DYNAMIC ANALYSIS OF THE SOUTHERN AFRICA POWER POOL (SAPP) NETWORK

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ABSTRACT

Synchronous generators have been connected through overhead transmission lines and interconnected to a regional power system network to improve reliability, enhance the security of supply, trade electricity and share the available natural resources for energy fuel supply. The interconnected power system experiences disturbances during normal operation such as load variations and faults, causes stress on the generators to control and remain in synchronism. This dissertation analyses the natural damping oscillations that will emanate during a disturbance in the interconnected power system and provide understanding to the system operator to monitor and operate effectively the Southern African Power Pool (SAPP). It is required to carry out the performance analysis and characteristics of the generators during the disturbances in order to identify the synchronizing and damping torque in respect of rotor angle and speed deviations. In power system control, the frequency is monitored continually since the speed of the generators is synchronized into the transmission lines. Any small variation on the interconnected system will affect the others machines. The effect can either be the system maintaining its stability or loss of synchronism. The latter can be avoided by identifying the nature and behaviour of oscillations and determining effective means to minimize them in interconnected power pool. It can also notify the system operator of an impending power outage. In this research investigation, a simplified model of the Southern African Power Pool is modeled using DIgSILENT Powerfactory power systems analysis software tool, using input data of the primary plant (synchronous generators) and associated interconnected power system network. Nodal and modal analysis tools were used to determine the dynamic status of the interconnected power network. A dynamic analysis will enable participating members of the power pool understand the nature of oscillations when affected by different types of events with continuous monitoring of the modes and eventually assist in re-tuning of secondary control equipment to improve the service delivery of electricity of a pool such as of the Southern African region.

The study has identified the focal points of power oscillations in the modelled SAPP grid through simulations that affects the behaviour of system voltages during a disturbance and require to control damping oscillations on the synchronous generators.

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2. This thesis has not been submitted for any degree or examination at any other university.

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Professor Innocent E. Davidson

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LIST OF ACRONYMS/ABBREVIATIONS

ABOM	Agreement between Operating Members
AC	Alternating Current
ACE	Area Control Error
ACSR	Aluminium Conductor Steel Reinforced
AGC	Automatic Generation Control
AVR	Automatic Voltage Regulator
CPS	Control Performance Standards
DC	Direct Current
DIgSILENT	DIgital SImuLation of Electrical NeTworks
DRC	Democratic Republic of Congo
EAPP	East Africa Power Pool
GCR	Grid Code Requirement
GW,MW,W	Units of Active power
Hz	Hertz
IEEE	Institute of Electrical and Electronic Engineers
IPP	Independent Power Producer
kA, A	units of current
kJ/kg	Units of carilofic values
kV	Units of Voltage
MCR	Minimum Continuous Rating
mmf	Magnetomotive force
MVA	Units of apparent Power
MVAR	units of reactive power
NERSA	National Regulator of South Africa
NRS	National Regulation Standard
SADC	Southern Africa Development Community
SAPP	Southern Africa Power Pool
SCADA	Supervisory Control and Data Acquisition
UTC	Universal Time Co-ordinated
WAPP	West Africa Power Pool

CHAPTER 1

1 INTRODUCTION

1.1 Overview of Southern Africa Power Pool

In August 1995, Southern Africa Power Pool (SAPP) was formed as a regional electricity power pool during the Southern Africa Development Community (SADC) summit that was held at Kempton Park, South Africa by signing an Inter-Governmental Memorandum of Understanding by member governments of SADC (excluding Mauritius)[1, 2] . On 23rd February 2006, a revised Inter-Governmental Memorandum of Understanding was signed by Ministers responsible for Energy in SADC[3]. The revised inter-Governmental Memorandum of Understanding was due to the wind of change in the electricity sector reforms that has been restructured in SADC and includes the introduction of electricity independent power producers.

There are twelve member countries in SAPP who are represented by the electric utility companies in SADC with additional two members as Independent Power Producer and Independent Transmission Company. The electric utility companies from Botswana, Mozambique, South Africa, Lesotho, Namibia, Democratic Republic of Congo, Swaziland, Zambia and Zimbabwe are Operating Members who are trading electricity power energy through the available market practiced in SAPP. Three countries, namely: Malawi, Tanzania and Angola are termed non-operating members [3, 4].

The operating members further signed other governing agreements that enable SAPP to sustain equal participation for member utilities and thereafter provide reliable power system in the interconnected electrical pool[2]. These are:-

a. Inter-Utility Memorandum of Understanding - This agreement serves as the fundamental basis for management and operating principles of SAPP and also will uphold management of the utilities to abide on the interconnection being organized by the member government. This agreement will be signed by all member countries;
b. Agreement between Operating Members (ABOM)- This agreement is signed by only operating members which has established the specific rules of operation and pricing.; and
c. Operating Guidelines which provide standards and operating guidelines that are used for system planning and operation of the power system amongst member utilities.

Since the member utility companies were already operating their electricity networks before the establishment of SAPP, therefore, the design, planning, and operations were based on each country ‘s assessment and need. Moreover, the cross-border electricity trading existed in Zambia and Zimbabwe, South Africa and Mozambique, and South Africa with Lesotho, Swaziland, Botswana, and Namibia. The establishment of SAPP has facilitated the development of a competitive electricity market in the SADC region such that non-operating members are engaged in projects to extend transmission network and to upgrade into operating members in the pool [5]. Some operating members have increased their generation capacity and strengthened their transmission networks.

1.1.1 SAPP Network

SAPP has an installed capacity of 61GW generated using power generation technologies, namely: coal 62% from 38GW generated on thermal generation, hydro represents 21% from the total generated 13GW , wind represents 4% of a total generation of 2.5GW, distillate 4% from various different type of fuels such as ethanol, diesel and petrol driven generating machine and 2.7GW the total generation, nuclear 3% and a total generation of 1.9GW, Solar PV represents 2.97% and a total generation of 1.8GW , Open Cycle Gas Turbine has a total generation of 0.936 GW and representing 1.51% , Solar concentrated solar panel 0.6GW and is representing 0.97GW and remaining generation in the mix comes from landfill 0.002GW and Biomass 0,0042GW [2, 4]. The exploitation of these natural resources for the production of electric power requires careful planning in order to optimize the use of these resources effectively and to obtain maximum benefits at least cost, taking into consideration the need for minimal adverse environmental impact.

SAPP Network is an interconnection of electric power supply networks from nine operating members in the Southern Africa Region transmitting over long distances mostly in AC transmission line and a DC link between Mozambique and South Africa at various voltage levels from different types of generating plants[1]. There are two types of grid for the electricity trading in the region, the first one can be termed as cross-border supply, the initial bilateral arrangements before the inceptions of SAPP where electricity was traded from one country to the other such as the South Africa and Mozambique at 533kV DC, 400kV and 132kV, South Africa and Swaziland at 132kV, South Africa, and Lesotho 132kV transmission lines.

The second one can be termed as the interconnected electricity supply AC at 220kV and a 330kV line running from the Democratic Republic of Congo running continuously through Zambia, Zimbabwe, connecting at 400kV in Zimbabwe for Botswana up to South Africa. The second type has been connected to mostly hydro generators. This implies that the SAPP network has a complex mix and dynamics in its operation arising from different physical origins of electricity production and a need to understand the natural response to disturbances when affected in the interconnected grid.

The SAPP Network is operated by Control Coordination Centre to monitor the energy interchange and electricity trading and the operating member has its own Area Control Centre for monitoring and controlling the power system operation. The control centres will control the voltage and frequency to achieve reliable and safe power system being traded in the region. The SAPP Control Centre will only operate on the interconnected system that is required to be transferred from one country to the other as per trading arrangement. The operation of the SAPP Control Centre shall be to advise the operating member to control voltage and frequency being transferred within the trading period and the rest of the utility responsibility.

1.2 Problem Formulation

The power system is extensively studied to assess its power flow and stability when subjected to large disturbance. The assessment requires the data on the transmission line, transformer and generator parameters to evaluate its impact on the system. However, customers also require the usage of electricity through the connected transmission lines and the collective usage of the power provides a profile to the total generation capacity of the network. SAPP power network experiences disturbances on the interconnected system that take time to be explained by the operating member states on the cause of such failure of power and affects the synchronized generators. The Area Control Centres will visualize the sudden drop in frequency without the option to avoid power failure. In some instances, protection relays have operated within the SAPP network and affected another country but the later country will not realize the cause of fault that affects transmission lines and synchronous generating machines.

A SAPP power system at its normal operating conditions is continually subjected to disturbances and it is expected that the dynamic characteristics of the synchronous generators, transmission lines will operate to control such disturbances to reinforce the system to remain in synchronism. However, considering the available monitoring devices of SAPP interconnected power system, it is very difficult to study and analyse system model based on assumptions of load and generated power being constant for the system. In this research, it intends to investigate dynamic stability of the SAPP network, and its impact on the behaviour of the generators when under the state of disturbance basing on the available loading and generating power data. The research also intends to provide further general knowledge of monitoring the power network on the interconnected network on the impact when a disturbance has occurred in the system.

1.3 Aims and Objectives

The aim of the research study is to analyse simulations on the modelled grid from the four participating SAPP members with interconnected power system. The grid simulation will be conducted on the whole modelled SAPP grid and on the likely disturbance in the interconnected system such as the faults on transmission lines and synchronous generators. In order to:-

a) Determine the effects of frequency relative to speed and rotor angle on its related parameters on generating machine and transmission for SAPP network;
b) Analyse the simulated results and determine the magnitude of disturbances for SAPP power system;
c) Determine the dynamic performances that should be required to be undertaken when operating SAPP power system; and
d) Identify the available standards to be applied for system reliability indices for effective operation of SAPP power system

1.4 Motivation

Presently the power networks worldwide are interconnected with other operating utilities and depends on the use of system control to effectively utilize the available plants hence reliability and value for money have become the source of electricity market reform and further expansion of electricity development. This is the motivating factor that needs to be understood on how other successful pools have operated their interconnected power system and their electricity supply become free from unnecessary outages and disturbance. SAPP should be the mirrored to other African power pools that operate the power pools with effective performance in the electricity network.

Power system dynamic analysis is one of the studies required to be undertaken by SAPP region in order to improve the controllability of the generating machines that are designed to produce at least maximum power output so that it can withstand any sought of change whilst in synchronism. This being the case, it will then provide a general behaviour in particular machines when an event of disturbance has occurred to the system operator.

1.5 Hypothesis

The simulation of steady state stability will basically check power flow from a branch to the other branch at normal operation and dynamic stability analysis will be simulated to check the effects of disturbance on the system and the simulations will further compute the required generator characteristic to determine the initial oscillation modes for the system where excitation and speed governor are controlling the synchronous generators. This means that the power flow will be determined by the capacity and loading of the network by using the Newton–Raphson algorithm that converges the required solution for the large network and the eigenvectors for modified SAPP grid.

Dynamic Analysis will, therefore, study the power system at generation plant that has been subjected to small variations in load and generation at steady state conditions. It will further analyse the effects of rotor angle due to insufficient synchronizing torque and also the behaviour of rotor oscillations when there is insufficient damping torque[6]. SAPP network will be represented in the single line diagram as the model in the DIgSILENT Powerfactory software engineering tool in order to realize and understand the effects of small signal disturbance so that sufficient damping torque is provided in the network.

The fundamental aspects of power stability will be based on the mathematical analysis of state variable in the dynamic system that will derive the analytical techniques to encompass the power system behaviour and pinpoint the other dynamics necessary for its operation by use of simulation software[7].

1.6 Research Questions

There are a number of system disturbances reported every month in SAPP network. The root cause will be investigated and analysed after following the sequence of events at a particular time of the disturbance through the tripping of transmission and generation equipment. The post fault analysis would be reduced when power system analysis could have included the effects of small signal stability. Therefore, the research proposal seeks to answer the following research questions during investigations:

a) What are the dynamic performance constraints apart from the transient studies that may limit member countries from achieving the declared capacities for the SAPP network?
b) What strategic interventions are required in the SAPP network in order to perform optimally at the desired operating conditions?
c) What are other most effective instrumentation/control tools and or strategies that can be used to evaluate the dynamic performance in the SAPP Area Control Centres?
d) Using information obtained from the dynamic performance studies, how can the SAPP network be optimally operated technically and economically using its operation guidelines

1.7 Methodology

The aim of the research study is to analyse effects of small disturbance in the interconnected power system in particular with dynamics of generating machines and events of disturbance caused by the transmission lines in SAPP Network

a) Literature Review on the fundamental principle of steady and transient state for multi generating machines interconnected in a power pool.

b) Literature review on the theory and assessment of the small signal analysis and relate to the simulated results. The literature review will assess SAPP Operating Guidelines;

c) Literature review to identify solutions for the system improvements on the grid networks that will provide the improved delivery service for SAPP Network to reduce system disturbances.

d) Develop single line diagram for the high voltage SAPP Network using in the Digital Simulation of Electrical Network (DIgSILENT) Software;

e) Obtain data for the machines in generating stations, transmission lines and load that has been connected in SAPP Network;

f) Run a simulation of the developed grid on SAPP Network;

g) Analyse the simulated waveforms and determine the magnitude of disturbances for SAPP power system;

h) Determine the dynamic performances and place the required solutions to be undertaken to improve efficiency when operating SAPP power system;

i) Identify the available standards to be applied for system reliability indices for effective operation of the SAPP power system;

CHAPTER 2

2 LITERATURE REVIEW

Power system dynamic analysis can be described as the behaviour of the system between the occurrence of a major disturbance and return to a steady state condition of a power network. It encompasses the time the system is disturbed from a loaded condition through the disturbance to the next action applied to the system equipment and controller to remain in synchronism. It requires acquiring knowledge of characteristics and modelling of the individual system component to determine the required dynamics of an interconnected power system[8]. However, the dynamic analysis dwells on power system stability to operate and control energy balance in order to provide sufficient restorative actions to counter disturbances.

Kundur et al[9]has defined power system stability in the Joint Task Force on Stability terms and Definitions as: "*the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance , with most system variables bounded so that practically the entire system remains intact".* The definition has termed the word 'electric power system' which comprises of the high voltage primary plant and associated secondary equipment in the power network that will carry generated voltage and the current drawn by end users. The primary plant equipment normally carries a potential charge of the nominal rate of the voltage and secondary equipment provides a replica of the high voltage and primary current flowing in the primary plant. The signal is used to provide an operational status indication of the plant whether open or closed position.

The output values from the secondary equipment are used for indicating measuring instruments, provide measured values for protection equipment and remote indications on the status of the primary equipment in the substation. The primary plant in substations are adequately planned and designed to perform their designed function but due to abnormal conditions, they will be subjected to faults and change of load as the main physical disturbance, protection relays acquires the measured values from the output of the secondary equipment to initiate and eliminate the abnormal condition and also control abrupt change of parameters that has occurred in the primary system.

The physical disturbance that has been stated in the definition can be stated to be the large disturbance that has been studied extensively throughout the history of the power system. This requires the protection system to detect, act and isolate the faulted part in the system either this can be done immediately or time delayed depending on the magnitude of the fault or disturbance that is caused by normal and sudden load changes. The physical disturbance depends on the natural cause and should be able to be controlled by operating the affected part only and still remain in synchronism. It is also important to understand that the synchronous generators supplying the interconnected power system are also affected by such disturbance event[10].

The South African Grid Code has defined in its preamble that the interconnected power system consists of the transmission network that can consist of the wire, electrical components connected to the network. It also includes measurable components from the secondary equipment that coordinate the operation to one power system in transmission level, generating station connected to the national grid and international grid and the system operator[11]. Based on this definition of an interconnected power system, dynamic stability analysis forms part of a vital study to examine the damping oscillation of the synchronous machines that the measurable components supporting the transmission network will not be able to indicate immediately the disturbance of any nature. However, the damping oscillations of the power system require the understanding of the characteristics of the generator design and its performance when affected by a disturbance in the system. This is then required to analyse the behaviour of the generators when affected by the disturbance system.

An interconnected network such as the Southern Africa Power Pool (SAPP) is made up of hydro-based and coal-based generation sources for the extensive generation of electrical power to be consumed and traded amongst operating members in SAPP. The design and size for the hydropower stations are quite different from that of thermal stations. This investigation will study and analyse the effects of damping oscillations in such a complex interconnected power system.

National electrical grids were established to serve each country .With regional integration, these networks had to become interconnected to facilitate energy trading and maximising the economics of scale, which an interconnected system have over non-interconnected disparate systems. In Africa ,SAPP has low access to electricity of 24% if compared to 36% in East Africa power Pool (EAPP) and 44% from West Africa Power Pool (WAPP) and this is due to a level mixture of economies of member countries [12]. The low access of electricity in Southern Africa means that average population of the Southern Africa Development Community (SADC) use different sources of energy. South Africa has the highest electricity consumption and when even compared to the rest of Africa and generates 62% of the total power in SAPP Pool[3]. The interconnection of the grid is complex due to unilateral directional of power flow and the system is forced to operate close to the maximum limit to suffice the market demand [13]. When a disturbance occurs, the system misbehaves due to scattered location supplied with electricity, low electricity consumption and also inadequate maintenance of power equipment [14].This then necessitates the need to undertake different studies to suffice the growing demand for electricity in the regional in order to reduce the public outburst when the quality of supply and services deteriorates due to mitigation of system operation in the interconnected power system.

The generation of electricity will rotate synchronous machines and physical movement of the equipment will be required for massive mechanical machinery to produce electricity that will be synchronised into the network. The analogy is the conversion of systems from mechanical to electrical energy and turns to be electrical to mechanical energy when under any disturbance .Therefore, another complexity arises when multi-machines supply the interconnected power system, when a disturbance occurs the electromechanical oscillations will change its phenomena and synchronism might be disturbed in the power system [15].The occurrence of unstable oscillations have been known through various tests on 132 kV line with a single generator and also through a various study on mathematical derivations [16].The recent study occurred in an interconnected power pool where a heavily loaded transmission line feeder circuit breaker failed to eliminate a fault causing the source of supply breaker to isolate the fault and caused a total shutdown of the network . An investigation that was carried out revealed that automatic generation control equipment tried to restore supply as per operation condition of load dispatch but the load stress caused other lines to trip and limited reactive power from the generators that were producing a low capacity of power[17] . The investigation revealed the system outage was caused by damping oscillations on the network after carrying out modelling and simulation of the system network.

The main power generations in the Southern Africa are based on the water and coal as the main source of energy. Most of the hydro generations in Zambia, Zimbabwe, DRC and Mozambique has its supplied been consumed in South Africa and South Africa has its main supply from thermal and other sources of energy. Most countries have resolved to accelerate new development of generation plants and its evacuation power in the countries where available natural resources can sufficiently make an impact in the incremental of access of safe and reliable electricity supply. The essence of high level studies is essential to be undertaken to improve dynamic modelling on the new plant and the old plant to verify the power plant dynamic data that is required in most utilities in the Southern Africa so that will determine the different characteristics and behaviour of different equipment connected to the system under any type disturbance [13]

2.1 Mechanical Energy on Synchronous Machines.

The fundamental relationships and mathematical equations of the synchronous machine are as follows:

2.1.1 Hydro Power Generation

In hydro-electric power generation, energy conversion takes place in accordance with the Law of Conservation of Energy, from water falling from a height (potential energy) and impinging on turbine blades to initiate rotation (kinetic energy).

Countries that have suitable hydro generation potentials, such as Zambia, Democratic Republic of Congo, Zimbabwe, have sites, which are developed after feasibility studies are conducted to ascertain the technical, economic, environmental and Social impact assessment[18] has been fulfilled with mitigating factors. Therefore generating capacity on hydro-electrical power will be a function of constant flow rate of the perennial river or into the storage and head to discharge hydraulic turbines basic equation for the hydropower generation is stated as follows[19]:

$$P=9.81\ \eta\ \rho\ Q\ H \qquad (2.1)$$

Where:

P = Power

η= Plant efficiency

Q= Discharge flow rate (m^3/s)

H= head (m)

ρ = density of water (kg/m^3)

2.1.2 Thermal Power generation

In an interconnected power utility such as SAPP, the natural resources to produce electricity will indirectly assist countries with trade cooperation and just like in Southern Africa, South Africa has abundant coal deposits about 53 billion tonnes and it will take ages to be depleted hence large generation of electrical power is guaranteed for the country [20] and the region.

Thermal generation plant referred in figure (2.1) is installed close to the site where coal is extracted or where there are an ease means of transportation to the generation station. The coal particles are crushed into dust in the pulverising mill in order to increase the surface area and aeration in the boiler. The pulverised coal is combusted and burn in the boiler to heat water to produce high-temperature high-pressure steam which is used to generate electricity by the turbines. The steam is also absorbed, condensed and reformed into water, ready to be recycled for the production of steam in the boiler. The temperature of the recycled water going into the boiler through the cyclone needs to be almost the same degrees with the already available water in the boiler.

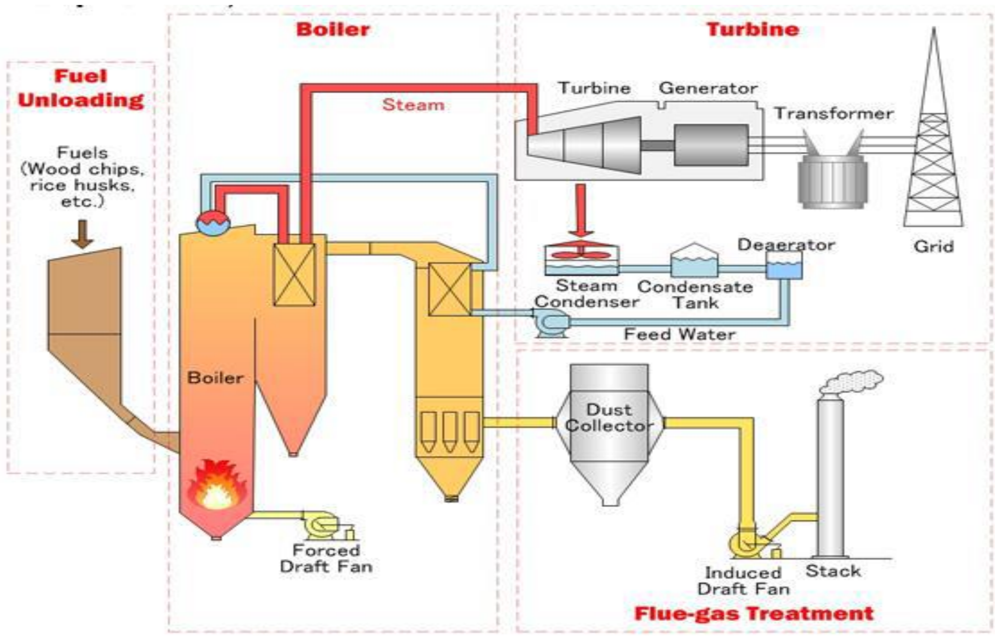

Figure 2-1: Illustration of a typical thermal power plant

Crushed coal is fed mechanically or pneumatically to the lower portion of the boiler as shown in figure 2-1. The forced draft fan will blow air at the bottom of the boiler so that air will be used to constantly burn the crushed coal. Steam and dust will leave the boiler. Fuel gas treatment will be initiated from the boiler and undergoes into processing cycles in the cyclone where dust is separated and fall into the dust collector. The induced draft fan will the used to release gas into air after being purified in the stack. From the dust collector, dust is recycled at the back of the boiler to provide uniform low portion of temperature. The dust collector also captures sulphur that further provides combustion efficiency through heat absorption in the walls of the boiler. Flue gas leaving the cyclones passes through the dust collector and induced-draft fan to the stack. Dust inventory in the boiler is controlled by draining hot ashes through an ash cooler. In the gasification process, coal is partially reacted with a deficiency of air to produce low heating value fuel gas.

Therefore, the thermal generation requires the quantification of coal with good calorific values kJ/kg, availability of water and transport to constantly supply the generating plants. The thermal generation plant relies on the heat to drive mechanical equipment for the production electricity.

2.1.3 Torque on Synchronous Machine

When a source of energy has been initiated to start flowing into the generation system, whether hydro or thermal, it will then turn the massive mechanical equipment by rotating the rotor and generate electricity through the stator windings. The generated voltage will be transformed at different levels before being consumed by the end user and mostly located at very long distance away from the generation plant.

When the generation system and its associated supply are synchronised into the grid, then the system is operating at normal conditions, it will be termed as steady state. However, when the steady state is disturbed, distorted torques will act on the rotor and the net torque will then the change speed to either accelerate or decelerate[21]as defined below.

$$T_a = T_m - T_e \quad (2\text{-}1)$$

Where:

T_a = accelerating torque ($N.m$)

T_m = driving mechanical torque ($N.m$)

T_e = load electrical torque ($N.m$)

From the equation (2.2), when the system is in the steady state then $T_m = T_e$, because the torque from the turbine and rotor shaft is synchronised with the corresponding voltage produced in the stator and load with constant synchronous speed, ω_s

2.1.4 Steady state of synchronous machine

In all type of generations, the energy source will drive a massive equipment for it to convert from heat or kinetic energy into mechanical energy through turbines and rotor through the stator windings to generate a symmetrical electrical voltage. Therefore, the stability of machines will be determined by angular momentum and inertia constant of synchronous generators because it is related to laws of motion. The inertia constant, **H,** denotes the kinetic energy stored in the rotating parts of the machine at synchronous speed per unit rating of the machine in **G** MVA

$$GH = \frac{1}{2}J\omega^2 \quad (2.2)$$

Where:

J = polar moment of inertia of the generating parts (Kg/m^2)

ω_s = angular synchronous velocity in electrical radians/s and

= *360f* electrical degrees per second

If M is the corresponding angular momentum, then

$$M = J\omega s$$

$$M = \frac{GH}{180\text{f}} \tag{2.3}$$

Where:

f = system frequency in Hertz.

The momentum of the machine, when disturbed, should have an impact on oscillation before such mass of the equipment will halt to a standstill also the weight of the rotating machine shall not stop immediately and hence will obey the laws of motion. The moment of inertia of synchronous generator is given

$$M = \frac{WR^2}{32.2}\ lb.f^2 \tag{2.4}$$

Where:

W = weight of the rotating parts of the machine and

R = radius of gyration but the manufacturer of the machine will only provide the value of WR^2.

From equation (2-1), where $T_m = T_e$ then to obtain power, torque is multiplied by synchronous speed, ω_s

$$T_m\omega_s - T_e\omega_s = P_m - P_e = 0 \tag{2.5}$$

Where:

P_m = represents mechanical Power

P_e = represents electrical Power

When electrical power, P_e changes, it means that the loading of the generator has changed and mechanical torque, P_m should be maintained to remain constant after the synchronous speed changed.

The motion of the rotor is then described by second order equation and obeys newton second law of motion. Hence, the equation of motion shall correspond to the total change of power as shown:-

$$P_a = P_m - P_e = M\frac{d^2\theta}{dt^2} \tag{2.6}$$

but now P_a shall be the total power generated by the machine and θ will represent the angular position of the rotor in the stator winding and when in steady state it will be $\frac{d\theta}{dt}$ equal to synchronous speed, so $\theta = \omega t + \delta$ where the constant $\boldsymbol{\delta}$ is called the power angle of the synchronous machine. If it is then substituted with equation (2.6), by combining with equation (2.3), $M = \frac{GH}{180f}$ and divide by G in the same equation (2.3), per unit of the machine is obtained and will be as provided in the below equation: -

$$\frac{H}{180f}\frac{d^2\delta}{dt^2} = P_m - P_e = P_a \tag{2.7}$$

Where:

H = Inertia constant of the machine

$180\,f$ = nominal speed = ($2 \times \pi \times f$) radian/s

$\frac{d^2\delta}{dt^2}$ = changes of load angle

The equation ((2.7) is the fundamental swing equation and states the required parameters necessary for dynamics and stability on steady state of the machine but has been realised without assuming the reality on variation of load and the following : -

Assumption 1: Angular momentum is taken as constant as 1.11x 10^{-4}H, and

Assumption 2: Damping $\frac{d\delta}{dt}$ has been neglected with the thinking of adequacy amplitude attained on the so called first swing and the system will be able to eliminate the disturbance and remain in synchronism.

