measured between one terminal and ground of the generator. This action causes the displacement of rotor field poles from the stator rotating field poles and the angle of displacement is what we call the rotor, load, or power angle (denoted by δ).

The current flow in stator windings causes a drop over a reactance referred to as synchronous reactance. The terminal voltage Vt is hence considered the result of field induced 'internal emf' E minus voltage drop across 'internal impedance'

jXs. This concept gives us representation of machine with the "Equivalent network"

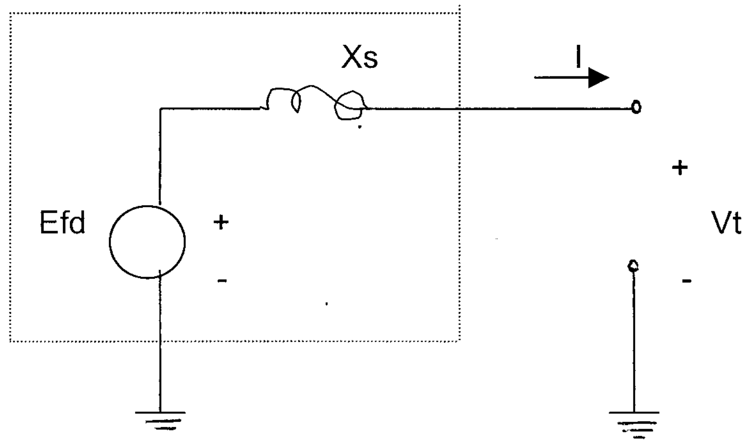

Figure 2.2: Generator Equivalent circuit model

The preceding discussion does not take into consideration the machine saliency for the salient-pole machine. In this regard, magnetizing effects in d- and q-directions are distinguished, and the stator current is resolved into components Id and Iq causing flux (ϕ) in d- and q- directions respectively. This gives d- and q-axis synchronous reactances Xd and Xq respectively. The phasor diagram representation is as shown in figure 2.3.

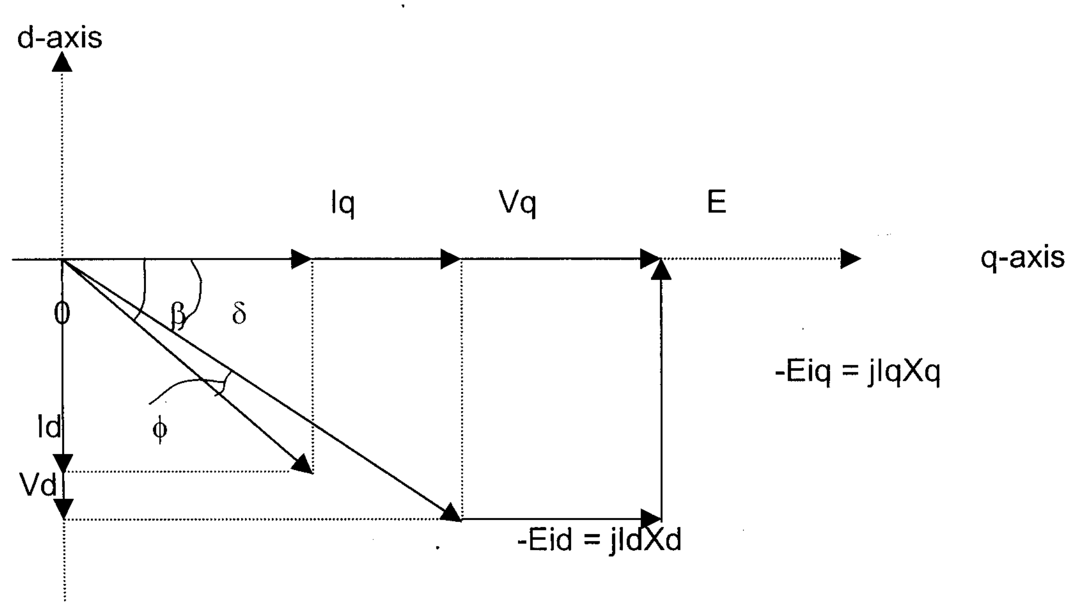

Figure 2.3: Resolution of I into components Id and Iq

2.2.1.3 Short- circuits

In all stability studies, effect of short circuits (faults), must be dertermined. This so because such conditions may cause instability of a machine. Under steady-state short-circuit conditions, amarture reaction of synchronous generator produces a demagnetising flux, which in terms of circuit is modelled as a reactance Xa in series with induced emf (figure 2.4), that is Xs = Xa + Xl (Leakage reactance representing leakage flux in magnetic circuit core and air)

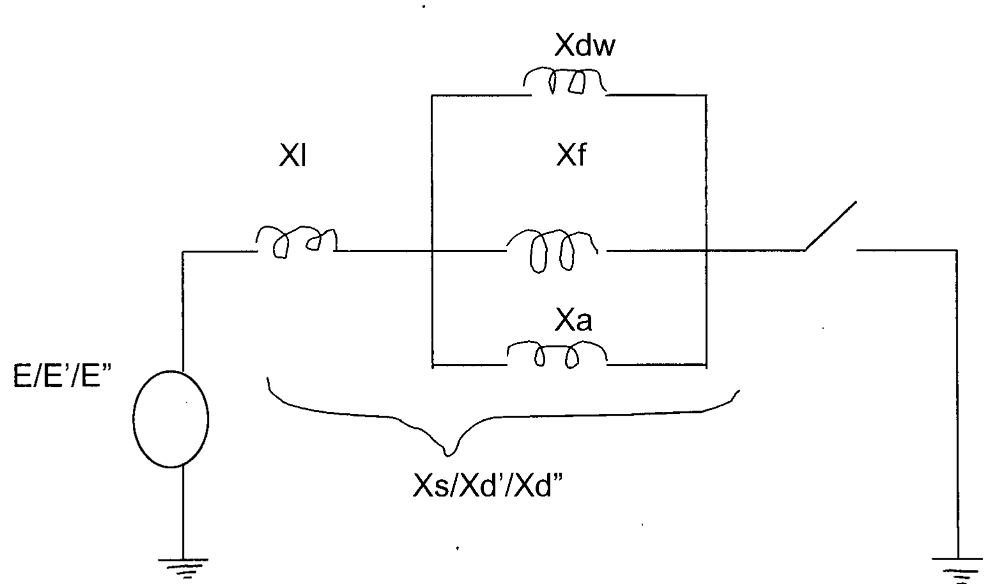

Fig 2.4: Approximate model during steady-state (E, Xs), transient (E', Xd') and sudtransient (E", Xd") short-circuit period.

Where: E'/E" is emf behind X'/X" respectively.

Steady-state = under normal operating conditions (Xf =Xdw = 0).
Subtransient = when short crcuit current appears in field and damper windings.
Transient = when short-circuit appears in field windings (Xdw = 0).

These currents are required to compute short circuit current for the circuit breakers.

2.2.1.4 Power and torque creation

The prime job of generators is to produce megawatts (real power). The electromechanical air-gap torque 'Tem' developed within the generator consistute the basic link between mechanical turbine power 'Pt' and electrical power Pg developed from generator terminals. This torque comes due to the principle of force on current-carrying-conductor in the presence of magnetic field density B.

The rotor is subject to an equal and opposite reaction force. This tends to decelerate the rotor, but will be prevented from doing so by accelerating the turbine torque. This behaviour of machine is described by mathematical dynamic models, in that the transients are basically electromechanical in nature, involving what is termed 'rotor angle swings'. These power system dynamics are characterised by the feature that the system is basically a spring-inertia oscillatory system (which is represented by a mathematical model as shown in equation 1.3), with inertia on the mechanical side and spring action on provided by the synchronous tie. A synchronous tie exhibits a typical behaviour that as
power transfer is gradually increased, a maximum limit is reached beyond which the system can not stay in synchronism (that is, it falls out of step), where power transfer is
proportional to Sinδ; δ being the relative internal angle of the machine.

2.2.1.5 Synchronous Machine Rotor Angles

Synchronous machines play a decisive role in the power system stability because during and after disturbances their rotor angles will oscillate to cause power flow oscillations in the system. Depending on the level of these oscillations, the electromechanical equilibrium in the system could be destroyed and the instability could occur. Therefore, power system stability is sometimes also referred to as synchronous machine rotor angle stability.

The following two equations are often referenced in power system transient stability studies:

❖ The Torque Equation (Generator Case)

$$T = \frac{\pi p^2}{8} \phi air\ Fr\ Sin\delta \ldots\ldots 2.3$$

where:	T	=	mechanical shaft torque
	P	=	number of poles
	ϕair	=	air-gap flux
	Fr	=	rotor field MMF
	δ	=	power (rotor) angle

The torque equation defines the relationship between the mechanical shaft torque, the stator voltage, the excitation system, and the rotor angle. Changes in any one of them will cause the rotor angle to readjust itself to a new position.

❖ Swing equation (Generator case)

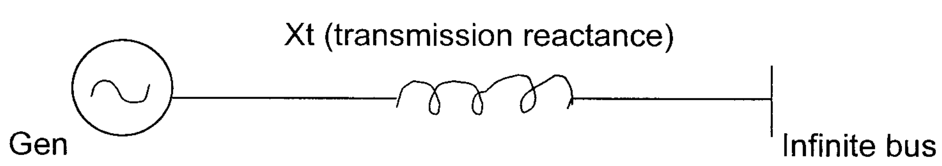

Fig. 2.5: Single generator connected to infinite bus

Dynamics of a single synchronous machine connected to an infinite, as shown above, Is governed by the non-linear differential equation;

$$M \frac{d^2\delta}{d^2t} + D \frac{d\delta}{dt} = Pmech - Pelect \ldots\ldots 2.4$$

where:

M	=	inertia constant
D	=	damping constant
Pmech	=	input mechanical power
Pelec	=	output electrical power

And $$M = \frac{H}{180f} \quad [\ s^2/\text{electrical degree}\ ] \ \ldots\ldots\ldots\ldots 2.5$$

Where: H = Inertia constant, f = System frequency

Equation 2.4 is called the ***swing equation*** and it is the **dynamic mathematical synchronous machine model**, which model rotor dynamics and shows that the solution of rotor angle is a function of balance between mechanical power and electrical power. Any change in the system that breaks this balance, will cause the rotor angle to undergo a transient and reach a new position in an oscillatory manner. This oscillation is usually called the *rotor angle swing*

For a multi-machine system, each machine has a swing equation describing its rotor dynamics. These equations can be lumped together by choosing a common base and carrying out the following computations:

$$Heq = H1mach\ Gimach/Gsyst + H2mach\ G2mach/Gsyst + . \ \ldots\ldots 2.6$$
$$Pe = Pe1 + Pe2 + \ldots\ldots\ldots\ldots 2.7$$
$$Pm = Pm1 + Pm2 + \ldots\ldots\ldots\ldots 2.8$$

Where: Gmach, Gsyst = machine, system base respectively.

2.2.1.6 Power produced

The generator power produced per-phase by a salient-pole synchronous machine is represented as:

$$Pp = \frac{E\ Vt\ Sin\delta}{Xd} + \frac{Vt^2(1/Xq - 1/Xd)\ Sin2\delta}{2} \quad [MW/Phase] \ldots\ldots 2.9$$

$$Qg = \frac{E\ Vt.\ Cos}{Xd} - \frac{V^2\ (Cos^2}{Xd} + \frac{Sin^2}{Xq}) \quad [Mvar/Phase].....2.10$$

Where: Qg is the generated reactive power

2.2.1.7 Power angle equation

In solving the swing equation 2.4, certain simplifying assumption are usually made and these are:

- Mechanical power input to the machine (Pm) remains constant during the period of
 electromechanical transient of interest.
- Rotor speed changes are insufficient – already been ignored in formulating the swing equation
- Effect of voltage regulating loop during the transient is transient is ignored, as a result the generated machine emf remains constant.

Solving the swing equation requires that the dependence of the electrical power (Pe) upon the rotor angle be determined. From the simplified per-phase machine model of equation 2.4 and the phasor diagram of figure 2.3

$$E = Vt + jXdId + jIqXq; \quad Xd < Xq \quad ....211$$

Where $I = Id + Iq$ 2.12

And for the purposes of stability studies E', transient emf of the generator remains constant or is an independent variable determined by the AVR loop, while the determined terminal voltage is a dependent variable. The simplified power angle equation is

$$Pe = \frac{E\ Vt\ sin}{Xd} = Pmax\ sin \quad ....2.13$$

From this equation, the steady-state limit is given by the limitation given by the maximum value of sin which is = 90° . The steady state stability limit is important because a system can be operated above its transient stability limit but not above its steady state limit.

2.2.1.8 Swing equation solution

The swing equation has no closed form solution exist except for the simple case Pm = 0. In a system where one machine is swinging with respect to an infinite bus, transient stability is studied by means of a simple equal area criterion which states that a system is stable if at some time

$$\frac{d}{dt} = 0 \qquad \text{..............................2.14}$$

and unstable if

$$\frac{d}{dt} \quad 0 \qquad \text{..............................2.15}$$

This criterion can generally be as shown in figure 2.6

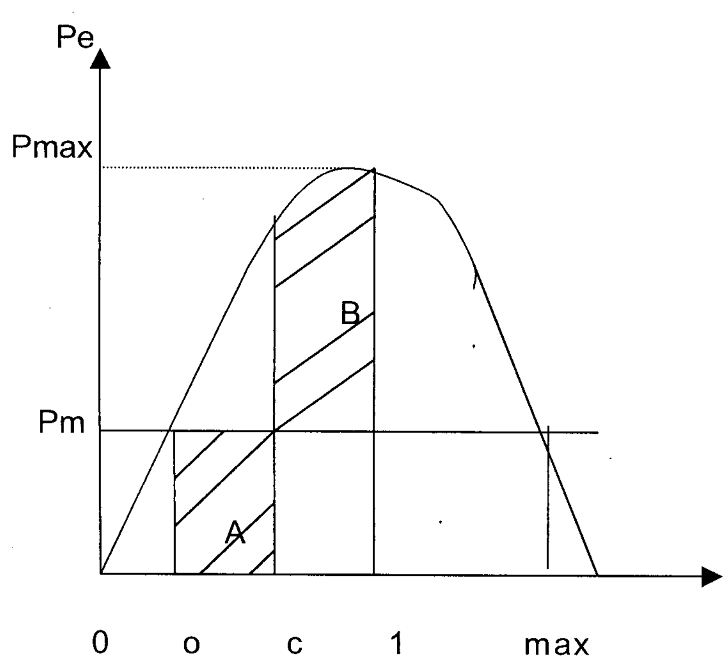

Figure 2.6: Equal area criterion

Where: o, c, 1 = initial, clearing and final rotor angle respectively

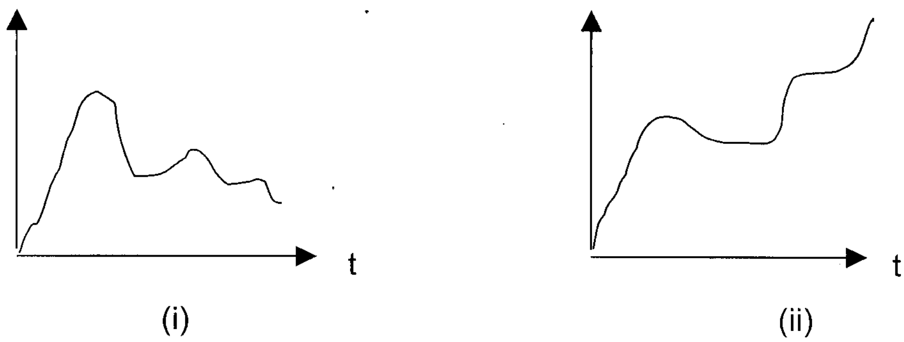

Figure 2.7: (i) Stable system and (ii) Unstable system

From the figure 2.6 the system is stable when A = B. The moment 1 = ma x, c becomes the critical clearing angle c r. If B becomes greater than A, the system is said to be unstable.

For lager and different systems from the previous one, other solution methods are used; for instance the point-by- point method. However, suitable computer programs are used to find the solution of the swing equation. These programs can be modified to include the effect of governor action and excitation control. The solutions obtained show the relation between rotor angle and time being considered. From this method, the system is said to be stable if the rotor angle swings reduce with time after a disturbance while unstable if it increases with time (figure 2.7).

2.2.2 Control of synchronous machines

Synchronous machines can be operated either unto individual loads, or in parallel, as part of huge interconnected power grids. For parallel synchronous machine operation, each operator must meet the following conditions;

(1) Generator and network frequencies must be the same

(2) Phase sequence of the generator should match that of the network

(3) Generator terminal voltage and network voltage must be equal

(4) Generator and network voltages must have equal phase.

Generator power, real and reactive, is entirely determined by the load itself. In order to maintain constant speed, it is necessary to control the prime mover power (torque) for torque balance (hence frequency maintained), which is done by the speed regulator the governor. Reactive power is determined by the generator excitation. Therefore, by over(strong) exciting it, the generator produces reactive power while by under exciting it consumes reactive power. The machine excitation is controlled by the voltage regulator

2.2.2.1 Saturation effects

Magnetic saturation considerably affects the performance of synchronous machines in respect to excitation, regulation and circuit impedances. The saturation phenomena is a function of magnetic material concerned and its working flux density, and is therefore a local effect that varies from point to point in space and (for varying flux densities) in time.

Particularly, in large scale disturbances, magnetic saturation which is non-linear (due to non-linear flux effects) will have an effect in levels. Therefore, different modelling techniques are used to take into account these effects. For instance, the diagram in figure 2.8 depicts one of these techniques

Where:

If = Field current corresponding to 100% terminal voltage on the air gap line (no saturation)

If100 = Field current corresponding to 100% terminal voltage on the open-circuit Saturation curve

If120 = Field current corresponding to 120% terminal voltage on the open-circuit Saturation curve

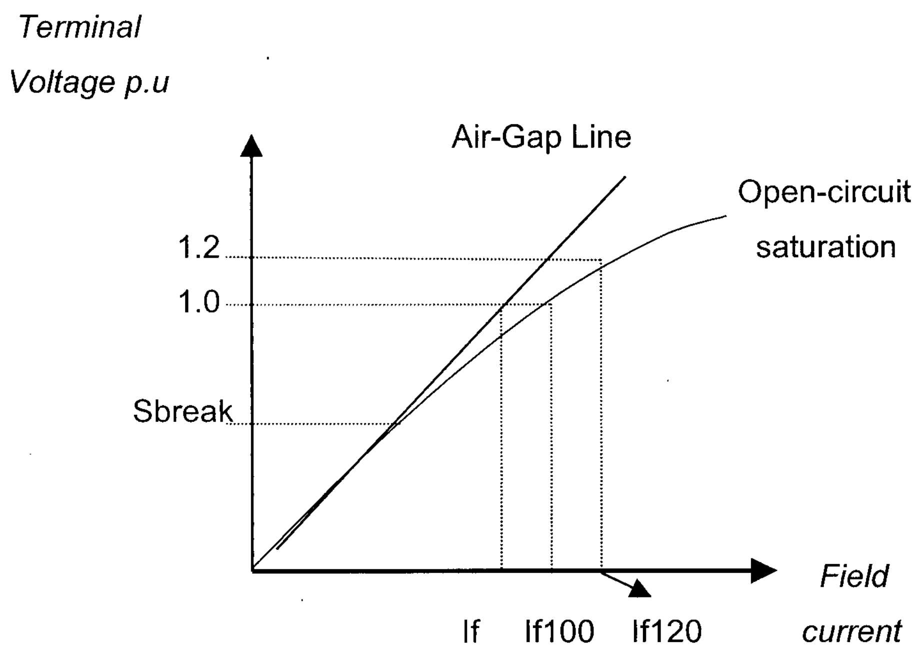

Fig 2.8: Synchronous machine saturation curve

For generator starting studies, another factor, Sbreak, is required to correct machine inductance as shown in the above generator saturation curve. The factor Sbreak is defined as %Vt at the saturation break point.

2.3 MEGAWATT-FREQUENCY (P-F) INTERACTION

Constant frequency is identified as a primary mark of a normally operating system. Some of the reasons why frequency should not be allowed to deviate are;

- Most motors run speeds directly related o frequency
- Generator turbines are designed to operate at precise speed
- For overal power system control
- Electrically operated clocks, depend on the system frequency.

$$P = \frac{d}{dt}\left[Wkin (f/f^{o})^{2} \right] \quad \ldots\ldots 2.16$$

where: ΔP = chang in real power P, Wkin = System kinetic energy, f,fo = system instatenous, normal system frequency respectively.

This is used for generation control because system load should correspond to generation. Hence to control generation, you need to track the load. Frequency is used as a sensor portion of control system for generation control.

2.4 BASIC GENERATOR CONTROL LOOPS

The figure in appendix 1 depicts two major control loops with which most large generators are equipped. The Automatic Voltage Regulator (AVR) loop controls the magnitude of the terminal voltage Vt, while the Automatic Load-Frequency Control (ALFC) regulates the megawatt output and frequency (speed) of the generator.

The AVR and ALFC interact through action of AVR the action of AVR on generator emf which in turn affects real power hence changes in AVR are felt in the AFLC. However, AVR is sometimes faster than ALFC hence sometimes these effects may not be felt.

2.4.1 Small signal analysis

Large scale analysis is necessary for studying the effects of major disturbances, but the differential equations involved are non-linear hence Laplace transform analysis can not be applied. For this reason, small signal analysis is used because differential equations involved are mostly linear (or can be linearlized) and control loops can be obtained. Then by appropriate additions or modifications, approximate large scale analysis models, are obtained.

2.5 GENERATOR MODELLING

The generator inputs are the mechanical power from the turbine (dynamic) and the exciter field voltage, to give the generator electrical power output. The relationship between Vf and Vt (terminal voltage) depends on the load. The transfer functions depend on the type of model being considered, whether steady-state, transient or sub-transient. This transfer function consist of the open circuit d-axis time constant given by

$$T'do = \frac{Lff}{Rf} \qquad [s] \quad \ldots\ldots\ldots\ldots 2.17$$

Where: Lff = Field self-inductance and Rf = Field resistance

2.5.1 The Exciter and AVR

The exciter is the main component in the AVR loop. It delivers power to the generator field. The basic role of the AVR is to provide constancy of the generator terminal voltage. The exciter designed with enough margin can give boost during small and slow, and emergency situations. Modern exciters may be either of brushless (rotating) or static design.

2.5.1.1 Exciter modelling

This takes into account the mathematical modelling of the exciter and its controls. The basic equation for a rotating exciter are

$$Vr = Re\ ie + Le.\frac{d}{dt}(ie) \quad \ldots\ldots\text{(for exciter)} \ldots\ldots 2.18$$

$$Vf = K1\ ie \quad \ldots\ldots\text{(for convertor)} \ldots\ldots 2.19$$

Where: Vr, ie = Exciter field voltage and current respectively

Le, Re = Exciter inductance and resistance respectively

Vf, if = Main generator field voltage and current.

K = Proportionality constant of exciter

and the transfer function obtained is

$$Ge = \frac{Ke}{1 + sTe} \quad \text{.................................2.20}$$

where: Ke, Te = Exciter gain, time constant respectively.

For the static excitation system, generator terminally fed exciters have different transfer functions and models.

Apart from exciter, the AVR has other accompanying associated equipment and give as represented in the following figure

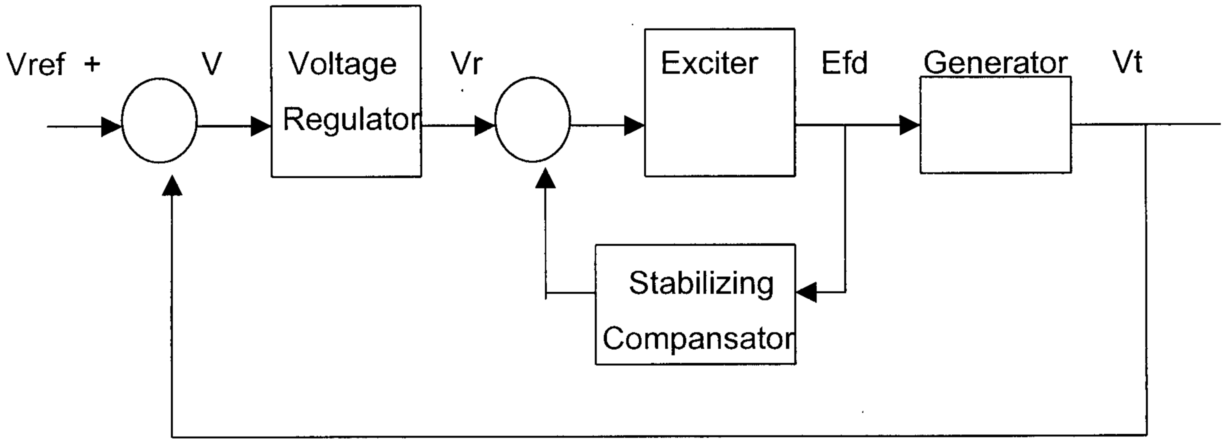

Figure 2.9: Excitation system model

2.5.1.2 The Automatic Load Frequency Control (ALFC)

The basic role of the ALFC is to maintain desired meawatt output of the generator unit and assist in controlling frequency of large interconnected power system. It consist of speed gvorning system which controls/maintains speed (hence frequency), by controlling the flow of water/steam to the turbine.

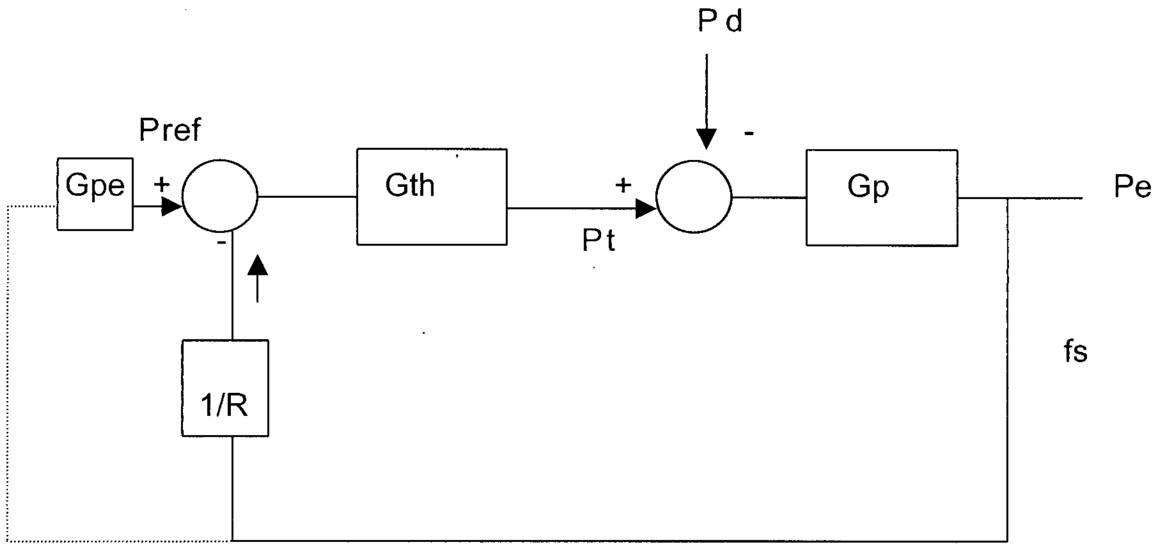

Figure 2.10: ALFC control loop (generally)

where: Pd, Pref, Pt, fs = Change in load or demand power, reference power, turbine power and line frequency respectively

Gpe, Gth, Gp = Reference, turbine and generator transfer function

R = speed droop

The speed droop is the parameter which shows significance of direct proportionality between turbine power and frequency of the system. This concept is used in controlling generation with respect to the system load.

2.5.2 Speed-governing system

The real power in a power system is controlled by controlling the driving torques of the individual turbines of the system. The frequency (speed) of the system is used as a sensor in achieving this control and the basic equation referred to is

$$Pg = Pref - (1/R)\ fs \quad \ldots\ldots\ldots\ldots\ldots 2.21$$

Where Pg = Change in generator output power

The droop helps in sharing of loads of generators in that it is used to obtain the requirement that generators working in parallel on the same network ought to have same regulation (expressed in per unit of their own rating) in order to share load changes in proportion to size.

2.5.2.1 Turbine-Generator

The turbine speed deviation correspond to the the difference between input and output generator power. The transfer function therefore involves valve power changes and response of the turbine to the control commands

$$Gt = \quad Pt/ \; Pg = Kt/ (1 + sTt) \ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.22$$

Where: Tt is the turbine time constant

The system can be represented as shown in the figure 2.11

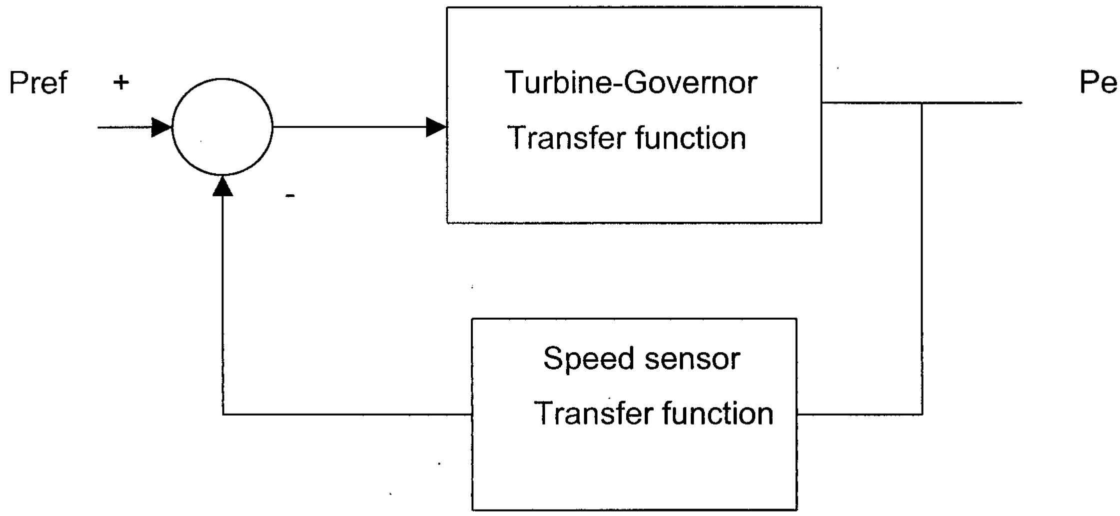

Figure 2.11: Turbine-governor representation

The models in this section give parametric system variables that requires consideration in order to carry out a transient stability study. Frequently, These models are adapted for the large signal cases because transient stability study is a large signal one.

2.6 POWER SYSTEM STABILITY ANALYSIS

The procedure of determining the stability of a system upon occurrence of a disturbance, followed by various switching off and switching on actions is called a Stability study. Steps (which apply to system of any size) to be followed in a stability study are outlined as follows:-

(1) Carry out a load flow study(prior to disturbance) using specified voltages and power

(2) Compute voltage behind transient reactances of generators. This fixes generator electromotive force (emf) magnitudes and initial rotor angle δo.

(3) For the specified fault, determine the power transfer equation $Pe(\delta)$ during fault. In this system Pe=0 for a three-phase fault.

(4) From the swing equation starting with δo, calculate δ as a function of time using the numerical technique of solving non-linear differential equation.

(5) After clearance of the fault, once again find $Pe(\delta)$ and solve further for $\delta(t)$. In this case, $Pe(\delta) = 0$ as when the fault is cleared, the system gets disconnected.

(6) After transmission line is switched on, again find $Pe(\delta)$ and continue to calculate $\delta(t)$.

(7) If $\delta(t)$ goes through a maximum value and starts to reduce, the system is regarded as stable. It is unstable if $\delta(t)$ continues to increase with time (figure 2.7)

(8) Calculation is ceased after a suitable length of time.

2.6.1 Computer stability analysis

As electric utilities have grown in size, and the number of interconnections has increased, planning for future expansion has become increasingly complex such that in most practical applications, even after machine lumping has been done, there are still more than two machines to be considered from point view of system stability.

The increasing cost of additions and modifications has made it imperative that utilities consider a range of design options, and perform detailed studies of the effects on the system of each option, based on a number of assumptions: normal and abnormal operating conditions, peak and off-peak loadings, and present and future years of operation (Nagrath and Kothari, "Modern power system analysis", page 448).

To assist the engineer in this power-system planning, digital computers and highly developed related programs are used, especially that they can suitably be modified to include the effect of governor and excitation controls. Such programs include power-flow, stability, short-circuit, and transients programs.

Power-flow programs compute the voltage magnitudes, phase angles, and transmission-line power flows for a network under steady-state operating conditions. Stability programs are used to study power systems under disturbance conditions, to determine whether synchronous generators and motors remain in synchronism.

The stability program combines power-flow equations and machine-dynamic equations to compute the angular swings of machines during disturbances. The program also computes critical clearing times for network faults, and allows the engineer to investigate the effects of various machine parameters, network modifications, disturbance type, and control schemes.

2.6.2 ETAP Power Station

In this project, the computer program being used is the ETAP Power Station program. ETAP Power Station is a fully graphical Electrical Transient Analyser program that can

run under Microsoft Windows. This program is designed to investigate the stability limits of a power system before, during and after system changes or disturbance, for the purpose of determining transmission network 's ability to withstand major faults without generators connected to it losing synchronism

The program models dynamic characteristics of power systems, implements user-defined events and actions, solves system network equation and machine differential equations interactively to find out system and machine responses in the time domain. From these responses, users can determine the system transient behaviour, make stability assessment, find protective device settings, and apply the necessary remedy or enhancement to improve the system stability.

To run a transient stability study on this program, you need to provide all the data required for Load flow calculations and machine dynamic data, load data and any control units, such as exciter and governor data.

Power station program provides three load flow calculation methods: Newton-Raphson, Fast decoupled and Accelerated Gauss-Seidal methods, and any one of these can be selected.

CHAPTER THREE

SYSTEM DESCRIPTION

Kariba North Bank Power Station (KNBPS) is a underground, hydro-electric power station on river Zambezi of Zambia. The power station consists of four (4) vertical salient-pole, totally enclosed synchronous generators, with each generator unit equipped with water cooler air coolers.

The generators, each rated at 167 MVA are connected in parallel through generator transformers to the common bus bars. To this bus are many power stations connected (Kafue Gorge, Kariba South, Vic Falls, etc), such that the bus frequency and voltage are considered constant (an infinite bus-bar). Therefore for successful generator parallel operation, the power station generators are controlled to operate at approximately constant frequency and voltage.

The one-line schematic diagram (for KNBPS) shows the connections at the power station. Each generator is directly connected to the generator transformers via the electric shaft bus bars from the underground machine-Hall to the transformer shelf (on surface). These generators are used to step up generated voltage, 18KV to 330KV of the common bus bar. The transformer is then connected to the common bus through the underground oil-filled high-voltage power cables (one cable per phase). The common bus comprise of 330KV transmission lines located at the switchyard (ref: appendix 2).

Each generator unit is provided with hydro-turbine, which is driven by water flowing from the reservoir (Kariba dam) through the tail-water case, intake gates, penstocks and the spiral casing through the guide vanes and hit the turbine runner (link between turbine and water). After driving the turbine, water leaves through the draft-tube via out-fall gates to the lower Zambezi river.

❖ ***General data***

Site: Kariba North Bank Power Station on river Zambezi (192 Km from Lusaka)
Type of station and turbine: Underground, vertical shaft Francis
Number of machines: Four (4)
Rated output and net head: 155 MW, 92m
Synchronous speed: 136.4 rev/min
Direction of rotation: clockwise
Reservoir: max = 489.2 m.R.L , min = 475.5 m. R.L
Tail water levels: max = 403.9 m.R.L, min = 381.6 m.R.L
Intake arrangements: One (1) turbine per intake, closing time = 1min
Penstocks: Type = Concrete lined rock tunnel
Outfall gate: Number = Two pairs

3.1 GENERATORS

The power station consists of four (4) generator units. To each unit is coupled another generator, the governor generator.

3.1.1 Main generator

This is a 3-phase synchronous generator, which is directly coupled with the Francis type water-driven turbine.

The generator is of umbrella type, that is without the upper guide bearing below the generator rotor. The generator stator is fixed to the foundation blocks. The stator core is laminated and the winding is a double-layer bar-type wave winding. The generator rotor is a 44salient-pole laminated core with damper windings on its pole faces.

Through the direct coupling to the rotor, the turbine provides rotational mechanical power to the generator and rotation is clockwise. Its speed is controlled by the governor system. A D.C voltage from the excitation system, which controls the generator terminal voltage, supplies the generator field windings. The generated voltage is tapped from the stator windings at the generator terminals.

3.1.2 Governor Generator

A three-phase synchronous permanent magnet generator serves as a governor generator. It supplies a electro-hydraulic speed regulator of the generator set. The generator set is provided with over speed protection device, which operates due to centrifugal forces.

❖ ***Technical data***

Main generator

Type: S-10258-44
Rated apparent power: 167MVA
Rated voltage: 18KV +/-10%
Rated current : 5356A
Rated power factor: 0.9 over/under excited
Frequency: 50Hz
Speed: 136.4 RPM
Direction of rotation: Clockwise
Direct-axis synchronous reactance (unsaturated): Xd = 81%
Quadrature-axis synchronous reactance (unsaturated) : Xq = 50%
Direct-axis transient reactance (unsaturated) : X'd = 30%
Direct-axis sub-transient reactance (unsaturated): X"d = 20.1.%
Quadrature-axis sub-transient reactance (unsaturated): X"q = 25%
Negative-phase sequence reactance: X2 = 24%
Zero-phase sequence reactance: Xo = 15.1%
Leakage reactance : Xl = 71%
(% => percent of machine base = 18000*2/167000000 = 1.94 ohm)
Short-circuit ratio K = 1.39
Time-constants at 75 degrees Celcius (°C)
-Direct-axis (at open stator winding): T'do = 6.22s

-Direct-axis transient (at short-circuit stator winding) : T'd = 2.11s

-Direct-axis sub-transient (at short-circuited stator winding): T"d = 0.06s

-Armature : Ta = 0.44s

-Rotor resistances: Rr (ohms) = 0.159 (at 20*C), and 0.1632 (at 26.5*C)

-Stator winding resistances: Ra (ohms) :-

-At 20*C => 0.003364 (nominal), 0.00332 (R), 0.00331 (Y), 0.00332 (B)

-At 27*C => 0.00336 (Y), 0.003355 (Y), 0.00336 (B)

-Stator winding capacitance (micro- Faradays): 0.83 (for each phase)

-Short-circuit ratio X/R = X"/R = X"d/R = 0.39/0.006 = 64.994

-Saturation effect: If = 875A, If100 = 995A, If120 = 1350A,

Sbreak = If_{Sbreak}/If = 2.857, S100 = If100/If = 1.137,

S120 = If120/If = 1.286,

-Harmonics:

Voltage waveform	*Between phases*	*Between phase and neutral*
3rd harmonic	0	3.5
5th harmonic	1.16	1.16
7th harmonic	0.3	0.3

-Moment of inertia of all rotating parts, J = $WR^2 = 27.85 \times 10^6$ [$kg\text{-}m^2$]

-Inertia constant, H = $5.48 \times 10^{-9} \times WR^2 \times RPM^2 / MVA$

(With RPM = 136.4 rpm and MVA = 167 MVA)

❖ ***Governor generator***

Type: SP-1352, 3-phase generator with permanent magnets with two windings on the stator

1-Winding: 380V, 2.3A, 1500VA

2-Winding: 380V, 0.046A, 30VA

Speed = 136.4rpm, Power factor = 0.3 over excited, Frequency = 25Hz

3.2 EXCITATION SYSTEM

The excitation system of the KNPS generators No. 1,2,3 and 4 are static excited as shown in figure of appendix 3

The generator field winding is supplied from the generator output terminals via excitation transformers (3E1, 3E2 and 3E3) and thyristor converters 2E1 and 2E3 (connected in parallel). Part of excitation system between the output terminals of thyristor converters and input terminals of the field winding comprises equipment for initial excitation.

The excitation system produces to the field winding a variable d.c power supply, regulated either by Automatic Voltage Regulator (AVR) or by Standby Voltage Regulators (SVR). The output of regulators is connected to control input of control pulse unit which gives control pulses to the thyristor converters.

3.2.1 Design and Principle of operation

Excitation transformers are single-phase step-down, whose primaries are star connected with isolated neutral while their secondaries are delta-connected (to enable zero sequence component of transformer magnetizing current (3^{rd} , 9^{th} ,15^{th} harmonics, etc.) to flow, which ensures approximate sinusoidal magnetic fluxes.

The parallel connection of the thyristor converters enable them work as one converter conveying ac power supply to dc excitation supply and as the output amplifier of the regulation circuit.

Thyristors are carried out in three-phase full controlled bridge connected and can be so controlled (depending on control angle) to vary continuously the output voltage. Each thyristor converter is provided with a power oscillator pulse amplifier. These form functional parts of control pulse system.
Discharge resistors 2E7r4 and 2E7r5 are used for quick discharge of the field windings in order to avoid over-voltages (in process of quick de-excitations)

3.2.2 *AVR/SVR*

The thyristor converters are controlled by means of their control pulse system. Voltage regulator consists of AVR and SVR. Depending on the mode of regulation, either AVR/SVR is in operation and the corresponding output voltage is used as the control voltage of the control pulse unit. In this way thyristor converters provide field winding with an adequate dc supply.

The SVR is provided in order to increase the reliability of the regulation loop. The voltage regulator basic unit performs functions as follows:

- To keep the generator voltage constant
- To distribute the reactive head approximately between the synchronous machines working in parallel.
- To contribute actively in maintaining a high level of static and transient stability in the network

The basic unit is equipped at its output with a unit which serves for adjusting to the required exciter voltage.

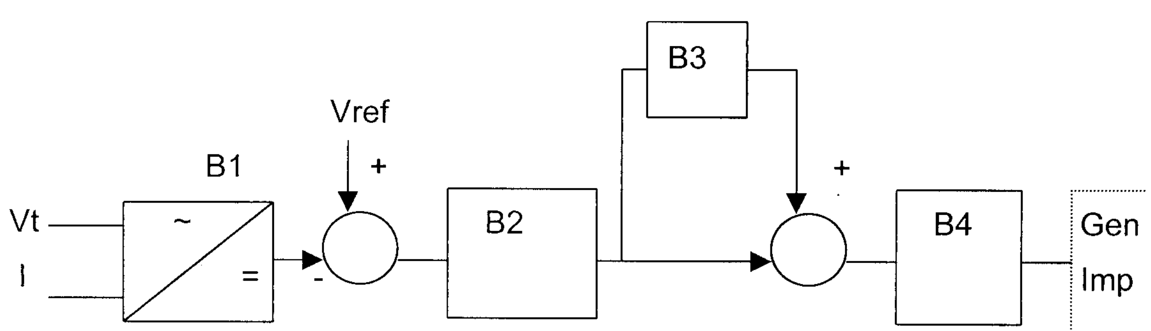

Figure 3.1: Excitation system basic unit

3.2.3 *The excitation control system stabilizer*

The excitation control system stabilizer on excitation voltage or current has been provided for improvement of the dynamic behaviour of control loop of generator. The two circuits in fig 3.2.1 shows the excitation system.

Where:

B1 = Voltage measuring unit with reactive component

B2 = Proportional amplifier with input filter and given by

$$\frac{Kp}{1 + sTf1}$$

with Kp = dynamic gain and Tf1 = filtering fixed time constant

B3 = Integrator given by

$$\frac{1}{sTi}$$

with Ti = Integrator time constant

B4 = Proportional amplifier with filter for adapting gain to exciter given by

$$\frac{Ka}{1 + sTf2}$$

with Ka = Output amplifier gain = 8/Kc, Kc = Ceiling excitation voltage factor and Tf2 = Valuable filter time constant

Gen imp = Generator impulsa excitation input

❖ ***Technical data***

Rated input (excitation)

-Voltage (line-to-line),V1:	18 000 V ± 10%
-Current, I1 :	70 A
-Power, S:	2180 KVA
-Frequency, f:	50 Hz
-Number of phases	3

Rated input of converters (output of excitation transformers)

-Voltage (line-to-line), V2:	935 V ± 10%
-Current, I2:	1350A
-Power, P:	2180 KVA
-Frequency, f:	50 Hz
-Number of phases,	3

Rated output (or converter output)

-Voltage, Vd:	375 V
-Current, Id:	1650 A
-Power, Pd:	620 KVA

*All values corresponding to maximum continuous rating (m.c.r)

Ceiling output (of converter)

-Voltage, Vdf : (a) Unloaded at 100% V1 = 1240V

(b) Loaded at 100%V1 = 1190V

© Loaded at 85%V1 = 1005V

(d) Loaded at 100% V1 and Idf = 1090V

-Current Idf: Limited = 4575 A ± 5%

and corresponding inputs = I1 = 194 A, I2 = 3750 A, P = 6050 KVA

Excitation (generator)

-Current and voltage at no load and rated input voltage : 1057 A, 180V , at 40°C

-Current and voltage at m.c.r conditions: 1650A, 375A, at 130°C

-Current and voltage at ceiling conditions and rated input voltage: 4575 A, 1040V, 130°C

Thyristor convertor

-Thyristor Peak Inverse Voltage (PIV):	1350V,
-Number of bridges:	5
-Number (No.) of thyristors per series arm	2

3.3 SPEED GOVERNOR

The VÖEST ALPINE speed type W is equipped with a mechanical actuator distributing pressure oil to the servomotors, via the control valves. This actuator consist of following
sub-assemblies:
-Speed sensing device (fly-ball pendulum with pilot control)
-Restoring mechanism with dashpot
-Speed adjusting device
-Guide vane limit device and position indication
-Temporary guide vane limiter

3.3.1 Speed sensing device

The speed sensing device consist of speed measuring device, of fly-ball pendulum directly connected to the pilot valve piston. The fly-ball pendulum is being driven by the synchronous motor, which is directly connected via an electric shaft to the permanent magnet generator (PMG).. The PMG is directly coupled to the turbine shaft. Any change of sped thus is causing a shift of the pilot valve piston.

3.3.2 Restoring mechanism with dashpot

Any shift of the pilot valve piston via intermediate linkage also moves the servomotor piston and this motion via the restoring rope levers and rod is being transmitted proportionally to the power piston of the dashpot. The compensating piston is sliding within the dashpot housing. This mechanism has the restoring action with the purpose of compensating the effect of the pilot valve piston, by re-centering moment. The motion depends upon the tension in the rope.

The sequence of motion is as follows:
Load change causes a speed deviation of turbine, the pilot valve piston will be displaced and thus main control valve piston and further on the servomotor piston (the regulating device of the turbine). The piston of the servomotor by its motion set

the turbine regulating system at an opening which corresponds to the load of the turbine. The turbine again tends to the steady nominal speed.

3.3.3 Speed droop device

For good turbine governing and especially electric parallel operation of machinery units, it is necessary that the drooping unit load will be correlated to increasing speed. The speed droop unit is used to set the proportional dependence of speed on the degree of load which is achieved by shift of the pilot valve cage.
The pilot valve piston follows the shift and therefore speed of the fly-ball pendulum changes. The deviation of speed is proportional to this shift. The speed adjusting device is controlled by adjusting motor speed while the guide vane limiting device sets the limit for opening of regulating system by governor.

❖ ***Technical data***

Type of governor: Mechano-hydraulic
Inertia provided by rotating parts: J = 27.58×10^6 [$kg\text{-}m^2$]
Signal source for speed or frequency detector: AC synchronous motor (connected to (PMG)

3.4 TURBINE

The generator units 1, 2, 3 and 4 at KNPS are equipped with vertically arranged Francis type spiral turbines. Each turbine is directly coupled to the generator. The turbine runner is of Francis-type and of high-grade stainless chromium cast steel.

3.4.1 Over-speed device

The over-speed device is mounted on the turbine shaft upstream of guide bearing as protection against over-speed (run-away speed = 260 rpm). At normal speed, the fly-ball is balanced by a spring and at over-sped, due to centrifugal action, the ball strikes the latch which releases piston of control valve and emergency stop valve is operated consequently initiating closure of guide apparatus.

Other associated equipment are spiral casing, draft tube and runner and turbine shaft.