2.1.5 Rotor Swing on two machines

From equation (2.6), where $P_a = P_m - P_e = M \frac{d^2\theta}{dt^2}$, it is can be expressed the same for each machine

$$M_1 \frac{d^2\delta_1}{dt^2} = P_{m1} - P_{e1} \quad (2.8)$$

$$M_2 \frac{d^2\delta_2}{dt^2} = P_{m2} - P_{e2} \quad (2.9)$$

Where:

1 and 2 are integers for M_1 , M_2, δ_1, δ_2, P_{m1}, P_{m2}, P_{e1} *and* P_{e2}

Let the power angle between two rotor axes from two separate machines but at the same generating station be $\delta = \delta_1 - \delta_2$ and when the equations (2.8) and (2.9) are combined, it will simplify the calculation, the result will be as follows:

$$M \frac{d^2\delta}{dt^2} = P_m - P_e \quad (2.10)$$

Where:

$$M = \frac{M_1 M_2}{M_1 + M_2}$$

$$P_m = \frac{M_2 P_{m1} - M_1 P_{m2}}{M_1 + M_2} \quad (2.11a)$$

$$P_e = \frac{M_2 P_{e1} - M_1 P_{e2}}{M_1 + M_2} \quad (2.11b)$$

The result of the rotor swing on two-machine has the same effect as a connection of resistances in a parallel circuit and being at the same station, the rotor angular momentum will be almost the same values and in most of the cases, it will be manufactured by one company.

2.1.6 Mechanical analysis of the synchronous machine

From the explanation on rotor dynamics, it has been observed that damping and kinetic acceleration have been neglected and dealt only with a steady state operation where at any slow change in the system the kinetic energy remains unchanged.

If a three phase fault is then considered, the worst scenario, where all voltages will be zero and consequently lose the load, the machine load will be reduced to zero and with a good protection system, the generator will be spinning getting ready to be synchronised into the system. When such moments occur then, the general energy equation should be considered where mechanical energy = electrical energy ± kinetic energy + losses.

From equation (2.6), where $M\frac{d^2\theta}{dt^2} + P_m + P_e = P_a$, is loaded synchronised machine and since the mechanical power will be constant, but when a fault occurs then the equation will be represented as follows

$$M\frac{d^2\delta}{dt^2} + K\frac{d\delta}{dt} + P_e \sin\delta = P_m \tag{2.11}$$

Where:

M	=	angular momentum
$K\frac{d\delta}{dt}$	=	damping velocity
$P_e \sin\delta$	=	electrical power
P_m	=	mechanical power

When a disturbance has occurred in the system, $K\frac{d\delta}{dt}$ will tend to accelerate and then decelerate before it settles down; and electrical power, $P_e \sin\delta$ will be equal to zero.

2.2 Primary plant of interconnected power system

The following primary equipment represents the electrical circuits with its characteristics and behaviour that are used in the interconnected power system. These equipment have been used for the study of dynamic analysis in the DIgSILENT Powerfactory software tool and will be examined as the transient behaviour of power pool.

2.2.1 The synchronous generator

The synchronous machine for ac generator is driven by a turbine coupled with rotor and rotor shaft to change the exerted mechanical energy into electrical energy. The electrical energy will be produced by the rotation of the rotor shaft coupled with field windings that will eventually generate the resultant magnetomotive force (mmf) with the stationary stator windings.

The field windings will be excited by being injected with a separate source current for the production of the magnetic field which will thereafter induce alternating voltages in the armature windings of the generator[22]. However, the high magnetomotive force that the separate source current will initiate when combined with the current in the armature windings, the resultant flux across the air gap between the rotor and generator generates voltage in the coils of the armature windings and provides the electromagnetic torque between stator and rotor.

It is important to note that the armature windings carry the electrical load for the grid and also operate at higher voltage than field windings hence will be subjected to sudden changes of load and faults hence requires mechanical strength and insulation.

The interconnected power pools such as SAPP will contribute to the pool with generators such as thermal and hydro types of generators that are connected to the grid. They difference of the generator arises from the type of energy sources being used for the generation of electricity and as such thermal and hydro have a different type of the rotor pole arrangements such as round and salient pole rotor respectively.

2.2.1.1 Armature reaction with the field windings

The armature windings are spaced and distributed at 120°electrical degrees apart to allow equal rotation of magnetic field by the rotor and thereafter voltage which has been placed at 120°electrical degrees will be produced in the windings with a constant time phase.

The rotation of the rotor at constant speed $\boldsymbol{\omega_s}$ will produce the magnetic field for the electrical energy that will undulate with the changes of its position relative to the design of the stator windings. At any moment when the machine is rotating magnetomotive force (mmf) is produced through the air gap designed in between the stator and rotor and due to the electromotive force from the field windings and the total mmf will have a sinusoidal spatial distribution with constant amplitude and phase angle $\boldsymbol{\omega_s t}$ as the function of time[7]. The whole sinusoidal wave will then move at a constant velocity of $\boldsymbol{\omega_s}$, electrical rad/s.

For the machine with P_f field poles, the speed of rotation of the stator field is

$$\omega_{sm} = \frac{2}{P_f}\omega_s \text{ mech. rad/s}$$

$$\eta_s = \frac{60\omega_{sm}}{2\pi} = \frac{120f}{P_f} \quad revs/min \tag{2.12}$$

Where:

ω_{sm}	= synchronous machine speed
P_f	= field Poles of the machine
ω_s	=Synchronous speed in radians per sec
f	= system frequency
η_s	= Speed in revs per sec

This the same as the synchronous speed, $\boldsymbol{\omega_s}$ of the rotor in equation (2.2), $GH = \frac{1}{2}J\omega_s^2$ that has been represented $\boldsymbol{\omega}$ as for the swings of the machine.

2.2.1.2 Electrical Equivalents for Synchronous Machines using Direct and Quadrature Axes

Figure 2-2, depicts the synchronous machine with a salient rotor and the phases of the generator terminal lie in the stator windings on a- axis, b-axis and c- axis where the windings a, b, and c respectively represents points that will be connected to the grid.

The field windings are represented by the windings labelled, **e** on d-axis and supplied through $\mathbf{v_e}$ and the windings Q and D on q- axis and extended d- axis represents the damping windings[23]

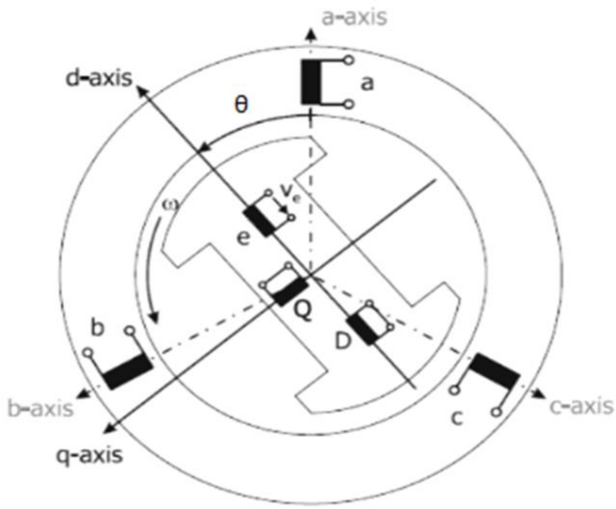

Figure 2-2: d and q axes for synchronous machine

The d and q axes for synchronous machine can be analysed by self-inductances and the linear flux -mmf relationship for each coil in the a ,b and c axes to be L_a , L_b and L_c be equal to each other and mutual inductance due to magnetically coupled windings L_{ab}, L_{bc} and L_{ca} in between each adjacent pair of concentrated coils[24] of the same axes.

In accordance with Faraday's Law[7], the self-induced voltage in respect of the instantaneous value of flux linkage, ψ, as such saturation and hysteresis of the magnetic circuit and eddy current in the armature is not considered. It considered in that manner so that the distribution of flux in the stator winding is systematically sinusoidal [25]. Where flux, $= Li$, the n the following is derived

$$u_a = \frac{d\psi_i}{dt} + r_a \tag{2.13}$$

Where:

r_a	=	resistor connected in series and,
i	=	current
u_a	=	induced voltage

t = time in electrical radians

On similar note the two magnetically coupled windings between coils a and b, the induced voltage will be derived as below

$$u_a = \frac{d\psi_1}{dt} + r_a i_1$$
$$u_b = \frac{d\psi_2}{dt} + r_b i_2 \quad (2.14)$$

Where:

r_a, r_b = resistor connected in series

i_1, i_2 = instantaneous current between coils in the phases

u_a, u_b = induced voltage between the coil in the phases

ψ_1, ψ_2 = flux in the phases

The self and mutual inductances of the stator circuits will change with the rotor position due to variations of permeance of magnet flux path caused by non-uniform air gap from the field windings hence the voltage for the stator circuit will be represented as below[7, 26]:

$$u_a = \frac{d\psi_a}{dt} - R_a i_a = \eta\psi_a - R_a i_a$$
$$u_b = n\psi_b - R_a i_b$$
$$u_c = \eta\psi_c - R_a i_c \quad (2.15)$$

Where

u_a, u_b, u_c = induced voltage in stator windings

ψ_a, ψ_b, ψ_c = flux in the phases between stator and rotor

R_a = Stator winding resistance

i_a, i_b, i_c = current flow in the stator windings

η = represents the differential d/dt

The common study of salient pole synchronous machine has been solved in terms of rotor with two axes of mechanical rectangular symmetry [27]called

a) Direct (d) axis are centred magnetically in the centre of north pole

b) Quadrature (q) axis, positioned 90° electrical ahead of the d axis

Various studies have shown that dq0 transformation suits very well when the synchronous generator has three phase balanced reactance and armature resistance in the machine. With this concept of a balanced circuit for the rotor and stator then disturbance of any sought will be solved by the circuit representation of dq0 transformation by equation (2.16) whether it's capacitive or inductive load[26, 28].

Figure 2-3 and 2-4 represents the simplified diagram for synchronous machines for d and q axis that has been adopted by IEEE standard definition [27, 29] to represent electrical circuit diagram of d and q axes based on the leakage and mutual reactance.

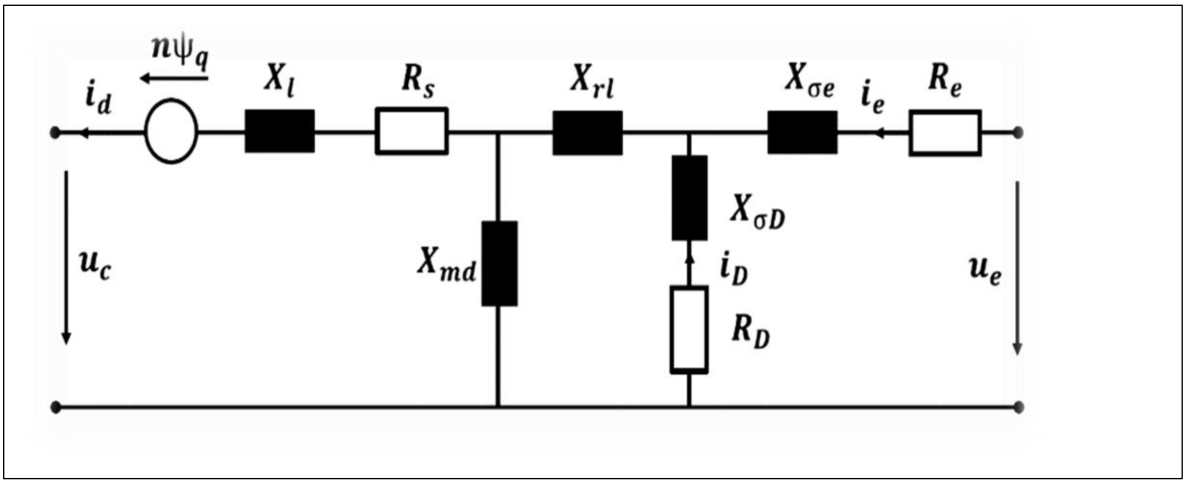

Figure 2-3: Simplified diagram of electrical circuits for d axis salient machines

R_D, R_Q

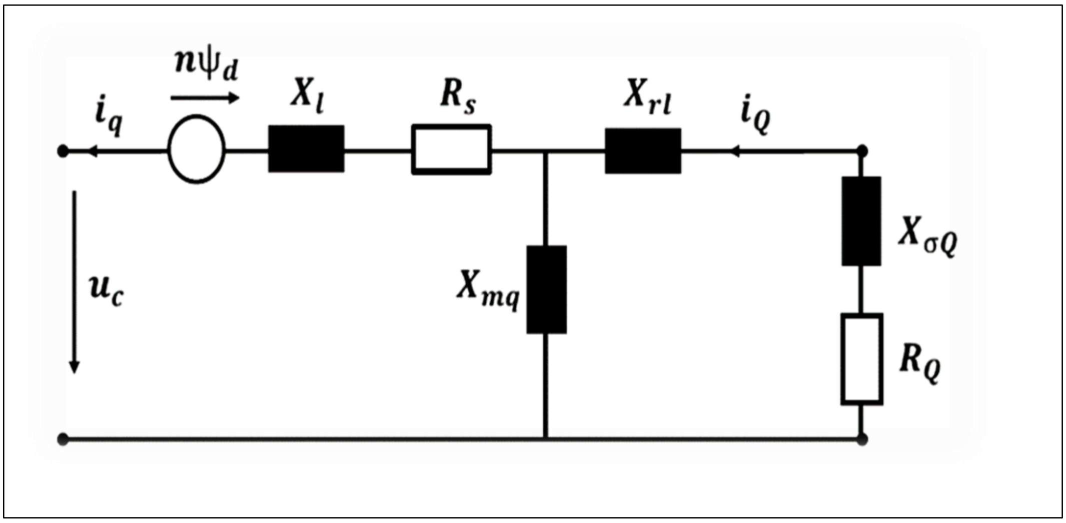

Figure 2-4: Simplified diagram of electric circuits for q axis salient machines

Where:

$\eta\psi_q, \eta\psi_d$	:	Total flux linkage with respect to efficiency of speed
i_d, i_q	:	Current flow in the d and q axes respectively
X_l	:	Stator leakage Reactance
R_s	:	Stator resistance in Ohms
X_{rl}	:	Armature leakage between field and damper winding
X_{md}	:	Mutual reactance between field and damping windings on d axis
X_{mq}	:	Mutual reactance between field and damping windings on q axis
$X_{\sigma D}, X_{\sigma Q}$	:	Damping reactance in extended d axis
$X_{\sigma e}$	:	Mutual reactance between damping and field windings
R_D, R_Q	:	Equivalent damping resistance
i_Q, i_D	:	Instantaneous d- and q axis damper winding current

Basically, the equivalent phase voltages on d and q axes for the stator in terms of phase flux linkages and currents from equation (2.15) by applying $dq0$ transformation will result in transformed components of voltages, flux linkages and currents as follow [7]:

$$e_d = p\psi_d - \psi_d p\theta - R_a i_d$$

$$e_q = p\psi_q - \psi_q p\theta - R_a i_q$$

$$e_0 = p\psi_0 - R_a i_0 \qquad (2.16)$$

Where:

e_q, e_d, e_0	=	transient voltages in dq0 axis in respect to stator windings
$\psi_q, \psi_d,$	=	flux in the phases between dq axis
R_a	=	Stator winding resistance
i_d, i_q, i_0	=	current flow in the in the dq0 axis
$\eta = p$	=	the differential operator d/dt
θ	=	phase angle between a-axis and d-axis (figure 2-2)
$p\theta$	=	angular velocity of the rotor
	=	$\omega = 2\pi f$ electrical rad/s

From equation (2.16), $\psi_q p\theta$ and $\psi_d p\theta$ show that flux and change of load angle has a common reference point to generate voltages on the other side on d and q axes and rotates in synchronism with the stationary armature coil. The terms also denote the change of flux $p\psi_d$ and $p\psi_q$ due to space between the rotor and stator (speed voltages) which will change due to frequency from the grid in terms of the voltage measured from the grid transformer.

When i_d, i_q, i_0 remains constant as the rotor moves then there will be no change to the stored magnetic energy. The rotor power output will be equal in magnitude and opposite in the sign to the rotor losses as has been shown in equation (2.11) and has been derived from where mechanical energy = electrical energy ± kinetic energy + losses

$$M\frac{d^2\delta}{dt^2} + K\frac{d\delta}{dt} + P_e \sin\delta = P_m$$

Where

$M\dfrac{d^2\delta}{dt^2}$	=	kinetic energy across the gap
$K\frac{d\delta}{dt}$	=	rate of decrease of total stored energy
$P_e \sin\delta$	=	electrical energy
P_m	=	Mechanical power

2.2.1.3 Saturation of mutual reactance of synchronous machines

The production of electricity is due to a magnetic force caused by rotation of the rotor to the windings of the stator. Principally, the flux density is proportional to magnetic field strength and until such a time it become saturated due to the material used for the permeance of flux and mostly iron is used for the windings the synchronous machine.

Therefore, the magnetic strength of the electromagnetic depends on the number of turns of the coil, current flowing through the coil or the type of material being used and then identify the maximum current that will require protecting the generator windings.

Generally, saturation effects are not considered when it's assumed to operate within the steady state value. In the winding circuits where reactance will be used to change into another measurand, saturation will exist in the reactance of synchronous machines. However, it will be proper to include the saturation of magnetising circuits in the reactance between axis and dq axes as x_{aq} and x_{ad} . Figure 2-5 presents the saturation of the synchronous generator between the terminal voltage on y-axis and excitation current on x-axis.

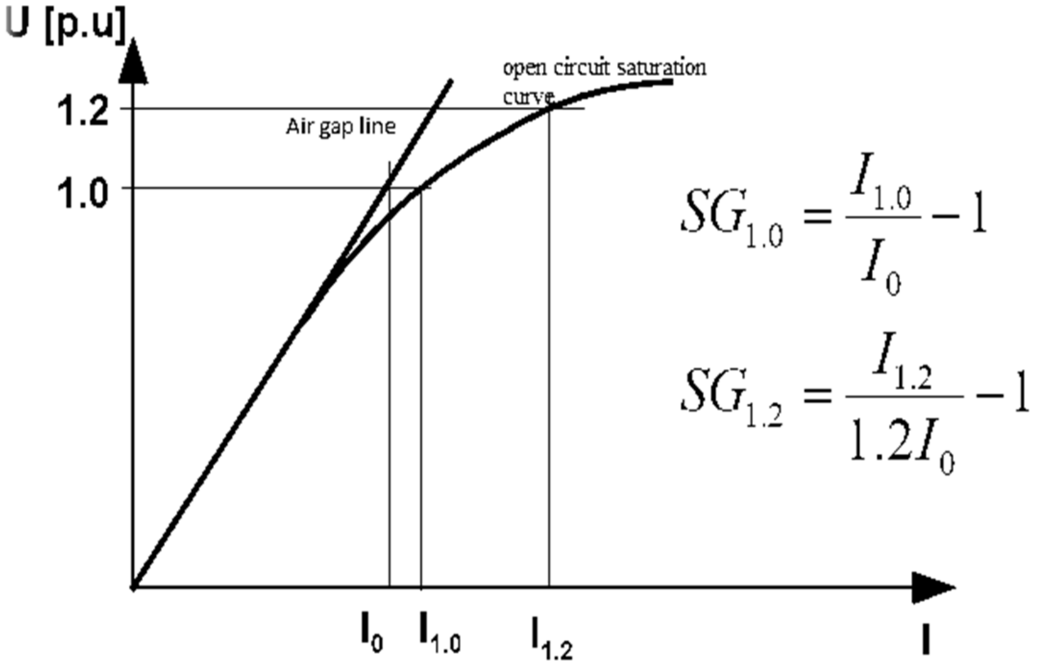

Figure 2-5: Open loop saturation for synchronous generator

The air gap line indicates the excitation current that is needed to overcome the reluctance of the air gap and to remain constant at an increase of voltage and current. The degree of saturation can be noted when the air-gap line departs with the open circuit characteristic curve. The values are given under open circuit conditions so that $U_{1.0}$ is actually behind x_l the leakage reactance and saturated magnetising inductance X_{rl}. The generation saturation SG shall be used as the basis of saturation functions [8].

2.2.1.4 Saturation of self-inductance on rotor circuit due to voltage regulation

It has been stated that field windings will be excited by being injected with a separate source current and thereafter induce alternating voltages in the armature windings of the generator. It is the excitation that will be used to regulate the generated voltage to prevent the saturation of the generator. However, in an event of any disturbances, if the change of voltage is within its dead band and has not reached the maximum or minimum voltage shall not change to the new voltage level and even if the settings can be changed to the minimum set[30].

In figure 2-6 indicates the characteristics of the power angle curve on the behaviour of excitation voltage at increased power. Considered the rated generator voltage and varied the exciter voltage. The shapes were achieved with beyond rated saturation in figure 2-6.

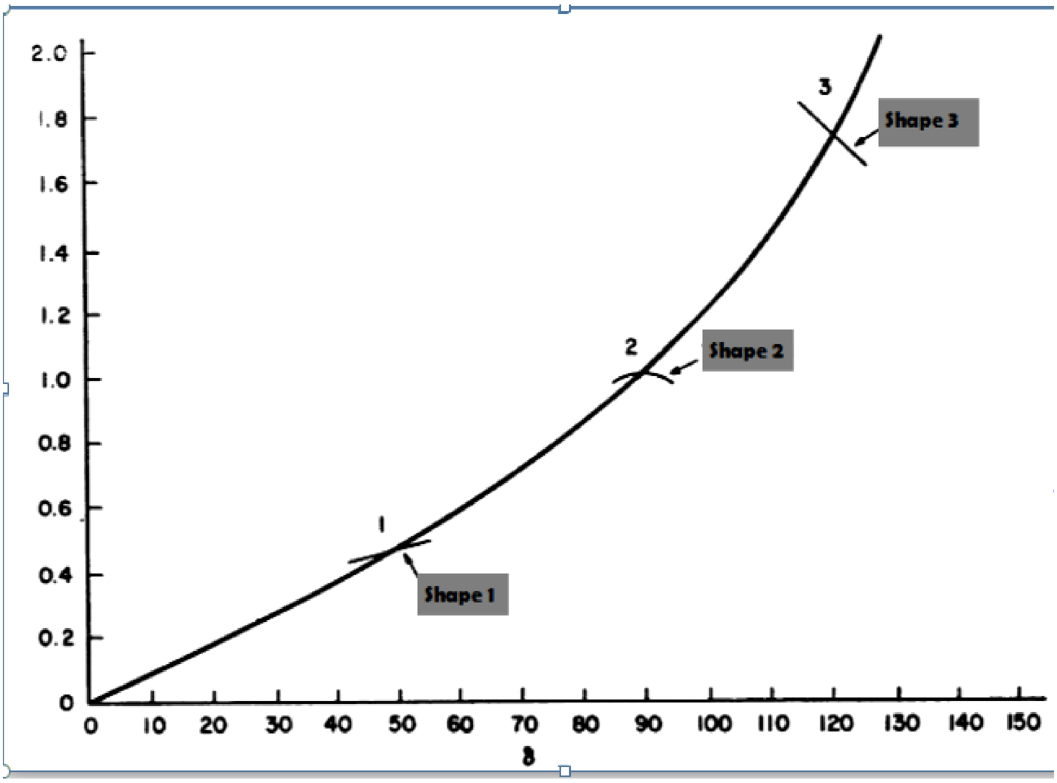

Figure 2-6: Power angle characteristics of the excitation for the synchronous generator

Figure 2-6 was obtained on the test that was carried on voltage regulator that was controlling excitation voltage by assisting or opposing the current flow in order to maintain the generator voltage preferably constant [31].   The figure shows an inversely proportional to power generated with the load angle at the terminal of the generator. Shape 1 presents that the machine is under excited at about 50% of the load with an increasing mode and corresponds to the air gap line. Shape 2 indicates the normal excitation at 100% load but will hold down voltages at full load. Shape 3 indicates that over excitation of generation.

Figure 2-7 was obtained by the simulation of the single generator. The generator was simulated with a fault that took a long time before being cleared and the result on the power angle has the three shapes that were done by actual test.

Figure 2-7 was obtained during the simulation on DIgSILENT Powerfactory software tool on a single short circuit fault near the generation station and the results of the power angle are generated as the mode of shapes. However, it can be noted that during the fault, the exciter will be regulating the voltages of the faulted generator. This gives the advantage to understand that the generator will undergo the different processing of excitation as shown as shapes in figure 2-7.The plot of figure 2- 7 has been labelled under excitation as in shape 1 of figure 2-6, normal as in shape 2 in figure 2-6 and over excitation for the shape of 3 in figure 2-6.

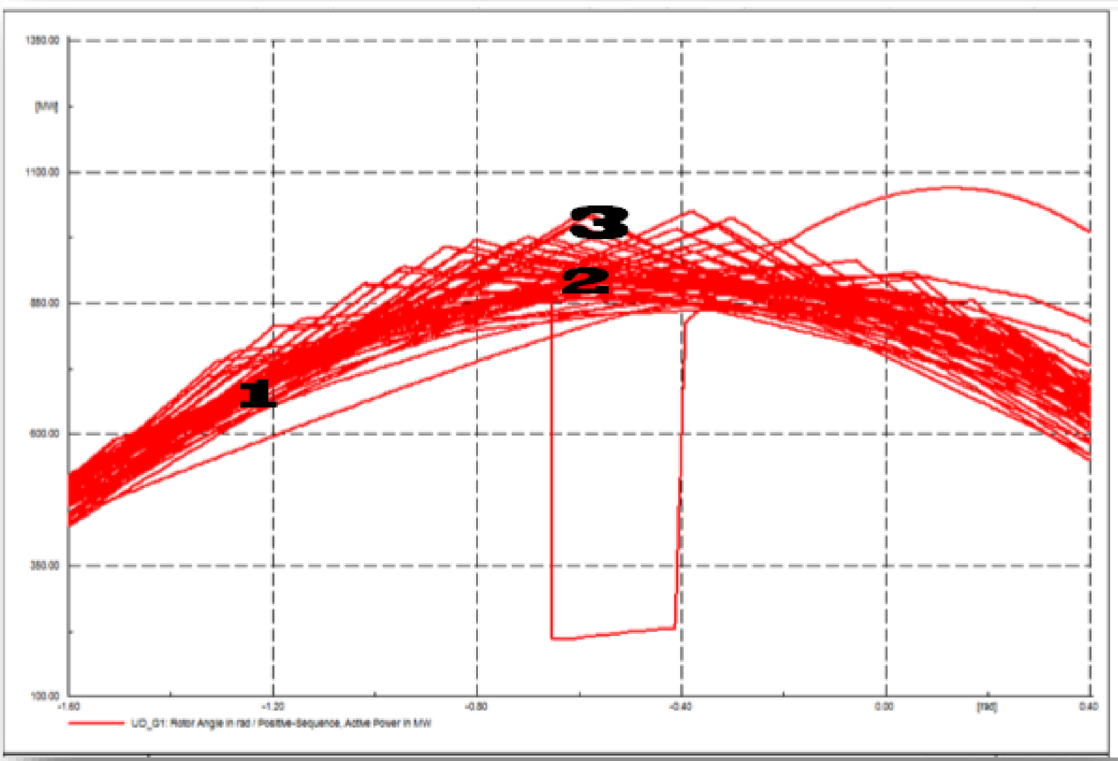

Figure 2-7: Saturation of synchronous generator during excitation

Figure 2-6 was produced at every instant value to measure the power–angle diagram but the approximation on the plot has been adequately detailed in figure 2-7. In order to obtain a detailed information it requires speed and accuracy of the measuring instrument. The measurement that was taking individual value for testing excitation is improved in simulation to produce more data than using analogue measuring devices.

2.2.2 Transmission Overhead Line

The generated power is then transferred from the generating stations and travel long distances through transmission lines in open country to the customer. It is required to understand the environmental conditions in order to equate both characteristics of mechanical and electrical with climatic details such as temperature, wind velocity, altitude, soil resistivity and etc. through its route so as to maintain safety factors on the pylons and clearances [32].

The power transfer of electricity in Southern Africa will share the unbalance of energy source available from the production of electricity through an interconnected transmission system. The advantage will be the availability of adequate shared capacity and economic utilisation of energy. The other advantage on the interconnection of transmission network within the region pool is the reduction of the reserve generating capacity required for the system and also the use of the cheapest available energy fuel required for the time of production[33].

The benefit of interconnected transmission network can be much emphasised when the design criteria has been broadly studied to achieve the desired power transfer between the generating stations and the load centres in reliable and cost effective manner. The conductor being an important material for the transfer of electricity needs to be analysed on its economic factors and technical performance to survive on an open air with vulnerable weather conditions and constantly provide electricity to the grid [34]. It is therefore required to undertake a process to optimise the choice of conductor and relevant tower configurations. The construction of transmission line is associated with a capital investment and requires much attention for its life expectancy on the line. The extensive study will be required for the analysis of insulations, associated hardware, structure of the tower, foundation and the tower configuration required for parameters of the line[34, 35].

The following are some of the requirement to be evaluated on the general construction and operation of the overhead line as defined in the SAPP steady state security assessment contingency analysis[36]

2.2.2.1 Planning criteria

The planning has been defined as the known factors required for the design and construction of transmission line. It will assess the physical analysis of the transmission line such as the line length after carrying geophysical survey. In SAPP each member will consider developing its own criteria that will conform to minimum transmission planning requirements [36]such as :-

a) Stability limits on a single and poly transmission circuits, servitude and the passing through a substation shall be avoided;
b) Interconnected power flow will not cause to the grid a possible danger when operating under normal or contingency conditions ; and
c) Adequate reactive power will be determined when operating in SAPP grid so that the operating transmission voltages are within the required statutory requirement.

2.2.2.2 Environmental factors

The environmental factors have three aspects that are can be considered for the transmission line [37]and mostly these factors depends on the national environmental policies on

a) Electrical field impact where an analysis will analyse the impact of radio interference caused by the undesired electromagnetic radiation caused by corona limits on the transmission line. The radio interference will mainly have noticed by the people living close the line if they experience the noises on the television and inaudibility of radio.

b) Visual impact determines the limitation of design due to a tradition practised in the country likewise no line shall cross over the cemetery. It is common in almost all countries that no line should pass through natural conservation areas for the safeguard of the animals and staff. The most common problem of visual impact is the passing through a sugar cane fields and during harvest the lines are affected due to smoke and the flames onto the lines.

c) Physical Impact where the transmission has a limited right of way and makes difficult to carry maintenance and reinforcement of the structures is at risk. This will also make difficult for the manoeuvring of equipment during maintenance.

2.2.2.3 Power transfer capability

Power transfer capability will measure the reliability of power from one station to the other under the agreed condition with SAPP coordination centre and the bilateral agreement.

The following are the outlined transfer capability required for the flow of power in the SAPP grid[38]:-

a) System Conditions

It is based on the system conditions that has been availed during scheduled power transfers. The modelling of the transmission line will be based on the line parameters. It should be realised that resistance, reactance and capacitance of overhead line on transmission network are possibly the available electrical parameters that can be derived on the potentially charged conductor. In principle, the resistance of the line will be derived from the length of the line and also the data provided by the manufacturers. The reactance will be determined by the number of coiled strands and distance of the line. Similarly, the charged conductor with respect to the air and ground will determine the capacitance of the line. These parameters make an impact on the transfer of electricity from one point to the other.

b) Critical Contingencies

The generation and transmission power systems will be evaluated to its contingencies to determine the performance of the systems under disturbance. This will be achieved by detailed calculation of overhead line parameters by using the empirical method of the related permittivity of the material, system frequency and size of the conductor and most theories have been developed with and without earthing. The conductor is taken to be parallel with the earth as shown in Appendix 1. The wave propagation on the transmission line will conduct due to voltage gradient in respect of virtual earth and the reactance of the line. The line constants will provide symmetrical results based on the geometry of the tower configuration [39].

The transmission line is mostly earthed on the foundation of any tower or selected towers depending on the other fundamental analysis for the power system. The use of the earth provides a return path where electrical intensity in the dielectric strength shall be used to calculate the self and mutual impedance. Therefore the geometry and coordination of the system are employed to intensify solution [40].

c) System Limits

The agreements will limit the transmission network to be capable to transfer power within the acceptable thermal, voltage, stability specifications.

There are different methods to determine the line performance both analogue and software packages, the load capability depends on the load angle that will be determined by surge impedance loading that is also equal to the line charging in reactive power where a large conductor has an advantage over the reduced stability limitations[41]. The thermal, line voltage and steady state limitations on extra high voltage will have a loadability characteristics that will be required for analysis on the attainable limits. The limits will be considered on assessing different plans that can yield the least cost and provide high technical performance for the transmission line[42].

2.2.2.4 **Determination of overhead transmission line inductance**

It has been known that the economics and technical operations play an important role in the high voltage transmission line to transfer bulk loads and also making sure that the thermal limits are reduced so that the delivered voltage should be within the accepted limits.

Basically, the line parameters are expressed as follows: -

a) Line Inductance measured in Henrys per metre
b) Line shunt capacitance measured in Farad per metre
c) Line resistance measured in ohms per metre
d) Line shunt admittance measured in Siemens per metre

It can be noted from expressions that the measurements are in per metre that means the parameter will vary with the distance of the line and as such in simple terms, to find the inductance of the line it is necessary to consider both internal and external flux flow in the cylindrical conductor

$$L_1 = L_i + L_0 = \frac{\mu_r \mu_0}{8\pi} + \frac{\mu_0}{2\pi} \ln \frac{D}{r} \quad {}^{Henry}/_{metre} \tag{2.17}$$

Where:

D	=	the distance between conductors
r	=	Conductor radius (m)
μ_0	=	relative permeability of free space (H/m)
	=	$4\pi\ x\ 10^{-7}$ H/m
μ_r	=	relative permeability of conductor
L_i	=	internal inductance of conductor
L_0	=	external inductance of conductor

Therefore, substituting equation (2.17), the total inductance will be simplified as follows:-

$$L_1 = 2\ x\ 10^{-7}\left(\frac{\mu_r}{4} + \ln\frac{D}{r}\right)\ \text{H/m} \tag{2.18}$$

If the internal reactance is considered to be $\frac{\mu_r}{4} = 0$ then equation (2.18) will equal to

$$L_1 = 2\ x 10^{-7}\left(\ln\frac{D}{r'}\right)\ \text{H/m} \tag{2.19}$$

The equations (2.17) , (2.18) and (2.19) have been considered for single phase and the following will be achieved when

a) The three phase lines with equilateral spacing and will be represented as follows

$$L_a = 2\ x 10^{-7}\left(\ln\frac{D}{D_s}\right)\ \text{H/m} \tag{2.20}$$

Where:

D_s = the distance from AB, BC and CA being having equal spacing between phases

b) The unsymmetrical spacing on unbalanced circuit that has been transposed and inductance will be calculated as follows

$$L_a = 2\ x 10^{-7}\left(\ln\frac{D_{eq}}{D_s}\right) \tag{2.21}$$

Where

D_{eq} = distances between phases and equal to $D_{eq} = \sqrt[3]{D_{AB}D_{BC}D_{CA}}$

D_S = geometric mean radius (GMR) of the conductor

2.2.2.5 **Geometric mean radius (GMR) of a Conductor**

A geometric mean radius of the conductor is taken as the radius that allows the inductance formula to be reduced to a single term and due to internal flux linkages in the conductor on its diameter.

The manufacturer of the conductor will provide the GMR in the data sheet and the data will be used for defining the conductor type of a high voltage overhead transmission line and shall be used as the input in the geometrical and electrical characteristics of the conductor. In case, when the manufacturer has not provided the GMR can be calculated as equation (2.21) but shall be assumed as the conductor will provide uniform distribution of current over its cross section hence the effects of individual wires intertwined in the conductor is neglected [43].

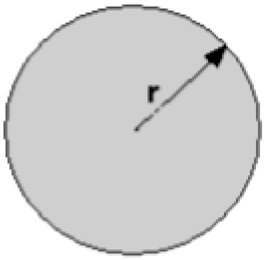

Figure 2-8: Representation of a single conductor with radius r

From equation (2.18), $L_1 = 2\times10^{-7}\left(\frac{\mu_r}{4} + \ln\frac{D}{r}\right)H/m$ considers a cylindrical conductor and for a solid conductor, inductance will be calculated as follows:-

$$L_1 = L_i + L_0 = \frac{\mu_0}{8\pi} + \frac{\mu_0}{2\pi}\ln\frac{1}{2r} \quad {}^{Henry}/_{metre} \tag{2.22}$$

Where:

r	=	Conductor radius (m) as shown in figure 2-8
μ_0	=	relative permeability of free space (H/m)
	=	$4\pi\ x\ 10^{-7}$ H/m
L_i	=	internal inductance of conductor
L_0	=	external inductance of conductor

Since current flows in the external conductor, it means geometric mean radius of the conductor will be represented for external inductance and equal to

$$L_o = \frac{\mu_o}{2\pi}.\ln\frac{1}{2.gmr} \tag{2.23}$$

Therefore, Geometric Mean Radius can be expressed as $GMR = r.e^{-\frac{1}{4}} = 0.788r$ and is the same as the one obtained from cylindrical conductor.

2.2.2.6 **Determination of inductance on a bundled conductor**

At an extra high voltage above 220 kV, corona effects will cause power loss due to resistive effects on the conductor and communication interference will be excessive with one conductor per phase is connected to a transmission line that is carrying 220 kV above [44]. It will be reduced tremendously when more than one conductor is bundled in close proximity to fulfil electromagnetic radiation requirements and the phase current shared amongst the sub-conductors held by spacers conforming a symmetrical bundle conductor.

In the calculation of the electrical parameters, the bundled sub-conductors will be replaced with a single conductor of the same equivalent radius. The line parameters such as internal impedance and geometrical impedance because of external flux shall be taken as a single conductor connected to the centre of the bundle.

The equivalent conductor shall assume that the bundle is symmetrical and equal current flows in the conductor and a general formula shall be represented as follows

$$radius_{equiv} = \sqrt[n]{n.r.R^{n-1}} \tag{2.24}$$

Where:

r = radius of an individual sub-conductors

n = the number of sub-conductors

R = radius of the bundle that will be calculated from the bundle spacing for “a”.

When the bundle spacing is not provided and the radius of the conductor is known. The figure 2-9 refers

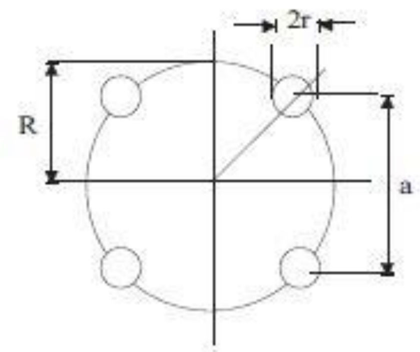

Figure 2-9: Symmetrical representation of a bundled conductor

$$a = 2R.\sin\frac{\pi}{n} \qquad (2.25)$$

Where:

r = radius of an individual sub-conductors

n = the number of sub-conductors

R = radius of the bundle that will be calculated from the bundle spacing for “a”.

Given that D_s^b be GMR of a bundled conductor and D_s the GMR of the individual conductor bundled

Given also ***d*** be the space distance of the bundle conductors

Then $D_s^b = \sqrt[4]{(D_s^2 d^2)} = \sqrt[2]{D_s d}$ for two strand bundle

a) Three strand bundle $D_s^b = \sqrt[3]{D_s} d^2$

b) Four strand bundle $D_s^b = \sqrt[16]{D_s^4 d^{12} 2\frac{1}{2}^4}$

$$D_s^b = 1.09\sqrt[4]{D_s} d^3$$

All bundled subconductors will be within the same voltage and the matrices for the geometric will be equal to phase conductors. The unsymmetrical bundle conductor shall also assume uniform current distribution amongst the sub conductors. An example of calculating the line parameters have been shown in Appendix A-1: Calculation of reactance bundled conductor

After determining the inductance on either individual or bundled conductor, the reactance of the conductor will be calculated as follows

$$X_L = 2\pi f L_1 \ \Omega/m \quad (2.26)$$

Where:

X_L = reactance of the conductor

f = system frequency

2.2.2.7 Determination of overhead transmission line capacitance

Most transmission lines in SAPP are constructed on short and medium length within the 300km and then a substation is constructed to avoid long distance and hence shunt impedance is often neglected but since the overhead line provides a voltage gradient with the earth then

A charged conductor, q_a is representing on a single conductor and equal to with a reflected negative charge, $-q_a$ to ground, the earth is then considered as the reference point, often times the lowest point on the sag is considered and self-charged voltage shall be represented as

$$V_a = 2qa \log_e \frac{2h}{r} \quad (2.27)$$

Where:

h = height above the ground and

r = radius of the conductor.

However, the mutually charged voltage where the potential of a conductor, a is in respect of a charge on the conductor b , q_b is the representing the charge between two conductors. The three phase whether running lateral or parallel, one phase is considered as the reference point hence mutual effects shall occur between the conductors with the reference phase and shall be represented as

$$V_a = 2qb \ \log_e \frac{D'}{D} \quad (2.28)$$

Where:

D' = spacing between *b* and ground at the image of *a* (with reference to ground) and

D = distance between *a* and *b phases*

When capacitance $C = \frac{q}{v}$ and the capacitance reactance is equal to $X_c = 1/\omega c$, since the conductor will run above the ground in the air, then

$$X_c = \frac{1}{2\pi\mu_0 \log\frac{2h}{r}} \tag{2.29}$$

Where:

μ_0 = permittivity of free air

= 8.864×10^{-9} F/m

h = height above the ground and

r = radius of the conductor.

2.2.2.8 **Determination of the overhead line constants**

There are various methods used to calculate overhead line constants and the results have been analysed and compared by most Engineers [44]. Most of the methods of calculations are based on obtaining the series impedance by determining the self and mutual magnetic circuits for transmission overhead line. The line impedance has three parts to be considered in the calculation of the line constants.

Most manufacturers had produced charts and graph to be used in the designing and determining conductor size and tower configuration which have been further improved by software tools to simulate the requirements for the transmission route.

The below states methods that can be used to achieve the line of constants by way of calculation and as follows

a) Calculation of overhead line impedance of a symmetrical system

i. Positive sequence impedance, $Z_p = R'_i(\omega) + j\omega . L'_i(\omega)$, the formula considers the voltage drop due to resistivity of the conductor and magnetic field within the conductor. The skin effect is dependent of frequency on both resistance and reactance;

ii. Zero impedance Z'_G actual impedance for the conductor and that will conduct in the return path to earth; and

iii. Negative Impedance $Z_m = R'_i(\omega) + j\omega . L'_i(\omega)$ that considers the finite earth conductivity and proximity effects. It will depend on the earth resistance and type of line geometry.

b) Calculation of overhead line on series impedance of unsymmetrical system

This method has been used commonly for calculation impedances for protection relays and each conductor is calculated basing on self-impedance of each conductor, Z_p and Z_m mutual impedance between conductors with a common earth return as given by the Carson equations[40] :

$$Z_p = \mathrm{R} + 0.000988\mathrm{f} + \mathrm{j}0.0029\ \mathrm{f} \log_{10} \frac{D_c}{dc}$$

$$Z_m = \mathrm{R} + 0.000988\mathrm{f} + \mathrm{j}0.0029\ \mathrm{f} \log10 \frac{\mathrm{D}_c}{\mathrm{D}} \qquad (2.30)$$

Where:

R	=	conductor ac resistance (ohms/km)
dc	=	geometric mean radius of a single conductor
D	=	spacing between parallel conductors
f	=	System frequency
D_c	=	equivalent spacing of the earth return path, $216\sqrt{\frac{\rho}{f}}$
ρ	=	earth resistivity (ohms/cm^3)

It can be shown that the sequence impedance such as positive Z_1, negative Z_2 and zero, Z_0 sequences be relative to self and mutual impedances by the following

$$Z_1 = Z_2 = Z_p - Z_m$$
$$Z_0 = Z_p + 2Z_m \qquad (2.31)$$

At 50 Hz system, the equation (2.30) can be substituted in equation ((2.31) and will provide

$$Z_1 = Z_2 = R + j0.145 \log_{10} \frac{\sqrt[3]{ABC}}{d_c}$$
$$Z_0 = (R + 0.148) + j0.434 \log_{10} \frac{D_e}{D_s} \qquad (2.32)$$

Where:

A, B, C = the spacing between conductors of ab, bc and ca

D = $\sqrt[3]{ABC}$

D_s = $\sqrt[3]{d_c D^2}$

= $\sqrt[n]{n \times r \times R^{n-1}}$

c) Calculation of overhead line on shunt impedance of unsymmetrical system

From equation (2.27), where $V_a = 2qa \times \log_e \frac{2h}{r}$, if the resistive leakage is ignored, it follows that self and mutual shunt impedances with the combination of equation (2.29) then the positive impedance is expressed as:-

$$Z_p = -j0.132 \log_{10} \frac{2h}{r}$$

$$Z_p = -j0.132 \log_{10} \frac{D'}{D} \qquad (2.33)$$

Where:

D' = distances above the ground are related to the conductor spacing for the overhead lines 2h=D'.

D = Distance between conductors a and b

During normal balanced system conditions, only positive sequence currents and voltages can exist in the system, and therefore the normal system impedance network is a positive sequence network, Z_1. The negative sequence $Z_{2,}$ will exist during an unbalanced fault and normally are the same as positive sequence and as such for the overhead will then be,

$$Z_1 = Z_2 = -j0.132 \log_{10} \frac{D}{r} \tag{2.34}$$

Where:

D' = distances above the ground are related to the conductor spacing for the overhead lines 2h=D'.

r = radius of conductor

The zero sequence network will result due to fault that will return through an either a neutral or earth and the magnitude shall vary due to winding arrangement and method of earthing and for the overhead is as follows

$$Z_0 = -j0.396 \log_{10} \frac{D'}{\sqrt[3]{rD^2}} \tag{2.35}$$

Where:

D' = distances above the ground are related to the conductor spacing for the overhead lines 2h=D'.

r = radius of conductor

D = Distance between conductors a and b

It should be noted that the terms are similar as the series impedances and on unsymmetrical spacing of the overhead, the following will derived

$$Z_1 = Z_2 = -j0.132 \log_{10} \frac{\sqrt[3]{ABC}}{r}$$
$$Z_0 = -j0.396 \log_{10} \frac{8h_a h_b h_c}{r\sqrt[3]{A^2}B^2C^2} \tag{2.36}$$

Where:

A, B, C = spacing between conductors of ab, bc and ca

$h_a h_b h_c$ = sagging of the conductor (distance from the conductor to ground, and

r = radius of the conductor

However, at given point, the reactance and susceptance of the conductor will be provided in the manufacturer's data sheet and it will be used for calculating the equivalent impedance of the line. The calculation of the impedance from the formulas depends on the line configurations and conductor spacing, not only dependent on the voltage level.

2.2.3 Power transformers

When the electric power is generated by the synchronous generator, it will be stepped up at a rated energy capacity of generated power to be transferred to load centres. Then, Kirchhoff laws are applied, it will be noted that current will have a higher value on the secondary side than on the primary side of the transformer.

Transformers are installed in the network to reduce transmission current at a high voltage and be transferred to load centres with considerable heat loss due to I^2R on the conductors and also maximise the receiving voltage to the load centres.

The design of the transformer shall depend on

(a) Voltage where it will require to identify the loading so as to determine the transformer winding turns, the capacity required the required voltage regulation and tap changer; and

(b) Thermal aspects to check the variation of temperature change at loading that will provide a selection of equipment to operate within acceptable temperatures.

2.2.3.1 Transformer voltage

Primarily, the first transformer in the network will be the generator transformer that will step the voltage to high or extra high voltages. The synchronous machine will generate voltage and evacuate induced voltage in a three phase star connections and then transfer into three phase delta connection. This will allow voltage to be transferred in transmission line on three phase voltage at a reduced current and ideally with the same power.

The behaviour of the transformer depends on the secondary current that will induce a voltage in the secondary winding coil and also produces own magnetic field to reduce the original field in the steel core laminations that will come from primary winding mainly on the step-down transformers at the load centres. As this reduces the field in the primary and allows more current to flow until a turns balance is reached [32].

This then leads to an expression of $N_1 I_1 = N_2 I_2$ and also $V_1 N_2 = V_2 N_1$and then the flux levels rise is not proportional to the load current. The magnetic field induced in the secondary windings will be at par with primary current. The total magnetizing flux will be as the result of magnetizing current only and magnetic flux levels do not therefore reach very high levels under abnormal short circuit and as such from $N_1 I_1 = N_2 I_2$ with substitutions this equation $V_1 I_1 = V_2 I_2$ is derived.

2.2.3.2 **Transformer Vector Group**

The transformer windings are interconnected on each phase and represent the induced magneto-motive force between same terminals and imaginary neutral point in some cases like delta and zigzag type. There are four known groups of interphase connections for three phase transformer with the same displacement between HV and LV windings. They are characterised as an angular representation like an analogue clock where the group I, II, III IV will be represented as 0, 6, 1, 11 and the equivalent phase displacement can be obtained by multiplying with 30°[45].

The transformer vector group is required to be known in order to determine the phase polarity for the parallel connection with other transmission lines and equal participation with the regulated voltage to supply distribution network. It will also be required to provide a neutral earth either directly or impedance for the system in the substation.

2.2.3.3 **Transformer voltage regulation**

The transformer voltage will rely on the secondary current and due to unpredictable load, it will cause the voltage drop in the transformer. This will also be contributed by the magnetising circuit caused by the inductance to set up of the magnetic field and resistance to represent heat losses in the core. The transformer will be fitted with on-load tap changer for the transmission voltages to be regulated in it [32].

$$\Delta V = \frac{\sqrt{(Rp)^2 + (Xq)^2}}{100\%} \tag{2.37}$$

Where:

$\Delta V\%$	=	volt drop at given load
R	=	winding Resistance expressed in percentage
X	=	leakage reactance expressed in percentage
P	=	power factor $\cos\theta$ expressed in percentage
q	=	sin θ expressed in percentage

Equation (2.37), it indicates that the only variable that will change voltage will be power factor that will originate from the load and the rest become the specified impedance of the transformer.

2.2.3.4 Transformer thermal consideration

Transformers will be subjected to heating that will eventually reduce its efficiency and then affect its performance.

Heating due to I^2R caused by the winding resistance from the load and magnetising current will eventually cause heat in the transformer windings immersed in oil that is used for insulation in most transformers and oil itself. It is required to effectively provide the additional cooling effects for the transformer to perform effectively and prolong the life of insulation.

2.2.3.5 Transformer impedances

The characteristics of the power transformer in a network will be represented by an equivalent impedances hence positive and negative sequence values will be the same for the two and three windings transformers. The zero sequence will depend on the winding vector group and neutral point of the transformer and or source generators within the system[32, 45].

The required parameter to be addressed in the design of the transformer is the short circuit impedance because losing a transformer in the network provides overload to the alternative source. The reactance of the transformer will give the rating and voltage size shown in a percentage on its nameplate as manufacturer's data.

The required positive and negative sequence diagram in three phase winding is represented as follows:

$$Z_L = \frac{1}{2}(Z_{LM}+Z_{LH}+Z_{MH})$$
$$Z_M = \frac{1}{2}(Z_{LM}+Z_{MH}+Z_{LH})$$
$$Z_L = \frac{1}{2}(Z_{LH}+Z_{MH}+Z_{LM}) \quad (2.38)$$

Where:

L = low voltage side,

M = medium voltage side and

H = high voltage.

2.2.4 Power System Loads

The load is an essential component of the power system that has led to the capital development of the whole power network but it's the most complex component to determine the character behaviour. The promulgation to represent the real behaviour of the load during power system study had started years back and was done to sustain continuous supply from the generator through calculation of variations of power relative to its load angle[46].

It is very difficult to determine loads for the interconnected power system and moreover most of power utilities define load by categorizing in tariff regimes where the customers will be charged by energy consumption or capacity of power such as

a) Residential includes the domestic usage of electricity in residential areas but a will vary with income level;

b) Commercial includes usage of electricity for the purpose of business and also offices. This category will too depend on the usage of electricity; and

c) An industrial regime where the usage of electricity is for the running of machinery and this category the charges are normally by capacity charge and energy consumption.

The other method to determine the load is to log the variation of the load at a determined half hourly rate through the years. The method will provide a load profile for an interested transmission line but shall not determine the behaviour of the loaded equipment. It is still very difficult to be used in power system studies but at least most utilities will use this load for simulation. It is because most utilities carry data logging on major substations for system operation and such data can be used as actual loading for the system simulation but will not know the type of load being used.

2.2.4.1 **Load modelling**

During the modelling of the SAPP power grid, the load will be represented as a bulk power delivery points that will be aggregated from the different loads at the transmission substation[47].