❖ ***Technical data***

Type: Vertical Francis
Output (maximum): 155 MW
Minimum guide vane opening time under any condition : 10s

3.5 TRANSFORMERS AND HIGH-VOLTAGE POWER CABLES

The station is provided with a number of transformers, ranging from generator (main), station, excitation up to voltage transformers.

3.5.1 Generator transformers

These transformers are step-up transformers rated 167 MVA each and located at the transformer shelf (above ground, below the switchyard). Each generator unit is connected to one transformer, which step-up generated voltage from 18 KV to 330 KV. The output of each transformer is connected to switchyard common bus-bars via the underground cables.

❖ ***Technical data***

Type: TTTy 820-0 (ASEA), Core type
Rating (m.c.r) : 167 MVA
Rated frequency : 50 Hz
Altitude above sea level: 528 m
Installation: Out-door
Turns ratio: 330 / 18 KV

Type of: -windings: High Voltage(HV) = Wye (Y), Low Voltage (LV) = Delta ( )

-Cooling : Oil-Filled Air-Filled (OFAF)

I.E.C vector group : Yd1

Method of system earthing: Solid

Efficiency at rated 0.9 power factor (p.f) lagging: 99.4 %

Resistance of windings: HV = 1.51 /phase, LV = 0.00909 /phase

Impedance voltage : 14.5 % (of base impedance, Zbase = 18^2 / 167 = 1.94)

X/R ratio 0.281 / 0.00909 = 30.9 (with X Z)

3.5.2 Excitation transformer

The excitation transformers are used to step down the terminal voltage to suitable required exciter voltage rectifier. Their details are as shown;

- ***Technical data***

Maker: Rade Kon ár , Type : MBN 880-24

Ratio: 18 KV / 935V

Rating: 3x800KVA = 2.4 MVA

Vector group: Yd5

Rate amps (line): HV = 77 A , LV = 1480 A

Impedance: 6 %

Tappings: ± 2½ % / ±5 %

Adopted tapping: ± 5 %

3.5.3 Station transformer

This type of transformer steps down the generator terminal voltage to the required value needed for feeding station loads.

- ***Technical data***

Maker: Hawker Siddenley

Ratio: 18/3.5/1.01 KV tap 7

Rating: 3x1.167 MVA = 3.5 MVA

Vector reference group: Yy0 / Yd11

Impedance: 6.45 %

Adopted tap: 7 (at 18/3.7625 KV)

3.5.4 Generator Neutral-earthing transformer (GNET) and resistor

This is a protective voltage transformer which steps down voltage to a value suitable for feeding the protective relays. It is alternatively used for earthing the generator neutral through its primary.

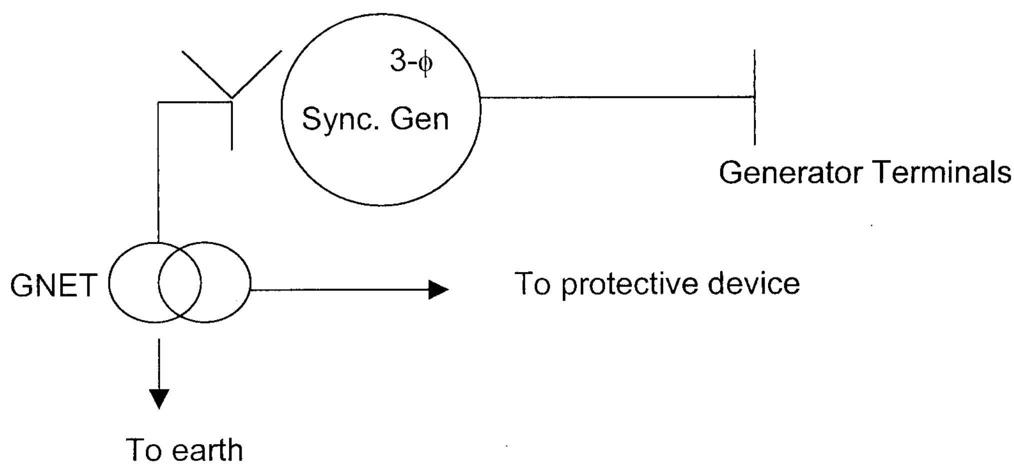

Figure 3.4.5: Generator Neutral-Earthing transformer

❖ ***Technical data***

Type: Voltage transformer

Maker: UNELEC ,

Ratio: 20KV / 231 V (10.4 KV / 120 KV on per phase)

Impedance: 3%

Loading resistor : 0.19 at 20 C

Resistor rating : 600 A for 1minute (min)

Secondary resistor plus resistance to earth: 140 M

Resistor DC ohms at 25 C = 0.2

3.6 HIGH-VOLTAGE POWER CABLES

The high-voltage power cables are under-ground oil-filled cables, which connect output of generator transformers to the common bus-bars. Each cable is connected to one-phase.

❖ ***Technical data***

Voltage between phases: 330 KV

Number of cores: 1

Type of cable: Oil-filled

Conductor (copper, annular shape) overall diameter: 25.4 mm

Screen round conductor : Carbon paper

Insulation thickness between conductor and sheath: 24.1 mm

Screen under lead sheath sheaving : Thickness : 0.13 mm

Sheath thickness : min : 2.7 mm - 3.3 mm, diameter over sheath : 82.6 mm – 92.9 mm

Overall diameter of completed cable : 94.2 – 101.5 mm

Minimum radius of bend round : 2.9 – 3.1 mm

Maximum continuous current carrying : 350 – 320 A

Ambient temperature (temp.): 85°C

DC resistance (per 1000m, 20°C) : 0.0461

AC resistance (per 1000m, 20°C): 0.0588 / 1000m

Reactance/1000m: 0.137 – 0.141

Electrostatic capacity: 0.185 F

Charging current / conductor / 1000m of completed cable at normal voltage: 11.1A

3.7 CIRCUIT BREAKERS

Each generator-transformer-cable set is provided with a HV circuit breaker, of type DLF, for protection against high currents. The circuit breaker is filled with dry air only, at high pressure. The breaker has poles, which make contacts when in closed position (relaxed) and open contacts for open breaker position (compressed by high-pressure air). These breakers are rated at 330KV, 350 A continuous current rating.

3.8 COMMON BUS-BARS

The under-ground cables connect the transformer output to the common bus at the switchyard. These buses are simply transmission lines. There are two transmission lines for on each path running from the switchyard to Kariba South Powers Station and Leopards Hill switchyard.

❖ ***Technical data***

Type : Stranded

Maximum working tension: 1000N

Maximum rated current: 1600 A

Nominal section and materials: 2x604 mm^2

Cross section (No. and diameter of wires) : 61x 3.55 mm

Overall diameter of conductor : 32.1 mm

Resistance / km: 0.0487

3.9 CONNECTION WITH OTHER POWER STATIONS

The station with its four (4) parallel connected generators is parallel connected to other power stations, which are;

Country	Power station	Rating (MW)
Zambia	Kafue Gorge	900
	Vic Falls	108
Zimbambwe	Kariba South Bank	666
Mozambique	Cahora Bassa	2040
South Africa	Drankensberg	1000
	Palmiet	400
Namibia	-	-

CHAPTER FOUR

DEVELOPMENT OF MODELS

The generator and its associated excitation and governor systems comprise a complex system. In order to achieve stability of this machine, there is need to control these complex systems. And to understand and control such a complex system, qualitative mathematical models are used to control and analyse relationship between system variables.

The models developed in this project are based on both the available collected data from KNPS and standard models available in ETAP power station program, which are mostly according to IEEE standards. These models are but an approximation, just to enable the study proceed. Having all the required data from the power station would require the modification of these models to suit the exact behaviour for this power station.

The models are referred to as *dynamic models* because they are developed to describe what is observed in practice. The development of these models is based on *small signal analysis* in that the machine dynamics are assumed linear. This is in order to enable modelling of the linear part of the system, which with added assumed models, model the approximate system behaviour, which is non-linear and requires the large-signal analysis.

4.1 GENERATOR (SYNCHROUS MACHINE) MODEL

The generator's basic function is to convert mechanical power, provided by the turbine to electrical power by the turbine. This power together with the generator field enables the machine produce the required electrical power. The block diagram for the generator is as shown in figure 4.1 on the next page.

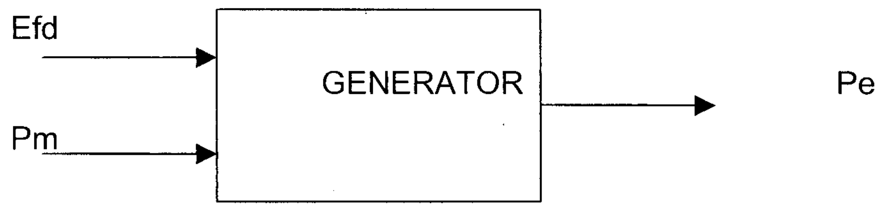

Figure 4.1: Generator block diagram

There are a number of different types of synchronous machine models to choose for transient stability studies and frequency dependent models for generator starting and frequency dependent transient stability studies. The complexity of these models ranges from the simple Equivalent Model to the model that includes the machine saliency, damper winding, and variable field voltage. These models are:

- Equivalent Model
- Transient Model for Round-Rotor Machine
- Transient Model for Salient-Pole Machine
- Sub-transient Model for Round-Rotor Machine
- Sub-transient Model for Salient-Pole Machine
- Frequency Dependent Model

4.1.1 Notations and Symbols

The following notations are used in defining various parameters for synchronous machine models:

Xd"	=	Direct-axis sub-transient synchronous reactance
Xd'	=	Direct-axis transient synchronous reactance
Xd	=	Direct-axis synchronous reactance
Xq"	=	Quadrature-axis sub-transient synchronous reactance
Xq	=	Quadrature-axis synchronous reactance
Xq'	=	Quadrature-axis transient synchronous reactance
Xl	=	Armature leakage reactance
Ra	=	Armature resistance

X/R = Machine X/R ration (= X"/Ra)

Tdo" = Direct-axis sub-transient open-circuit time constant

Tdo' = Direct-axis transient open-circuit time constant

Tqo" = Quadrature -axis sub-transient open-circuit time constant

Tqo' = Quadrature -axis transient open-circuit time constant

S100 = Saturation factor corresponding to 100 percent terminal voltage

S120 = Saturation factor corresponding to 120 percent terminal voltage

H = Total inertia of the shaft

D = Shaft damping factor

4.1.2 General Concept of Modelling Synchronous Machines

An equivalent internal voltage source and its equivalent resistance and reactance generally model a synchronous machine. The equivalent internal voltage source is connected to the machine internal bus behind the equivalent resistance and reactance, as shown in the diagram.

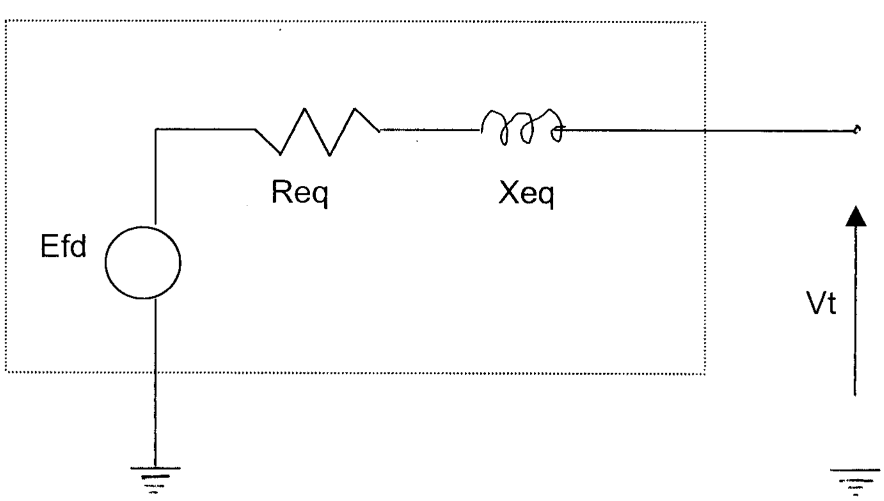

Figure 4.2: The generator equivalent circuit model

Depending on the structure (round-rotor or salient-pole) and design (with or without damper windings), the equivalent internal voltage and equivalent impedance are calculated differently. These differences are reflected in differential equations describing different types of synchronous machine models.

Park's transformation is adopted and the following notations and symbols are employed in the differential equations for synchronous machine models:

Efd	=	Term representing the field voltage acting along the quadrature-axis. It is calculated from the machine excitation system
f(·)	=	Function to account machine saturation effect
Eq"	=	Quadrature-axis component of the voltage behind the equivalent Machine Sub-transient reactance
Ed"	=	Direct-axis component of the voltage behind the equivalent machine Sub-transient reactance
Eq'	=	Quadrature-axis component of the voltage behind the equivalent machine transient reactance
Ed'	=	Direct-axis component of the voltage behind the equivalent machine transient reactance
Eq	=	Quadrature-axis component of the voltage behind the equivalent machine reactance
Ed	=	Direct-axis component of the voltage behind the equivalent machine reactance
Ei	=	Voltage proportional to field current
It	=	Machine terminal current
Id	=	Direct-axis component of machine terminal current
Iq	=	Quadrature-axis component of machine terminal current

4.1.3 Saturation

The synchronous machine saturation effect needs to be considered in the modeling. This effect is represented by two parameters S100 and S120 as defined in figure 2.8

For generator starting studies, another factor, Sbreak, is required to correct machine inductance as shown in the above generator saturation curve. The factor Sbreak is defined as %Vt at the saturation break point.

4.1.4 Inertia constant

Total inertia of the generator shaft including the prime-mover & coupling gear in MW-Sec/MVA. The inertia constant H is related to the shaft moment of inertia, square of generator synchronous speed in RPM, and the generator rated MVA.

$H = 5.48 * 10^{-9} * WR^2 * RPM^2 / MVA$ (for WR^2 = Moment of inertia in $kg\text{-}m^2$)

4.1.5 Sub-transient Model for Salient-Pole Machine

The type of generator model developed for this study was the sub-transient model for salient-pole machine. This model depends on differential equations and includes the damper winding effect for a salient-pole machine. The same conditions are held true as with the transient model for salien-pole machines:

$$X'q = Xq$$
$$Rh = Ra$$
$$Xh = Xq$$

and the time constant T'qo is meaningless.

Following differential equations are involved to describe this model:

$$Eh = Et + (Rh + jXh) It$$

$$\frac{dE''q}{dt} = \frac{1}{T''do} [E'q + (X'd - X''d) Id - E''q]$$

$$\frac{dE''d}{dt} = - \frac{1}{T''qo} [E'd - (X'q - X''q) Iq - E''d]$$

$$\frac{dE'q}{dt} = \frac{1}{T'do} (Efd - Ei)$$

$$\frac{dE'd}{dt} = 0$$

$$E'q = Ehq + (X'd - Xh) Id$$
$$E'd = 0$$

$$Eq = Ehq + (Xd - Xh) Id$$
$$Ed = 0$$

Ei = Eq + f (Eq)

Where Et = Open circuit terminal voltage, while parameters with subscript 'h' shows on-load measured parameters and SE = f(Eq) is a saturation factor.

The above equations models the salient-pole synchronous generator, with machine saturation taken into account.

4.2 EXCITATION SYSTEM

The excitation system consist of the main exciter and the AVR (both fed from generator terminals). This system makes up the control mechanism for the generator terminal voltage.

Basically, the Excitation system has terminal voltage (Vt) and reference voltage Vref as inputs. Hence its model takes these factors into account and therefore is a feedback system with its block diagram representation as shown below

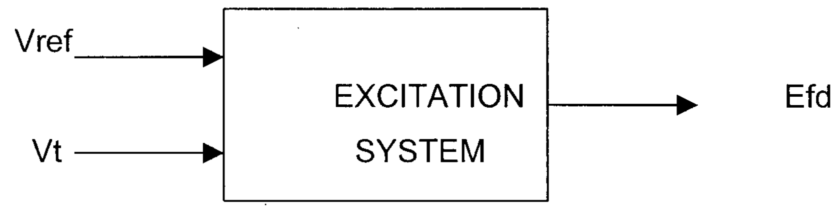

Figure 4.3: Excitation system block diagram representation

To accurately account for dynamics from exciter and AVR systems in power system transient responses, complete modelling of these systems is usually necessary.

The model developed in this project developed corresponds to IEEE type exciter and AVR systems, whose equivalent transfer functions and its parameter names are in accordance with the IEEE recommended types from the following references:

- IEEE Committee Report, "Computer Representation of Excitation System", IEEE Trans. on PAS, Vol. PAS-87, No. 6, June 1968.
- IEEE Committee Report, "Excitation System Models for Power System Stability Studies", IEEE Trans. on PAS, Vol. PAS-100, No. 2, February 1981.
- IEEE Std. 412.5-1992, "IEEE Recommended Practice for Excitation System Models for Power System Stability Studies", IEEE Power Engineering Society, 1992

4.2.1 Excitation System Saturation

Following is a typical block diagram for exciters:

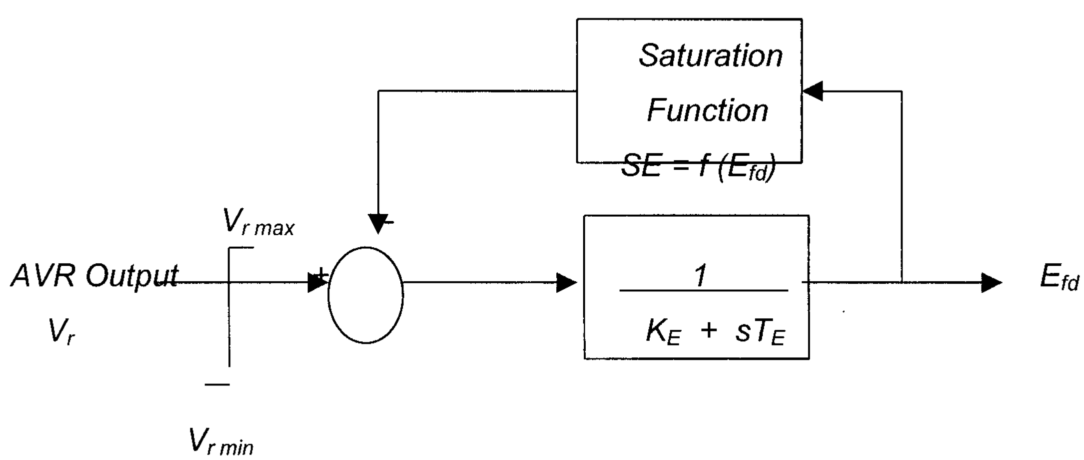

Figure 4.4: Typical Excitation system saturation

This diagram shows the output of the AVR is applied to the exciter after a saturation function SE is subtracted from it. The exciter parameter KE represents the setting of the shunt field rheostat when a self-excited shunt field is used.

It should be noted that there is a dependency between exciter ceiling *Efdmax*, AVR ceiling *VRmax*, exciter saturation SE and exciter constant *KE*. These parameters are

related by the following equation (the sign of KE is negative for a self-excited shunt field):

$$Vr - (KE + SE)Efd = 0 \quad \text{for} \quad Efd\ min < Efd < Efd\ max$$

At excitation ceiling (*Efd* = *Efdmax*) the above equation becomes:

Therefore, it is important that the exciter parameters entered satisfy the above equation, when applicable. PowerStation will check this condition at run time and flag any violations.

The exciter saturation function (SE) represents the increase in exciter excitation due to saturation. It is defined as:

$$SE = \frac{A - B}{B}$$

Where the quantities A and B are defined as the exciter field currents which produce the exciter output voltage on the constant-resistance-load saturation cure and sir gap line, respective, as shown in the exciter saturation curve in figure 4.6, where:
SE is assumes to be specified at the following exciter voltages:

Saturation Factor	Exciter Voltage
SEmax	Efdmax
SE.75max	0.75Efdmax

The type of model developed for the excitation system in this study corresponds to the IEEE Type ST1 - Potential-Source Controlled-Rectifier Exciter (ST1). This type of Exciter and AVR system models the Excitation system (exciter and AVR system), which is supplied through a transformer from the generator terminals as is the case with KNBPS. The model is as shown in figure 4.6.

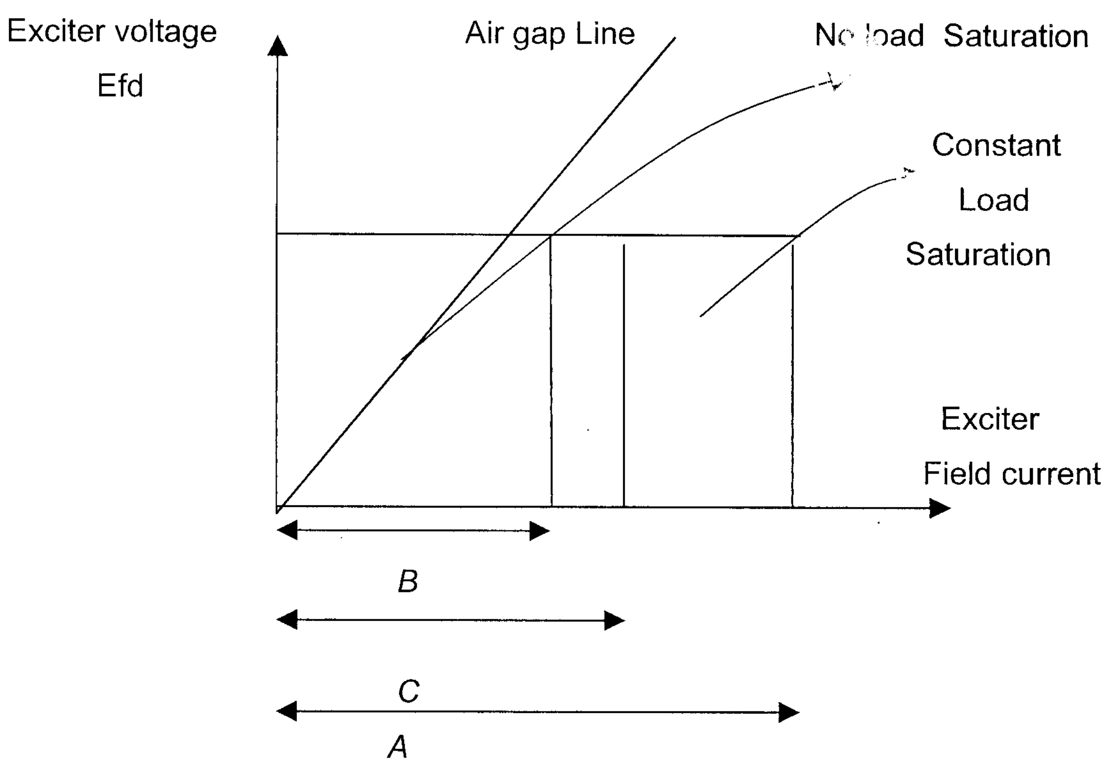

Figure 4.5: Excitation saturation curve

Where:

$$GR = \frac{1}{1 + sTR}, \quad GCB = \frac{1 + sTc}{1 + s\,TB}, \quad GA = \frac{KA}{1 + sTA}, \quad GF = \frac{sKF}{1 + sTF}$$

and Parameter definitions and their units are given as follows:

Parameter	Definition	Unit
VRmax	Maximum value of the regulator output voltage	p.u.
VRmin	Minimum value of the regulator output voltage	p.u.
VImax	Maximum internal signal within voltage regulator	p.u.
VImin	Minimum internal signal within voltage regulator	p.u.
KA	Regulator gain	p.u.
KC	Regulator gain	p.u.
KF	Regulator stabilizing circuit gain	p.u.
TA	Regulator amplifier time constant	Sec.

TB	Voltage Regulator amplifier time constant	Sec.
TC	Voltage Regulator amplifier time constant	Sec.
TF	Regulator stabilizing circuit time constant	Sec.
TR	Regulator input filter time constant	Sec.