The static load has been expressed to be the active P and reactive, Q power components at any instant time as an algebraic function of the bus voltage magnitude and frequency at the same instant. Polynomial Model has been developed for use of power system analysis that has been also been used in DIgSILENT Powerfactory where voltage dependency of loads has been used to represent the model [48, 49]

The polynomial model is commonly referred to as ZIP model because it can be comprised either the sum of constant impedance, Z, or constant current, I and or constant power, P [48, 50].

$$P = P_0 \left[aP\left(\frac{v}{v_0}\right)^{e\_aP} + bP\left(\frac{v}{v_0}\right)e\_^{bP} + (1-aP-bP)\left(\frac{v}{v_0}\right)e\_^{cP}\right]$$

$$Q = Q_0 \left[aQ\left(\frac{v}{v_0}\right)^{e\_aP} + bQ\left(\frac{v}{v_0}\right)e\_^{bQ} + (1-aQ-bQ)\left(\frac{v}{v_0}\right)e\_^{cQ}\right] \qquad (2.39)$$

Where:

P, Q = Active and reactive power

P_0, Q_0 = Initial bus load

e^{-aP} = voltage exponent of the voltage-dependent active load

e^{-bP} = voltage exponent non-frequency dependent active and reactive power load

e^{-cP} = exponent of frequency sensitivity coefficient for active and reactive power load

e^{-aQ} = voltage exponent for uncompensated reactive load

e^{-bQ} = voltage exponent for reactive compensation term

e^{-cQ} = exponent of frequency sensitivity coefficient for reactive compensation

aP = frequency dependent fraction of active power load and reactive power

bP = non-frequency dependent active and reactive power load

cP = frequency sensitivity coefficient for active and reactive power load

= $(1 - aP - bP)$

aQ = uncompensated reactive load

bQ = reactive compensation term

cQ = frequency sensitivity coefficient for reactive compensation

= $(1 - aQ - bQ)$

v_0 = initial voltage of the busbar from power flow base

v = per unit voltage base

It can have been seen from the equation above on exponential model that the parameters of a and b are exponents for the model are equal to 0,1, or 2 representing constant power, constant current or constant characteristics respectively[48]. However, from the load model formula in equation (2.39), it can be noted that the initial voltage is referenced at the busbar and as such the distribution network voltage drop to supply load at the furthest point will be neglected. An accurate representation of power system load shall require detailed system behaviour. Load representation on distribution network can be added up and the total sum be used as the reasonable analysis for the network after considering the following[51]:

a) Adding the load that have different characteristics on the common busbar, and
b) Evaluating load changes with known load characteristics from the transmission substation

It can be observed that consumer electronics presently has changed the appliance voltages to operate within a range of voltages. It is from this prospects that the voltage exponent of the voltage dependent on active load will not effectively have an impact on equation (2.39) as the variation of voltage to the load will vary according to the source voltage by almost hundred percent.

In the pursuit to mitigation of accurate power system load, the National Electricity Regulator of South Africa (NERSA) developed the Electricity Supply- Quality of Supply standard where it describes the required voltage quality for the normal flow of electricity to the end user. The required voltage parameter has been explained where appropriate on the compatibility levels, limits and assessment methods. The compatibility levels and limits require measurement of the voltage at the point of common connection which be similitude with the as the common busbar to the end user customer [52]. The standard has also provided the provisions of instrument standard for measurements that the utility and customer may use for monitoring to assess compatibility levels [53] on the quality of voltage. The use of voltage dependence has been evaluated on continuous monitoring to measure voltages changes on pre and post-disturbance analysis at a different magnitude of faults on the power network. It further analysed on the load parameters for different loads categorised as industrial, residential and commercial and it was concluded that automatic recording will measure the actual behaviour of the system loads[51].

The power quality measurements can enhance continuous measurement of the voltage at different points of connection in the Southern Africa that is also one of the objectives of SAPP coordination centre.

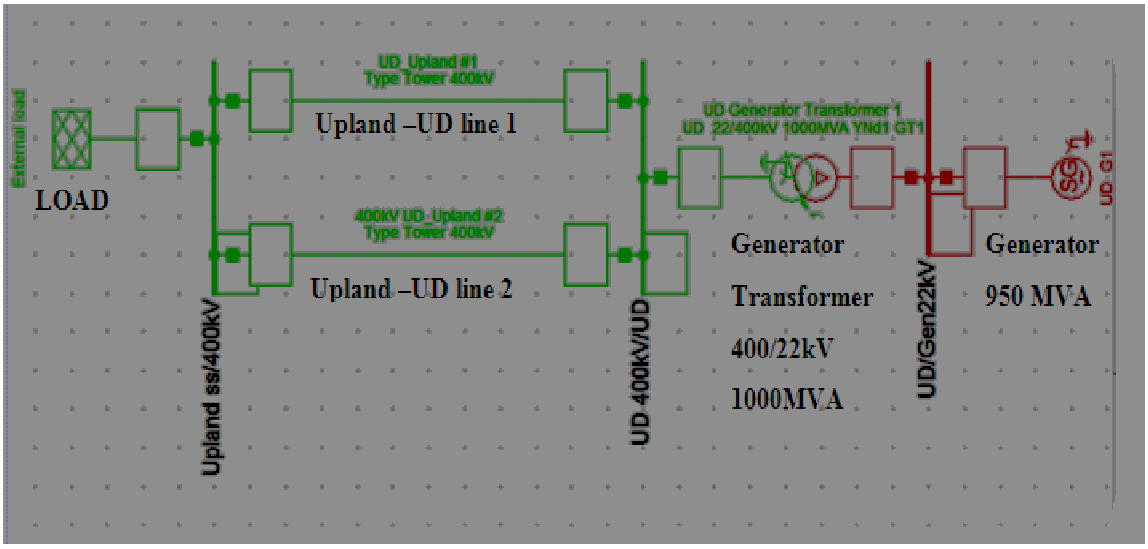

Figure 2-10: Single line diagram for a single synchronous generator

2.3 Simulation analysis of a single machine

When an analysing power network and its characteristics, it has been the tradition to start with a single machine feeding an infinity load in order to determine and derive parameter performance of the system. It is then decided to consider a single line diagram of the network in the model to be studied having the largest machine in the model and supply an immediate substation at 200km from the generating station refer to figure 2-10.

The generating station **UD** has a generator nominal rated power of 950 MVA, 0.9 power factor at 22 kV and a transformer is stepping up to 400 kV, rated 1000 MVA and then evacuate the power to the nearest substation with two parallel lines from UD generating station to Upland substation with a Tern type of conductor bundled with four conductors per phase . Tern type of conductor is used by the Canadian Standard sizes of Aluminium Conductor Steel Reinforced (ACSR) for the 400 kV [54]. Normally, the choice of the conductor will consider weight kg/km, the resistivity of the conductor per km and the normal rated current to be transferred from generating station to Upland substation. It will be noted that the current will highly be rated because assumptions have been made that other generation plants will be constructed and commissioned and thus the reason for the choice of the rated current to be 3.2 kA refer to Appendix A-2: specification of a conductor Tern.

The loading at the Upland substation has been considered as infinity because the exact load to be fully consumed at the Upland Substation is assumed to be unknown. Therefore, the generator will generate power to its fullest capability and be able to know the maximum loading of the network.

2.3.1 Power flow analysis on single line diagram

The generated power will be evacuated to Upland Substation and the equipment has been designed to satisfy capacity of power and the purpose of load flow analysis will be to check the loading capacity for the power network and as such the following can be calculated.

a) The maximum current the generator can safely load has been calculated by using the power equation at a given capacity in MVA and will be calculated as current (I_1),

$$I_1 = \frac{rated\ MVA}{\sqrt{3}\ x\ rated\ V} \tag{2.40}$$

Where:

Rated MVA	=	950 MVA
Rated V	=	22 kV
I_1	=	rated current generated

The generator controls such as excitation voltage and damping have been neglected in the power flow analysis to fulfil the condition in equation(2.7), where $\frac{H}{180f}\frac{d^2\delta}{dt^2} = P_m - P_e = P_a$

b) The current that will be transferred to Upland substations from the generator transformer 400/22 kV, 1000 MVA shall be calculated using the ratio of power transformer voltage, $V_1 I_1 = V_2 I_2$ and shall be expressed as

$$I_2 = \frac{V_1}{V_2} I_1 \qquad (2.41)$$

Where:

I_2	=	Secondary side current of the transformer;
I_1	=	Primary side current of the transformer
V_1	=	Primary (high) side voltage of the transformer
V_2	=	Secondary (low) side voltage of the transformer

c) The two overhead lines Upland –UD lines 1 and 2 are running in parallel to Upland Substation at the same distance, tower configurations, conductor size, sagging and all these means the impedance will be the same. Hence it will be expected to have equal share of loading to the Upland Substation and the calculation has been explained in Appendix A: Details of transmission line parameters

d) Generator transformer will be used to step up voltage at constant tap, 6 because the function of tap changing depends on the secondary current where the generator is supplying the initial voltage for the power network. The busbar UD/Gen 22 kV is imaginary created in the DIgSILENT Powerfactory tool to separate two different equipment of the generator and generator transformer .It may also be considered as the cable connecting the generator terminals and secondary side of the generator transformer.

The results in figure 2-11 refers to the power flow at steady state and the generated load is 91.8% on SG, UD_G1 and the loading of the transformer at 92.3%, the difference between the loading arise due to the power rating of the generator and the transformer at rated power factor.

The single machine power flow in figure 2-11 provides two sets of results at a busbar and transmission line as follows:

i. The output data appearing between UD_G1 and busbar UD/Gen 22 kV from left to right denotes active power, MW, reactive power MVAR, and current flow, kA. The same is applicable to power values on the external grid;

ii. The results that appearing between UD 400 kV/UD and Upland ss/400 kV represents the loading on transmission line and from left to right are voltage, kV, angle in electrical degrees and current in kA

The receiving end power has been reduced due I^2R power loss of the transmission line has been reduced from 855 MW to 845 MW.

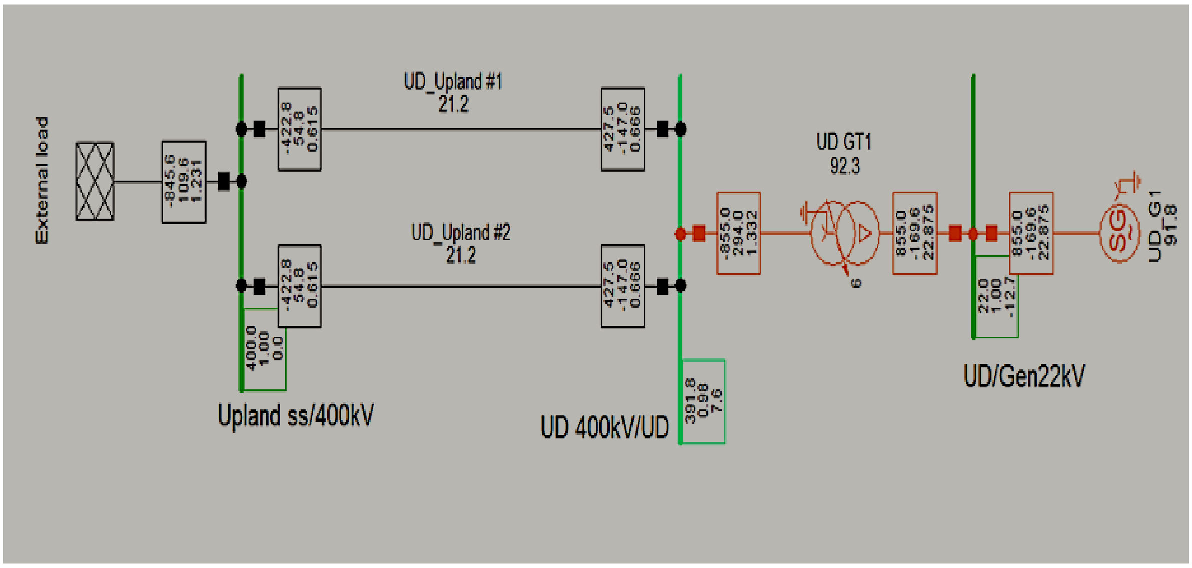

Figure 2-11: Results of simulated load flow for single machine

2.3.2 Transient power analysis of power network

From figure 2-11, it has been noted that the equipment associated with power evacuation at fully capacity of the generator rating at 950 MVA is adequate for loading each transmission overhead line to external grid. When the power network is operating at steady state the equipment capacity will sufficient for power delivery to the load. The system is simulated with faults to analyse the effects of disturbances in the network at three different positions.

2.3.2.1 Busbar fault at UD 400 kV/UD

A fault was initiated on the 400 kV busbar to last for 0.1 s and open breakers after 5 s.

A disturbance was initiated at busbar as shown in figure 2-12 to isolate all associated breakers within the 100ms but the power parameters were oscillating beyond the set time of the event. A very low time was considered in order to analyse the behaviour and characteristics of the equipment when subject to a disturbance when it is known that protection relays pick fault within 3 or 4 cycles.

The position of the fault has interrupted the generator transformer but virtually looks overloaded due to the fault current values and all the circuit breakers in the single line diagram have isolated the fault at the 400 kV busbar. The high loading percent is caused by the high reactive power due to very high impedance caused by the infinity load on the external grid.

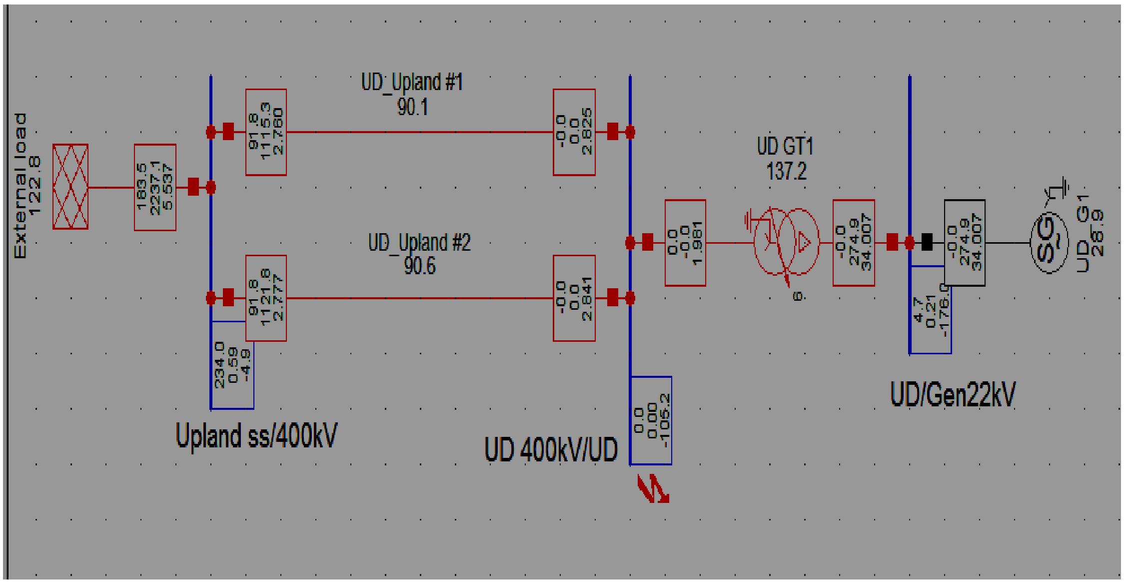

Figure 2-12: Simulation fault results of three phase fault on 400kV busbar

The disturbance on the busbar has affected the generator as it represents about 26% of loading for the first swing and consequential swings. The system absorbed the reactive power during the interruption due reactance that was induced by the fault current.

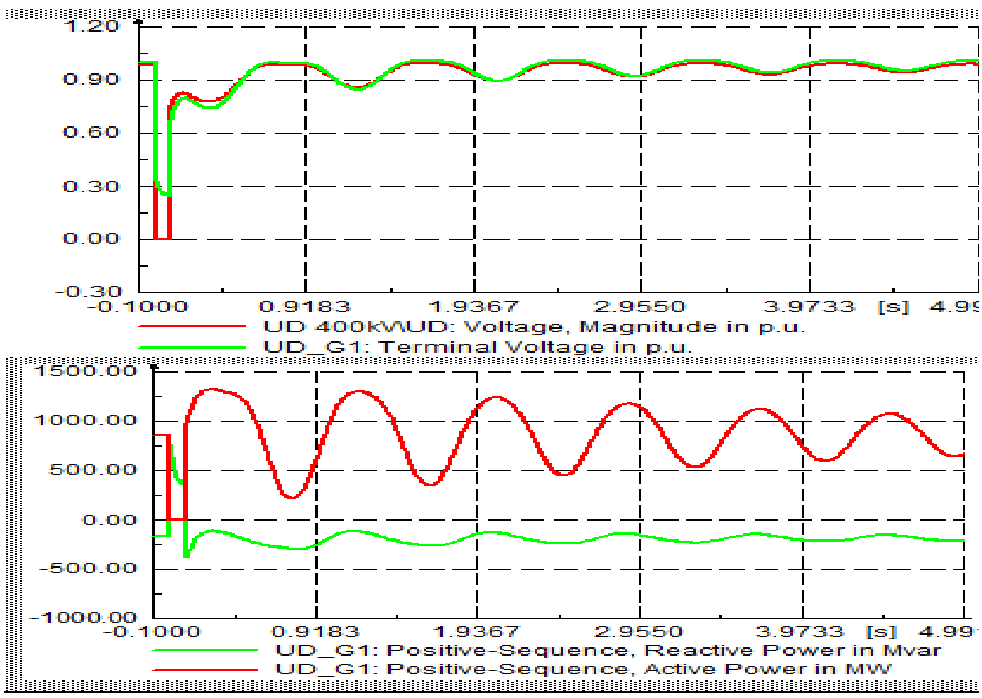

Figure 2-13: Indicating oscillation of active and reactive power after disturbance

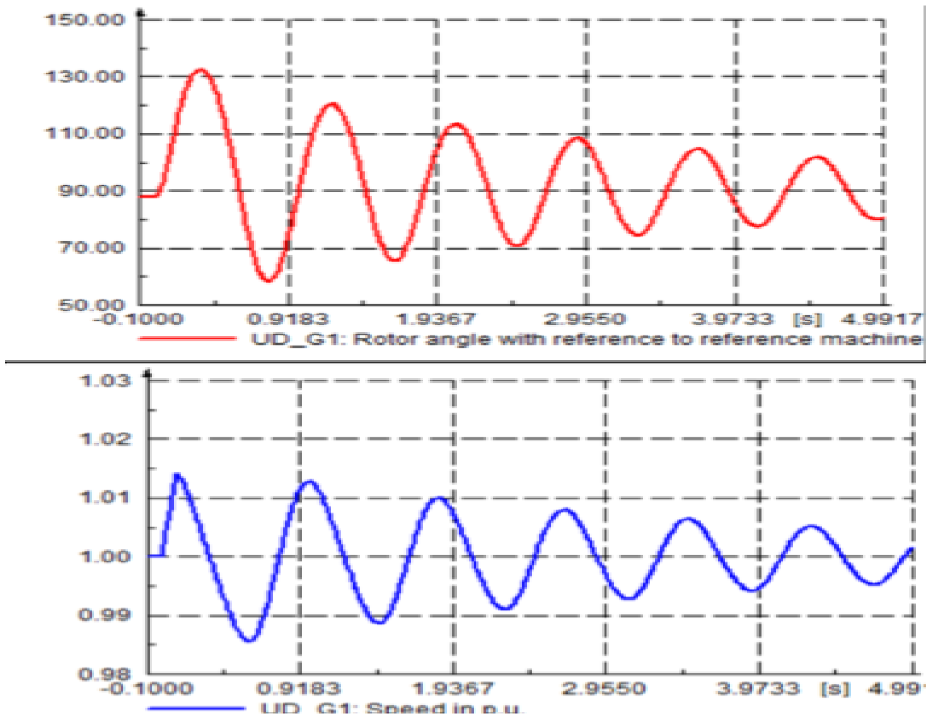

Figure 2-14: Rotor angle and speed behaviour after disturbance on busbar

Figure 2-13 indicates that system parameters are oscillating after the disturbance has occurred but the rotor angle and speed were too affected refer to figure 2-14. It can be noted that the rotor angle and speed are also damping oscillating

The change of speed for 1.5% from the figure has affected the parameters and deviated the rotor angle to increase to about 40% hence causing the machine to oscillate after a disturbance has been cleared within 100ms.

2.3.2.2 **Faults on Transmission line**

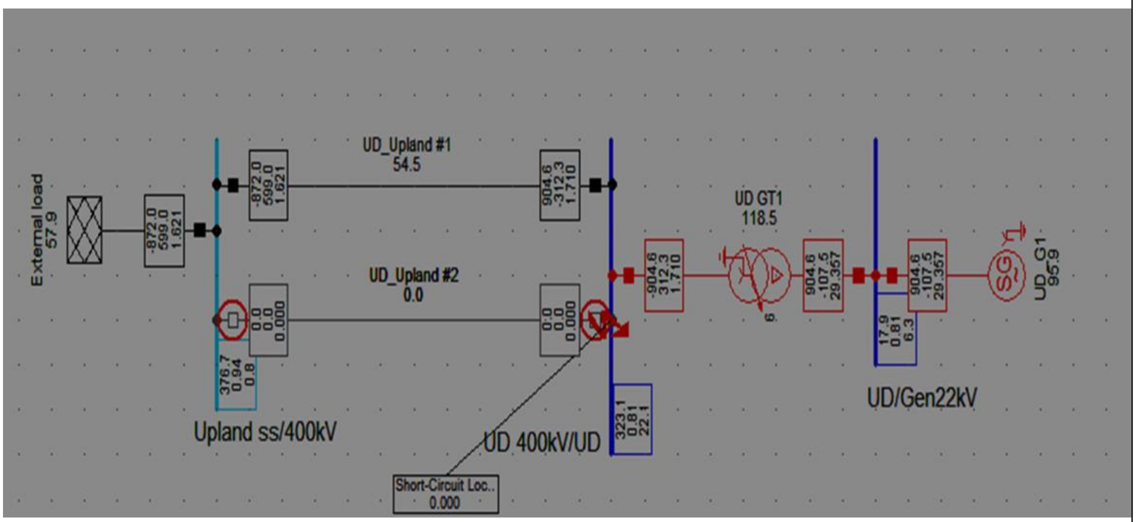

Figure 2-15: Single phase fault on Transmission line near the busbar

The power system can be subjected to a disturbance at any point in the network. However, a disturbance on the transmission line is considered and analyse the effects of power to the network. It is common practice on the take-off transmission line surge arresters are installed to divert excess voltage into the ground .The surge arrester will erupt and conduct to the ground through the earthing bond of the substation . A fault was initiated on UD_Upland #2 at the position indicated in figure 2-15 at the same time of 0.1s and delayed the isolation time on the circuit breakers.

Basing on the results in figure 2-15 the disturbance of transmission line has affected the synchronous generator and caused overloading due to overcurrent on the generator that has increased its value to 29kA instead of the nominal current of 24kA, the delay to isolate faults may slowly cause damage to the stator windings. The UD_Upland #1 has been loaded to 54.5% due to reactive power and visibly there was fault reactance that has been transferred to un-faulted line hence the overload between the generator and its transformer.

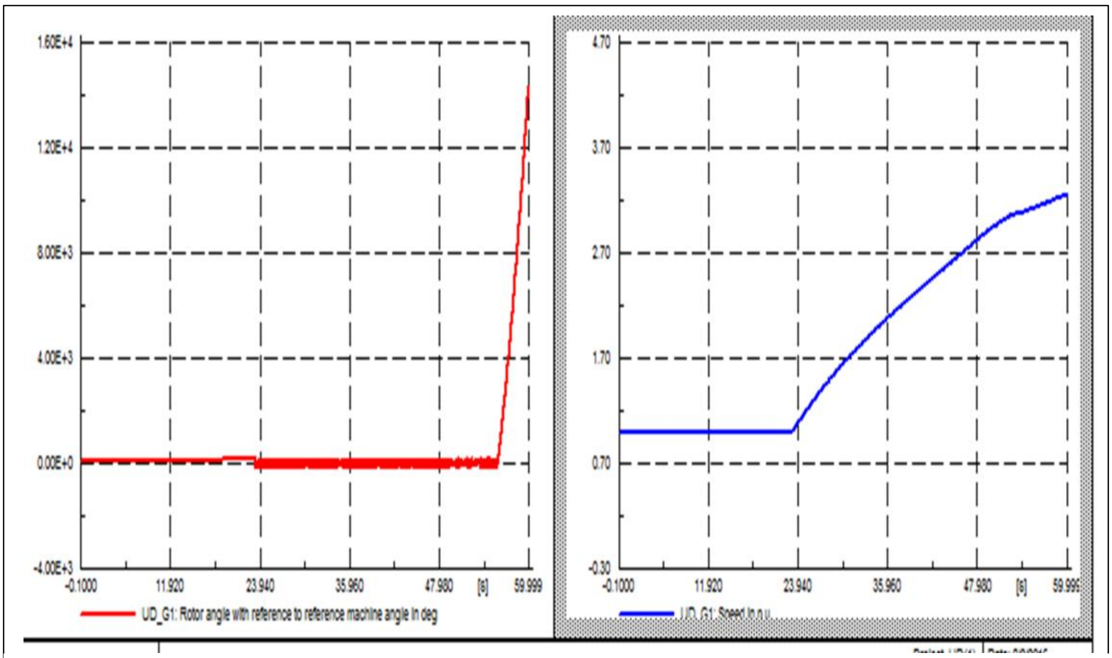

Figure 2-16: Rotor angle and speed after fault at transmission line

Figure 2-16 refers , it indicates the overshoot of a rotor angle and speed of the synchronous machine UD_G1 due to delay initiated to isolate the fault by opening the circuit breakers hence the overshoot started at almost 24 s on the rotor speed that also caused instability of active power from figure 2-17. At the same time of 24s, the reactive power started to increase due to fault reactance.

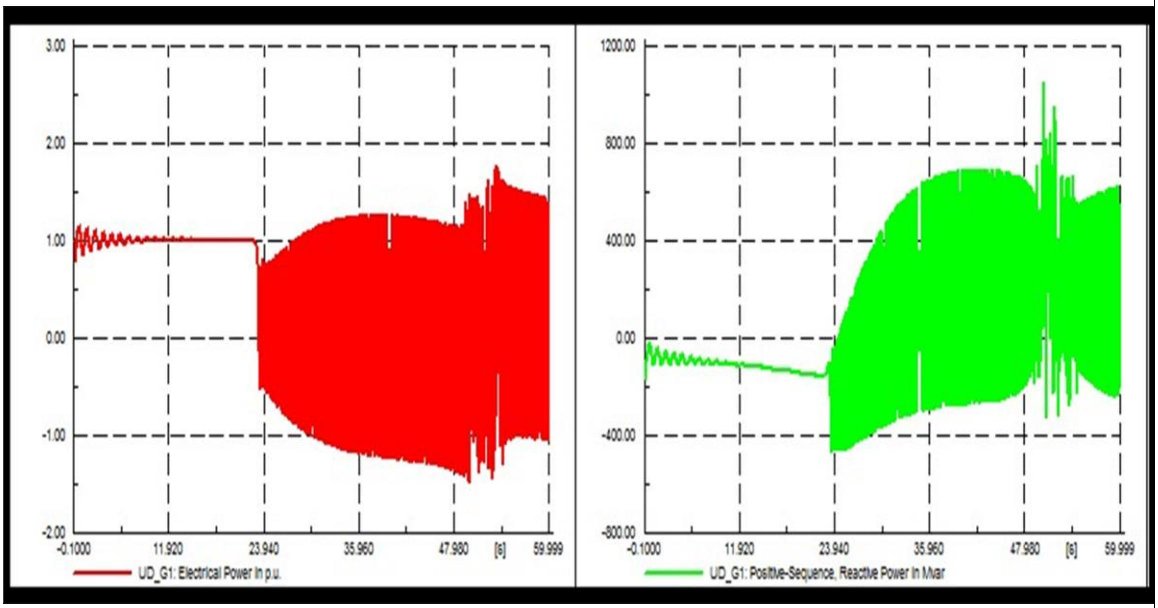

Figure 2-17: Simulation results of single phase fault close to close busbar

From figures 2-16 and 2-17, it can be learnt that the delay to isolate a fault causes overshoot of the rotor speed hence instability to the network. It is proper to analyse the power network in order properly mitigate faults without delays.

2.3.3 Synchronous generators with controller

It has been noted that the system when experienced with disturbance, it had turned into uncontrollable oscillations that could even damage the stator windings due to flux density caused by the rotor speed. In this regard, it can be noted that reactive power will need to be controlled so that it should not absorb the required active power when a fault has occurred.

It should also be noted that steady state output values provides the minimum operations of the system if compared with the results obtained under a system disturbance.

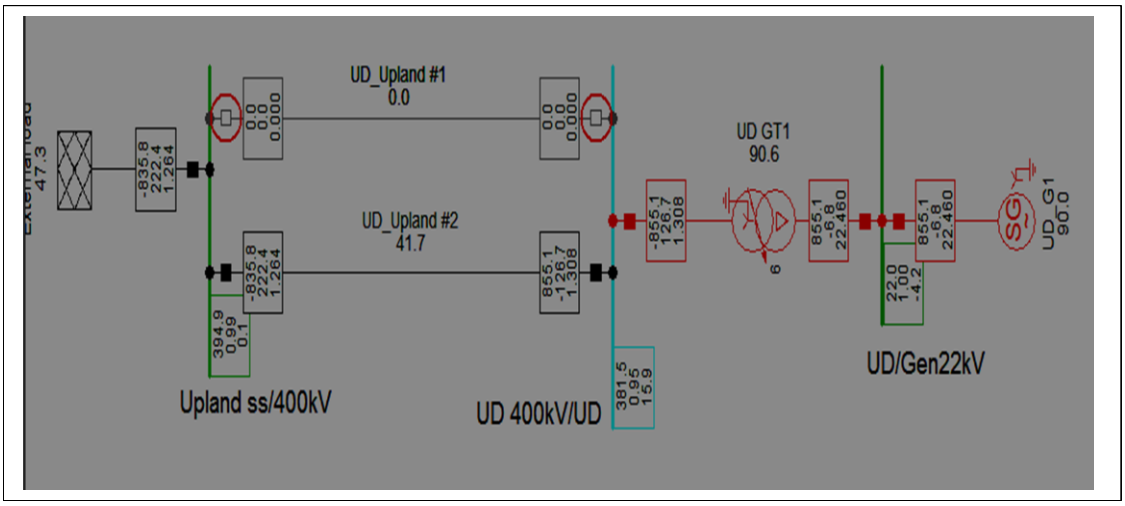

Figure 2-18: Simulation results of three phase fault on the transmission line

Figure 2-18 indicates a transmission fault after installing a voltage and speed controller the previous simulations had no controllers in the synchronous generator. The reactive power has been reduced with the introduction of the controller. Even though the controller has been introduced in the synchronous generators the damping oscillation still occurs in the measured parameters as shown in figure 2-19.

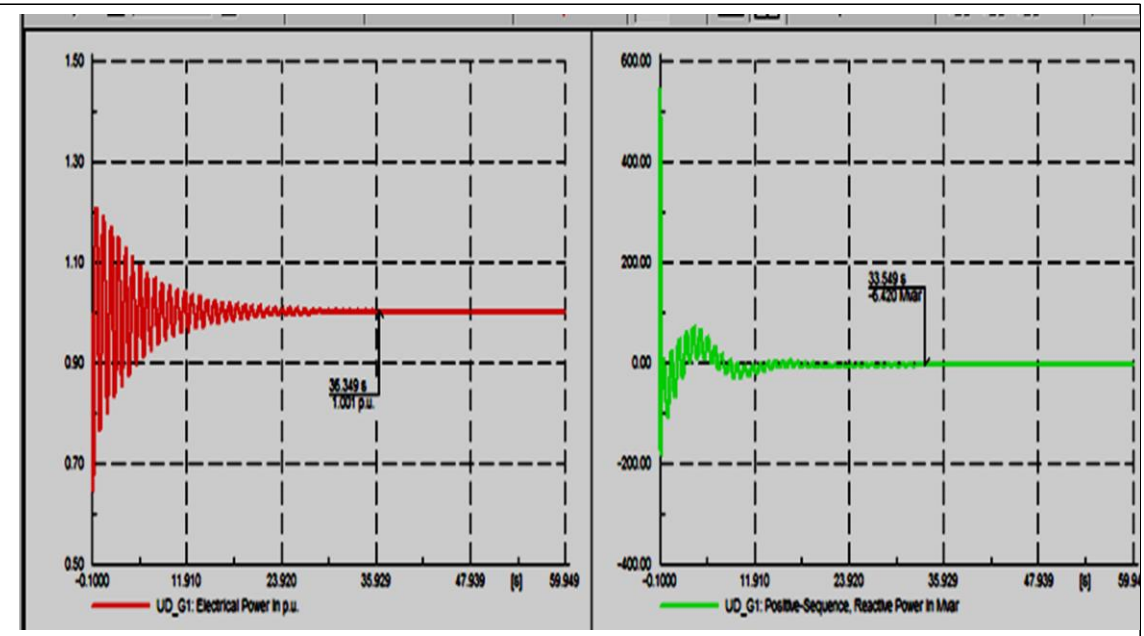

Figure 2-19: Simulation results with voltage and speed controllers

The effects of the controllers has improved the damping oscillating of the single line diagram. it is a requisite to understand the characteristics of any other equipment and for proper utilisation of its behaviour and figure 2-20, shows a different behaviour of the rotor angle before it settles to normal position.

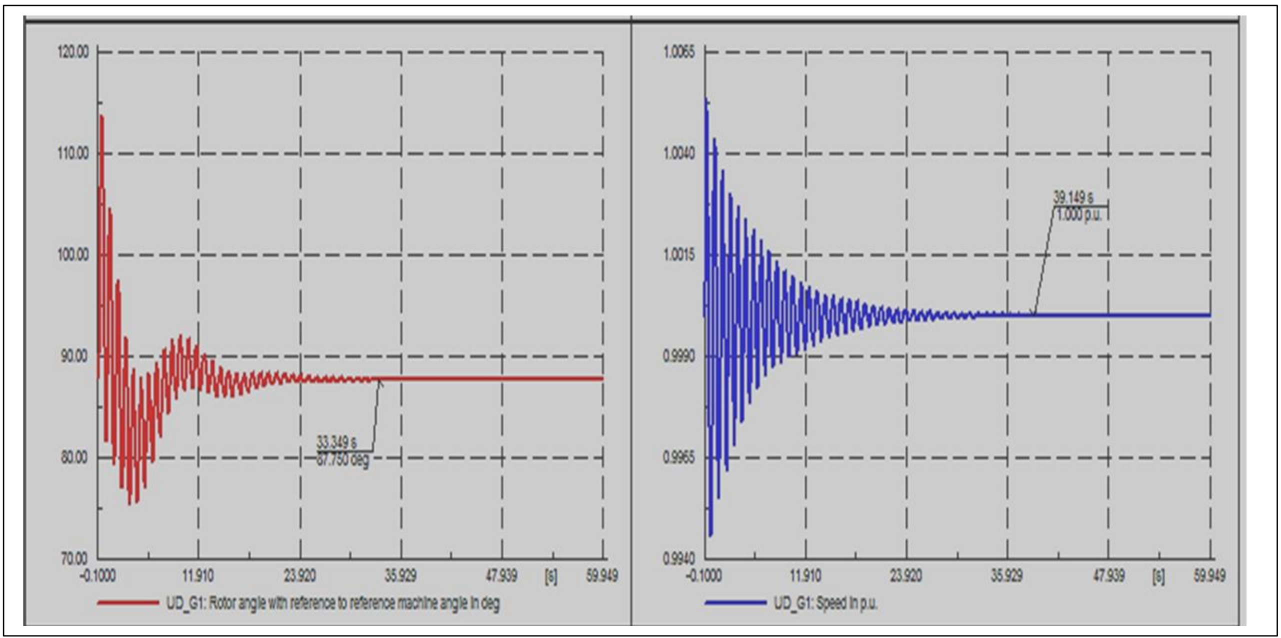

Figure 2-20: Rotor angle and speed effects with controller

From the results obtained in the simulation, it can be concluded that when the system is disturbed damping oscillations due occur and cannot be neglected as stated in equation (2.6), where $P_a = P_m - P_e = M\frac{d^2\theta}{dt^2}$ and this equation considers only the first swing whilst the other decaying oscillation are not considered.

The transmission guidelines provided by the South African grid code states that the HV breaker tripping and fault operation of the unit clearing times shall include breaker operating times, depend on system conditions [55] and shall be as follows:

a. 80ms where the point of connection is 400 kV or above
b. 100ms where the point of connection is 220 kV or 275 kV
c. 120ms where the point of connection is 132 kV and below.

Basing on the guided breaker clearing time plus the protection graded times, then the actual clearing will be higher than 0.12 ms. The breaker time can apply on the instantaneous tripping and during the fault time the system will be oscillating waiting for the isolation.

2.3.4 Fault analysis on single line diagram

The results of the simulated single line diagram on faults at different positions indicate a decaying damping oscillations occurring on the generator rotor speed and angle in return affects the power parameters such as voltage and current.

When the fault occurred, the parameters immediately changed its amplitude to a first swing and subsequent damping oscillations of the power parameter. The first (highest) amplitude is derived from power dissipation by the resistance of the generator, and then subsequent oscillations are due to system frequency imposed on the oscillatory torque of the generator rotor due to unilateral direction components to the machine [56].

When a disturbance occurs on the system, the generator will require to balance up the kinetic energy that causes the mechanical torque and the potential energy derived from the kinetic energy. The balance of energy decay causes the magnetic energy in the generator circuit to increase due to fault that has occurred in the system and the rotor speed will oscillate in the first cycle with highest amplitude and the rest cycles in the decayed oscillations[10].

2.4 Damping oscillations in the overhead line

In electric circuit theory, the nature of the waveforms is called damped sinusoid due to excitation and forced functions as shown in figure 2-20, the following formula is derived

$$v = V_m e^{\sigma t} \cos(\omega t + \theta) \tag{2.42}$$

Where

v	=	instantaneous voltage
V_m	=	maximum voltage
σ	=	neper per second
ω	=	radians per second

From the principles of RLC circuits of a second order linear system[7, 57] it can be emulated to the transmission line with RLC parameters at any substation to be represented as a node of the circuit and voltage drop is calculated as follows:

$$\frac{d^2 v_0}{dt^2} + (2\zeta\omega_n)\frac{dv_o}{dt} + \omega_n^2 v_o = \omega_n^2 v_i \tag{2.43}$$

Similarly the equation is presented as follows

$$\lambda^2 + 2\zeta\omega_n\lambda + \omega_n^2 = 0 \tag{2.44}$$

Where:

ω_n	=	$\frac{1}{\sqrt{LC}}$
	=	the undamped natural frequency
ζ	=	$\frac{R/2}{\sqrt{(L/C)}}$
	=	damping ratio
v_o	=	initial voltage

v_i = instantaneous voltage

The undamped natural frequency shall oscillate with constant amplitude because it depends on the inductance and capacitance of the transmission line .The undamped natural frequency is also called a resonant frequency.

Furthermore, the undamped natural frequency depends on the line constants and when disturbed the electromagnetic of the parameters will cause the disturbance to propagate at almost the speed of light. If the equations (2.19) and (2.29) are substituted in the undamped natural frequency, $\omega_n = \frac{1}{\sqrt{LC}}$ then the speed of light is achieved where it approximately to 3.00×10^8 rad/ sec

Therefore, the disturbance on the system shall travel at the speed of light throughout the network of synchronised grid due to an equivalent calculation of the undamped frequency.

Naturally, the system response will rely on the damping ratio, ζ and any variation on the ratio shall also change the frequency of the system, ω_n and the time scale will be adjusted accordingly.

The equation (2.44) is second order differential with real and different roots to a quadratic equation hence can be solved by formula, and

$$\lambda = -2\zeta\omega_n \pm \sqrt[2]{\zeta^2 - 1} \qquad (2.45)$$

When the damping ratio in the above solution of quadratic becomes, $\zeta < 1$ then the eigenvalues solution will be a conjugate complex and be equal to

$$\lambda = -\zeta\omega_n \pm j\omega_n \sqrt[2]{1 - \zeta^2}$$

Where:

λ = eigenvalue

ζ = damping ratio

ω_n = undamped frequency

It all means that the conjugate complex pair of eigenvalue is given [7]by

$$\lambda = \sigma_i \pm j\omega \qquad (2.46)$$

Where:

i	=	integer number and
ω	=	$2\pi f$ oscillatory mode
σ_i	=	real part of the complex in neper per sec

When the real part of the complex is negative, $-\sigma_i$ then the system is stable and the damping frequency, ζ will be represented by the actual or damped frequency at a ratio of

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \qquad (2.47)$$

In general terms, it's imperative to understand the power system stability behaviour during a time when the sudden change has occurred in the system in order to analyse the pre and post change of load and generation even more on the interconnected system. It has been noted in the above sections, after system disturbance the power network, undergoes into damping oscillations and settles with a new operating condition.

2.5 Calculations of parameters in synchronous generator

Figure 2-10 refers, a synchronous generator, 950 MVA generating at a voltage of 22 kV and stepped up by the transformer. Considering the generated voltage to be $V_1\angle\delta$ and the voltage generated with a load angle of δ, the voltage at the load side be presented as $V_2\angle 0$.

Let δ be load angle that leads V_2 at the infinity busbar, at the furthest end of the circuit to the right hand side, so that when δ changes during the disturbance then the rotor will oscillate as the voltage, V' provides a reference phasor , therefore the current flow is calculated as follows:-

$$\tilde{I}_t = \frac{V'\angle 0^{\circ} - V_2\angle - \delta}{jX_T} = \frac{V' - V_2(\cos\delta - j\sin\delta)}{jX_T} \qquad (2.48)$$

Equation (2-1) refers, $T_a = T_m - T_e$ where on steady state the mechanical power was equal to electrical power, further to the equation it can be included that the electrical torque will be equal to electrical power because of the air gap that exists between the rotor and stator, the notion will take to the attention of a fact that when the stator resistances is considered negligible and then:

$$T_e = P = \frac{V'V_2}{X_T}\sin\delta \tag{2.49}$$

When the operating condition changes under a disturbance the load angle will change from its operating condition to a new condition hence load angle become $\delta = \delta_0$

$$\Delta T_e = \frac{\partial T_e}{\partial \delta}\Delta\delta = \frac{V'V_2}{X_T}\cos\delta_0\,(\Delta\delta) \tag{2.50}$$

The change of operation will be required to be expressed in state space format where the power system will be analysed on the dynamic performance. Equation (2.7) refers, $\frac{H}{180\,f}\frac{d^2\delta}{dt^2} = P_m - P_e$ will be required to add the component of damping that should be proportional to the speed of the rotor.

$$p\Delta\omega_r = \frac{1}{2H}(T_m - T_e - K_D\Delta\omega_r) \tag{2.51}$$

$$p\delta = \omega_0\Delta\omega_r \tag{2.52}$$

Where:

$\Delta\omega_r$ = the change of speed in per unit

δ = the rotor angle in electrical radians.

The angle is referenced to the synchronous rotating such a-axis in figure2

ω_0 = the base rotor electrical speed in radians/s

p = the differential operator d/dt with time in seconds

Equation (2.51) has to be linearized and requires to substitute with ΔT_e in equation (2.50) so that

$$p\Delta\omega_r = \frac{1}{2H}(\Delta T_m - K_s\Delta\delta - K_D\Delta\omega_r) \tag{2.53}$$

Where:

K_s = the synchronizing torque coefficient

$\frac{V'V_2}{X_T}cos\,\delta_0$

Equation (2.52) will be linearized with

$$p\Delta\delta = \omega_0 \Delta\omega_r \tag{2.54}$$

Expressing the equation (2.53) and equation (2.54) into vector matrix:-

$$\frac{d}{dt}\begin{pmatrix}\Delta\omega_r \\ \Delta\delta\end{pmatrix} = \begin{bmatrix}\frac{K_D}{2H} & -\frac{K_s}{2H} \\ \omega_0 & 0\end{bmatrix}\begin{pmatrix}\Delta\omega_r \\ \Delta\delta\end{pmatrix} + \begin{pmatrix}\frac{1}{2H} \\ 0\end{pmatrix}\Delta T_m \tag{2.55}$$

Equation (2.55) refers to have the input state space as provided in equation as follows

$$\dot{x} = Ax + bu$$

$$y = cx + du$$

However, the solution had a second order differential equation that was solved by quadratic formula, the solution to the equation (2.55) can be solved by the use of Laplace transformation and will be able to provide the stability control block diagram that can be used for dynamic analysis for the synchronous machine.

When the load angle changes, the initial operating in reference to E' and δ and then by using the simple method where equation (2.53) shall be used to find the solution by Laplace and after also substituting in the equation (2.54), $\Delta\omega_r$ and results will be in equation (2.56).

$$\therefore\ \Delta\omega_r = \frac{\Delta\delta}{\omega_0}$$

$$\Delta\delta = \frac{\omega_0}{s}\left[\frac{1}{2Hs}(-K_S\Delta\delta - K_D\Delta\omega_r + \Delta T_m)\right] \tag{2.56}$$

$$= \frac{\omega_0}{s}\left[\frac{1}{2Hs}(-K_S\Delta\delta - K_D s\frac{\Delta\delta}{\omega_0} + \Delta T_m)\right]$$

$$s^2\Delta\delta = -\frac{K_S}{2H}\omega_0\Delta\delta - \frac{K_D}{2H}s\,\Delta\delta + \frac{\omega_0}{2H}\Delta T_m)$$

Therefore the characteristic equation is given by the parameters for the synchronous generator

$$s^2 + \frac{K_D}{2H}s + \frac{K_S}{2H}\omega_0 = 0 \tag{2.57}$$

Where:

K_D = damping torque coefficient in torque per speed deviation

K_S = Synchronising torque coefficient in per unit torque per radians

H = Inertia constant, H

s = Laplace operator

ω_0 = Rated speed in electrical radians= $2\pi f_0 = 2 \times \pi \times 50$

$\Delta\delta$ = rotor angle deviation in electrical radians

A similar notation of damping oscillation format is obtained which has been derived in equation (2.57) and introduce the K factors that are used for the designed control for the machines.

Therefore, the undamped natural frequency is presented as

$$\omega_n = \sqrt[2]{K_s \frac{\omega_0}{2H}} \tag{2.58}$$

Where:

Damping ratio

$$\zeta = \frac{1}{2}\frac{K_D}{2H\omega_n} \tag{2.59}$$

$$= \frac{1}{2}\frac{K_D}{\sqrt{2HK_s\omega_0}}$$

When the synchronising torque coefficient varies the natural frequency will vary correspondingly but the damping ratio vary in opposite direction because it depends on the speed deviation from the damping torque coefficient. Therefore a high value on the inertia constant will decrease the damping ratio and natural frequency and of course it inertia constant is the designed value of the generator.

2.5.1 Modal analysis for power system network

Modal Analysis uses its calculation to obtain the power oscillation of the network by use of the eigenvalues and eigenvectors[7] that have been computed after the natural oscillation has occurred on the steady and transient states .

The modelled SAPP grid have over 500 state variable for calculation in the Powerfactory software tool. The calculation of eigenvalues and eigenvector are based on the complex frequency discussed in section 2.5 where the solution of the quadratic equation (2.58) is solved by use of matrix to determine the stability analysis.

There are two methods used for computation of the modal analysis used to determine the dynamic stability of the power system [49]:-

(a) QR/QZ method is used to compute the eigenvalues of real non-symmetrical matrices and used for the purpose of analysing the small signal stability hereafter referred to dynamic analysis. It calculates hundreds of state variable of the power system network the eigenvectors to find the solution small disturbance in the linear characteristics.

(b) Arnoldi/Lanczos method is generally used to carry out selective method calculations of the system eigenvalues for the power system. It is easy to identify the critical areas.

2.5.1.1 Simulated modal analysis of single generator

The QR/QZ method was used to calculate the stability of the power system and the results are shown in figure 2-21. It can be noted that there are over 10 modes to be analysed for its characteristics and behaviour on single generator. It means that a power system such as SAPP with almost 10 generators will be populated with modes. This will give a difficult task to analyse each and every mode plotted.

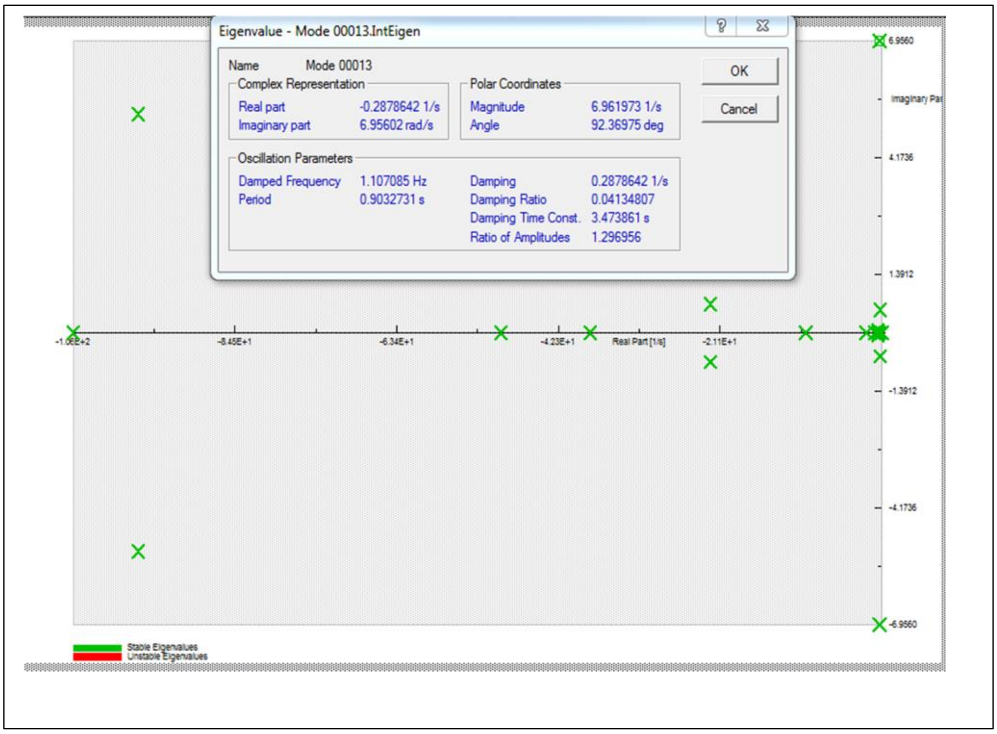

Figure 2-21: Illustration of stability plot in modal analysis

(a) From figure 2-21, the complex representation is provided in the rectangular form and as such from equation (2.46), the complex pair of eigenvalue λ=-0.2878642+j6.95602

(b) the polar coordinates of the eigenvalue shall be solved mathematically from the polar coordinates where it is the square of the real and imaginary parts of the above bullet as

$\boldsymbol{\sigma} = \sqrt{-0.2878642^2 + 6.95602^2}$

$\omega = \arctan\frac{6.95602}{-0.2878642}$.

Polar coordinates have been representing as $6.961973\angle 180^\circ - 87.6302543^\circ$.

(c) damping frequency refers to equation (2.47) and results to

$$\frac{\mathbf{-0.2878642}}{\sqrt{\sqrt{-\mathbf{0.2878642^2+6.95602^2}}^2}}$$

The period time $=\frac{2\pi}{\omega} = \frac{2\pi}{6.95602}$;

(d) DIgSILENT calculates the ratio amplitude by referencing to the next oscillation and used the following formula

$$\sigma_i = \frac{1}{T_p}.\ln(\left(\frac{A_n}{A_{n+1}}\right) \quad (2.60)$$

Where

A_n and $A_{n+1}$are amplitudes of two consecutive swing maxima or minima respectively.

After obtaining the natural modes, the system will exhibit oscillatory stability by the conjugate complex that has been subjected to complex frequency to provide the damping of the rotor to be plotted in the complex or s plane The stability of the plotted graph will lie on the negative real part on the left hand of the complex plane, s shown in figure 2-22 denoting electromechanical oscillation being stable on the simulated generator[7, 58].

In figure 2-21, the stability of the system lies on the left-hand side due to local oscillation mode, it lies on the plane of 180°. The generator requires being implemented with stability control so that it should operate in the second plane of 90 degrees.

CHAPTER 3

3 MODELLING AND OPERATION OF SAPP GRID

Power system modelling is the representation of all system components and elements in a standard electrical diagram with graphical symbols as provided by the National Regulator of South Africa incorporation with South Africa Bureau of Standards on NRS 002 [59]and has been used to represent SAPP network. The graphical single line diagram is used for the power flow studies which provides information on the voltage magnitude and angle at each bus and real and reactive power at different nodes.

SAPP grid has been interconnected to different national power systems and covers geographic surface area of over 1,219,912 square kilometres[60]. When modelling to study different performance measurement, it is not a prerequisite to detail the entire network[61]. This is due to the available speed of the operating system of the computers that might slow down due to iterative methods to calculate the solution for the required assessment. The dynamic analysis will require to analyse performance of the synchronous generators. Therefore, the interconnected generators, transmission lines and load were modelled for the SAPP dynamic analysis.

DIgSILENT, a short-form abbreviation of DIgital **SI**mu**L**ation of **E**lectrical **N**e**T**works is one of the computers aided electrical engineering tool used in power system modelling and analysis. The Powerfactory tool is a licensed software from DIgSILENT. It is used for parameter calculations and analysis of transmission, distribution, and industrial electrical power systems with an integrated graphical single-line interface. The software is designed with integrated and interactive software package for practical usage of the electrical power system and control

The interactive single-line diagram means that it is possible to model by utilizing the drawing functions embedded in the software tool, editing capabilities of the required data for any equipment including calculating from the diagram and entered data the solutions for all relevant static and dynamic calculation features studies.

The DIgSILENT Powerfactory software tool has been used for the study of the SAPP grid because it’s the most common software tool used in the Southern Africa, by organizations involved in planning, consultants, and educational institutions in South Africa.

3.1 Parameter for modelling in dynamic studies

When modelling the SAPP grid, it is necessary to have a knowledge of the generators, substations, transmission lines and load. It is also necessary to know the data for various equipment for the designed model. For a massive network as the SAPP, it is not feasible to acquire all the data for the high voltage and secondary control equipment. Thus, a reduced order model of the SAPP network was analysed and using the dynamic model of the generators. The available data acquired have been detailed in the appendices A and B for the generator and transmission lines.

3.1.1 Direct energy transfer functions on generator

In carrying out stability analysis, the mechanical energy in the power network also plays a vital part on the oscillation of the turbine and rotor shaft in the synchronous generators. In case of severe disturbance, machine energy functions have been studied to acquire the system transient energy for direct method by use of Lyapunov functions [62]. The direct energy transfer method tend to provide the transfer of mechanical energy to oscillate and be absorbed by electric energy without losing synchronism. The direct energy function is developed based on the conserving energy on the use of mechanical energy should operate within the limits and any oscillation should settle on within the limits set on an individual generator [63] This can be likened to the releasing of a body of mass from a top on a saddle to accelerate and come to rest. Similarly the energy functions were using the synchronous generator frame as reference in the mathematical derivations from equation (3.61) the other approach was to identify the centre of inertia where all the critical fault should be directed to the machine**.** Therefore analysing this direct method of energy functions it is required to:-

a) Determine accurately the unstable equilibrium area; and
b) Determine a sound proof that the mechanical energy functions can cause system outage.