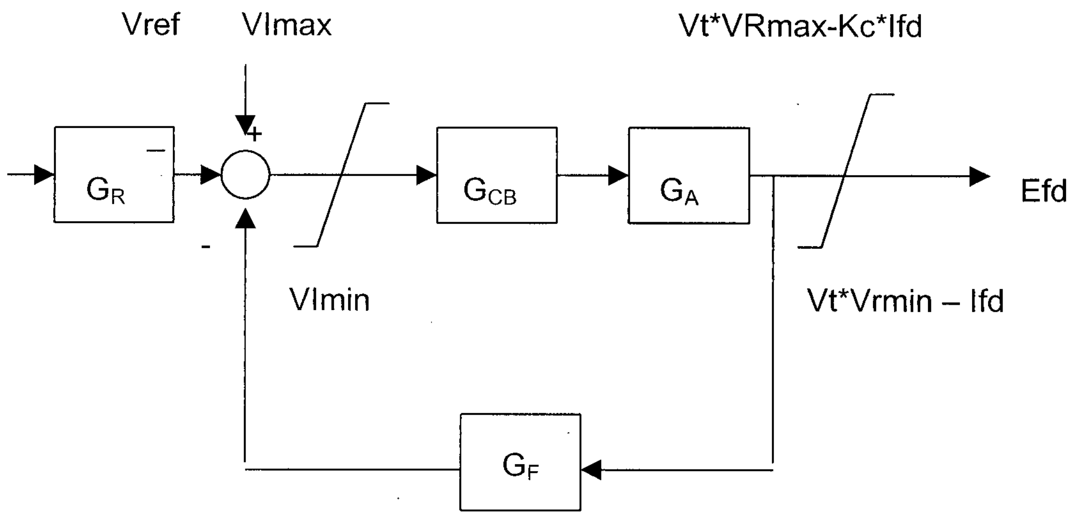

Figure 4.6: Excitation system model

4.3 GOVERNOR AND TURBINE MODELS

The modelling of the governor and turbine system in transient stability studies is also essential for a time frame of more than a second.

In this study, the governor-Turbine model developed corresponds to the ETAP general purpose turbine model as shown in figure 4.7

Where:

$$Gsr = \frac{1}{1 + sTsr}, \quad Gdrp = \frac{1}{1 + sTdrp}, \quad G_{T1} = \frac{1}{1 + sT1},$$

$$Ga = \frac{1}{1 + sTa}, \quad Gt = \frac{1}{1 + sTt}.$$

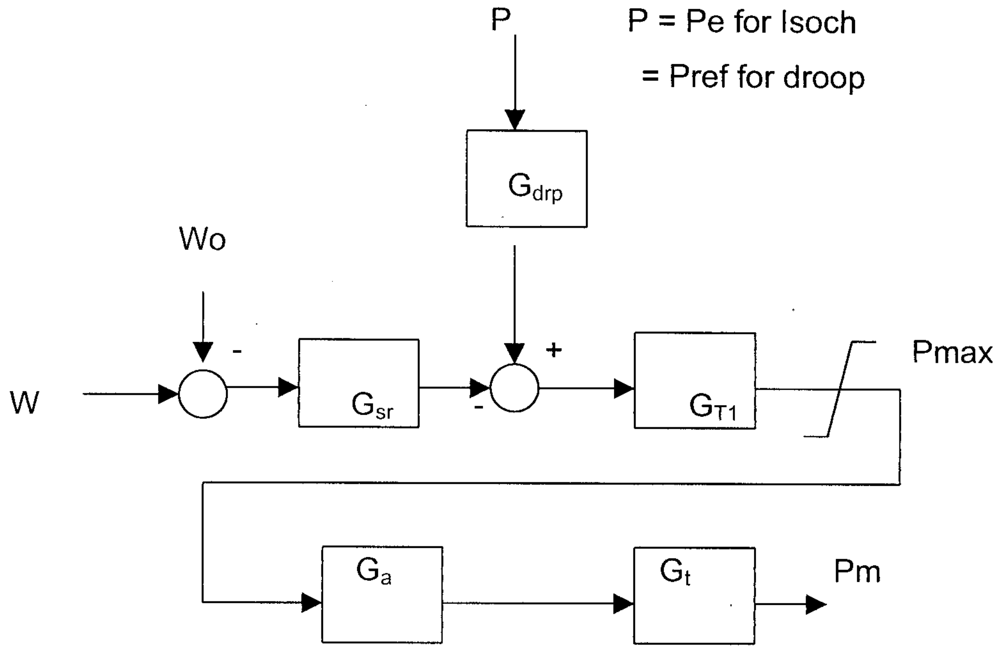

Figure 4.7: Governor-Turbine system model

and Parameter definitions and their units are given asfollows:

Parameter	Definition	Unit
Mode	Droop or Isoch	
Droop	Steady-state speed droop	%
Pmax	Maximum shaft power	MW
Pmin	Minimum shaft power	MW
Ta	Actuator time constant	Sec.
Tc	Governor reset time constant	Sec.
Tdrp	Load sensor time constant	Sec.
Tsr	Speed relay time constant	Sec.
Tt	Turbine relay time constant	Sec.

All these models describing the systems in this chapter, perform designated functions in order to achieve control of generators with respect to required conditions (parallel conditions). These individual systems interact, in that they are feedback systems

whose performances depend on the generator output and the respective control set references values.

The system overall model can therefore be represented as shown in the block diagram of figure 4.8.

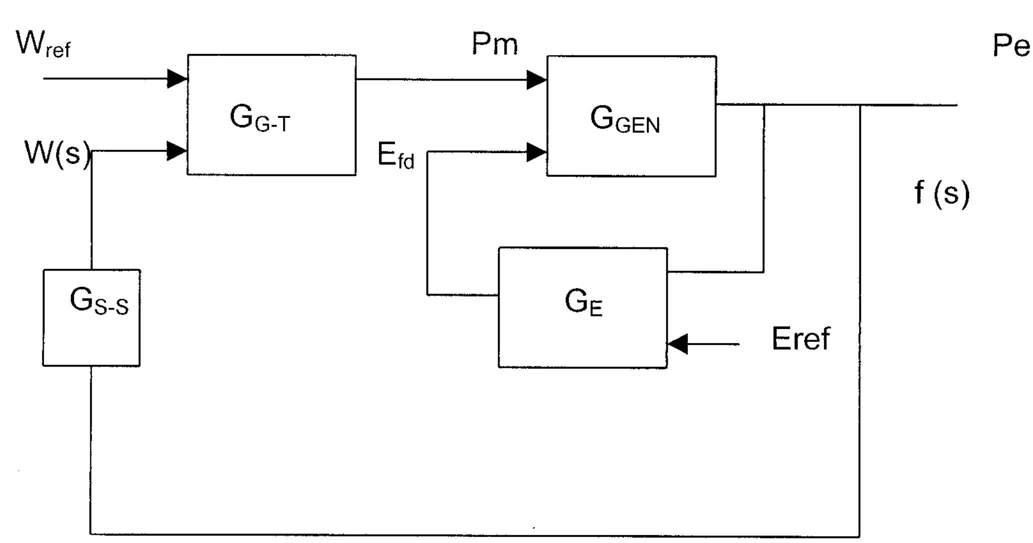

Figure 4.8: Overall system model block representation

Where:

W(s) = The system speed proportional to system frequency f(s)

$G_{G\text{-}T}$, G_E, $G_{S\text{-}S}$ = Governor-Turbine and Excitation systems, and speed-sensing device Transfer functions

The models developed in this chapter show the approximate transient stability models, which can be modelled into any simulation program to carry out a transient stability assessment of the Kariba North Bank Power Station system.

CHAPTER FIVE

SYSTEM STABILITY

Power system stability is the property of a power system, which insures that it remains in electromechanical equilibrium throughout any normal and abnormal operating conditions. Because the power system stability is an electromechanical phenomena, it is thus defined as the ability of designated synchronous machines in the system to remain in synchronism with one another following disturbances such as fault and fault removal at various locations in the system. The stability of a system is essential in that it enables safe and sustained normal system operation.

The transient stability assessment carried out on Kariba North Bank Power Station system generators is in essence to predict the system behaviour in case of a severe fault occurring on the system. This in itself is a very vital tool and study because it gives an allowance of avoiding unforeseen future severe effects on the system operation.

Parameters required for this study are clearly displayed in the models developed in the previous chapter. These parameters play a vital role in system stability because of their direct effect on system stability. It is therefore essential that even the enhancement or improvement of system stability be centred on these parameters, assessing and implementing their positive effect on system stability.

The transient stability study was carried out using the Electrical Transient Analyser Program (ETAP), a computer software in which each project provides all the necessary programmatic tools and supports for modelling and analysing an electrical power system. In this program every project consists of an electrical system that requires a unique set of electrical components and interconnections. In ETAP Power Station software, each project provides a set of users, user access controls, and a separate database in which its elements and connectivity data are stored.

5.1 SYSTEM MODELLING INTO SOFTWARE

ETAP Power Station program provides a fully graphical editor to construct a one-line diagram. From the One-Line Diagram Edit Toolbar, one graphically add, delete, move, or connect elements; zoom in or out; display grid on or off; change element size, orientation, symbol or visibility; enter properties; set operating status; etc.

Having graphically built one-line diagrams (as shown in appendix 4; for sample study, load flow, short-circuit and transient stability simulation studies can therefore be performed. The system engineering properties of each circuit element can be edited directly from the one-line diagram and calculation results displayed on the one-line diagram for convenience. In addition, configuration capability allowing to configure the operating status of the various electrical elements use to construct the one-line diagram in the project is provided. Electrical components such as circuit breakers, fuses, and switches can have open or closed status; loads and motors may be operating continuously, intermittently, or can be spare.

After modelling the system into the program, simulation for a specific study is then carried out. In the first step of simulation, the program checks for errors in the project file that may obstruct the simulation process. If any errors are detected, the process is terminated and errors are printed for correction.

5.2 SHORT-CIRCUIT ANALYSIS

The PowerStation Short-Circuit Analysis program analyzes the effect of three-phase, line-to-ground, line-to-line, and line-to-line-to-ground faults on the electrical distribution systems. The program calculates the total short-circuit currents as well as the contributions of individual motors, generators, and utility ties in the system. (Fault duties are in compliance with the latest editions of the ANSI/IEEE standards (C37 series) and IEC standards (IEC 909 and others)).

- ***3-Phase Faults - Device Duty***

This three-phase fault study is performed per ANSI C37 Standard. This study calculates momentary symmetrical and asymmetrical rms, momentary asymmetrical crest, interrupting symmetrical rms, and interrupting adjusted symmetrical rms short-circuit currents at faulted buses. The program checks the protective device rated close and latching, and adjusted interrupting capacities against the faults currents, and flags inadequate devices. Hence is used for circuit breaker rating.

5.2.1 Short-Circuit Calculation Methods

ETAP PowerStation provides two short-circuit methods based on ANSI/IEEE and IEC Standards. In ANSI/IEEE short-circuit calculations, an equivalent voltage source at the fault location, which equals the pre-fault voltage at the location, replaces all external voltage sources and machine internal voltage sources.

All machines are represented by their internal impedances. Line capacitances and static loads are neglected. Transformer taps can be set at either the nominal position or at the tapped position, and different schemes are available to correct transformer impedance and system voltages if off-nominal tap setting exists. It is assumed the fault is bolted, therefore, arc resistances are not considered. System impedances are assumed to be balanced three-phase, and the method of symmetrical components is used for unbalanced fault calculations.

5.2.2 Short-Circuit Required Data

<u>Bus Data</u>

Required data for short-circuit calculation for buses includes:

- Nominal kV (when the pre-fault voltage option is set to use nominal kV)
- %V (when the pre-fault voltage option is set to use bus voltage)
- Type, such as MCC, switchgear, etc., and continuous and bracing ratings

Branch Data

Branch data is entered into the Branch editors, i.e., 3-Winding Transformer Editor, 2-Winding Transformer Editor, Transmission Line Editor, Cable Editor, Reactor Editor, and Impedance Editor. Required data for short-circuit calculations for branches includes:

- Branch Z, R, X, or X/R values and units, tolerance, and temperatures, if applicable
- Cable and transmission line length and unit
- Transformer rated kV and MVA
- Base kV and MVA of impedance branches

For unbalanced short-circuit calculations you will also need:

- Zero sequence impedances
- Transformer winding connections, grounding types, and grounding parameters

Utility Data

Required data for short-circuit calculations for utilities includes:

- Nominal kV
- %V and Angle
- 3-Phase MVA sc and X/R

For unbalanced short-circuit calculations, you will also need:

- Grounding types and parameters
- 1-Phase MVA sc and X/R

Synchronous Generator Data

Required data for short-circuit calculations for synchronous generators includes:

- Rated MW, kV, and power factor
- X", X', and X/R
- Generator type
- IEC exciter type

High Voltage Circuit Breaker Data

Required data for short-circuit calculations for high voltage circuit breakers includes:

ANSI Standard Circuit Breaker:

- Max kV
- Rated Int. (rated interrupting capability)
- Max Int. (maximum interrupting capability)
- C & L rms (rms value of closing and latching capability)
- C & L Crest (crest value of closing and latching capability)
- Standard
- Cycle

ETAP Power Station program calculates the interrupting capabilities of the circuit breaker from the rated and maximum interrupting capabilities. This value is calculated at the nominal kV of the bus that the circuit breaker is connected to.

Other Data

There are some study case related data which must also be provided, and you can enter this data into the Short-Circuit Study Case Editor. The data includes:

- Standard (ANSI/IEC)

- XFMR tap option (transformer tap modelling method)
- Pre-fault voltage
- Report (report format)
- Machine X/R (machine X/R modelling method)
- Faulted buses
- Cable/OL heater (select this option to include cable and overload heater elements)

5.2.3 Short-Circuit Output Reports

PowerStation provides short-circuit study output reports with different levels of detail. These are complete and output reports, depending on the requirements. The output results can be used to set circuit breakers and other protective devices at appropriate values.

5.3 LOAD FLOW ANALYSIS

The ETAP Power Station Load Flow Analysis program calculates the bus voltages, branch power factors, currents, and power flows throughout the electrical system. The program allows for swing, voltage regulated, and unregulated power sources with multiple utility and generator connections. It handles both radial and loop systems. Different methods are provided for selection in order to achieve the best calculation efficiency.

The Load Flow Study Case Editor contains solution control variables, loading conditions, and a variety of options for output reports. Three methods are available: Newton-Raphson, Fast-decoupled, and Accelerated Gauss-Seidel.

Note that for the Newton-Raphson, a few Gauss-Seidel iterations are made first to establish a set of sound initial values for the bus voltages (since convergence of the Newton-Raphson method is highly dependent on the initial bus voltages).

5.3.1 Maximum Iteration

This specifies the maximum number for iterations. If the solution has not converged before the specified number of iterations, the program will stop and inform the user. The recommended and default values are 2000 for the Gauss-Seidel method, and five for the Newton-Raphson and Fast-decoupled methods.

5.3.2 Precision

This value for the solution precision is used to check for convergence and determines how precise you want the final solution to be. For the Gauss-Seidel method, precision is applied to check the difference between bus voltages after each iteration. For the Newton-Raphson and Fast-decoupled methods, the precision is compared with the difference in power for each bus (MW and Mvar) between iterations. If the difference between the iterations is less than or equal to the value entered for precision, the desired accuracy is achieved. The default value for precision is 0.000001.

5.3.3 Acceleration Factor

This field is only present if the Accelerated Gauss-Seidel method is used for the convergence acceleration factor to be used between iterations. Typical values are between 1.2 and 1.7, and the default is 1.45.

5.3.4 Initial Condition

Initial conditions for all bus voltages and angles are specified in this section for load flow calculation purposes. These are either using bus voltages or fixed values.

5.3.5 Load Flow Required Data

Bus Data

Required data for load flow calculations for buses includes:

- Nominal kV
- %V and Angle (when Initial Condition is set to use Use Bus Voltages)
- Load Diversity Factor (when the Loading option is set to use Diversity Factor)

Branch Data

Branch data is entered into the Branch Editors, i.e., Transformer, Transmission Line, Cable, Reactor, and Impedance Editors. Required data for load flow calculations for branches includes:

- Branch Z, R, X, or X/R values and units, tolerance, and temperature, if applicable
- Cable and transmission line, length, and unit
- Transformer rated kV and kVA/MVA, tap, and LTC settings
- Impedance base kV and base kVA/MVA

Utility Data

Required data for load flow calculations for utilities includes:

- Operating mode (Swing, Voltage Control, or Mvar Control)
- Nominal kV
- %V and Angle for swing mode
- %V, MW loading, and Mvar limits (Qmax & Qmin) for voltage control mode of operation
- MW and Mvar loading for Mvar control mode

Synchronous Generator Data

Required data for load flow calculations for synchronous generators includes:

- Operating mode (Swing, Voltage Control or Mvar Control)
- Rated kV

- %V and Angle for swing mode ? %V, MW loading, and Mvar limits (Qmax & Qmin) for Voltage Control mode of operation
- MW and Mvar loading for Mvar control mode

Static Load Data

Required data for load flow calculations for static loads includes:

Static Load ID

- Rated kVA/MVA and kV
- Power factor
- Loading Category ID and % Loading
- Equipment cable data

Other Data

There are some study case related data which must also be provided. This includes:

- Method (Newton-Raphson, Fast-decoupled, or Accelerated Gauss-Seidel)
- Max Iteration
- Precision
- Acceleration Factor (when Accelerated Gauss-Seidel method is selected)
- Loading Category
- Initial Condition
- Report (report format)
- Update (for bus voltages and transformer LTCs using load flow result)

5.3.6` Output Report

Load flow report options include critical and marginal under-voltage and over-voltage buses, and an option for bus voltages to be printed in percent or kV. The Branch

Loading Summary Report displays cables and two-winding transformer loadings and overloaded conditions.

5.4 TRANSIENT STABILITY ANALYSIS

The ETAP PowerStation Transient Stability Analysis program is designed to investigate the stability limits of a power system before, during and after system changes or disturbances. The program models dynamic characteristics of a power system, implements the user-defined events and actions, solves the system network equation and machine differential equations interactively to find out system and machine responses in time domain. From these responses, users can determine the system transient behavior, make stability assessment, find protective device settings, and apply the necessary remedy or enhancement to improve the system stability. In the Initial Load Flow section, solution parameters for initial load flow calculation in transient stability analysis are specified.

5.4.1 Solution Parameters

❖ ***Simulation Time Step***

This is the integration time step in seconds in transient stability simulation. This number should be set smaller than the smallest time constant in the system so you can see all the exciter and governor responses. The smaller this number is, the more calculations are required, so the calculation time increases. The recommended value is 0.001 seconds. However, if the integration time step is too small, round up errors may increase.

❖ ***Plot Time Step***

This value determines how often PowerStation should record the results of the simulation for plotting. For instance, if you specify 20 steps, PowerStation will plot points at every 20 simulation time step, i.e., for a simulation time step of 0.001, the plot time step will be .02 seconds. The smaller this number is, the smoother your plots will look, but the plot files on the hard disk may grow quite large.

❖ ***Initial Loading***

In the Initial Loading block of the Transient Stability Study Case Editor, you can specify the system initial operating loads by selecting a loading category and diversity factors (bus dependent or fixed global values).

❖ ***Loading Category***

Normal loading category is used as the percent loading of each load as entered for the selected Loading Category, i.e., no diversity factor is considered. While Maximum bus loading option is used for motors and static loads to be multiplied by the maximum diversity factor of the bus which they are directly connected to. Using this option, the initial loading for transient stability studies with each bus having a different maximum diversity factor can defined. Minimum bus loading option is used for loading of all motors and static loads to be multiplied by the bus minimum diversity factor of the bus that they are directly connected to. Using this option defines the initial loading for transient stability studies with each bus having a different minimum diversity factor.

5.4.2 Transient Stability Calculation Methods

Performing the power system transient stability study is a very comprehensive task. It requires knowledge of machine dynamic models, machine control unit models (such as excitation system and automatic voltage regulators, governor and turbine systems, and power system stabilizers), numerical computations, and power system electromechanical equilibrium phenomena.

5.4.3 Transient Stability Required Data

To run a transient stability study, you need to provide all the data required for load flow calculation. In addition to that, you need to provide machine dynamic model data, load model data, and any control units, such as exciter and governor data. Required data for transient stability calculations include:

Bus Data

- Bus ID
- Nominal kV
- Load Diversity Factor (when Loading option is set to Maximum or Minimum diversity factor)

Branch Data

2-Winding and 3-Winding Transformers

- Transform ID
- Bus Connections
- Rated kV and MVA
- Impedance and tolerance
- X/R ratio
- Tap and LTC settings

Cable/Transmission Line

- Cable or Transmission Line ID
- Bus Connections
- Type, size, rated kV, # of conductors per phase, and length
- Use library data or enter cable's resistance and susceptance values

Impedance

- Impedance ID
- Bus Connections
- Resistance, reactance, and susceptance values

Current-Limiting Reactor

- Current-Limiting Reactor ID
- Bus Connections
- Rated current and kV
- X/R ratio, impedance, and tolerance

Protective Device Data

- Protective Device ID
- Bus and Branch Connections
- Status

Utility Data

- Utility ID
- Bus Connections
- Operating mode (Swing, Voltage Control, or Mvar Control)
- Nominal kV
- %V and Vangle for Swing mode
- %V, MW loading, and Mvar limits (Qmax & Qmin) for Voltage Control mode
- MW and Mvar loading for Mvar Control mode
- 3-Phase MVAsc and X/R values

Synchronous Generator Data

- Synchronous generator ID
- Bus Connections
- Operating mode (Swing, Voltage Control or Mvar Control)
- Rated kV
- %V and Vangle for Swing mode of operation
- %V, MW loading, and Mvar limits (Qmax & Qmin) for Voltage Control mode of

operation

- MW and Mvar loading for Mvar Control mode of operation
- Rated MVA
- Model type (None, Equivalent, Transient, or Sub transient)
- Machine type (Round-Rotor or Salient-Pole)
- Xd”, Xd’, Xd, Xq, Xl, X/R, Tdo’ for Equivalent model
- Xd”, Xd’, Xd, Xq’, Xq, Xl, X/R, Tdo’, Tqo’ for Transient model Round-Rotor machine type
- Xd”, Xd’, Xd, Xq”, Xq’, Xq, Xl, X/R, Tdo”, Tdo’, Tqo”, Tqo’ for Sub transient model Round-Rotor machine type
- Xd”, Xd’, Xd, Xq’ (= Xq), Xq, Xl, X/R, Tdo’ for Transient model Salient-Pole machine type
- Xd”, Xd’, Xd, Xq”, Xq’ (= Xq), Xq, Xl, X/R, Tdo”, Tdo’, Tqo” for Sub transient model Salient-Pole machine type
- S100, S120, H, and Damping
- Sbreak for Generator Start-up Study
- Exciter Type and all associated parameters or fixed excitation
- Governor Type and all associated parameters or no governor action

Static Load Data

- Static Load ID
- Bus Connection
- Quantity
- Status & Associated Demand Factor
- Rated kVA/MVA & kV
- Power Factor
- Loading Category ID & % Loading
- Equipment Cable Data

Study Case Parameters

- Study Case ID
- Max. Number of Iterations
- Solution Precision
- Acceleration Factor
- Simulation Time Step
- Plot Time Step
- Initial Loading Category
- Initial Loading Condition (Normal, Maximum, Minimum, Global Diversity Factor, % Constant KVA and % Const Z, or Operating P & Q)
- Total Simulation Time
- Events & Actions
- Dynamic Modelling Information
- Plots/Tabulated Selection

Study Case parameters are entered into the Transient Stability Study Case Editor.

5.4.4 Transient Stability Output Reports

ETAP Power Station program provides transient stability study results at all different levels of detail, depending on your requirements. The results are reported in three different formats: a text output report (complete and text report formats are available), a one-line view display, and plots.

5.5 SAMPLE STUDY

The sample study was carried in for acquaintance with the software. This study corresponds to an example from a book "Modern power system analysis", by D I Kothari and I J Nagrath, second edition, page 456-462.

The one-line diagram, input data and results are shown in appendix 4-14, and the input data was as shown in below

Gen1 500MVA, 25 kV, Xd = 0.067 p.u, H = 12MJ/MVA

Gen2 300MVA, 20 kV, Xd = 0.01 p.u, H = 9MJ/MVA

	R	X	Half line charging
Line 4-5	0.018	0.11	0.113
Line 5-1	0.004	0.0235	0.098
Line 4-1	0.007	0.04	0.041
Transf: 2-4	-	0.022	-
Transf: 3-5	-	0.04	-

*All values in p.u on the 100MVA, 220kV base.

The fault applied on the Bus P was a three-phase bus system fault, which was cleared by simultaneous opening of the circuit breakers CB2 and CB3.