Similarly to equation (2.11) refers, the motion of generator is represent as

$$M\frac{d^2\delta}{dt^2} + K\frac{d\delta}{dt} + P_e = P_i$$

This can be expressed in terms of speed so that $\delta = \omega$

$$M_i\frac{d^2\omega_i}{dt^2} + K_i\frac{d\delta}{dt} + P_{ei} = P_1 \tag{3.61}$$

Where:

δ = angle of voltage behind transient reactance indicative of generator position

ω_i = rotor speed

M_i = generator Inertia Constant

K_i = damping coefficient

i = 1, 2, 3…..n

The approach to transfer energy functions to electrical circuits from speed is very difficult to be achieved because requires to identify the centre of inertia of the multi-machine. The interconnection power network is dynamic and as such critical group of machines that have been referenced as the centre of inertia can change due to complex variations of the system[62].

However, the use of Lyapunov function to analyse as a direct method is still understudy and the method will not be used for the dynamic analysis. The transient analysis involves severe faults that require protection system to isolate and dynamic analysis involves the changes that take place by the controller to adopt the sudden changes of load and also during the fault to remain in synchronism. Therefore the direct method is still being studied on transient analysis, the modelling studies have not justified whether a system remains in synchronism after disturbance. The method shows mathematically efficient alternative to time domain simulations. Even though, the developments show that direct method by Lyapunov functions can offer alternative computing on real-time time-domain simulations, the methods has lurked development to provide analytical insight into the behaviour of power systems and providing theoretically principled estimates for power system stability[64].

3.1.2 Rotor equivalent electrical circuit

Powerfactory software tool uses the stator and field winding electrical circuits for modelling the dynamic stability analysis. The equivalent circuit diagrams of the standard synchronous machine is referred to the rotor system and presented in the Park coordinates dq – reference frame. There are two axis modelled, the d-axis for the two rotor loops on the rotor representing the field excitation winding and one damper winding on the q-axis on salient rotor. The round rotor will have two damper windings[65]

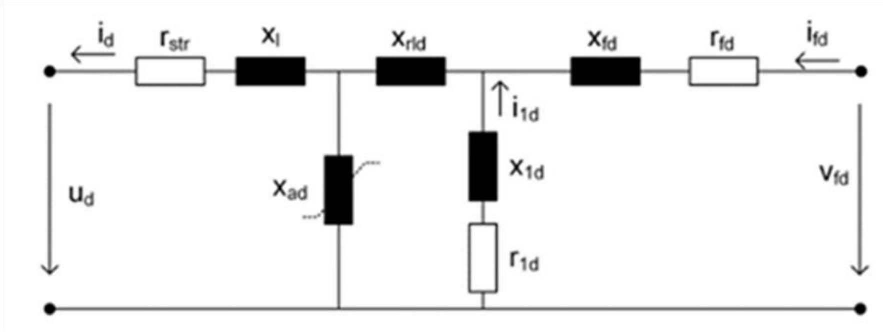

Figure 3-1: Rotor circuit as represented in DIgSILENT for d-axis

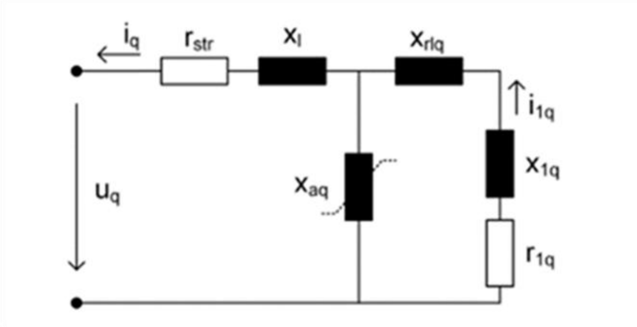

Figure 3-2: Rotor circuit as represented in DIgSILENT for q-axis

Where:

r_{str}	Stator resistance
r_{fd}	Resistance field windings
r_{1d}	Resistance damper winding d axis
r_{1q}	Resistance damper winding q axis
x_l	Stator leakage reactance
x_{ad}	Reactance of synchronous machine d axis
x_{aq}	Reactance of synchronous machine q axis
x_{rld}	Mutual reactance between field and damper windings- d axis
x_{rlq}	Mutual reactance between field and damper windings-q axis

x_{fd} Mutual reactance between field and d axis

x_{1d} Reactance of damper windings d axis

x_{1q} Reactance of damper windings q axis

From figures 3-1 to 3-2, it can be noted that the resistances r_{fd}, r_{1d}, r_{aq} and r_{str} are connected in series with inductance x_{fd}, x_{1d} and x_l for the field, damping and stator windings. It is based on the characteristic of the resistance and inductance connected in series that will be fundamental to the stability analysis. This is contrary to the assumption that was made in the mathematical deviation that assumed that the voltage behind the stator reactance, X_l was fixed at voltage magnitude. It is the behaviour of current in series of resistance and inductance (RL) circuit behaviour that will be adopted in the modelling of synchronous generator. The voltage behind reactance will then be essential applicable on the machines that are interconnected in the power pool [61, 66].For the interconnected power system to remain coherent, the stator resistance, X_l, that represents the voltage behind the reactance will be used to describe the dynamic equivalency technique . The technique will identify the groups of machines and each group will be represented as the single generator model that will be used to evaluate the coherency analysis of generators when subjected to a disturbances.

The currents i_{fd}, i_{1d} and i_d are flowing through the resistance and inductive circuits of the field winding, damper winding and stator winding. Current flow through the resistance will reduce the current flow and dissipate heat. The current flow in the inductor will grow its current before reaching its maximum current. The energy conversion is associated with the change of current with time such as that $L\frac{di}{dt}$ will be form the magnetic field due to flux generated and flow of current in the inductor also be used to excite the start of the generator.

The voltage V_{fd} is the voltage that will be used for the change of voltage in the excitation circuit transformed from the grid and U_d will be the generated voltage from the change of flux. $\eta\psi_d$, through the stator inductance X_l.

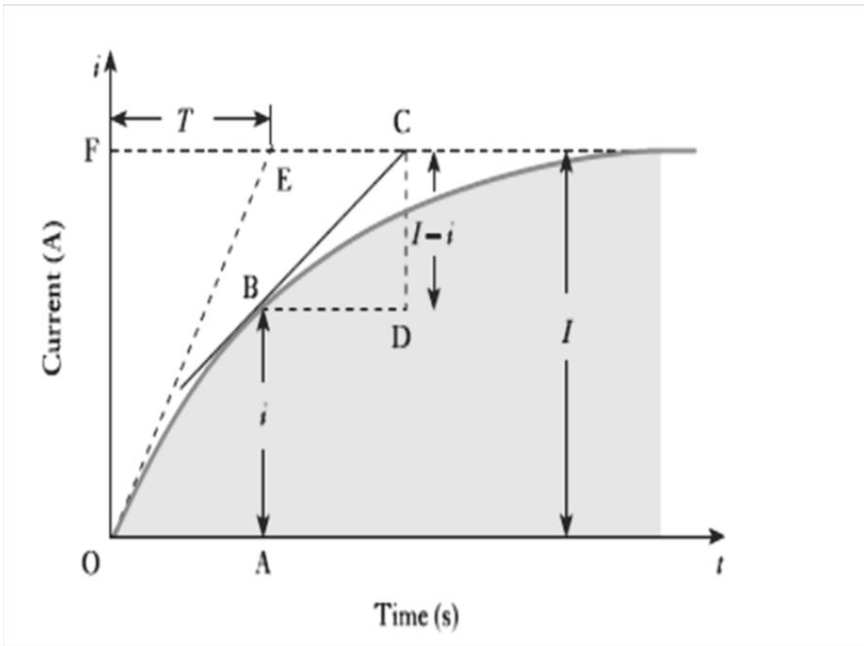

Figure 3-3: Growth of current in inductive circuits

Figure 3-3 shows the growth of current in the RL circuit that will correspond to the d- axis circuit provided in figure 3-1. The rate of growth of current at any instant is in such manner that it continues at an increasing rate and reaches its maximum value of I amperes in L/R seconds. Hence this period is termed as the *time constant* of the circuit and is usually represented by the symbol T [67]. However, time constant are derived when the circuit is closed or open positions. The generator will use the field winding operation to open and close the regulating voltage circuits and hence manufacturer will determine and provide the time constant relative to the self and mutual reactance to the customer.

Due to saturation effects, where current flow will flow from the source of voltage such as the field winding and stator windings, the resistances provides maximum value whilst the inductor will be charging to reach its maximum and also provide the discharge path on open circuit.

It can be observed that the generator model will require to determine the equivalent circuit in order to assess detailed parameters on the effects and merits of the damping, field windings and excitation control. The dq rotor referenced frame in the generator model for the time domain simulations will use the rotor fluxes, the synchronous speed and load angle as the state variables.

3.1.3 Determination of parameters for model

The equipment that are installed in the network undergo various stages before being commissioned. The equipment will be designed and specified depending on the studies carried out for the installation. The equipment will also be tested to verify compliance of the delivered and or installed equipment. It is normal to keep records relating to design, specifications and compliance by pre and commissioning tests before energized .The filing and keep safe of such information will reasonably be required for assessing power system performance (including actual unit performance during abnormal conditions). Often times the equipment will be tested as provided by the grid code requirement where a regulatory body established as the technical requirement.

The conduct of tests and different studies will therefore demonstrate that each high voltage equipment is regularly checked as a compliance to the technical requirement. In order to have a common technical approach to the functioning of the network, a regional harmonization code has to be developed amongst the regulators in the Southern Africa. Such grid code will provide testing procedures to be carried out on new units, after every outage where the integrity of any grid code requirement may have been compromised. This will demonstrate the compliance of the unit with the relevant grid code requirements. The utility shall continuously monitor its compliance in all required equipment in order to respect the connection conditions of the Grid Code.

3.1.3.1 Manufacturers parameters

Manufacturers of the power system equipment have different design procedures to run software packages for the production of the equipment. However the routine calculation of the standard equivalent circuit parameters are required to be adhered to. The utility and the manufacturers will reserve the rights to disclose the specifications used for the network. It is then necessary for the manufacturers to provide a standard reactance and time constants in the direct and quadrature axis in case of synchronous generators for the utility to use system analysis. If a non-standard method has been used by the manufacturers, then the manufacturer will require to derive its parameters for the interest of the utility.

The manufacturers may provide different parameters definitions, symbols and methods of applications depending to the origin of region of the world. There are instances when for example sub transient, transient and synchronous reactance are in the format like $X''_{di}, X''_{dv}, X'_{di}$ and X_{du} for the direct axis[65] and in the Powerfactory tool have used without subscripts *i, v and u*. It is appropriate to understand the notations that have been provided by the manufacturers hence the quantities means the same as "i" the short circuit current equal to rated armature current and designated often as unsaturated parameters. The "ν" applying to variations associated with faults due to sudden three phase short circuit from the rated terminal voltage.

The use of the numerical methods are applied for commercial and in house software packages for the application on its own simulation design to the required specifications. The designed circuits will be used to predict the required specification and further to the equivalent model. In power system transient analysis, the utility will normally provide the fault levels at the point of connection and that will be used for the simulation of the manufacturers but for the dynamic performance, then the simulated circuit will be used for different operating conditions.

3.1.3.2 **Test result parameters**

The testing of equipment in the power system network is challenging because of the high voltages required to be handled during the tests. However, in case of voltage, it is the low voltage that will be used and be translated as the ratio of the primary voltage. The secondary voltage from the testing equipment will be used to be injected on the high voltage equipment for example on 330 kV the maximum secondary voltage 110 volts will be used for injecting supply. The injected voltage will be proportional to maximum secondary voltage. The dividend is multiplied by the primary voltage to provide an equivalent of the primary voltage for 330 kV.

The voltage injection can be used to measure reactance in the generator windings if access is made easily accessible, but a fuse wire should be used to short the other terminals. The fuse wire will protect the instrument and damage to the windings.

The purpose of testing on equipment does not only imply to obtain the equipment values but also to checks wiring and operation of the equipment.

3.1.3.3 **Parameters of the synchronous machine used in Powerfactory tool**

The parameters used by the Powerfactory tool and are elements shown in the equivalent circuits in figures 3-1 and 3-2 and detailed in the Appendix B-3. It can be observed that current flow in the machine circuits are flowing in loop such that there is mutual effects during the operation. The output current will have the effects of damping and field windings.

From equation (2.16) the per unit stator voltage that provides the generated voltage to the grid have been expressed as follow:-

$$e_d = p\psi_d - \psi_q p\theta - R_{str} i_d$$

$$e_q = p\psi_q - \psi_d p\theta - R_{str} i_q$$

$$e_0 = p\psi_0 - R_{str} i_0$$

Further to equation (2.16), rotor voltage equations can be derived from the field winding in figure 2-3, where V_{fd} is determined as source of voltage to the rotor and it has used the normal circuit calculations[7].

$$V_{fd} = p\psi_{fd} + R_{fd} i_{fd}$$
$$0 = p\psi_{1d} + R_{1d} i_{1d}$$
$$0 = p\psi_{1q} + R_{1q} i_{1q} \qquad (3.62)$$

Where:

V_{fd}	Voltage across the field windings
R_{fd}	Field windings resistance
R_{1d}	Resistance damper winding d axis
R_{1q}	Resistance damper winding q axis
x_l	Stator leakage reactance
ψ_{fd}	Flux in the field winding
ψ_{1d}	Flux in the d axis winding
ψ_{1q}	Flux in the q axis winding
p	The differential operator d/dt
$p\psi$	Differential difference of flux related to time

The equations (2.16) and (3.62) have defined the stator and rotor voltage circuits , but it is required to understand the effect of stator and rotor mutual flux linkages. Powerfactory tool introduced a variable reactance X_{ad} and X_{aq} in the d and q axis equivalent circuits figures 3-1 and 3-2. In other explanations of parameters on mutual reactance X_{ad} and X_{aq} are provide at a fixed value. The variable reactance will be used for parameter conversion of short circuit to equivalent circuit parameters and for the mutual linkages then

$$x_{ad} = x_d - x_l$$
$$x_{aq} = x_q - x_l \quad (3.63)$$

Where:

X_{ad} = mutual leakage reactance on d axis

X_{aq} = mutual leakage reactance on q axis

x_l = stator reactance

x_d = reactance on d axis

x_q = reactance on q axis

The arbitary variables are introduced in the powerfactory tool for the mutual reactance in order to introduce to new variable after disturbances. The new variable will be used for the dynamic analyis and other applicable studies.

Table 3-1: Typical values of generator parameters

Symbol definitions		Description	Expected Values on Synchronous[7, 8]	
PF	**STD**		**Thermal**	**Hydro**
r_{str}	r_{str}	Stator resistance	0.0015-0.005	0.002-0.02
x_l	x_l	Stator leakage reactance	0.1-0.2	0.1-0.2
x_{rl}	x_{rld}	Mutual reactance between field and damper windings- d axis		
x_{rlq}	x_{rlq}	Mutual reactance between field and damper windings-q axis		
x_d	x_d	Synchronous reactance d -axis	1.0-2.3	0.6-1.5
x_q	x_q	Synchronous reactance q axis	1.0-2.3	0.4-1.0
x_{ds}	$x_d^{'}$	Transient reactance d- axis	0.15-0.4	0.2-0.5
x_{qs}	$x_q^{'}$	Transient reactance q- axis	0.3-1.0	-
x_{dss}	$x_d^{''}$	Subtransient reactance d- axis	0.12-0.25	0.15-0.35
x_{qss}	$x_q^{''}$	Subtransient reactance q- axis	0.12-0.25	0.2-0.45
t_{ds}	$t_d^{'}$	Short circuit transient time constant d-axis	3.0-10.0s	1.5-9.0s
t_{qs}	$t_q^{'}$	Short circuit transient time constant q-axis	0.5-2.0s	-
t_{dss}	$t_d^{''}$	Short circuit subtransient time constant d-axis	0.002-0.05s	0.01-0.05s
t_{qss}	$t_q^{''}$	Short circuit subtransient time constant q-axis	0.02-0.05s	0.01-0.09s

From table 3-1, when the short circuit transient time constant is not provided by the manufacturers, then the short circuit subtransient can be entered. The short circuit time constants are the most important parameters because will provide saturation at the loading of the generator. The subtransient is normally called the open loop time constants and will require to be converted as short circuit parameters as follows:

$$t_d^{''} = t_{d0}^{''} \frac{x_d^{''}}{x_d'}$$

$$t_q'' = t_{q0}'' \frac{t_q''}{x_q'}$$

$$t_d' = t_{d0}' \frac{x_d'}{x_d}$$

$$t_q' = t_q'' \frac{x_q'}{x_d} \quad (3.64)$$

For the salient synchronous machine, the transient reactance x_q' and the transient time constant t_q' in q–axis are not required due to unequal values and saliency effectiveness not significant on the generated voltage, stator current, power and excitation over normal operating point. Therefore subtransient time constant t_q'' is then calculated using transient reactance x_q on q axis instead of the subtransient reactance on q axis.

The behaviour of the synchronous machine when subjected to the three phase fault will respond in the electrical transient characteristics. The existence of resistance and reactance in the synchronous machine ensure that current will not grow spontaneously but with slow growth due to flux in the reactance windings. When the synchronous machine is disturbed then the flux will still be slowly discharging through the resistance. However, the slowly decaying of ac component is due to the relatively slow decay of the flux linking the transient circuits.

Synchronous machine models have been used in Powerfactory tool with a number of different investigations undertaken to analyse adequately the parameters with various techniques by both models on mathematical and experimental on the actual machines. Several assumptions have been made in the evaluating the synchronous electrical parameters and as such theories have been derived when determining the parameters [68, 69]. The development of mathematical model has resulted in the development of the Powerfactory to be able to simulate the machine tests on different types of analysis required for system design, planning and operation.

It can easily be noted that the common assumptions made during the test corresponds to the study of dynamic analysis. The machines were tested on sudden 3 phase short circuit on the generator terminal and stator decrement test with field winding short circuit amongst the assumptions made during the investigations.

The understanding of measurable time constants will not suffice the determination of direct axis circuit parameters but will need to carry standard tests to make approximations[69] .It is for this reason arbitary variables are introduced in the powerfactory tool for the mutual reactance such as $x_1, x_2, x_3, T_1, T_2, a$ and b have been introduced for the determinaton of direct axis[49] . The mathematical calculations derive the damping time constants that is related to equation (2.57), where a second order equation was achieved through the single line diagram

$$s^2 + \frac{K_D}{2H}s + \frac{K_S}{2H}\omega_0 = 0$$

It is through the mathematical derivations that has produced the second order polynomial equation. There are various ways of determining its values

$$T_{\sigma ld} = \frac{-a}{2} - \sqrt{\frac{a^2}{4} - b}$$

$$T_{\sigma fd} = \frac{-a}{2} + \sqrt{\frac{a^2}{4} - b} \qquad (3.65)$$

Where:

$T_{\sigma ld}$ = Mutual Time constant between stator and damper windings

$T_{\sigma fd}$ = Mutual time constant between field and damper windings

a, b = approximated variables.

The equations described for a single machine system but the SAPP power stations are often comprised of six machines utmost per station. When modelling the generators, the number of machines at a station will be presented to provide the general picture of once off simulation on the system operations.

3.2 Power system monitoring instruments

The accurate measurement of the voltage, current, frequency, power, phase angle depends on the requirement for the power system. The measurements provides power system control ranging from automatic closed loop control to recording of data for statistical purposes. The measured parameters provides direct visual reading as well as processed reading for remote from electrical measuring transducers.

Transducers are used as interfaces to generate an accurate small direct current analogue output usually in milliamps which corresponds to the parameter being measured. Unlike, tapping directly from the secondary output of the current and voltage transformers require isolation points in form of shorting and links respectively. The transducers provides a galvanic isolation quote the book of sourcing between the input and output. This provides and advantage to the output requirements to have light specified insulation requirements.

The outputs of the transducer are used for a simple presentation of measured values for the system operator in the Control Area and SAPP Control Centres to determine system control strategy. However the same values are used for the automation scheme in power control system such as Automatic Generation Control (AGC), Automatic Voltage Regulator (AVR), plotting of disturbance recorder.

3.2.1 Input source of a transducers

The transducer obtains its input from current and voltage transformers installed either outdoor or indoor substations. For overall accurate measurements of the transducer, the input originates from the metering class instrument transformers. There are normal two types of current transformers metering and protection instrument transformers that differs on accuracy. It is also common to apply transducers on protection class instrument transformers and this has characterized to withstand significant short term overload on their current inputs. It can also withstand up to 300 % of full load continuously hence the input circuit will be staggered at low impedance for current and high impedance for voltage input.

3.2.2 Output signal of a transducer

The output signal of the transducer is usually current and common ranges are 0-10 mA, 0-20 mA and 4-20 mA. This means that the required parameters have to be programmed to suit the ranges of values to be monitored. It means also that in case of voltage range of the transducer can be added to display devices without limits and without any need of adjustments of the transducer. The value of voltage range determines the maximum loop impedance of the output circuit. Hence, when the voltage range is high then it facilitates remote location of an indicating instrument.

In case of the output of the transducer being used for control purposes then measurements are placed to avoid open circuit in the internal circuitry. When the transducer is faulty, a constant current is continually injected to raise the voltage and provide falsified values in the loop for monitoring the power system.

3.2.3 Accuracy of transducers

Transducer plays an important role in providing the system operator with measured and monitored parameters. The Supervisory, Control, and Data Acquisitions (SCADA) depend on the output of the transducer to acquire data for the control of the power system. The accuracy of the transducer varies in the essence of the condition to be used on the power system and depends on how it's closely monitored and operated at all times.

The accuracy of the transducer is affected by factors that can be ignored or not to be relevant but the user have little or no control of it. This factors include the ambient temperature, external heat, input quantity distortion and unbalanced input[70]. The accuracy of a transducer is checked under an agreed set of conditions known as reference conditions. The intrinsic error is determined under reference conditions. All the transducer with the same intrinsic error are expressed as percentage such that a transducer with an intrinsic accuracy of 0.1 % of full scale has a class index of 0.1[71].

The transducer provides improved communication facilities where it allows several types of transducer to be transferred in the same link. The programmable scaling is done remotely without interference of the plant in the substations.

Under disturbance in the system the transducer will not provide the output signal immediately and it will take to time to respond to the change of the power system. This is due to the transformation that is undertaken in the transducer to provide an indication. The transducer will take a value from its source for example if the current is 0.8A from a full secondary current of 1A it has to reproduce an output of 8mA dc. Then when immediately a disturbance has occurred it takes time to readjust what is being processed.

3.2.3.1 **Current transducer**

The current transducer is connected to the secondary of instrument current transformer with an input of 1 and 5 amps. The current transducer provides the loading of the power system in amperes. The current transducer provides indications to the indicating instruments proportional to the input.

(a) Primary current	=	300A
(b) Secondary current	=	1A
(c) Transducer input	=	range of 0 – 1A secondary of (a)
(d) Transducer output	=	range of 0 – 10mA
(e) Current input of transducer	=	0.84A measured in (b) and (c)
(f) Transducer actual output	=	(b) x(c)

	=	0.84 x 10
	=	8.4mA
(g) Actual current flow	=	(a) x (d)
	=	0.84 x 300
b) Current flowing in the high voltage	=	254 A

The current flow in the power network is unidirectional. It is very difficult to know the direction of current flow whether it's being imported or exported in an interconnected power pool.

3.2.3.2 **Voltage transducer**

The voltage transducer is connected to the secondary of an instrument voltage transformer with an input of normally 110 volts and 63.5 volts on high voltage transmission line. The voltage measurement in the power system is usually at the rated high voltage with ± 10%. For this reason. The voltage transducer has a suppressed zero type of measurement. It provides the voltage at specific range. In case of synchronizing voltmeter, the indications are provided in the inverse linear to assist in synchronizing the generators into the grid.

Measurements of voltage using the transducer becomes different and requires careful considerations.

(a) Primary voltage	=	330 kV
(b) Voltage transformer	=	330 kV/110 V phase to phase
(c) Voltage transducer - Input	=	0 -10 mA
	=	110 V/10 mA

If (c) is considered for the output of transducer, then at 330 kV will be the maximum voltage indications. The voltage fluctuates on the network and as such measurements for the transducer require to further extend the output range. Then, this provides the readings on the indicating instruments compatible to changes of voltage in the system.

However, the voltage range input for the transducer need to be extended reasonably. When it is considered as the required statutory requirements of ±5%. The design of the transducer will be different from the standard output for the transducer. The accuracy of the transducer will depend on the requirements of voltage measurement. Mostly the voltage output is ranged up to 150 V.

(d) Voltage transducer input	=	150 V/10 mA

(e) Primary voltage can be measured = 450 kV

The statutory requirement for the measurement of the power system is beyond the standard that had been determined in the SAPP Contingency Analysis[36]. It's very difficult to carry primary injection at very high voltage. The only secondary test will be carried to confirm the right measurement of voltage is indicated on the instruments. It is required to recalibrate the voltage transducers with the real time frequency response to ascertain the accuracy with the subscribed input of the transducer[72].

The output for the voltage transducer becomes more complex when the 4-20 mA is used as the output of the transducer. This is due to upper reading of 4 mA output from the transducer at zero reading. This type of transducer has a fixed reading that does not consider the over range adjustment as mentioned in (d) of the voltage transducer. This type of transducer adjusts the primary voltage to suit the maximum of the transducer output.

If the indications are not scaled properly, it will then provide unrelated monitoring information for the power system. The general rule for measurement, the full primary value should be directly proportional to the full indication of the instrument. If the full input to the transducer has drifted away then the indicated value will not remain the same.

3.2.3.3 **Synchronization**

This voltage measurement is very essential in the power system. It is the same voltage that is required for synchronizing torque coefficient required for the electrical power to absorb the load as defined in equation (3.66)

$$T_e = \frac{V^{'}V_2}{X_T}\sin\delta \qquad (3.66)$$

Synchronization is performed at a busbar of different supply sources and angle required to be connected from a common point of breaking point. In the Interconnected power pool such points are referred tie bus or tier. The two known place requiring synchronizations are:

1) Generator and grid
2) Two grid supplies connecting on transmission lines

The synchronizer is installed to determine that the two voltages are in synchronism. The two grid supplies will be monitored by the voltmeter and phasor angle instruments. When the two voltages are approximately equal to each other and also the phasor angle is zero. The synchronizer provides a close contact to for the circuit breaker separating the two grid. In true sense the voltmeter will be measuring the magnitude of the voltage and the phasor angle determine equal frequency between the grids.

3.2.3.4 **Frequency transducers**

It has been noted that the voltage and current transducers derives their input for instruments indications from instrument current and voltage transformers. The combination of the voltage and current does not provide frequency. However frequency monitoring obtains its frequency from the secondary output of the instrument voltage transformer. The transducer does sample the rate of cosine waveforms that crosses zero to provide the frequency of the system. It also determines the sampling number and value that has crossed zero at specified time to inversely proportionate for frequency.

Accurate measurement of frequency is quite important to the interconnected power system. However, most manufacturer provides an error percent of 0.1% and 0.01% for the frequency indication with a centre zero. The centre zero provides an indication from zero to 50 Hz on right hand side and 50 Hz to zero on the left hand side.

3.2.3.5 **Phase angle transducer**

This type of transducer provides a measurement of power system for the power factor. It is upon the indication of the power factor when the power angle can be calculated for system. It is achieved by the input from both the current and voltage instrument transformers. The scaling of the transducer for the indicating instruments will be centre zero as $-180^{\circ}..0..180^{\circ}$ the output of the transducer will then be taken the same format for indicating instruments $-10mA..0..10mA$. This notation of range denotes whether the power factor will be leading or lagging. The output of $-10mA$ on the indicating instruments means lagging measurement and $10mA$ means that the measurement has a leading power factor indication. When the load angle changes then the indication will be according to the input from the transducer.

In SCADA monitoring, the power factor will be programmed to provide for real value of the angle and it all depends on the point of measurement, similarly the transducer will use the zero crossing waveform and provide the mean sample as the power factor value.

3.2.3.6 **Power transducers**

The power transducers such as the active and reactive power measurement require to realise the nature of load on the network. The connection of power transducers are shown in Appendix C for the following type of loads.

i. Balanced load

The balanced load has the behaviour of the delta connection. The current flow in the delta connection is equal in all phases at $\sqrt{3}I$ and voltage will be the same at phase to phase or when a neutral is introduced to the system. A separate connection of earth wire provides a neutral to the 3 phase delta connection. The system is defined as 3phase 3wire balanced system when phase to phase voltage is used for measurement and 3 phase 4wire balanced system when the phase to ground voltage is utilized for the input of the transducer

For the delta connection, a single current transformer is installed to measure the power flow and also a single phase to phase voltage transformer is installed for measurement.

ii. Unbalanced load

The unbalanced load is the star connected load where it is assumed that the phases carry different current value and there are three different configurations

a) 3phase 3wire unbalanced load
The current transformers are connected to two phases and the voltage transformer connected to three phase A, B, C thus phase to phase voltage. The current transformer connection to the phases is being termed 3 phase because 3 wire are connected to phase A, Phase B and Phase C

b) 3 phase 4 wire unbalanced load
The current transformers are connected all three phases and voltage transformer has been connected on the three phases including neutral.

c) 3 phase 4 wire unbalanced ($2\frac{1}{2}$) load
The connection of the current transformer is the same as 3 phase 4 wire unbalanced load and differs on the voltage connection where only two phases and a neutral are used for measurement.

The power transducer uses secondary output of current and voltage instrument transformers. The power transducer also use the multiplier that combines the current, voltage and phase angle to provide the power calculation in the transducer. The output is scaled accordingly to provide the primary values of the power system.

iii. Scaling of power measuring instrument

The power measurement like the active and reactive is indicated from the product of voltage, current and phase angle. The scaling will be carried as follows whether balanced or unbalanced loads.

(a)	Current Transformer Ratio	=	300A/1A
(b)	Voltage transformer Ratio	=	330kV/110V
(c)	Power factor	=	0.8660
		=	120° symmetrical components
(d)	Primary Power calculation	=	$\sqrt{3}$ x current primary x voltage primary
		=	$\sqrt{3}$ x300Ax330kVx0.8660
		=	148.5 MW
(e)	Secondary power calculation	=	$\sqrt{3}$ x1Ax110Vx0.866
		=	165 W
(f)	Active Power scaling	=	150 MW
(g)	Reactive power scaling	=	Power triangle formula
		=	$\left(\sqrt{3}x300\,x330\,kV\right)^2-\left(148.5MW\right)^2$
		=	$\sqrt{\left(171.4MVA\right)^2-\left(148.5MW\right)^2}$
		=	85 MVAR

In normal cases, experience has shown that the reactive power is scaled half of the active power. It becomes contrary to the power triangle calculation. If the transducer is specified as secondary input of the instruments transformers as in (e) then the transducer will not indicate the 148.5 MW on the system. The active and reactive power need to be specified as per installed specifications of the instrument transformers to be applicable and accurate for monitoring on the import and export of the energy consumption.

3.2.4 Energy Metering

Unlike all the above stated instruments, energy meter register and store its consumption and demand. The others provide only instantaneous measurements

Meters and instrument transformers for energy metering is applicable on metering specifications as outlined by a Technical committee in International Electromechanical Commission. It is so specialized form of measurement on electrical power, reactive and for the purpose of trading within the operating members of SAPP and also consumers

The energy metering read and record active and reactive energy. It presents the energy delivered to or received at each connection point, with an appropriate degree of accuracy specified in applicable IEC 60687 to be not less than +/- 0.2%.

The energy metering records power over a number period, so the energy is measured in units of kWh. The energy meter uses power waveform to register the energy. It picks the peaks and zero crossing average at an hourly period. The zero crossing are indicated by pulses flashing on the meter. The energy meter, therefore, specifies the number of pulse rate in one hour. If the pulses are flashing at fast rate then it means the high usage. The energy meters are programmed to continue and average the power even if the consumption did not complete the hourly period. This will enable to register energy consumption.

The maximum load demand is another measurement that is carried out as a power capacity in energy meter. The meter keeps access memory of all highest peaks in the waveform and sort accordingly. The maximum load will indicate the highest the meter registered during the billing period.

The energy metering equipment shall have the following characteristics[73]:

(a) Three phase four-wire system as explained in the power transducer;

(b) Record in the required billing period for power, energy and maximum demand available in data registry. The recorded parameters should be displayed for reading with its instantaneous and accumulated data. The meter should be a programmable and reset after the billing period for the cycle of billing period;

(c) The meter should be able to measure all the four quadrants on reactive power , import and export on active power to show the direction of power flow;

(d) When a backup register is used, the data register should store separately the information from different metering points. It should be properly labelled whether main or backup meter;

(e) The data memory in the meter should be able to store at least one year with intervals programmable from 5 minutes to 30 minutes in non-volatile memories;

(f) The meters should be capable to be interrogated by local ports or telemetering or the available serial communication for data collection from the meter;

(g) The meter should have the capabilities to provide alarm when tampered , indicate status when faulty,

(h) Meter shall be at a secure and well protected, visible and accessible, conforms to tropical environmental conditions. The meter kiosk should be sealed to prevent unauthorised access.

The metering system provides measurement for the consumed energy and capacity energy on each installed point. The energy meter provides both import and export metering at all interconnections of power system. It will provide the main and check meter in case of the failure of the main meter, the check meter should be referred to take the readings for the billing period..

The main and backup meters should be installed as close as practicable at the installed point and where the location is placed at different position, SAPP connection agreement should determine and agree on the adjustment of loss that may incur between the two meters. The adjustments of the loss should include transformer and line loss compensation.

3.2.5 Disturbance recorders

Power system suffers from different types of disturbance and often times just like indicating instruments, protection operates without any record for the system operators. The detailed record of disturbance will enable the post fault analysis determine the nature of the fault. The analysis will also provide subsequent operations on pre and post faults on the affected plant. A detailed recording of the fault distinguishes between cause and effect in its plotting. If the effects are spread over wide area of SAPP grid, records of the disturbance from a number of locations from utilities can assist to determine the location of the disturbance.

3.2.5.1 Characteristics of the disturbance recorder

(a) It is characterised with multi-channel analogue input waveform for recording required data. The analogue channels are provided to record current and voltages on the faults to be recorded at a substation or generation plant. The waveform that it produces has to be captured with analogue conversion to digital. This type of recorder have surpassed its existence in technology.

(b) The digital multi-channels are embedded in main protection relays such as distance relay on the transmission line. They have an advantage to store several records that can be downloaded for analysis. The digital inputs are provided to capture signals such as circuit breaker opening, protection relay operation, inter trip, magnitude of current and voltage during the disturbance;

(c) The triggering effects are made available for both analogue and digital input channel to record and quantify the occurrence of the disturbance in the power system. It is operational norms of the disturbance recorder to have relevant threshold to initiate the trigger facility;

(d) The recording time can be programmed to register for disturbance that can last several minutes. The recorder captures events over a wide range of timescales by programmable sampling rates. It ranges from the short term transients while also ensuring sufficient data to be collected on the long term transients; and

(e) Time synchronization is also vital on interconnected network so that faults time are aligned from one recorder to the other of the same event.

3.3 Technical operations of SAPP Grid

The objective of SAPP guidelines ensure that operating members participate and benefit from the pool in an environmental that will be in sustainable manner .It also equally operate the electric power network of Interconnected power pool such as Southern African Power Pool (SAPP) safely, efficiently and effectively.

Therefore, interconnected utilities in SAPP must comply with the requirements agreed and be able to formulate more detailed requirements for system operations of each member country. It further enables all the Operating Members to be able to participate in securing the smooth operations of SAPP grid and a benchmark the performance the signed interconnection agreement.

The SAPP guidelines are meant to harmonize the operations amongst national utilities in the Southern Africa Power Pool. Then, achieve high levels of system reliability and control at busbar tie of the interconnection. It specifies the basic operating policy of how an Interconnected Power pool such as SAPP implements and establishes technical and operating experience on various system operations.

3.3.1 Generation control

A secure and interconnected power system requires controlling its generators accurately and adequately in order to reduce time error, frequency deviations, and inadvertent energy interchanges. The generation power station operates with automatic generation control (AGC) to generate sufficient capacity for the network. The automatic generation control balances continuously the generation and interchange schedules of its available load. This eventually regulates the interconnection frequency. The power pool being a market oriented amongst the operating members ensures the fair system operations and energy trading. The operating members will declare the available generators and the capacity to participate in the power trading. In this regard, the economic dispatch is installed so that the obligation to supply is achieved by use of AGC. The AGC schemes enhance the balance of power with the required load to be dispatched as an economic operations to the operating members and customers[74].

3.3.1.1 Area Control Error of the Interconnected Power Pool

The instantaneous difference that arises due to net actual power and scheduled interchange as used hourly. The error includes the effects of frequency bias including correction for meter error. A Control Area means the national electrical power system. It controls up to the points of Interconnection of another country. The area that maintains continuous balance between the generation and load, the consumption of electricity and the scheduled interchanges under its control with other Control Areas.

The Area Control Error (ACE) is determined by specifying limits prescribed by the relevant control performance standards and the Automatic Generation Control (AGC) shall continuously compare:

i. The actual frequency and scheduled frequency and;
ii. The total net actual interchange and total net scheduled interchange

ACE [75]has been defined mathematically as:

$$ACE = (NI_A - NI_S) - 10\beta(F_A - F_S) - IME \tag{3.67}$$

Where:

NI_A = Actual Net Interchange

Algebraic sum of tie line flows between the Control Area and the Interconnection

NI_S = Scheduled Net Interchange

The sum of all scheduled transactions with other Control Areas

β = Control Area Frequency Bias

Frequency bias setting $MW/0.1Hz$

F_A = Actual Frequency

F_s = Scheduled Frequency

IME = Interchange Meter Error, mostly negligible

For equation (3.67), if the ACE is negative, then the area power system have insufficient generated power for the interconnected power system at the agreed schedule net power. The frequency bias setting, $10\beta(F_A - F_S)$ assists the Control Area to support the frequency. If the scheduled power, NI_S is subtracted form, NI_A and when the actual frequency, F_A is less than scheduled frequency, F_s the value of ACE decreases. The area would produce sufficient generation to supply its own load and the agreed schedule will not manage for any additional output to assist the SAPP pool.

The key control to the whole operation is the difference of error between scheduled and generated power for own consumption should be negative and equal to the required value. The SAPP does not have continuous measurement of the system response and normally use estimates on the frequency bias setting. The closer the frequency bias matches the actual system frequency response, the better AGC will be able to distinguish between internal and external imbalances and reduce the number of unnecessary control actions. Therefore, the basic requirement of tie-line frequency bias is that it matches the actual system response as closely as practicable.

All Generating 5 MVA or greater units have to be equipped with governors operational with a droop between 2% and 10% with an initial setting of 4% for Frequency Response to ensure that the Control Area continuously adjusts its generation to its load plus its net scheduled interchange unless restricted by regulatory mandates. The maximum ACE dead band setting in the AGC shall be a MW value equivalent to frequency deviation of ±0.05 Hz. SAPP frequency bias setting is equal to $6.67\beta(F_A - F_S)$ because frequency dead band for the governors on generators is set to less than ±0.15 Hz.

3.3.1.2 **Time and frequency control**

The most continuous role of the system operator to work around the clock is partly to closely monitor and provide remedial actions on the system frequency. The SAPP grid produces electricity from synchronous generator that is directly proportional to torque multiplied by angular speed. The change of ultimate power being generated will mean that angular speed has changed hence requires to adjust the rotor of the synchronous generator.

Frequency deviation is defined as the difference of frequency at 50 Hz between load and generation. The change of frequency requires to correct the time because at every cycle the power will shift from the standard time. Frequency being maintained at nominal is not sustainable due the integral frequency that the clock displays. The effects of integral will slowly retard or advance the true time. This is due to the average creeping of the cycle that would not be exactly on nominal frequency and then regulating only the frequency in the system is not a simple task. The satisfactory operation of the interconnected power systems will depend on largely the accuracy of frequency transducers, disturbance recorders and time error associated with AGC equipment [76].

SAPP grid and any other power network in Southern Africa require to maintain frequency at scheduled 50.00 Hz. The frequency bandwidth has to be agreed upon the SAPP operating members for operating limits on frequency deviation and time error .At the time when the frequency is being corrected then thus the only time when frequency can become higher than the normal rate. The frequency can be operate high value to establish the required Interconnection reliability. Time error is monitored and corrected at Control Area.

The reference point of time is taken as UTC (Universal Time Co-ordinated) plus two (2) hours through the satellite. The synchronous generator has synchronized frequency to operate continuously. When the load is slowly increasing then the angular speed tend to slow down and the frequency decreases. When the time is not corrected then the generator will start to convert the store the kinetic energy into the decelerating rotor. Therefore, frequency of the Interconnection is maintained between 49.85 Hz and 50.15 Hz for at least ninety-five percent (95%) of the time within ±30 seconds under normal conditions.

Systems using time error devices that are not capable of automatically adjusting for leap-seconds should arrange to receive advance notice of the leap-second and make the necessary manual adjustment in a manner that will not introduce a disturbance into their control system. The available record that can be analyzed on frequency can be visualized on the disturbance recorder otherwise frequency at SCADA and indicating instruments are for instantaneous monitoring only

3.3.1.3 **Active (Real) Power (MW) Supply**

Every System Operator controls its active power demand in order to ensure a sufficient level of operating reserve for the each country. The system operator will consider:

(a) Availability of generation or transmission equipment;
(b) Errors in forecasting,
(c) Loss of generating units;
(d) Forced outage rates, maintenance schedules;
(e) Regulating requirements ;and
(f) Load diversity between Control Areas.

In case of forced outage each country utility takes appropriate steps to reduce its Area Control Error to zero within agreed time and to protect against total shut down of the system.

It is imperative that each operating members to adequately understand the system operation by undertaking different extensive study of its system. This will enable for countries to declare the real annual peak demand with reference to the largest generator in its power system. The annual peak demand should reflect the power which was consumed within the boundary of the power system of each Operating Member, whether the power came from imports (or purchases). The annual peak demand should however exclude exports and any load that was reduced. The need for the country to tackle effectively the non-technical losses that may occur namely by the customers.

The declaration of the annual peak demand assists member countries to determine minimum System Operating Reserve Requirements (SORR) and is expressed as follows and has been indicated in Table 3-2 for the year 2013.

$$SORR = PORR \times \left(\frac{2D_s}{D_t} + \frac{U_s}{U_t}\right) \tag{3-68}$$

Where:

SORR = Minimum System Operating Reserve Requirement

PORR = Total Pool Operating Reserve Requirement

D_s = Individual System's Annual Peak Demand

D_t = Total Sum of Individual System's Annual Peak Demand

U_s = Individual System's Largest Unit

U_t = Sum of Individual System's Largest Units (sum of (U_s)

Table 3-2: Operating Reserve for SAPP members in 2016

Utility Name	Largest Generator [MW]	Maximum Demand [MW]	Spinning Reserve [MW] e	Quick Reserve [MW] f	Operating Reserve [MW] g = e + f
ESKOM	930	33374	504.3	504.3	1008.5
ZESA	220	1589	47.8	47.8	95.6
ZESCO	180	1522	41.6	41.6	83.2
BPC	150	610	27.2	27.2	54.4
EdM	38	830	14.6	14.6	29.1
CEC	10	765	10.0	10.0	20.1
NamPower	92	629	19.6	19.6	39.2
SNEL	65	1317	23.7	23.7	47.5
LEC	24	140	4.8	4.8	9.7
SEC	10	227	3.9	3.9	7.8
TOTAL	1719	41003	698	698	1395

Source: www.sapp.co.zw

Table 3-2 provides the sharing of spinning reserve between Operating Members. This operating reserve is sufficient to reduce the Area Control Error within agreed minutes after the loss of generating capacity. Therefore the Operating reserve need to be shared sufficiently throughout the system and inclusive of the generation capacity at standstill, transmission bottlenecks and the national requirements.

3.3.1.4 **Voltage control**

The loading of power system captivates the grid to operate with capacitive and inductive loads. Then the voltage in the system differs due to characteristics of capacitive and inductive where the voltage increases and decreases respectively. Voltage control operated within adequate capacitive and inductive reactive resources maintains the specified limits of the voltage levels inside the systems and at the points of interconnection.

3.3.1.5 **Protection coordination**

Protection relays operates under detected faults condition and greatly influences the operation of interconnected system. Protection schemes are designed to protect the power system from any other possible equipment in the interconnected system from different types of faults.

The requirement of electrical power system to any consumer relies on the reliability, secure and economy. It is for the sake of security that the power system should be designed and managed to deliver acceptable power to the customer. Therefore, due to severe faults that do occur in the power system that can cause extensive damage to the power system equipment inclusive the customers. It is for this reason the economy plays another important that require huge capital to replace due to damage caused by the faults and reducing reliability of the supply the customers. Therefore, the power system require designed network to detect and isolate the faulty part automatically.

However to achieve the elimination of the faulted, it is required to have high speed relays such as the line differential, distance relays that will act immediately on faults .The high speed relay require the adequate channels and fast communication network for the quick action. Periodically assessment of protection relays on functionality test for the relays associated with the interconnected lines is requisite. This is required to monitor performance of automated channel and failure alarms that provide indication for the fault in the network.

3.3.1.6 **Load shedding**

The load shedding is oftentimes experienced when there is no available support from the interconnected system due insufficient generation capacity and growing load. Load shedding shall be carried automatically by the relays or by switching the lines to avoid further compromise of system security.

When a severe under-frequency occurs, automatic load shedding shall operate as coordinated throughout the Interconnection together with other operations that occur during abnormal frequency or voltage conditions. Automatic load shedding shall be in steps and initiated by one or more of the following parameters: frequency, rate of frequency decay, voltage level, rate of voltage decay or power flow.

The operation of the power pool has dwelt much on manual calculations mostly on the area control error and determination of the control performance. It is very difficult to operate the power pool with exact and continuously balance between generation and load to maintain frequency. The set control performance standards at CPS1 and CPS2 [77] require proper real on time measurements. If such are not being used for the SAPP pool, SAPP Coordination Centre verification will be an uphill to be audited and appraise the Control Areas.

CHAPTER 4

4 SAPP GRID

SAPP grid has been developed as a circuit representing a three-phase power system and modelled with the synchronous generators, generator transformers, transmission lines, and loads. The SAPP grid has been also developed with the dynamic controller that will perform voltage, frequency and speed control for the operations of the synchronous generators. The SAPP grid has been further presented to resemble a power system network in the physical layout of an electrical circuit for the synchronous generation, transmission lines and associated substations. The modelling of SAPP grid in single line has an inclusion performance of the three-phase network. This can be evidenced when providing the components specifications such as the presentation of generator and transformer in figure 4-1**.** The star grounding in the transformer and generator provides a proof of three phase supply connection and also the delta-star connection symbol of the transformer indicates that the connection is based on a three phase calculation and performance. The components data are presented in absolute, real and per unit equivalent values. The DIgSILENT Powerfactory denotes a substation with a thick line in its circuit drawing. In the thick line the whole composition of a substation has been incorporated with circuit breakers, isolators and earth switches as per different types of busbar systems. The parameters in any network are identified with the equipment label for identification and denoting nomenclature for the power equipment. The symbols are drawn as per NRS *002* standard of a South African standard of a single line diagram for the representation of the transmission lines and associated apparatus of an electrical power system[59].

The presentation of the SAPP grid in one line diagram further shows the graphical path for the power flow from generation through the transmission line and distribution for the use of customers. However, the elements in single line diagram do not represent the physical size and location of the electrical plant in any station. It is a common understanding in the electrical engineering to organize the schematic drawing in such manner to acquire the needful information about the system.

SAPP single line diagram in DIgSILENT Powerfactory, therefore, has four purposes for:-

(a) **Interpreting the intended purpose of the installation of the power system**:
It is useful to understand the nature of study intended to be executed in the power system network. For example load flow is intended for analyzing the steady state of power system network hence there is no need for the isolation and protection system during the load flow

calculation. The isolation of the power system become necessary when analyzing the transient condition which requires the speed and time taken to execute the elimination of the event.

However, the dynamic analysis requires both the load flow and transient conditions with much emphasis on the response of the controllers modelled in the synchronous generators. The circuit breakers will be required when identifying the switchgear parameter for simulation and verifying whether it has taken the required instructions.

(b) **Serving as a basis to produce project diagrams:**
The implementation of projects in electrical engineering requires the single line to represent in simple presentation of the required equipment. The single line serves as the outline of acquiring electrical equipment from the particular functions at any point of the project plan and will assist to identify the specifications for manufacturers. These will provide the requirement for an input from the civil and mechanical engineers to provide specifications to support the heavy plants in the substation and generating plants.

(c) Analysing power system problem:
The information used for single line diagram varies per the principle of the studies to be undertaken for analysis. It is an easy way of undertaking simulations on the high voltage without causing outages to carry tests and obtain results. This also accounts to analyze the system behavior when subjected to different problems. In dynamic analysis, the dynamic controller has been added in the generator model and performs in the same manner when controlling the voltage and frequency on the synchronous generator.

(d) Determining the isolation points of the network:
When simulating the dynamic analysis, the simulation will require to show the isolation points, the circuit breakers are used to isolate the fault both on simulations and real operations. The single line shows the points of earthed equipment as shown for the transformer and synchronous generator in figure 4-1 and again the earthing path are normally isolated to prevent back energising through a negative sequence components. The earthed parts are shown to represent the star connected with the generator and transformer equipment.

The physical presentation can be seen in figure 4-1 where the power powers station are shown by the actual appearance, for example, the cooling towers at the power station , the transmission towers, and substations.

In the same figure 4-1 to the upper right-hand side, the synchronous generator is electrically represented by a circle and inscribed SG in vertical position has completed circuit to load as per representation in the DIgSILENT.

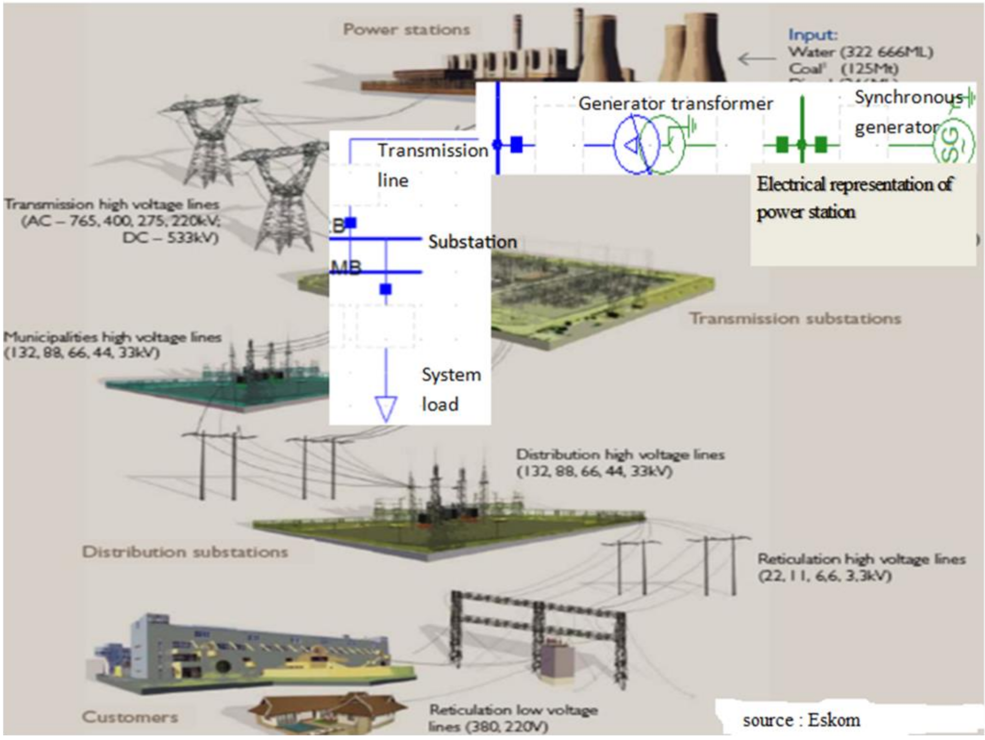

Figure 4-1: Typical power system diagram

4.1 Modified SAPP Grid

The network in the DIgSILENT has been further modified for easy reference as shown in figure 4-2. The transmission network for the SAPP grid provided in figure 4-2 has two major transmission voltage levels for the power evacuation and as such 330 kV and 400 kV voltages are mostly used in the network. Figure 4-2 shows the four crossborder blocks for east, north, central and west. This is representing the some of the four participating utilities in SAPP interconnected power system. Most of the hydro generators are based in the western and central blocks. The voltage levels on transmission lines are running at 330 kV and with less distance running on 220 kV. The central block has two combined types of generator, the hydro generation plants close to the crossborder of the western block and also thermal generation plant close to the northern and eastern blocks. The largest production of electricity was in the eastern block and based on thermal generation power plants. The voltage standards in the eastern block are run at 400 kV and above as the transmission lines totally different with voltage levels at west and central blocks. It was for this reason that the common point of connection with central and eastern has an inter-bus transformer of 330 kV/400 kV to transfer power between the grids.

The SAPP grid from figure 4-2, indicates that most of the generated power from the countries is consumed for own use. In the eastern block, the power is generated from four hydropower stations (H1_6 –H4_6) and its transmission line stretches up the northern part of the block to supply for its own use. The central block receives power from eastern block between H2_6 and H5_6 with two 330kV transmission lines. It can be noted that the three transmission lines to Sub 11, only one line runs straight to sub 17 from Sub 11, that can be suspected to be the dedicated line for SAPP together with a transmission line from T1_6 to Sub 22.The other two lines from Sub 11 flow through various substations before being connected to sub 17. It can further be noted from T1_6 that the two lines are connected to Sub 17 to perform as voltage control and increase power capacity for Sub 18 through to Sub 21. The other reason noted from the two lines from T1_6 to Sub 17 will be to provide an alternative transmission link to Sub 22. The latter reason for the two lines from T1_6 to Sub 17 will cause a major voltage drop between Sub 17 through Sub T1_6 to Sub 22 due to the distance being covered to be slightly over 500km.

The northern block is a consumer country that can be supplied from the central or the eastern block and also from eastern if need to do so. The SAPP grid presented in figure 4-2 shows that the national utilities will deliver the generated electricity to the country’s needs before supplying excess supply to Southern Power Pool for the regional power trading. However, SAPP electricity trading has been designed and agreed upon on the sale of excess power. This then means that it trades on a must not fail delivery of electricity for the power trading and hence the automatic generation control will dispatch the agreed power as committed by participating countries. The condition to deliver electricity at all cost has led utilities to adopt the load shedding on physical switching off customers due to inadequate generation capacity.