5.5.1 Conclusions

The result shows the following:

Fault applied	*Fault cleared*	*Observation*
0.00s	0.275s	Gen1 lost synchronism while Gen2 went into oscillations.
0.00s	0.080s	Both generators are stable, hence the breakers should be able to clear the fault within 4 cycles.

The results show that having a 3-cycle breaker would enhance transient stability of the system.

5.6 CASE STUDY

This was the study, which was carried out on the KNBPS system. The system was modelled by using available collected data as specified in chapter 3, while ETAP standard models and sample data was used for those parameters whose values were not available.

5.6.1 Input

The power station data as shown in chapter 3 was used as the input data for each engineering element in the modelled network (shown in appendix 15) of the case study.

5.6.2 Output data

The output data obtained from short-circuit (SC) study was used to set the breaker ratings as shown below.

Rated int. = Initial symmetrical SC current = 1642 kA
Maximum rated int. = 1.2 x Rated int. = 1.2 x 1642 = 2331 kA
C & L rms = 1.6 x Rated int. = 1.6 x 1642 = 3728 kA
C & L crest = 2.7 x Rated int. = 2.7 x 1642 = 6991 kA

The load flow output as shown in the load flow output file was used as the initial values for the transient stability study. Transient stability simulations were then carried out as described in section 5. and the output results obtained are as shown in the output plots of appendix 26-32.

The transient stability study results show that the generator near the fault lost synchronism even when the fault was cleared in the shortest time (in project) 0.0001s. Other generators were able to regain synchronism when fault was cleared in 0.01s, which is 0.5cycles. However, for a fault on the common bus, all generators lost synchronism regardless of how small (0.001s) the clearing time was. This result could be attributed to the fact that opening the breakers within the system isolates the generator itself hence the generator running without a reference.

CHAPTER SIX

DISCUSSION

6.1 SYSTEM MODELS

6.1.1 Generator models

The generator mathematical sub-transient model developed in this study takes into account machine saliency and the damper winding effects. However, the one used in the simulations was the transient model, with Ed" = Eq" = Tdo" = Tqo" = 0, because data available did not include Tdo" and Tqo" values.

6.1.2 Excitation System Model

The model developed is one corresponding to IEEE standard program model for systems supplied from the generator terminals through the transformer. However, to have an exact model, modifications based on exact power station data are required.

6.1.3 Governor-Turbine System Model

The model developed for the governor system is that corresponding to the General purpose one, available in the program. This however is not an exact representation of the governor system at KNPS. With data available, a number of modifications are required in order to have an exact model

Generally, the overall system model block diagram representation of figure 4.8 represents the exact interaction of the KNBPS control systems.

6.2 INPUT DATA

6.2.1 Generator data

Generator grounding was assumed to be through the reactor because it is physically grounded through a neutral-earth transformer a facility not available in the program. On the other hand, the generated reactive power (Mvar) limits were set at:

Maximum Mvar = 92.5 MVar

Minimum Mvar = -40 MVar

These maximum value was obtained from the capacitive Mvar given while the minimum was approximated from the typical capability chart.

6.2.2 Cable data

The operating current taken was 350A, which is the maximum rating of the cable. The cable shunt admittance was calculated as follows:

Charging current = 11.1A

Base admittance Ybase = $167 * 10^6 / (330 * 10^3)^2 = 1.5335 * 10^{-3}$ [Siemens]

Ycable = $(11.1/ 350) * (1.5335 * 10^{-3})$ per 555.09m = $2.6 * 10^{-5}$ [S/ 1000m]

6.2.3 Load data

- ***Excitation loads***

The power factor was assumed 90% since it is supplying static field windings.

- ***Station loads***

Most of the loads are motors conneted to station compressors and pumps. Power factor assumed was therefore 80%.

5.2.4 Circuit Breakers (CB)

The CB setting were calculated from the Short-circuit study simulation results.

6.3 SIMULATION RESULTS

6.3.1 Short-circuit

The short-circuit study was carried out for the purpose of determining the CB settings. The results (ref: Appendix A) show that the highest fault current was 1002kA on transformer buses 2,4,6,8, while the lowest was 0kA on generator terminal buses 3,5,7,9. This highest current was used for calculating CB settings.

6.3.2 Load flow

The load flow study was performed in order to determine the transient stability study initial values. The results obtained (ref: pages and appendix A) were obtained.

6.3.2 Transient stability

6.3.2.1 Sample study

The results show the generator rotor angle / rtime plots show that Gen 1 lost synchronism for 0.275s clearing time while remaining stable but oscillating for 0.08s clearing time. The results correlated to those given in the example.

6.3.3.2 Case study

The results obtained are not as expected, because the curves are not smooth. However, the results show that the generator near the fault was losing synchronism even for the smallest clearing time 0.001s. This is due to the fact that the generator has been disconnected from the rest of the system.

6.4 LIMITATIONS

6.4.1 Information

The data collection did not progress well because the Power Rehabilitation Project (PRP). This affected the system modelling and subsequently the results, typical values were used for missing data. For instance, D = 5% for generator damping, exciter was considered fixed and no governor system. Considering all the missing data would yield better results.

6.4.2 Assumptions

These could have contributed to unexpected results because physically, the power station has an effect on the common bus, the power station buses between generator terminals and transformer have losses and the typical values were not the exact values.

6.4.3 Program limitations

- The program only consist of standard models, which implies only those models corresponding to these standard ones can be used.
- The program is only designed for academic purposes, hence memory space is limited, which resulted in not being able to obtain the transient stability text output report.
- The simulation time and plot step have effect on the output transient stability plots of the generators. Hence need to choose appropriate values.

6.5 THE PRP (POWER REHABILITATION PROJECT)

One of the expected results of the power rehabilitation project is the upgraded rating of two of the generators to180MW. This has not been taken into consideration in this project because parameters required for this rating were not available. With this taken into consideration, power station system stability can be determined after such an expansion to the this system.

6.6 TRANSIENT STABILITY IMPROVEMENT

Considering the adverse effects that results from transient instability, which ranges from permanent damage to equipment and shut down process all the way causing the whole area outage, it is important to have a transient stable system. Some of the suggested ways of transient stability improvement are:

6.5.1 Steady-state stability

- Higher system voltage levels: Achieved by improving the excitation system to having fast responding, high-gain exciters se.
- Reducing transfer reactance: Achieved by reduced conductor spacing, increased conductor diameter etc.
- Series capacitive transmission-line compensation.

6.5.2 High-speed fault clearing breakers, for instance 2-cycle High Voltage (HV) breakers.

6.5.3 Single-pole switching

6.5.4 Lager machine inertia, lower transient reactance.

6.5.5 Fast valving.

6.5.6 Braking resistors.

6.5.7 Full load rejection technique.

6.5.8 Short circuit limiters.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSION

The transient stability models developed for Kariba North Bank Power Station as shown in chapter four (4) of this report, especially with adequate data for further modifications, can be used to improve (and enhance) system generators transient stability for existing structure and any future system expansions.

7.2 RECOMMENDATIONS

- The results obtained are not as expected, it is therefore recommended that, with more support and input from the power station personnel, more data should be collected, the system models developed in this project be modified and effectively performing a future study of assessing the power station system stability.

In the future stability study, it is recommended that the following be noted:

- The Power Station should be considered to have an effect on the common bus, which has been taken as an infinite bus in this study.
- The 180MW rating of two of the generated after station rehabilitation (PRP) to be taken into account. It could not be considered in this study because changes in the generator parameters like reactances must be considered
- Transmission lines from Kariba North to Kariba South and Leopards Hill switchyard be considered, and faults on the system transmission lines only be assumed for effective observation of the transfer reactance. For faults within the system, as considered in this study, would only require shutting down the generator near the fault.

- The suggested ways of improving system stability be taken into consideration.

Having considered the consequences of transient instability, which range from permanent damage to system equipment all the way to system outage, the company should invest in such a study and implementations of stability improvement techniques. This is because the cost of putting the system back into operation after instability consequences is far much higher than such a study and its implementations.

CHAPTER EIGHT

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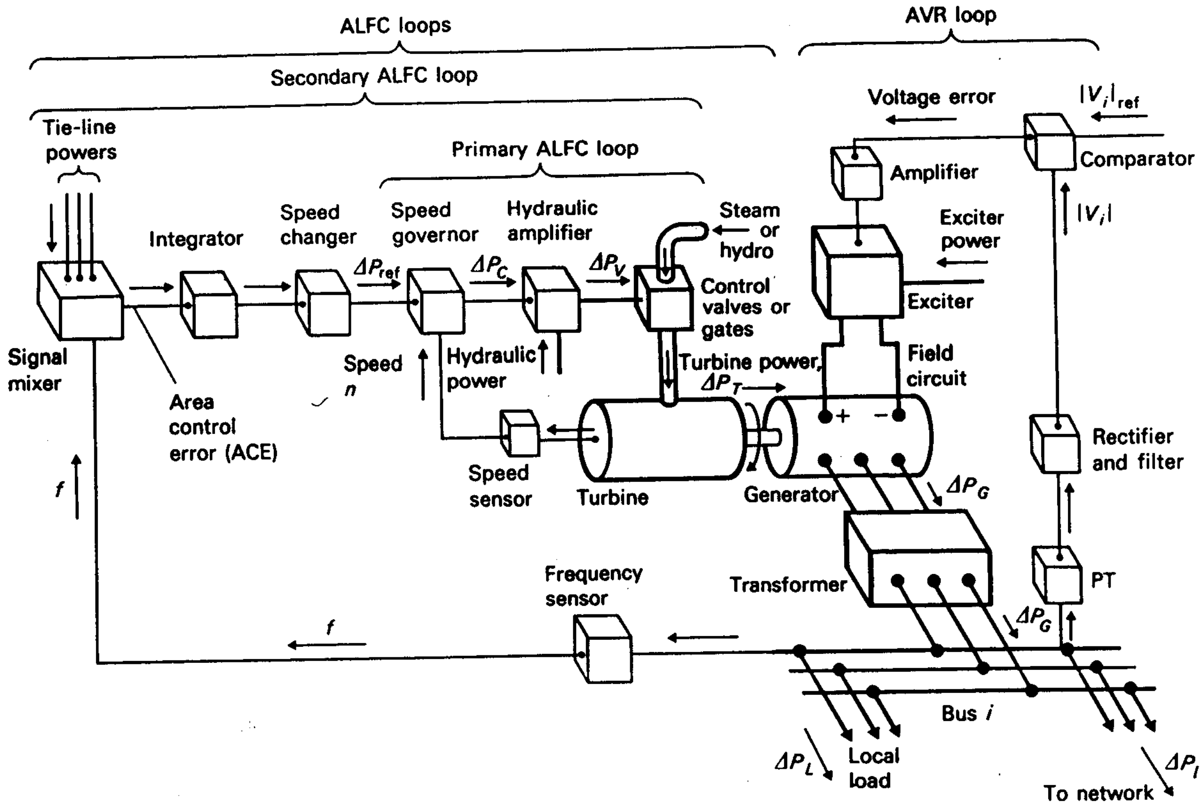
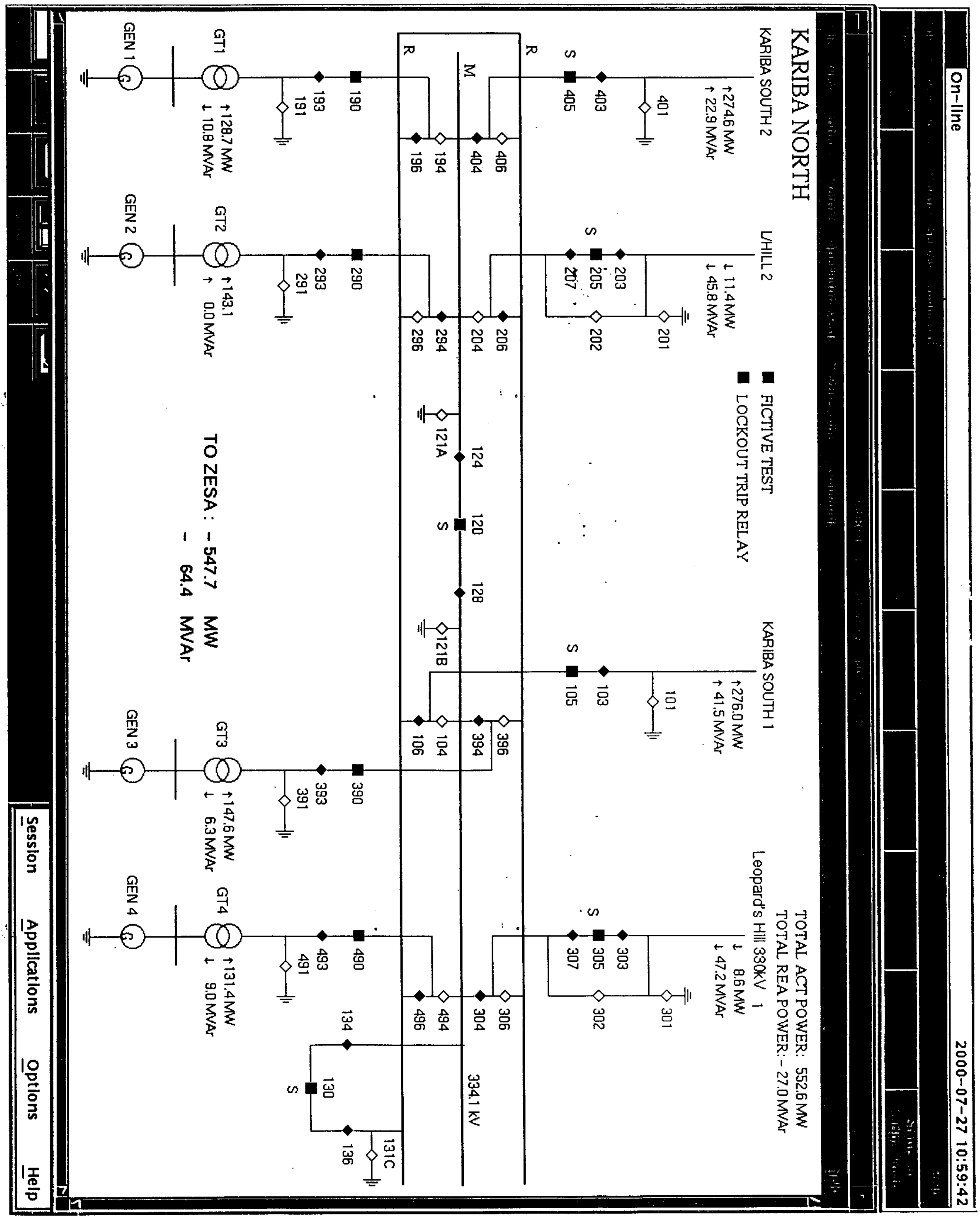
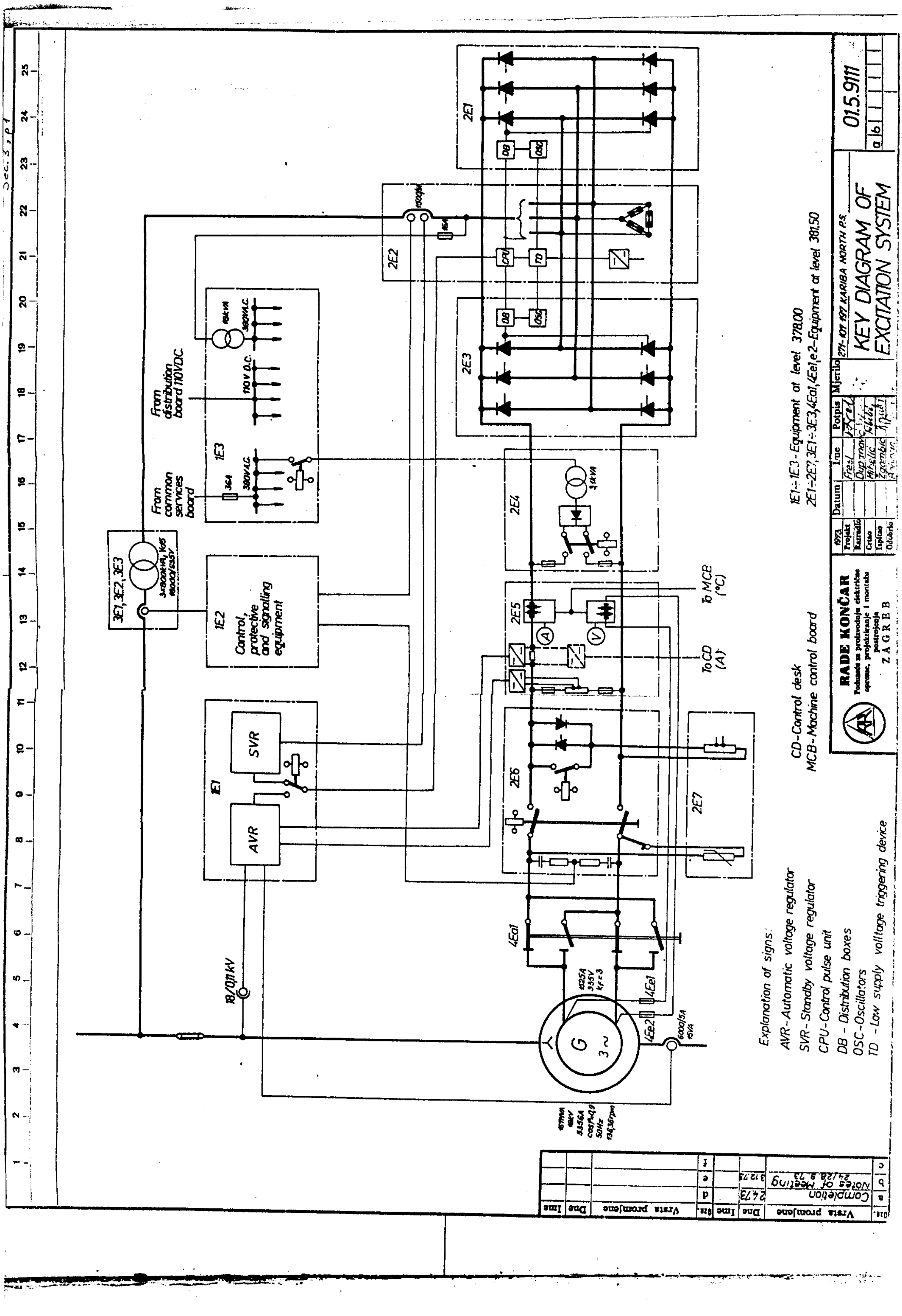
APPENDIX

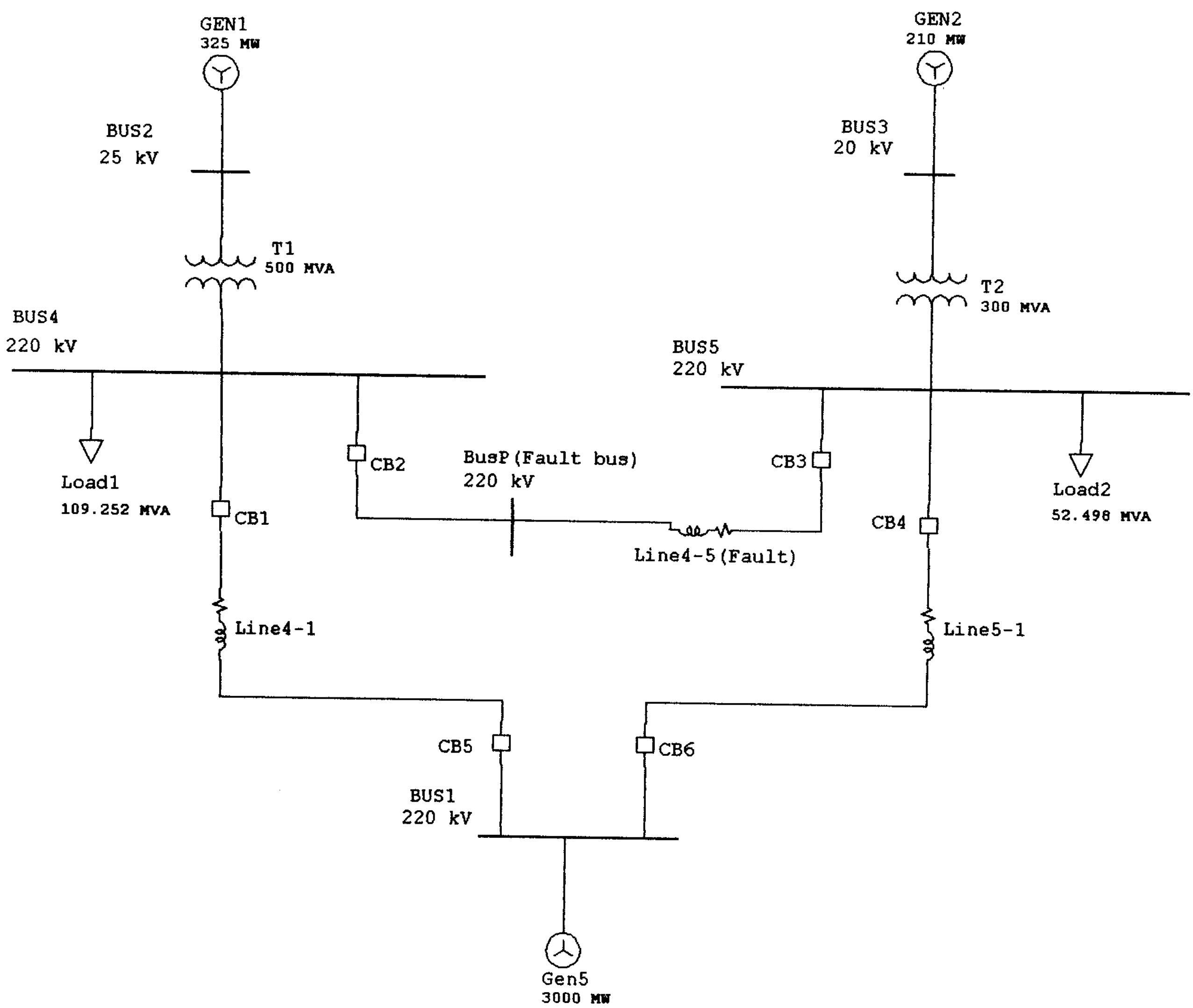


Figu 1 The automatic load-frequency and voltage regulator control loops of a synchronous generator.

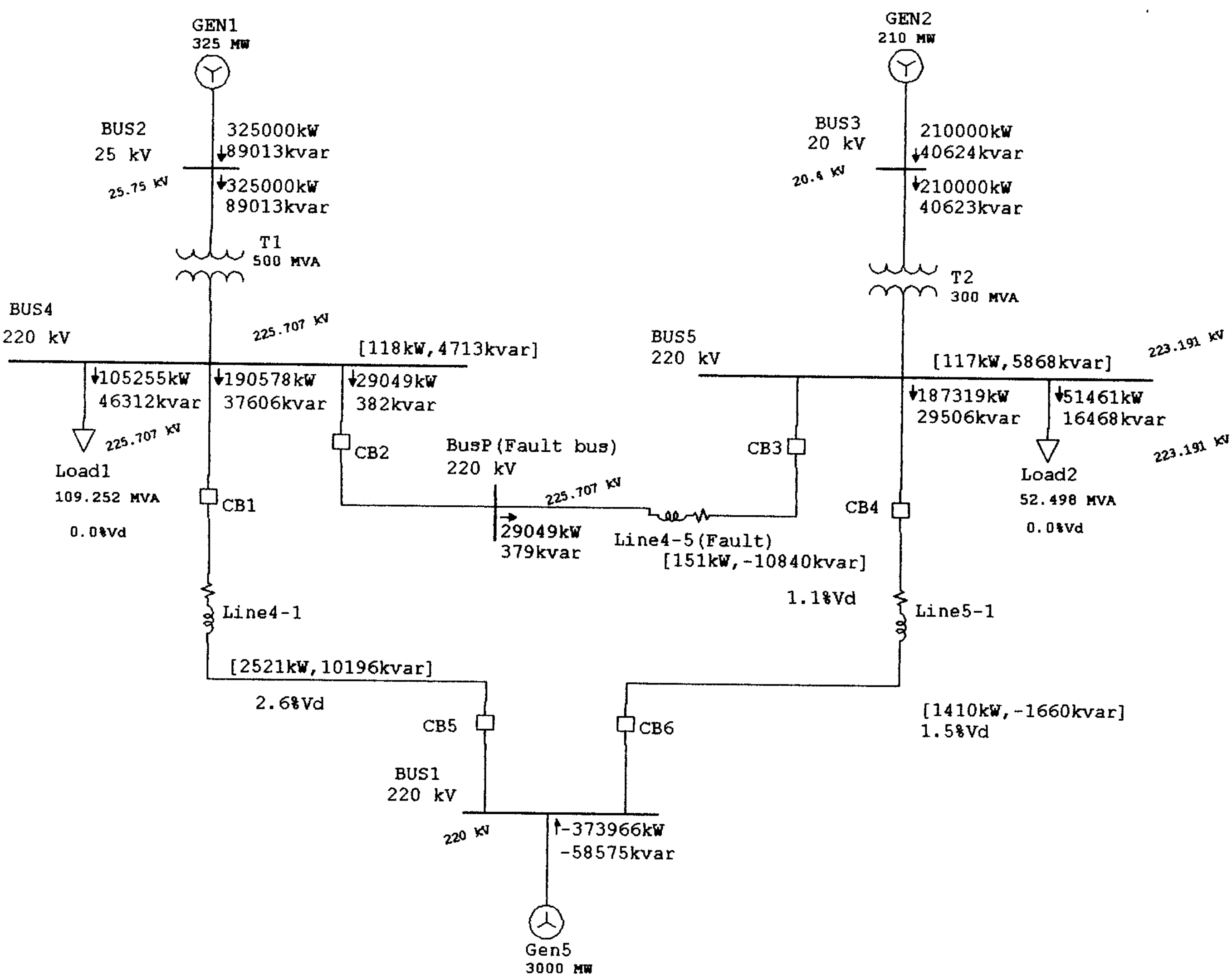

On-line
2000-07-27 10:59:42
KARIBA NORTH
KARIBA SOUTH 2
↑274.6 MW
↑ 22.9 MVAr
L/HILL 2
↓ 11.4 MW
↓ 45.8 MVAr
FICTIVE TEST
LOCKOUT TRIP RELAY
KARIBA SOUTH 1
↑276.0 MW
↑ 41.5 MVAr
Leopard's Hill 330kV 1
↓ 8.6 MW
↓ 47.2 MVAr
TOTAL ACT POWER: 552.6 MW
TOTAL REA POWER: - 27.0 MVAr
R
M
R
S
401
403
405
406
404
194
196
190
193
191
201
202
203
205
207
206
204
294
296
290
293
291
121A
124
120
128
121B
101
103
105
396
394
104
106
390
393
391
301
302
303
305
307
306
304
494
496
490
493
491
134
130
136
131C
334.1 kV
GT1
↑128.7 MW
↓ 10.8 MVAr
GEN 1
GT2
↑143.1
↑ 0.0 MVAr
GEN 2
TO ZESA : - 547.7 MW
- 64.4 MVAr
GT3
↑147.6 MW
↓ 6.3 MVAr
GEN 3
GT4
↑131.4 MW
↓ 9.0 MVAr
GEN 4
Session
Applications
Options
Help


KEY DIAGRAM OF EXCITATION SYSTEM
01.5.9111
RADE KONČAR
ZAGREB
271-107 197 KARIBA NORTH P.S.
1E1÷1E3-Equipment at level 378,00
2E1÷2E7,3E1÷3E3,4Ea1,4Ee1,e2-Equipment at level 381,50
CD-Control desk
MCB-Machine control board
Explanation of signs:
AVR-Automatic voltage regulator
SVR-Standby voltage regulator
CPU-Control pulse unit
DB - Distribution boxes
OSC-Oscillators
TD -Low supply volltage triggering device
From common services board
From distribution board 110VDC
Control, protective and signalling equipment
1E1
1E2
1E3
2E1
2E2
2E3
2E4
2E5
2E6
2E7
3E1,3E2,3E3
4Ea1
4Ee1
4Ee2
AVR
SVR
CPU
TD
DB
OSC
380V A.C.
110 V D.C.
18/0,11 kV
To MCB (°C)
To CD (A)
G
3~
Completion
Notes of Meeting
Vrsta promjene
Dne
Ime

ne-Line Diagram - OLV1



SAMPLE STUDY NETWORK



Load flow result

LOAD FLOW REPORT

Bus Info. & Nominal kV			Voltage		Generation		Motor Load		Static Load		Load Flow					XFM
ID	TYPE	kV	kV	Ang	MW	Mvar	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF	% Tap
*BUS1	Swng	220.000	220.000	0.0	-373.97	-58.58	0.00	0.00	0.00	0.00	BUS4	-188.06	-27.41	498	98.95	
											BUS5	-185.91	-31.17	494	98.62	
*BUS2	Gen.	25.000	25.750	4.9	325.00	89.01	0.00	0.00	0.00	0.00	BUS4	325.00	89.01	7555	96.45	
*BUS3	Gen.	20.000	20.400	4.0	210.00	40.62	0.00	0.00	0.00	0.00	BUS5	210.00	40.62	6053	98.18	
BUS4	Load	220.000	225.707	4.1	0.00	0.00	0.00	0.00	105.26	46.31	BUS1	190.58	37.61	496	98.11	
											BUS2	-324.88	-84.30	858	96.79	
											BusP(Fault b	29.05	0.38	74	99.99	
BUS5	Load	220.000	223.191	2.4	0.00	0.00	0.00	0.00	51.46	16.47	BusP(Fault b	-28.90	-11.22	80	93.22	
											BUS1	187.32	29.51	490	98.78	
											BUS3	-209.88	-34.76	550	98.66	
BusP(Fault b	Load	220.000	225.707	4.1	0.00	0.00	0.00	0.00	0.00	0.00	BUS5	29.05	0.38	74	99.99	
											BUS4	-29.05	-0.38	74	99.99	

* A regulate (constant kV) bus.

The flagged bus has a load mismatch of more than 0.1 MVA.

Project:	**PowerStation**	Page: 9
Location:	3.0.1C	Date: 07-13-2001
Contract:		SN: UNIVZAMBIA
Engineer:		Revision: Base
Filename: KANJELESA	Study Case: LF	Config.: Normal

BRANCH LOADING Summary Report

CKT / Branch		Cable & Reactor			Two-Winding Transformer				
								ANSI Loading (output)	
ID	Type	Ampacity	Loading Amp	%	Capability MVA	Loading MVA	(input) %	MVA	%
T1	Transformer				510.000	336.969	66.07	335.641	65.81
T2	Transformer				300.000	213.893	71.30	212.741	70.91

Project:	**PowerStation** 3.0.1C	Page: 10
Location:		Date: 07-13-2001
Contract:		SN: UNIVZAMBIA
Engineer:		Revision: Base
Filename: KANJELESA	Study Case: LF	Config.: Normal

BRANCH LOSSES Summary Report

CKT / Branch	Connected Bus Info.		From-To Bus Flow		To-From Bus Flow		Losses		% Bus Voltage		Vd
ID	From Bus ID	To Bus ID	MW	Mvar	MW	Mvar	kW	Kvar	From	To	% drop in Vmag
Line4-1	BUS1	BUS4	-188.1	-27.4	190.6	37.6	2520.6	10196.2	100.0	102.6	2.59
Line5-1	BUS1	BUS5	-185.9	-31.2	187.3	29.5	1410.1	-1660.0	100.0	101.5	1.45
T1	BUS2	BUS4	325.0	89.0	-324.9	-84.3	117.8	4712.6	103.0	102.6	0.41
T2	BUS3	BUS5	210.0	40.6	-209.9	-34.8	117.4	5867.9	102.0	101.5	0.55
Line4-5(Faul	BUS5	BusP(Fault b	-28.9	-11.2	29.0	0.4	151.2	-10839.8	101.5	102.6	1.14
							4317.0	8276.9			

Project:
Location:
Contract:
Engineer:
Filename: KANJELESA

PowerStation
3.0.1C

Study Case: **LF**

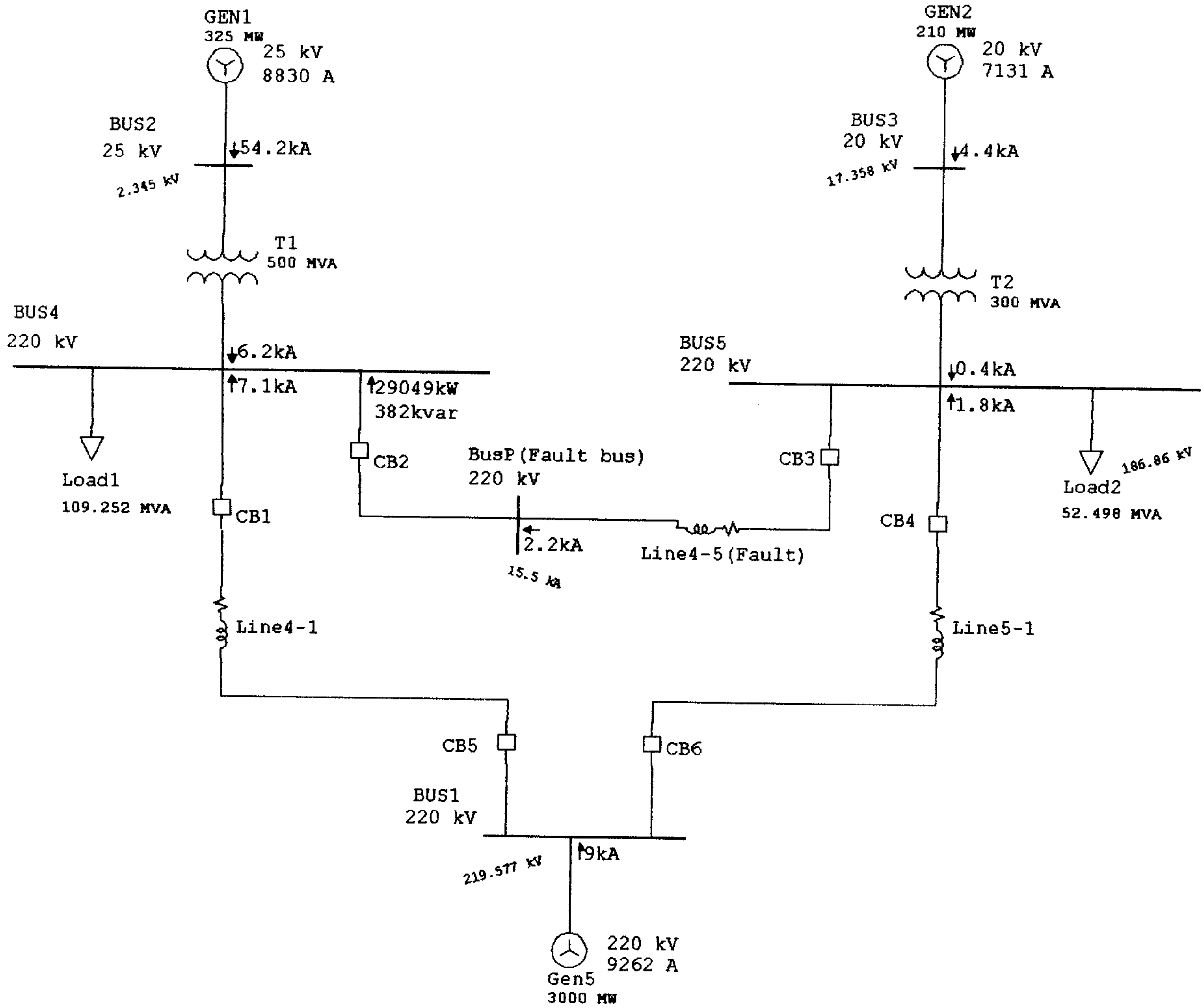
Page: **12**
Date: 07-13-2001
SN: UNIVZAMBIA
Revision: Base
Config.: Normal

SUMMARY OF TOTAL GENERATION, LOADING & DEMAND

	MW	Mvar	MVA	% PF
Swing Bus(es):	-373.966	-58.575	378.526	98.80 Lagging
Generators:	535.000	129.637	550.482	97.19 Lagging
Total Demand:	161.033	71.061	176.016	91.49 Lagging
Total Motor Load:	.000	0.000	0.000	100.00 Lagging
Total Static Load:	156.717	62.780		
Apparent Losses:	4.317	8.281		
System Mismatch:	0.000	0.000		

Number of Iterations: 2

Appendix 10



Short circuit result

SHORT-CIRCUIT REPORT

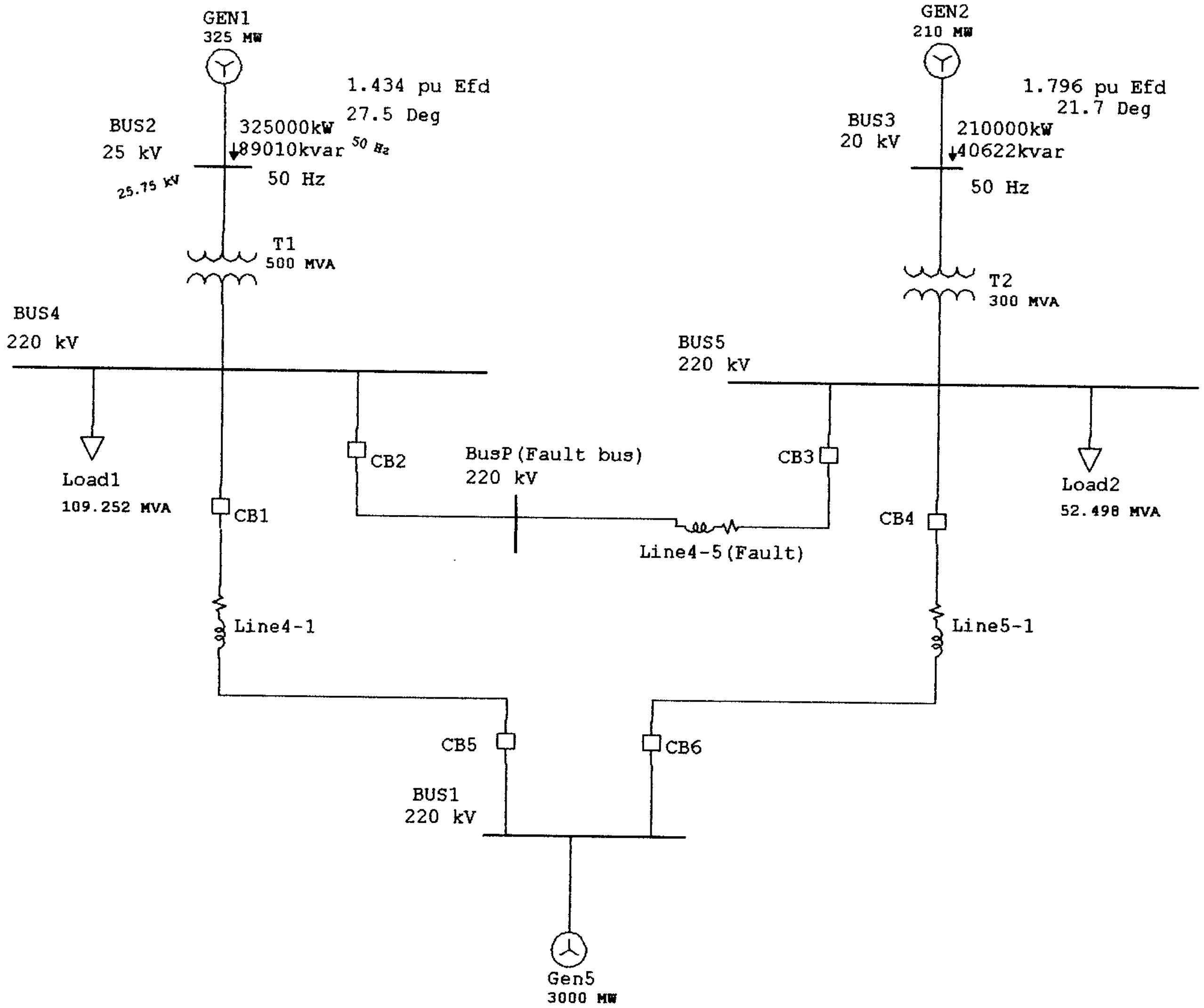
Three-phase fault at bus: **BusP(Fault b**

Nominal kV = 220.000, Prefault Voltage = 100.00 % of nominal bus kV
Base kV = 220.000, = 100.00 % of base kV

Voltage Factor (C): 1.10

Contribution		Voltage (%) & Initial Symmetrical Current (rms				
From Bus ID	To Bus ID	% V From Bus	kA Real	kA Imaginary	X/R Ratio	kA Magnitude
BusP(Fault b	Total	0.00	1.351	-15.435	11.4	15.494
BUS5	BusP(Fault b	84.94	0.266	-2.196	8.3	2.212
BUS1	BUS4	99.81	0.931	-7.080	7.6	7.141
BUS2	BUS4	9.38	0.154	-6.158	40.0	6.160

Peak Value = 38.97 kA (Method C)
Steady State = 12.37 kA rms (Maximum Value)

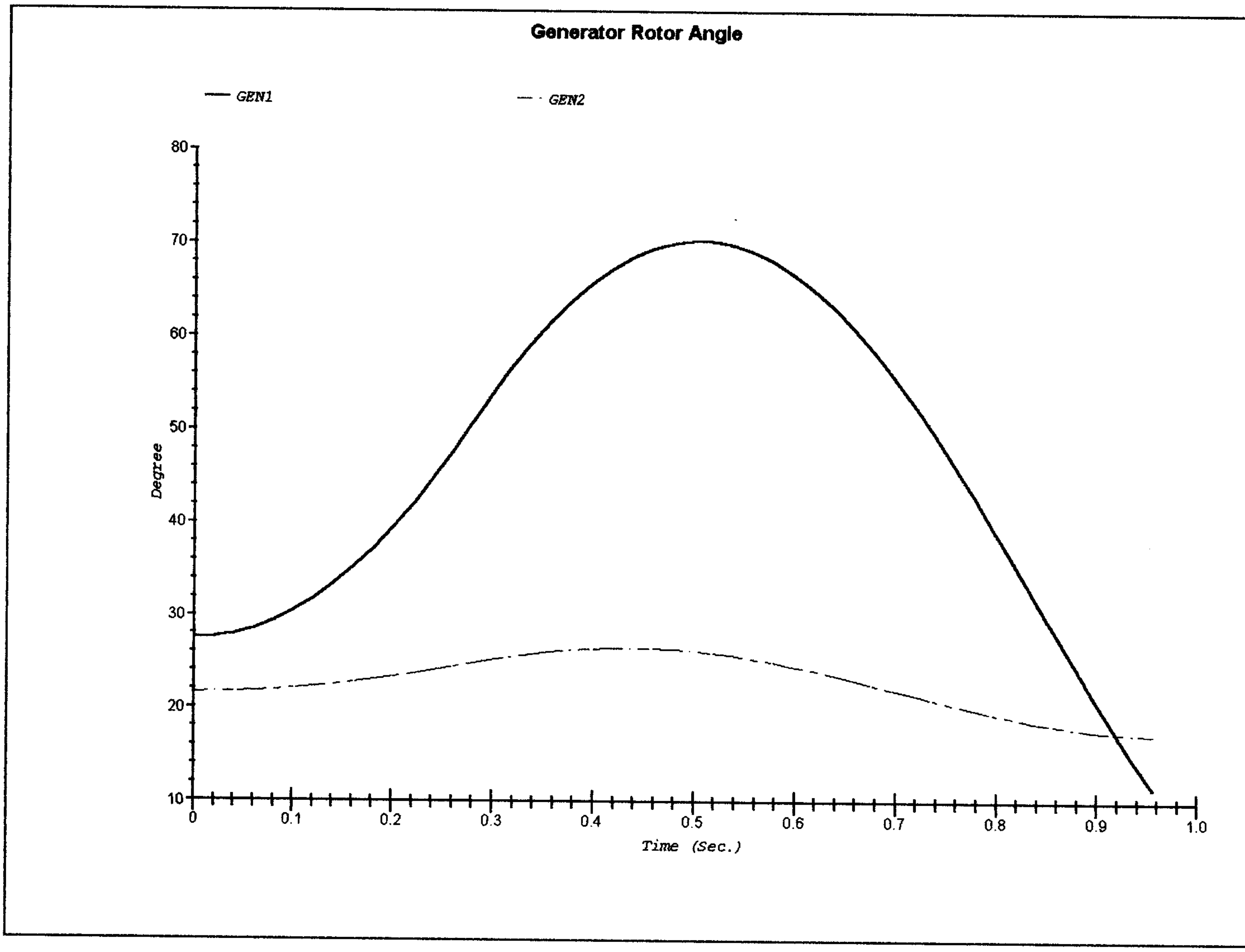


Transient Stability Study result.

Project:
Location:
Contract:
Engineer:

July 13, 20

Appendix 13



Project File: KANJELESA

Output Report: TS

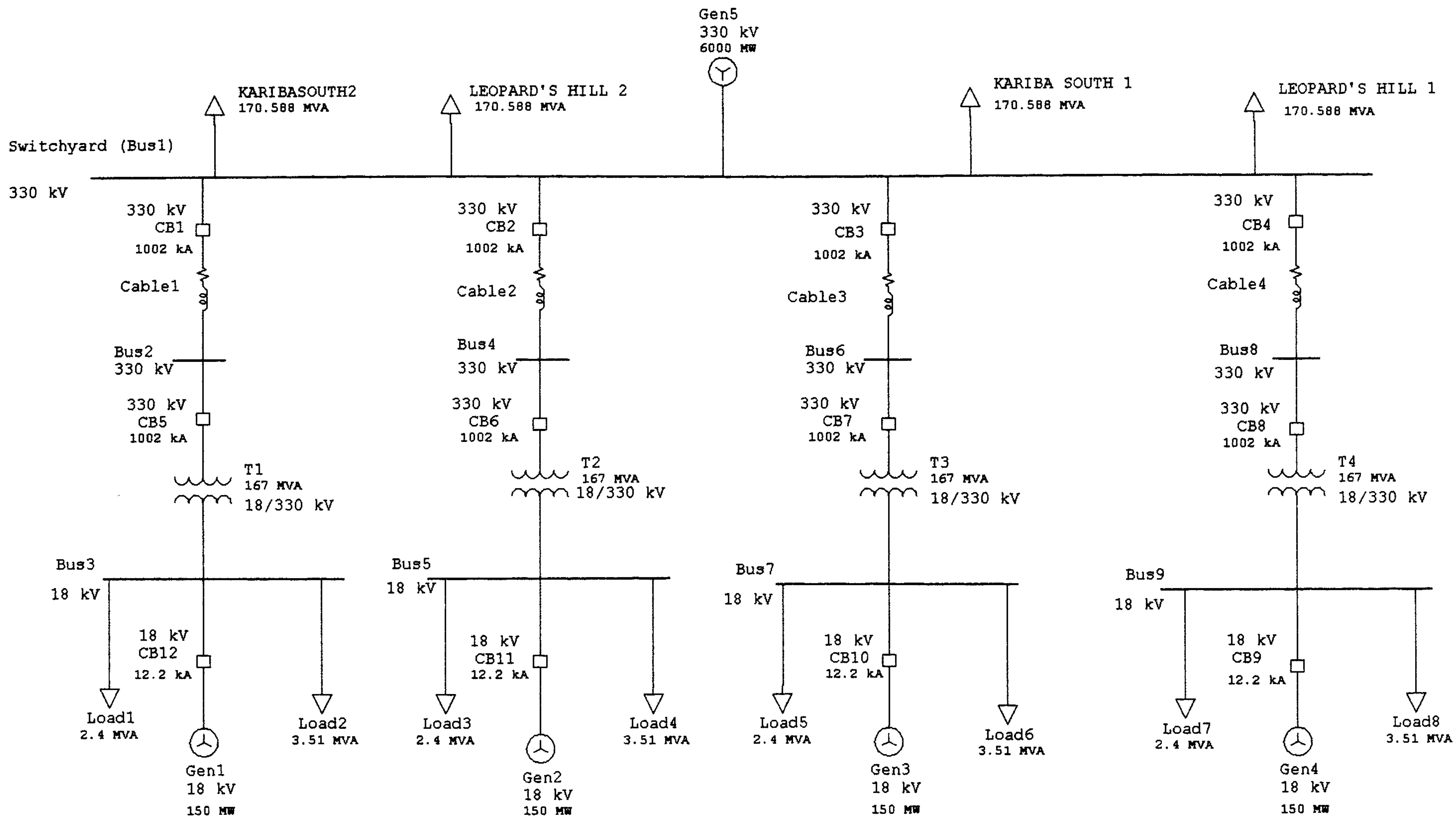
Fault on bus ? . Applied = 0.00s

Cleared = 0.275s

One-Line Diagram - OLV1

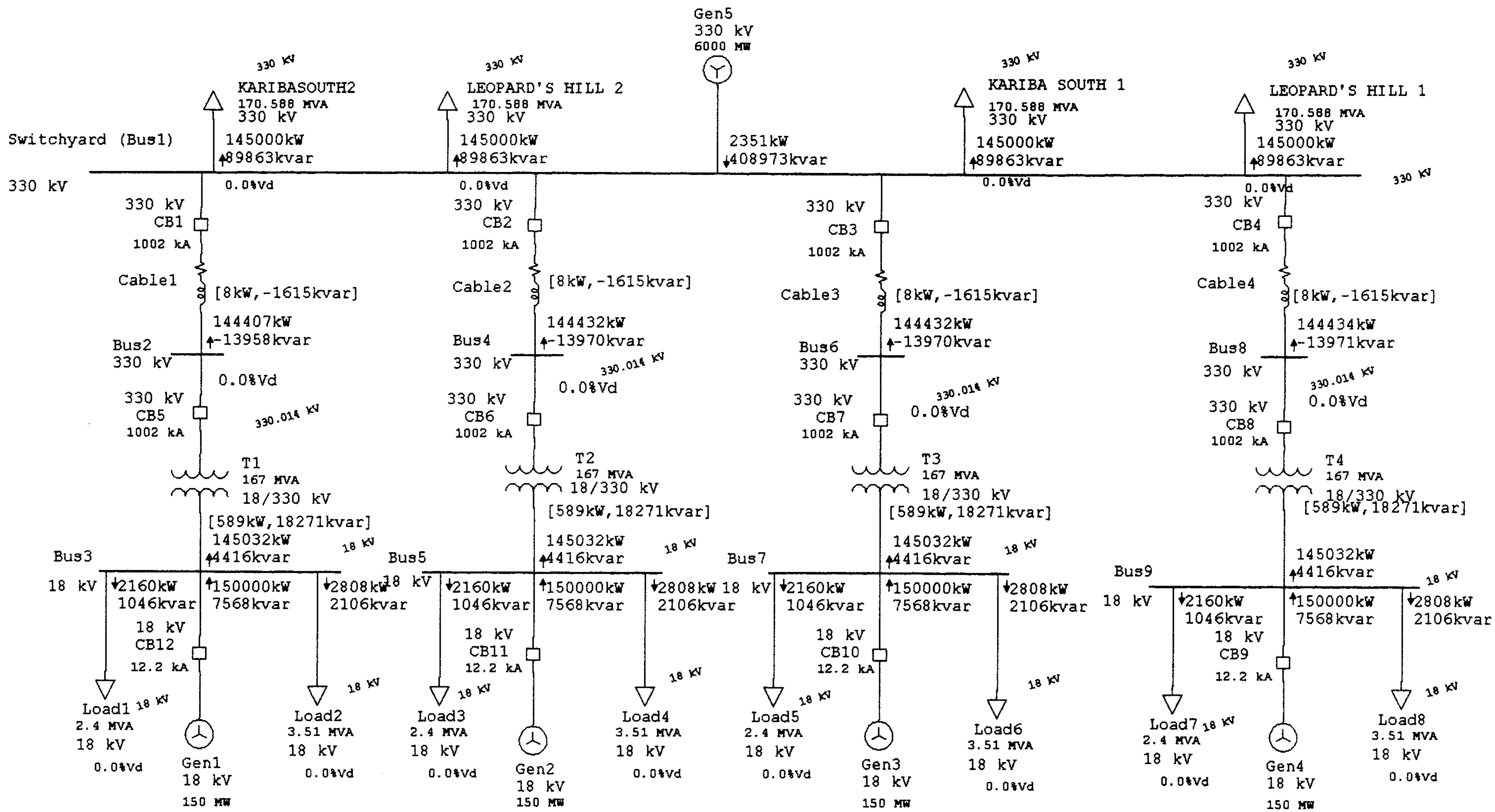
CASE STUDY

KARIBA NORTH BANK SYSTEM NETWORK MODEL (PROGRAM DIAGRAM)



One-Line Diagram - OLV1

LOAD FLOW RESULT



Project:		**PowerStation**	Page: **8**
Location:		3.0.1C	Date: 07-13-2001
Contract:			SN: UNIVZAMBI
Engineer:		Study Case: **LOAD FLOW**	Revision: Base
Filename:	KANJELESA@CASE-STUDY		Config.: Normal

LOAD FLOW REPORT

Bus Info. & Nominal kV			Voltage		Generation		Motor Load		Static Load		Load Flow				
ID	TYPE	kV	%Mag	Ang	MW	Mvar	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	% PF
Bus2	Load	330.000	100.004	0.0	0.00	0.00	0.07	0.00	0.00	0.00	Switchyard (	144.41	-13.96	253	-99.54
											Bus3	-144.44	13.85	253	-99.54
*Bus3	Gen.	18.000	100.000	7.2	150.00	7.57	0.00	0.00	4.97	3.15	Bus2	145.03	4.42	4654	99.95
Bus4	Load	330.000	100.004	0.0	0.00	0.00	0.02	0.00	0.00	0.00	Switchyard (	144.43	-13.97	253	-99.54
											Bus5	-144.44	13.85	253	-99.54
*Bus5	Gen.	18.000	100.000	7.2	150.00	7.57	0.00	0.00	4.97	3.15	Bus4	145.03	4.42	4654	99.95
Bus6	Load	330.000	100.004	0.0	0.00	0.00	0.02	0.00	0.00	0.00	Switchyard (	144.43	-13.97	253	-99.54
											Bus7	-144.44	13.85	253	-99.54
*Bus7	Gen.	18.000	100.000	7.2	150.00	7.57	0.00	0.00	4.97	3.15	Bus6	145.03	4.42	4654	99.95
Bus8	Load	330.000	100.004	0.0	0.00	0.00	0.02	0.00	0.00	0.00	Switchyard (	144.43	-13.97	253	-99.54
											Bus9	-144.44	13.85	253	-99.54
*Bus9	Gen.	18.000	100.000	7.2	150.00	7.57	0.00	0.00	4.97	3.15	Bus8	145.03	4.42	4654	99.95
*Switchyard (	Swng	330.000	100.000	0.0	2.35	408.97	0.00	0.00	580.00	359.45	Bus2	-144.40	12.34	253	-99.64
											Bus4	-144.42	12.35	253	-99.64
											Bus6	-144.42	12.35	253	-99.64
											Bus8	-144.43	12.36	253	-99.64

* A regulate (constant kV) bus.

\# The flagged bus has a load mismatch of more than 0.1 MVA.

BRANCH LOSSES Summary Report

CKT / Branch	Connected Bus Info.		From-To Bus Flow		To-From Bus Flow		Losses		% Bus Voltage		V % (in V
ID	From Bus ID	To Bus ID	MW	Mvar	MW	Mvar	kW	Kvar	From	To	
Cable1	Bus2	Switchyard (	144.4	-14.0	-144.4	12.3	7.9	-1615.5	100.0	100.0	(
T1	Bus2	Bus3	-144.4	13.9	145.0	4.4	589.4	18270.8	100.0	100.0	(
Cable2	Bus4	Switchyard (	144.4	-14.0	-144.4	12.4	7.9	-1615.5	100.0	100.0	(
T2	Bus4	Bus5	-144.4	13.9	145.0	4.4	589.4	18270.7	100.0	100.0	(
Cable3	Bus6	Switchyard (	144.4	-14.0	-144.4	12.4	7.9	-1615.5	100.0	100.0	(
T3	Bus6	Bus7	-144.4	13.9	145.0	4.4	589.4	18270.7	100.0	100.0	(
Cable4	Bus8	Switchyard (	144.4	-14.0	-144.4	12.4	7.9	-1615.5	100.0	100.0	(
T4	Bus8	Bus9	-144.4	13.9	145.0	4.4	589.4	18270.7	100.0	100.0	(
							2389.1	66621.1			

Project:
Location:
Contract:
Engineer:
Filename: KANJELESA@CASE-STUDY

PowerStation
3.0.1C

Study Case: **LOAD FLOW**

Date: 07-13-2001
SN: UNIVZAMBL
Revision: Base
Config.: Normal

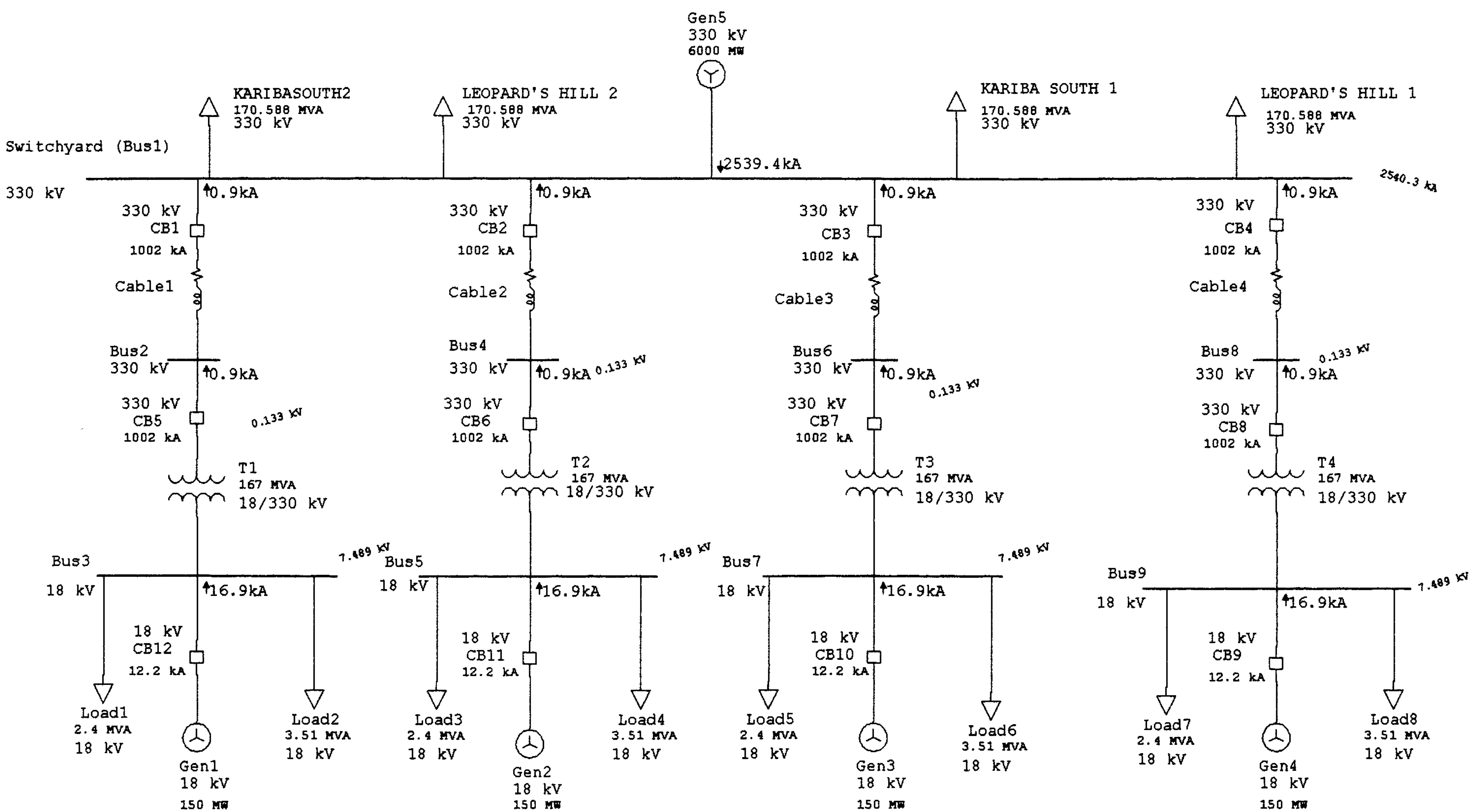
SUMMARY OF TOTAL GENERATION, LOADING & DEMAND

	MW	Mvar	MVA	% PF
Swing Bus(es):	2.351	408.973	408.979	0.57 Lagging
Generators:	600.001	30.272	600.764	99.87 Lagging
Total Demand:	602.352	439.245	745.496	80.80 Lagging
Total Motor Load:	.120	-0.019	0.122	98.77 Leading
Total Static Load:	599.871	372.060		
Apparent Losses:	2.360	67.204		
System Mismatch:	0.120	0.019		

Number of Iterations: 15

One-Line Diagram - OLV1

Short - circuit (bus 1)



SHORT-CIRCUIT REPORT

Three-phase fault at bus: **Switchyard (**

Nominal kV = 330.000, Prefault Voltage = 100.00 % of nominal bus kV
Base kV = 330.000, = 100.00 % of base kV

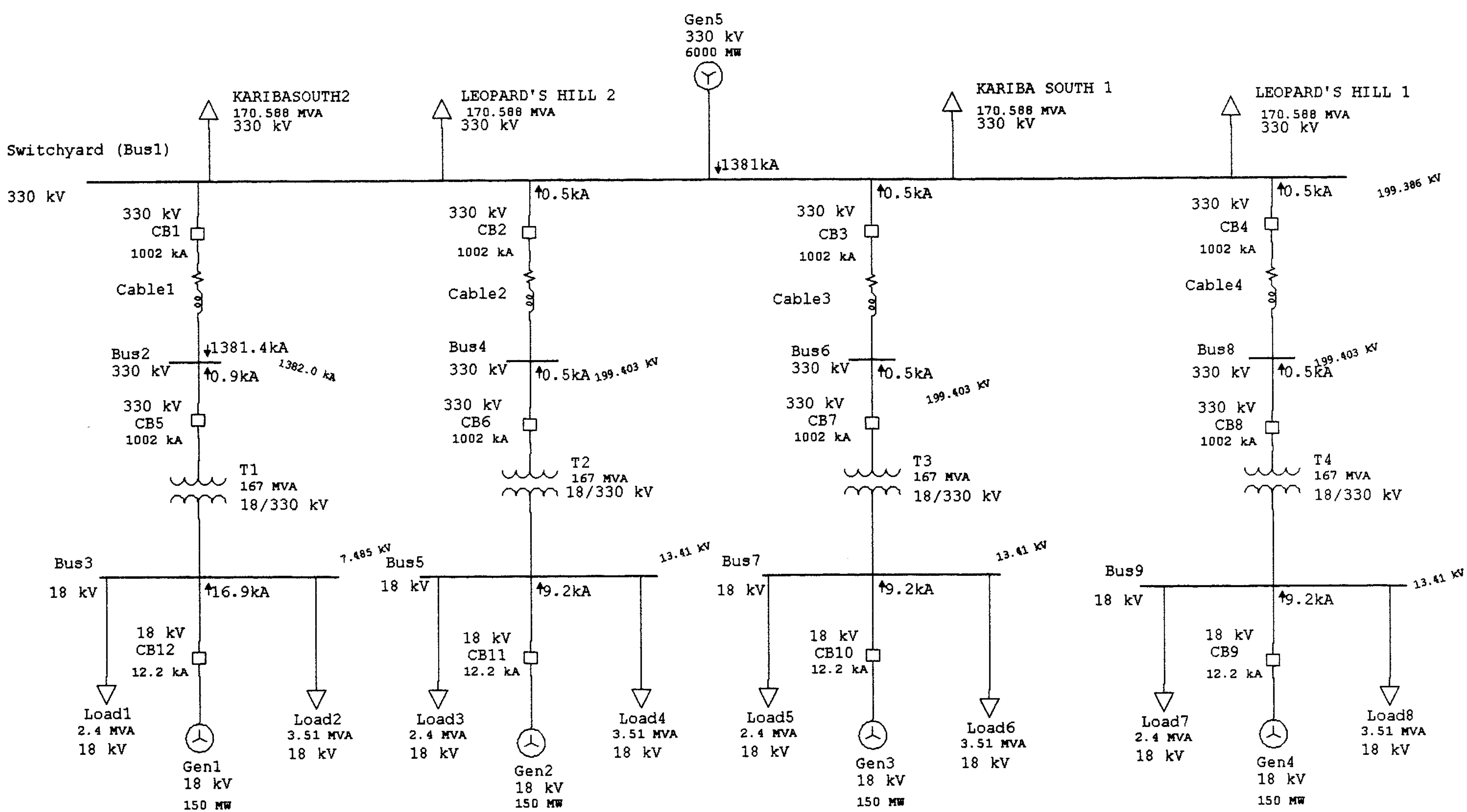
Voltage Factor (C): 1.10

Contribution		Voltage (%) & Initial Symmetrical Current (rms				
From Bus ID	To Bus ID	% V From Bus	kA Real	kA Imaginary	X/R Ratio	kA Magnitude
Switchyard (	Total	0.00	2485.297	-525.579	0.2	2540.262
Bus2	Switchyard (	0.04	0.021	-0.921	44.3	0.921
Bus4	Switchyard (	0.04	0.021	-0.921	44.3	0.921
Bus6	Switchyard (	0.04	0.021	-0.921	44.3	0.921
Bus8	Switchyard (	0.04	0.021	-0.921	44.5	0.921
Gen5	Switchyard (	100.00	2485.213	-521.895	0.2	2539.421

Peak Value = 3673.20 kA (Method A)
Steady State = 0.00 kA rms (Maximum Value)

One-Line Diagram - OLV1

Short circuit (bus 2)



Project:	**PowerStation**	Page: 8
Location:	3.0.1C	Date: 07-13-2001
Contract:		SN: UNIVZAMBIA
Engineer:		Revision: Base
Filename: KANJELESA@CASE-STUDY	Study Case: **ShortCircuit**	Config.: Normal

SHORT-CIRCUIT REPORT

Three-phase fault at bus: **Bus2**

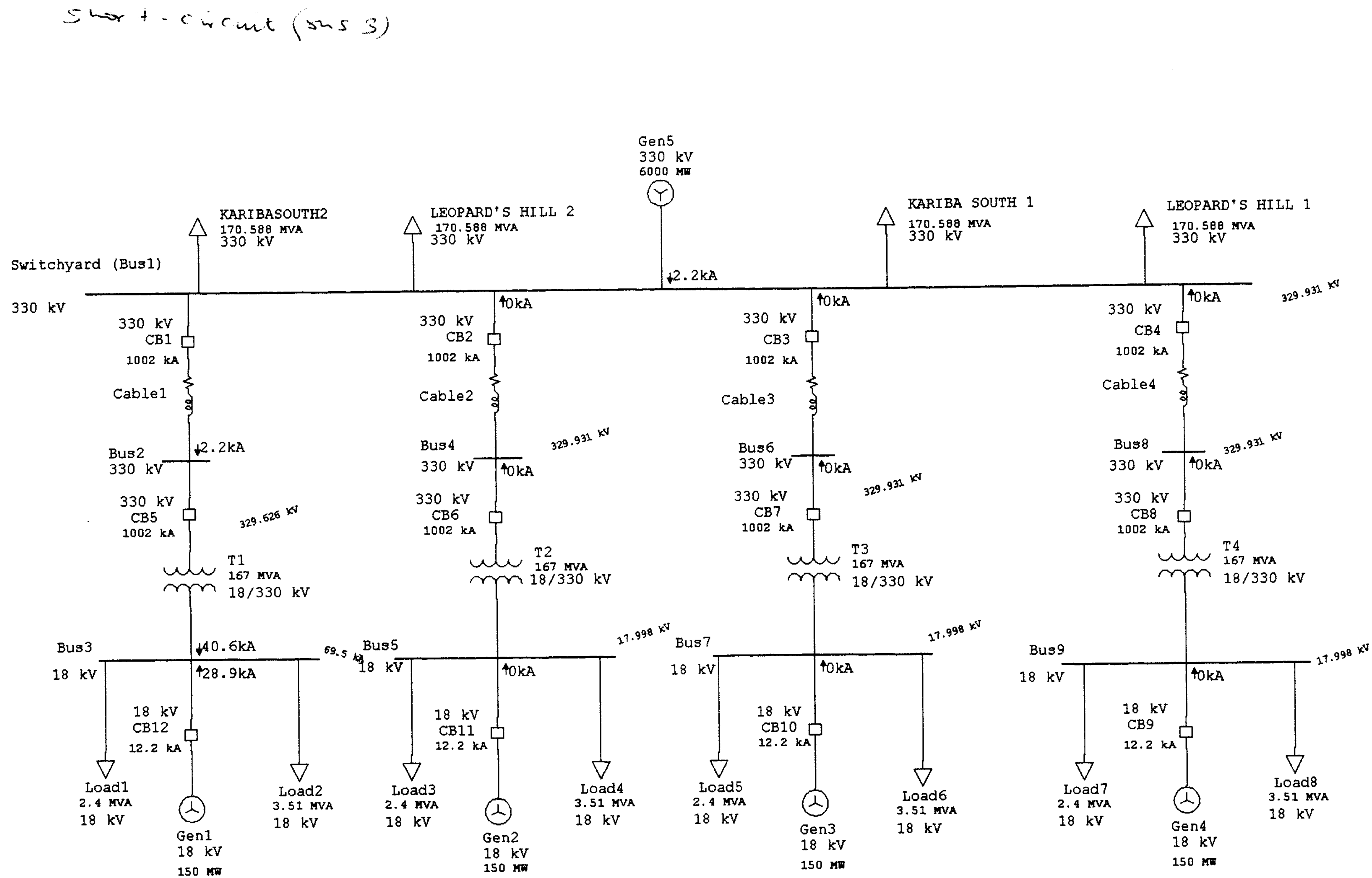
Nominal kV = 330.000, Prefault Voltage = 100.00 % of nominal bus kV
Base kV = 330.000, = 100.00 % of base kV

Voltage Factor (C): 1.10

Contribution		Voltage (%) & Initial Symmetrical Current (rms				
From Bus ID	To Bus ID	% V From Bus	kA Real	kA Imaginary	X/R Ratio	kA Magnitude
Bus2	Total	0.00	1008.883	-944.523	0.9	1382.016
Switchyard (	Bus2	60.42	1008.863	-943.601	0.9	1381.371
Bus3	Bus2	41.58	0.021	-0.921	44.6	0.922

Peak Value = 2071.29 kA (Method A)
Steady State = 0.00 kA rms (Maximum Value)

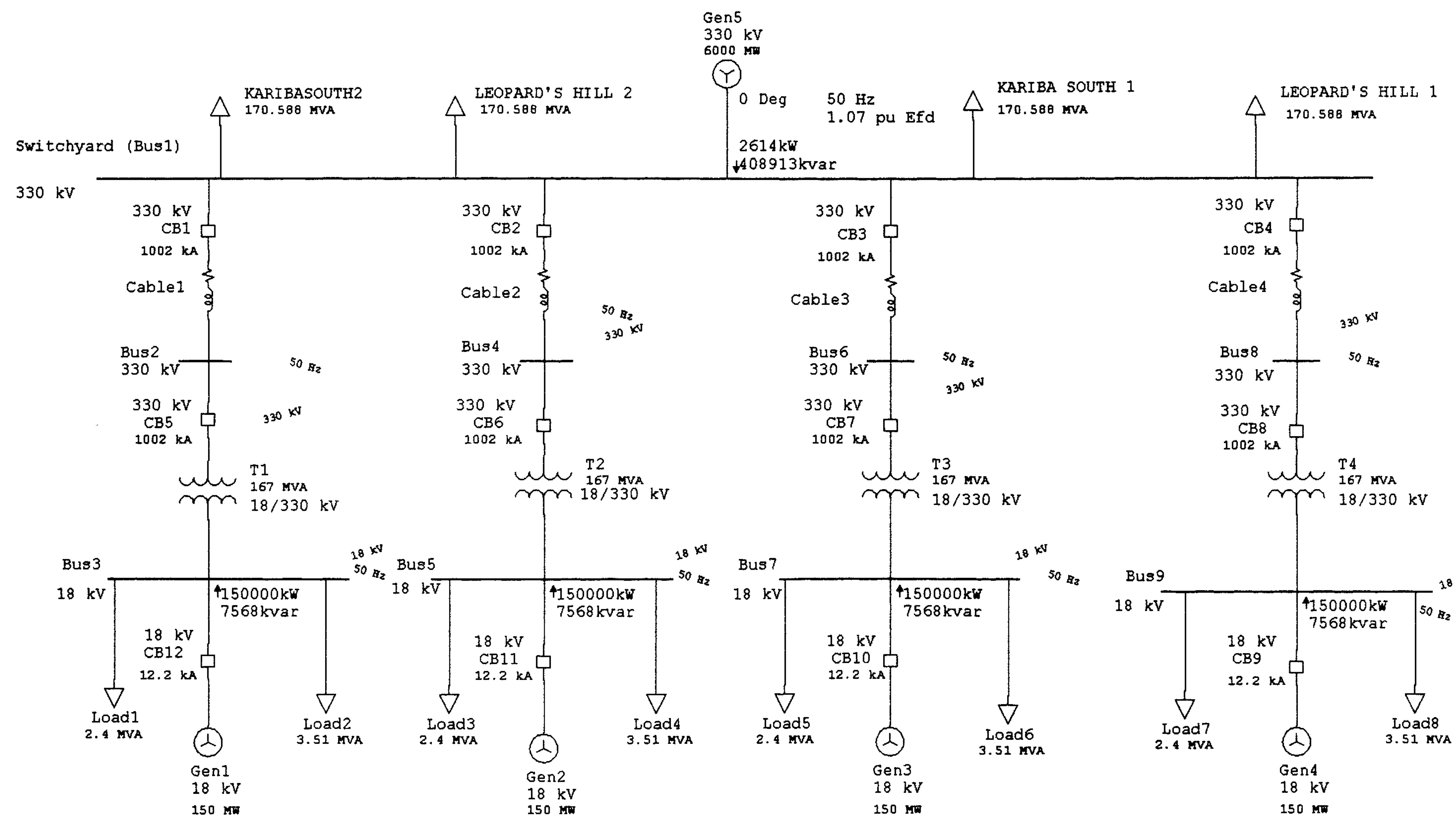
One-Line Diagram - OLV1



Appendix 24

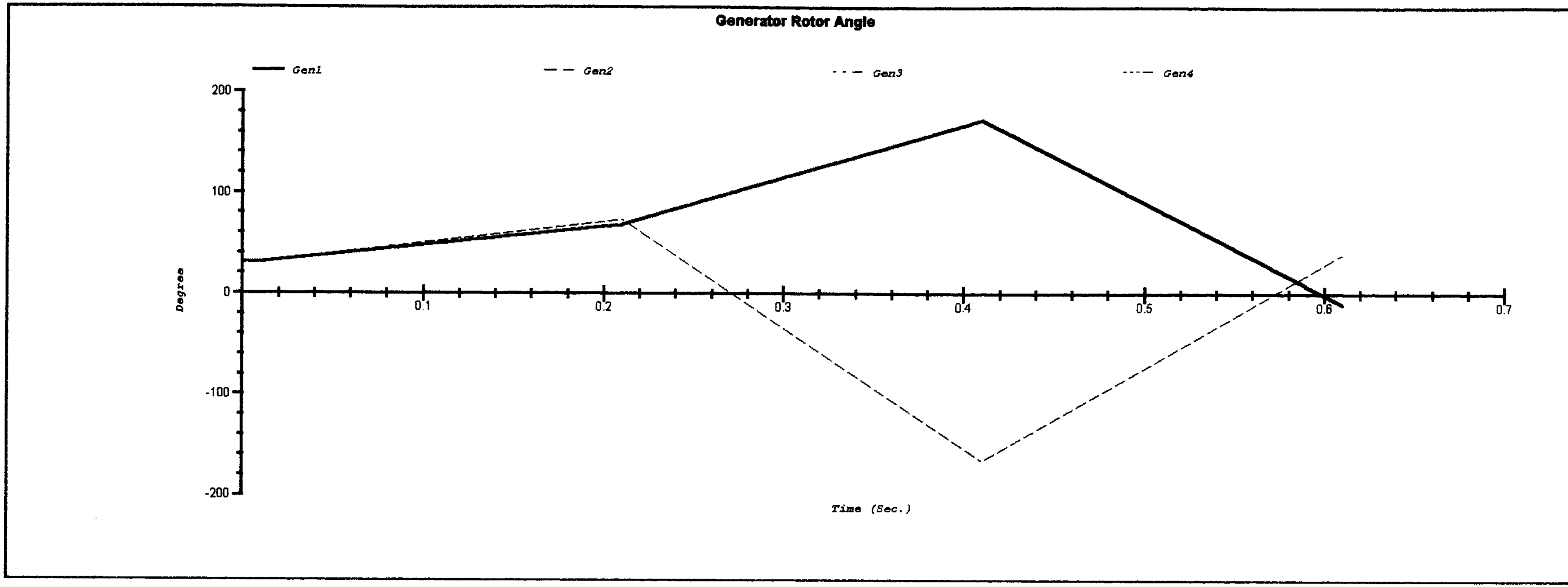
One-Line Diagram - OLV1

Transient Stability study result



Project:
Location:
Contract:
Engineer:

July 13, 2001



Project File: KANJELESA@CASE-STUDY

Output Report: Untitled

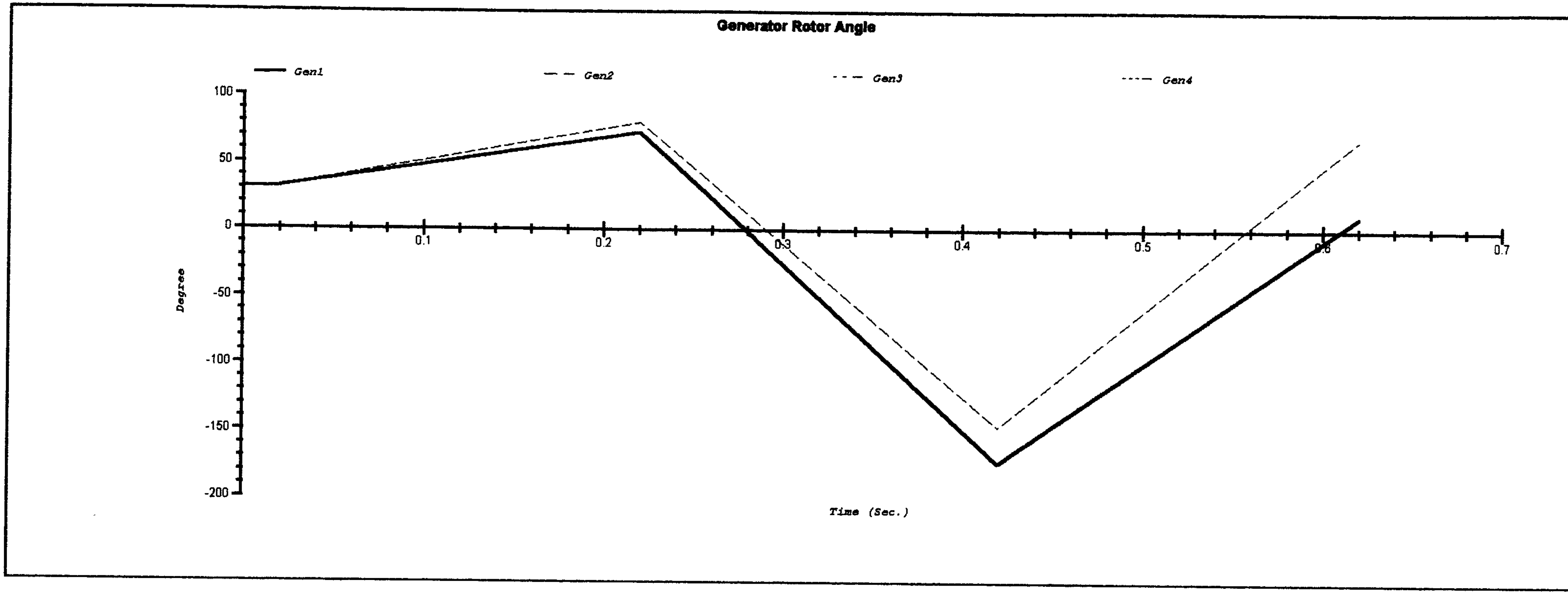
Fault on bus 2 (Switchyard) : Applied = 0.00s

cleared = 1.00s

Project:
Location:
Contract:
Engineer:

July 13, 2001

Appendix 2



Project File: KANJELESA@CASE-STUDY

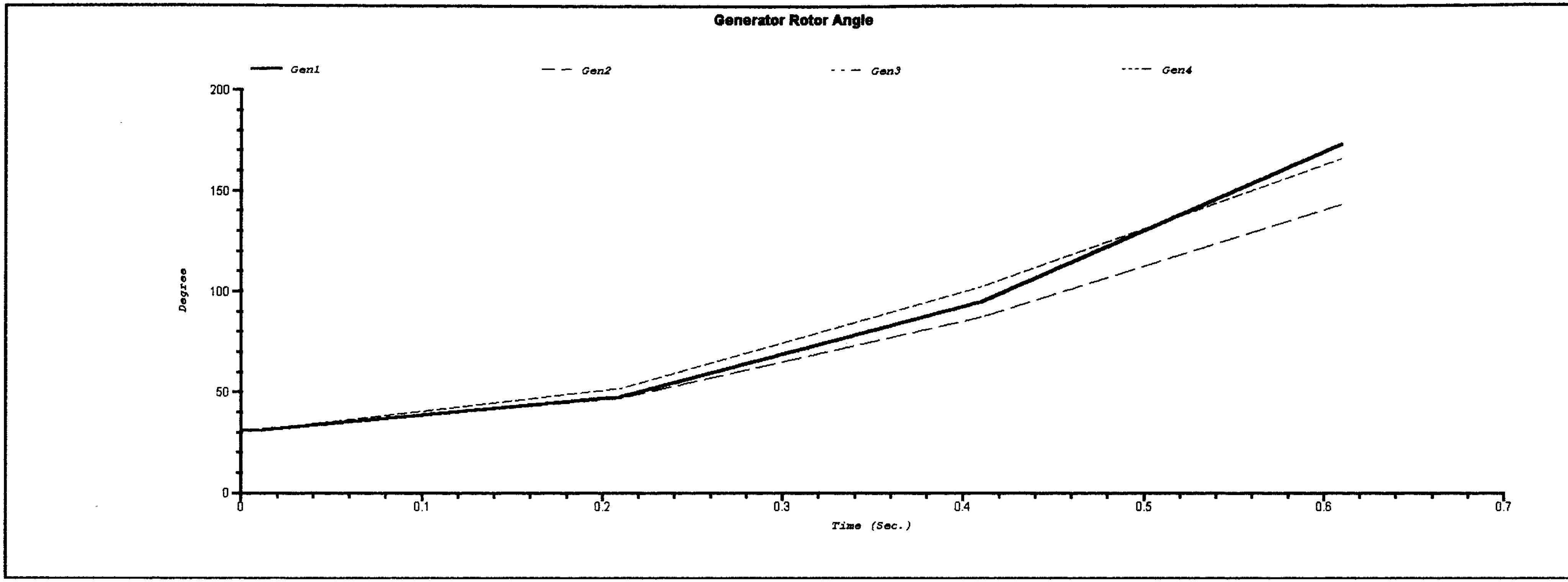
Output Report: Untitled

Fault on bus 1 (Switchyard bus) : Applied = 0.00s

Cleared = 0.001s

Project:
Location:
Contract:
Engineer:

July 13, 2001



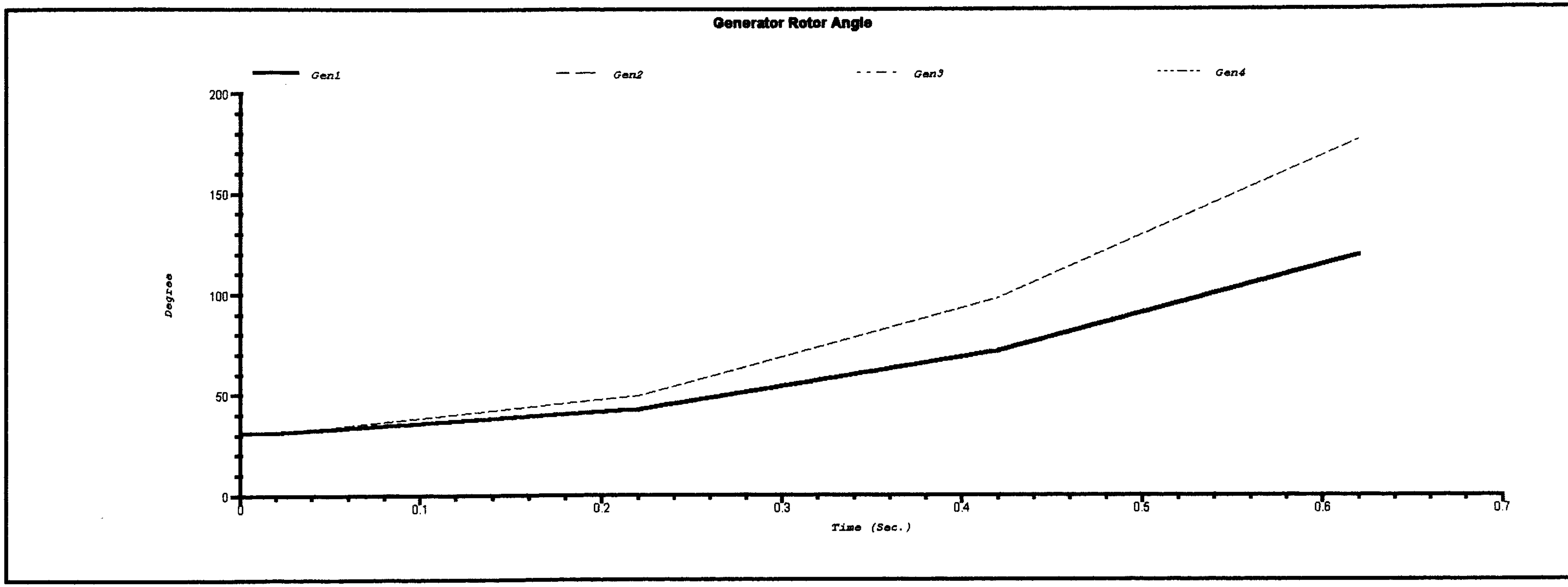
Project File: KANJELESA@CASE-STUDY

Output Report: Untitled

Fault on bus 2 : Applied = 0.00s
Cleared = 1.0s

Project:
Location:
Contract:
Engineer:

July 13, 2001



Project File: KANJELESA@CASE-STUDY

Output Report: Untitled

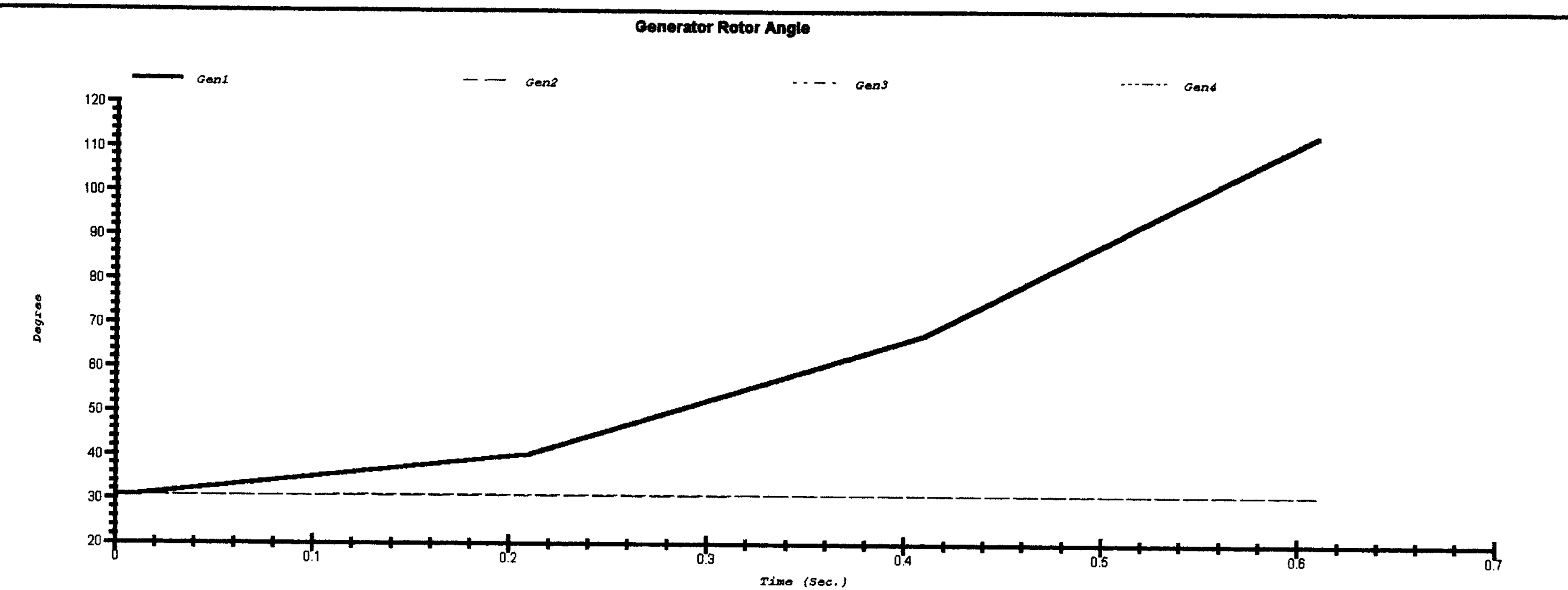
Fault on bus 2; Applied = 0.00s

Cleared = 0.001s

Appendix 30

Project:
Location:
Contract:
Engineer:

July 13, 2001



Project File: KANJELESA@CASE-STUDY

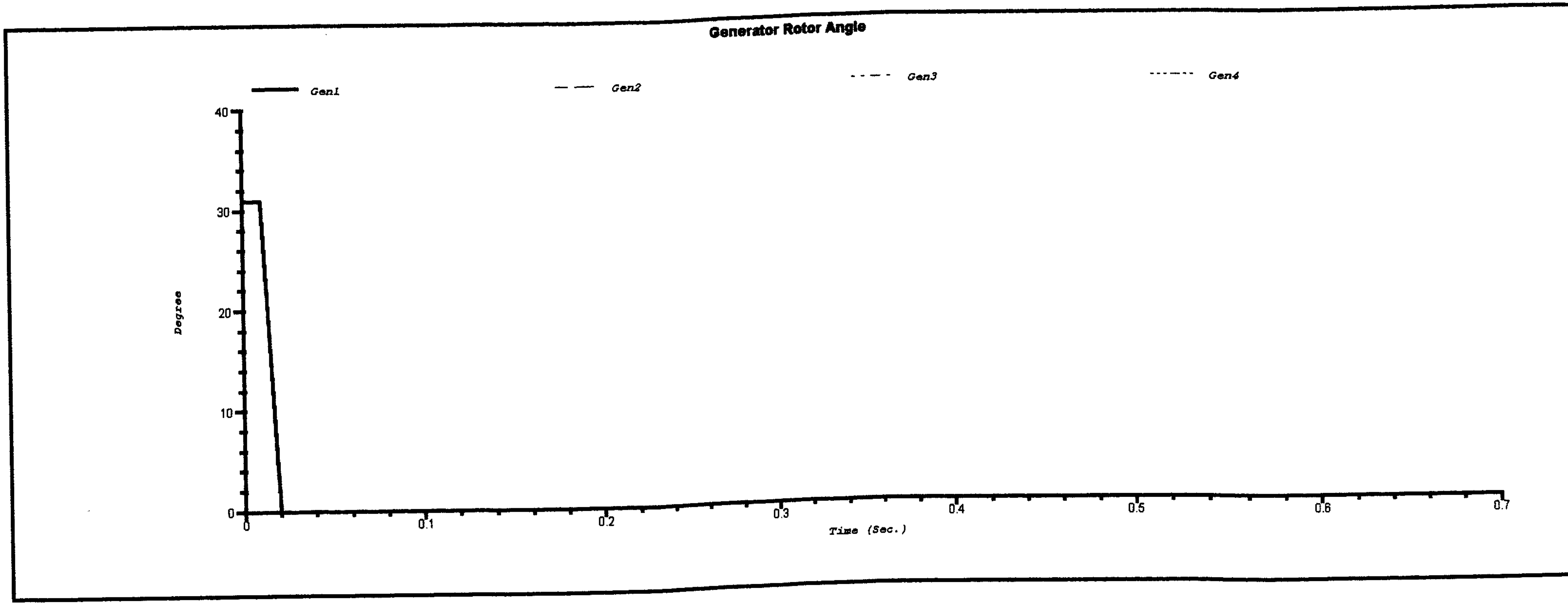
Output Report: Untitled

Fault on bus 3' Applied = 0.00s

Cleared = 1.00s

Appendix 3

Project:
Location:
Contract:
Engineer:



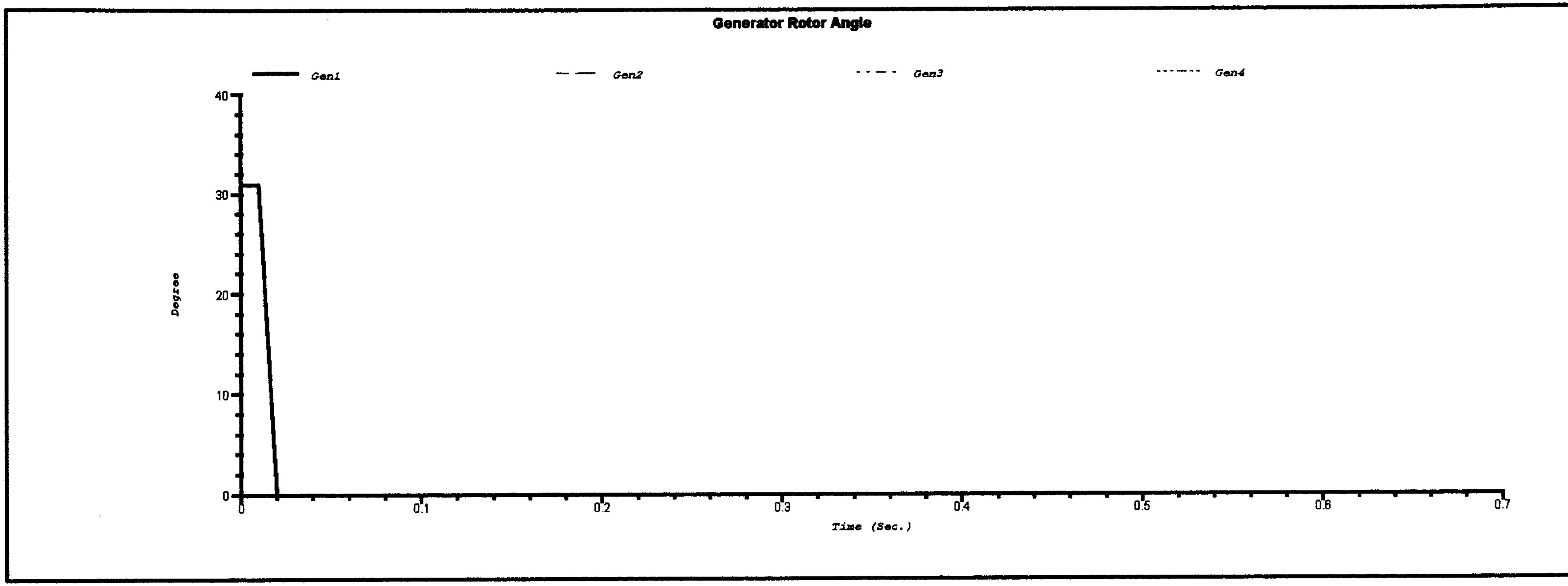
Project File: KANJELESA@CASE-STUDY

Output Report: Untitled

Fault on bus 3: Applied = 0.00s

Project:
Location:
Contract:
Engineer:

July 13, 2001



Project File: KANJELESA@CASE-STUDY

Output Report: Untitled

Fault on bus 3: Applied = 0.00s

Cleared = 0.01s

Appendix 32