In figure 4-2, the hydro generators are represented with small squares to denote the storage of water in a dam or run of river and as such H1_6 and H2_6 generates on average 150 MW per synchronous machine. H4_6 generates 10 MW per machine and considered to be the smallest generating plant in the modified SAPP grid. The modified SAPP grid has considered an Independent Power Producer, H3_6 with a generation capacity at an average of 60MW per synchronous generator. H3_6 belongs to the national utility in the central block and generate at an average of 110 MW per synchronous generator and provides a receiving power station from the western block.

The central has a thermal generating plant at T1_6 which generates an average of 100 MW per synchronous generator. The largest machine is located at T3_1 that generates about 720 MW. The largest generating plant in the network is T2_1 and also receives power from the other blocks.

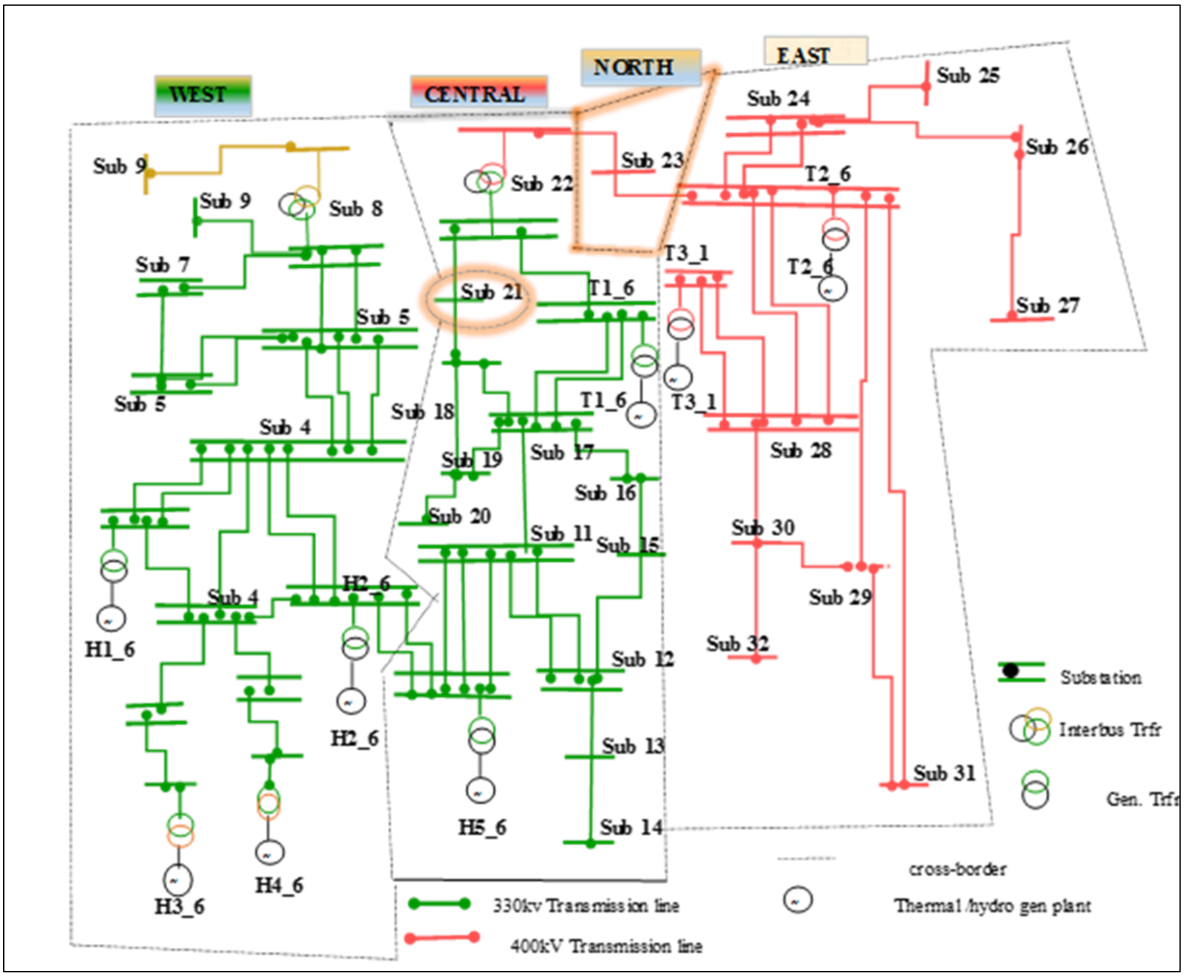

Figure 4-2: SAPP diagram for dynamic analysis

The major substations are represented with a dots inside two parallel line and the high voltage transmission lines are connecting power from generating power plants to the substation and also from one substation to the other. The major substations further connect to the loading centres for the distribution networks. The detailed data has been provided in Appendix A for transmission lines and Appendix B for the synchronous generators.

The single line diagram in figure 4-2 represents the model developed in DIgSILENT Power factory for the study of the dynamic analysis. In the simulation, figure 4-2 has been used to express the points for the occurrence of events for performance analysis of grid.

4.1.1 Conditions for SAPP grid simulations

The dynamic analysis for the SAPP grid has been considered on assumptions that interconnected power network under study has:-

a) The committed power considered as the committed generators. The hydropower generations in the west and central blocks are located on the same river and a site across its banks where the river forms an international boundary. The example for such scenario can be taken between H2_6 and H5_6. This set up has made the power evacuation easy to the region for the trading of electricity. It can be considered as the lossless electricity supply between the countries of the said generating stations.

b) The major consumer of the electricity from the hydro generation power has been considered to be east and north blocks. Therefore west block electricity power will be wheeled through the central transmission network to the intended customer of the said blocks of east and north

c) Adequate power transfer through the contingencies on the transmission lines. The N-2 and N-1 contingencies for eastern and central transmission networks. The N-2 contingency means when a line is switched off the other two lines are available to dispatch power without literally causing voltage drops. The N-1 means that when a transmission line is switched off there is another line to be used as the alternative route for the supply electricity to the next substation. The contingencies also assist the customers to receive continuous supply without transmission network causing the interruption of power. The eastern block has few contingencies used on its power evacuation. The west and central blocks have also designed for the wheeling of power to transfer power to the intended customer.

d) The simulations will be conducted on the transmission at various points on the transmission line and analyse the effects caused by switching.

4.2 The dynamic controllers for SAPP grid

The dynamic analysis depends on the power equation solutions by the differential equation and modal analysis. The single line presented only performs the load flow solutions and provided performance analysis of the synchronous generators.

It has been said that the generating plants in the SAPP generate from coal and water that initiates the kinetic energy to produce electricity as a source of energy. Hence the equation (2.7), stated that the total power generated depends on the mechanical power, electrical power and also the change of load angle.

$$P_a = P_m - P_e = M\frac{d^2\theta}{dt^2}$$

The generators from the equation require to generate a constant voltage in order to produce the required power due to changes of load and also the turbine speed is influenced by the field voltage. Therefore, the generators are installed with an automatic voltage regulator (AVR) to regulate the generated voltage and the governor to control the speed of the turbine forming the dynamic controllers.

The dynamic controllers form part of the SAPP grid because each generator has been modelled with a frame with system frequency droop or no droop. In the frame, it has the slots for the settings of the automatic voltage regulator, the governor and also power system stabilizer. The inclusion of frame in DIgSILENT dignifies the generator to simulate voltage regulation and control speed of the rotor .In order to model the dynamic controller for a synchronous generator, it is necessary to know the characteristics of the controller, type, calculation of the parameters, and requirements in grid code and tests in simulations.

4.3 General governor requirements for Southern Africa

Network Grid code produced by National Regulation of South Africa (NERSA) contains connection conditions for generators, distributors and end-use customers, and the standards used to plan and develop the Transmission System. In Grid Code Requirement (GCR) 6, in the Network Code defines the required governing design requirement for all generating unit above 50 MVA to have an operational governor capable of responding according to the minimum requirements set out by the South African Grid Code and further details the frequency deviation requirements[11].

The nominal frequency for the SAPP grid is 50 Hz and is normally controlled within the limits as defined by Southern Power Pool operational requirements. The system frequency could rise or fall in exceptional circumstances and synchronous generators must be capable of continuous normal operation for the minimum operating range as per connection agreement. The design of synchronous generating units must enable continuous operation, at up to 100% active power output. The tripping times for the generating units should be with the agreed range of frequency and as outlined in the SAPP Operational guidelines.

Synchronized generating units respond by automatically reducing active power if the frequency is above 50.5 Hz. Governing shall be set to give a 4% droop characteristic. The response requires being fully achieved within 10 seconds and be sustained for the duration of the frequency excursion. The unit needs to respond to the full designed minimum operational capability of the unit at the time of the occurrence and at least 15% of minimum continuous rating (MCR). Those units that are contracted for Instantaneous Reserve low frequencies shall provide the capacity for Instantaneous Reserve for high frequencies between the applicable dead-band and 50.5 Hz. These units are required to respond at least the same contracted capacity for low frequencies and according to the agreed droop characteristic. The response is required fully within 10 seconds, to an increase in system frequency above the allowable.

4.4 Modelling of the governor for speed controller

The speed governing system provides the means to control power and frequency on the turbine that can be taken as the load frequency control or the automatic generation control. Figure 4-3 is referred where the mechanical power provides the inertia for the change of speed and rotor angle for the electrical system under the change of load or disturbance. The load electrical power provides the source of the signal to the automatic generation control for the interconnected power pool to initiate the governor to change speed[78].

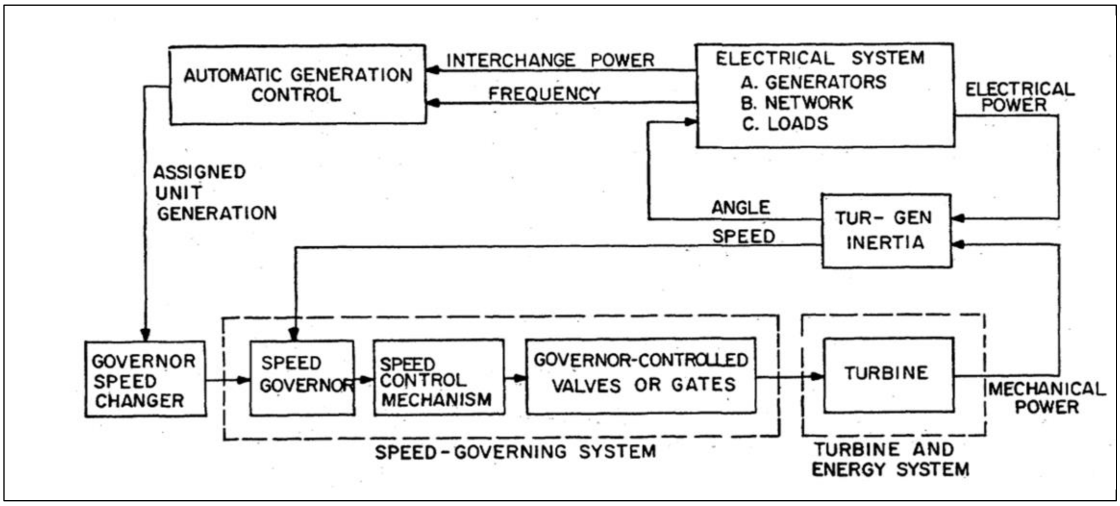

Figure 4-3: Functional block diagram for speed governor

In order to represent the power system dynamic studies, the detailed characteristics of the turbine and energy system need to be examined with appropriate equivalent requirements for simulations. The speed governing system for thermal and hydro generating plants differ in nature due to the process to utilize a source of energy. However, the principle is still the same where a change of speed is taken as the reference parameter and the feedback signal for the change of generated power by controlling inlet valve to the turbine of steam or water as the case it maybe.

4.4.1 Hydro generation governor

The common available SAPP turbines for hydro generators is the reaction type but the generation of plant require to fulfil as provided in equation (2.1) where power is:-

$$P = 9.81\ \eta\ \rho\ Q\ H$$

In all hydro generation, governor requires water to flow in a column to impact the movement of the shaft. It originates from the effects of water inertia diverted from a head with compressibility to build for pressure in the penstock. The water hammering is due to water inertia on the guide vanes to start to provide speed for the shaft. Figure 4-3 refers to the general arrangement of the hydropower generation as in given in equation (2.1).

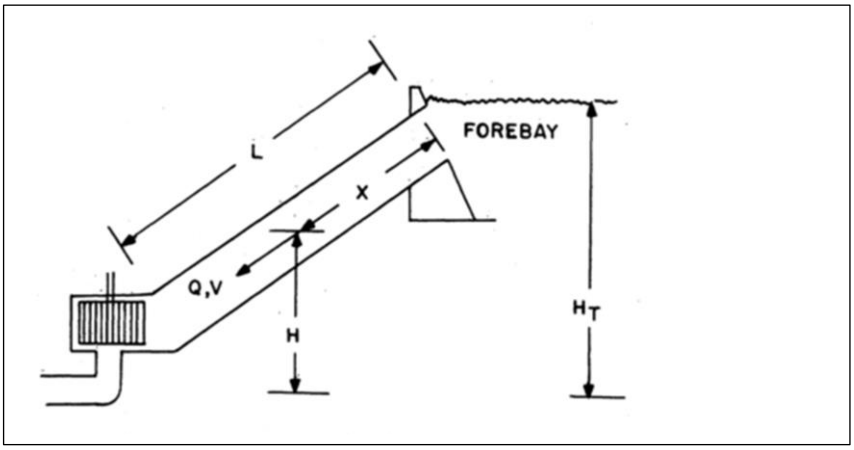

Figure 4-4: Typical water parts for hydro plant

When carrying out dynamic studies, the hydraulic turbine transfer function includes the flow of water in the water column for the generating plant. However, the following assumption is considered:

a) The hydraulic resistance is negligible due to changes of load in the grid and governor
b) The penstock is inelastic and water is incompressible. The movement of water in the column should be free to move without any diversions and leakage. The water should also strictly move to provide the speed of the shaft with an unrestricted head and tail race.
c) The turbine output power is proportional to the product head as then provided in equation (2.1)
d) The velocity of water varies directly with the gate opening and with the square root of the net head

Therefore, the characteristics of turbine and penstock are determined by relating equations from the above assumptions, However the assumption provide the rigid water column and incompressible fluid as per basic hydrodynamic equations.

4.4.1.1 **Calculation of hydro-governor parameters**

a) Velocity of water

The quantity of water depends on the water velocity, head, and the nozzle coefficient. It is also restricted by natural flow of the stream, hence water velocity is determined by:

$$V = K_u G \sqrt{H} \tag{4.69}$$

Where

V = Flow of water in meters^3 per sec

G = Gate position

H = Hydraulic head

K_u = a constant of proportionality- close to 0.98.

From the equation (4.69) it can be noted that the change of displacement will occur at operating points when the gate position and the hydraulic head at the intake affects the operation of the flow of water.

b) Turbine Power

The equation (2.1) provided in the literature review for hydropower generation where P= 9.81ηρQH is meant to maximize in the design. The turbine output flow relates and considers to the built pressure and flow of water. It is represented as follows:

$$P_m = K_p H V \tag{4.70}$$

Where

P_m = Turbine power output

K_p = efficiency of the turbine usually 0.8 to 0.9 pu

H = Hydraulic head at the surge chamber

V = flow of water in meters per sec^2

From the equation (4.70), the basic variables for maximum generated power require effective variations of the gate and flow of water.

c) Acceleration of water

The acceleration of water column due to change in head at the turbine is represented by newton second law of motion, may be expressed as

$$(\rho LA)\frac{d\Delta V}{dt} = -A(\rho a_g)\Delta H \tag{4.71}$$

Where

ρ	=	mass of density
L	=	Length of penstock
A	=	cross section area of the penstock
a_g	=	acceleration of due to gravity (9.81m/s)
ρLA	=	mass of water in the conduit
$\rho a_g \Delta H$	=	incremental change in pressure at turbine gate
t	=	time in seconds

The acceleration of water column is calculated based on the characteristics of physics, the design of the tunnel and pressure at the turbine. It is very difficult to determine the acceleration of water and input for the development of its control system.

d) Water time constant

The water starting time is commonly referred to the acceleration time taken for water in the penstock flow from intake to the turbine and in the case of available surge tank between the intake and turbine. This then means also depends on the physical dimensions of the intake, penstock and turbine inlet as can be noted in figure 4-4. The basic equation is

$$T_w = \frac{LV_0}{a_g H_0} \tag{4.72}$$

Where

T_w = Water time constant

L = Length of the penstock

V_0 = Initial velocity of water

a_g = acceleration of gravity (9.81m/s^2)

H_0 = Initial column of water at the intake

The water time constant T_w varies with a load of the generator. The more water flow means the more power output.

e) Turbine Gain

The amount of water flowing in the penstock depends on the gate position of the turbine. The gate position normally is indicated as the percentage and also is varied through a potential resistance to provide an indication to the system operator. Therefore the opening of the gates from no load to full load can also be represented as equal to 1 per unit.

The turbine gain is calculated as follows

$$A_t = \frac{1}{g_{fl} - g_{nl}} \tag{4.73}$$

Where

A_t = Turbine gain

g_{fl} = full load gate

g_{nl} = No load gate

4.4.2 Hydro governor system model parameters

DIgSILENT provides the default hydro governor control parameters that require being calculated for simulation studies. The detailed calculation methods for various parameters provided in the section 4.2.3 can be termed as the essential data for a hydro plant station. It is believed that similar values are used for the same type of governors on similar synchronous generators. In other ways, the calculation of the hydro governors can be termed as steady state calculation parameters for the input of the speed governor system. However, it is paramount to have knowledge of the type of waterways that has been used for water flow in the penstock to run the turbines.

The requirement of the governor to be installed on the synchronous generators is to control speed through water flow and load through the power transducer connected in the substation. It also necessary to understand the requirements of governing hydraulic turbine through its physical arrangement and dimensions. This will then provide a near behaviour of the interconnected system during modelling simulation.

The operation of speed/load control function on the governor requires a feedback speed error to control the gate position. In order to ensure satisfactory and stable operation of multiple power generation from different generators in the interconnected system, the speed governor requires having a droop characteristics. The purpose of the speed droop is to provide equal sharing between the generating units. According to South Africa Grid Network Grid Code, it is set at about 4% and it means the allowable speed deviation of 4% causes a 100% change in gate position and this represent a turbine gain of 25%.

Table 4-1 presents the detailed parameters required for the speed governor. In the required variables for the modelling of the governor, data is available at design study and inbuilt diagrams for the generating plants. It can be observed that most rivers vary its water flow due to drought and environmental degradation. It is essential for continuous monitoring of the water flow in order to develop hydrological data and forecast the power generation capacity efficiency.

The required data for the hydro governor required as per table 4-1**,** need to have knowledge of the physical design of the water tunnel for every power station. However, such data may not be shared utility companies in SAPP and the data is considered as non-disclosure of information (NDI). Equations (4.69- 4.73), provides the calculation of the required data for the hydro governor. It requires knowing the head and flow of water. For the sake of analysis of power system oscillations, the data has been sourced from different model designs provided in Powerfactory software.

Table 4-1: Required parameters for the speed governor

Variable	Units	Description
P_{rate}	MW	Rated Turbine Power
Q_{rate}	cc	Rated Turbine Flow
H_{rate}	m	Rated Turbine Head
G_{rate}	pu	Gate Position at Rated Conditions
Q_{NL}	pu of Qrate	No Load Flow
R	pu	Permanent Droop
r	pu	Temporary Droop
T_f	s	Filter Time Constant
T_g	s	Servo Time Constant
Gov_{db}	Hz	Governor deadband
H_{lake}	m	Lake Head
H_{tail}	m	Tail Head
pen_l	m	Summation of penstock, scroll case and draft tube lengths
Pen_a	m2	Penstock cross section area
Tun_l	m	Summation of tunnel lengths to surge tank
Tun_a	1/m	Tunnel cross section area
Sch_{are}	m2	Surge Chamber Effective Cross Section
$Sch_{\max}$	m	Maximum Water Level in Surge Chamber
$Sch_{\min}$	m	Minimum Water Level in Surge Chamber

4.5 Modelling of automatic voltage regulator

The automatic voltage regulator is also known as the excitation system is determined by understanding the performance of the synchronous generator during the delivery of voltage to the grid [79]. It is mainly installed to provide the direct current voltage source to field winding to excite flux for the generator to initiate its generation. The dc voltage is the separate supply from the battery for the operation and control of substation and associated equipment. It is required to have the dc voltage in order to have a continuous supply and steady fast in operation of equipment.

Basically, most of the generators are the separately excited type that requires a dc supply to provide a temporary magnetism to start running machines. The rotor is commonly a point where most of the excitation voltage is connected to the generator. The excitation system will automatically change over at the start of operation through the unit transformer of own machines. After machines are synchronized into the grid the excitation will turn its function as the voltage regulator for the generator.

The excitation system also responds to the grid disturbance so that the field winding provide consistent voltage limits. It provides specified range of voltage so that the thermal limits should be controlled in the generator to protect the rotor insulation due to high excitation voltage and current from the field winding. The control of the temperature in the stator windings protects excessive heating of the windings that cause damage to the insulation for the stator.

In power system, the excitation should effectively control voltage and respond rapidly to system disturbance to enhance transient stability and effects small signal due to change of operational level of the voltage and load in the system.

4.5.1 Types of excitation system [7, 8, 79]

The development of excitation control system on generators has been influenced by the developments in solid state electronics. The development has changed the analog integrated circuits with generators into digital technology where thyristors are used to provide power for the excitation system. The control, protection and logic functions implement the analogue circuitry by use of essential the digital components.

The change of technology in every aspect provides an advantage of being reliable, easy solutions to the complex strategies analysis, friendly connection with other controls on the generator and protection system for the generator.

The performance of the excitation control system depends on the characteristic of the excitation system, generator, and power system. It is convenient to classify its dynamic performance and achieve the required effectiveness responses.

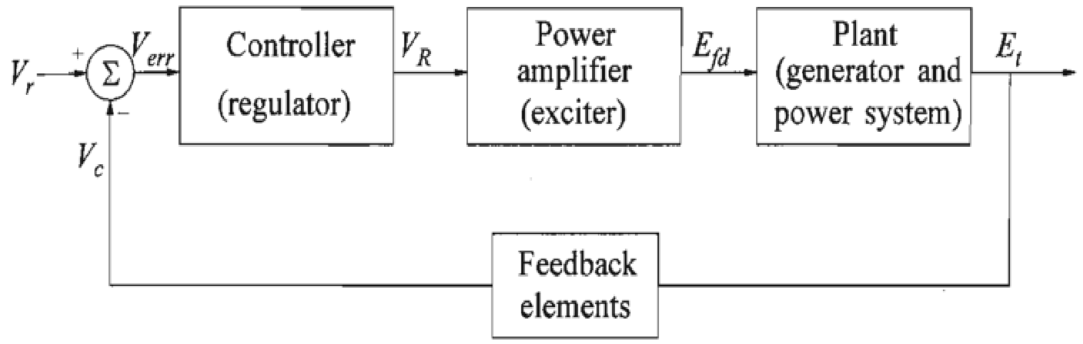

Figure 4-5: Functional block for automatic voltage regulator

From figure 4-5, the controller is the type of excitation used to perform the regulation of the voltage. The controller processes the voltage difference from the grid as a feedback control and sets the voltage of the excitation system. The power amplifier obtains source power from the grid and at the start of the machine provides voltage field windings for the generator. The voltage will be compared with the generated terminal voltage.

Based on the key characteristics of excitation system in figure 4-5**,** it is proper to identify and define the required measurements in order to determine, evaluate and specify the performance of the excitation control system.

The DIgSILENT library has provided the following types of excitation and it depends on knowledge of the status of the generators in the SAPP grid. The status of each generator requires knowing the history of normal rehabilitation and at a particular moment it will be able to predict the type of excitation system. The type of the excitation system used in the simulation has an effect on the fast response of voltage control. Therefore the effects of excitation on stability both in transient and dynamic modes of operation. In a literature review, it was learned that the change of terminal voltage to acceptable values will provide the ability to transfer the synchronizing coefficient power within the shortest time.

4.5.1.1 **DC Excitation System**

These type of excitation is becoming extinct and were used in the early invention of the synchronous generators. The principle of voltage regulation was to use the magnetic and rotating amplifiers for the ac excitation system [80]

It used the dc generators as a source of excitation power and provide current to the rotor of the synchronous machine through slip rings. The exciter was driven by a shaft of the generator or motor. The amplidyne was used as separately excited, the exciter field consisted of a permanent magnet as a pilot exciter. The amplidyne is a special type of the general class of rotating amplifier[80].

The controller achieved the voltage measurement through the slip rings of the generator, E_t which is used to regulate the required voltage in reference to the grid. However, the excitation was controlled through the use of amplidyne a form of the rotating amplifier for automatic supply of voltage to the generator terminal. The adjustment of field rheostat was to operate as a manual control of the exciter field in case of fault amplidyne or out of service.

4.5.1.2 **AC Excitation System 6**

These type of excitation system replaced the DC excitation due to technology change for performance improvement.

The alternators use the same ac of the synchronous machines and the exciter is connected to shaft of the same the turbine generator. The output of the ac in the exciter figure 4-5 is rectified by either automatically or manually to produce the required dc voltage for the generator field winding. The dc field requirement is produced by use of the ac alternator and by either rotating or stationary rectifiers.

On stationary rectifier, the characteristics of the thyristor are normally used to regulate the voltage. The conducting of the thyristors by firing a voltage provides self-excitation from the exciter alternator and uses an independent static voltage regulator to maintain its output voltage. In normal circumstances, there are two main operating modes to compliment the functions of the excitation system. The ac regulator automatically maintains the generated voltage from set limits of ac voltage on the regulator. The dc regulator acts as the backup, station dc supplies are available for operation and control of the generator. The dc supply will be inverted to provide the ac supply for the field armature.

Unlike the DC rotating rectifier, the AC rotating rectifier obtains and controls the voltage source whilst in motion. The rotating rectifiers supply the dc voltage directly to the generator field windings. However, the rotating structure comprises of the armature windings, permanent magnet rotor, and a rectifier connected in series in order to maintain the voltage at the generator terminal. The rotating structure moves with field windings and is supplied from a stationary field. The voltage regulator controls the voltage from the stationary field that supplies the ac exciter and when it is rotating maintains the armature voltage at the terminal of the generator. This type of rectifier does not require the manual operations, it is self-excitation.

4.5.1.3 **Static Excitation System**

An improved design of the AC excitation system has similar functions of the stationary rectifier but this type has a static rectifier different from the rotating rectifier. It provides virtually the same excitation character performance. The other difference worth noting is the source of power supply to the rectifiers. The AC excitation uses the line drop compensator to measure the voltage drop from the current and voltage transformers on the generated voltage. The AC excitation measures and validates the impedance of the system to regulate the on the reference voltage and acts as the feedback control as shown in figure 4-5.

The static excitation, therefore, uses supply from the unit transformer on the three phase, 400V from the LV side of the voltage at the generator transformer, the generator voltage at the generated rate and stationary dc supply.

The operation of the synchronous generator requires the excitation system to initiate the start of the machine. The generator requires the field winding to have a field current so that the magnetic excites the machine to start rotating and generate a voltage. The station dc supply momentarily provides the voltage supply to the field windings in order the generator to start generating voltage and the process to build up field flux in the generator is called the field flashing.

4.5.1.4 **Voltage –Source Controlled rectifier**

It is connected to the same generated voltage of the synchronous machine and also depends on the own generated voltage.

When the system experiences a fault condition, it stresses the generator terminal voltage due to the very small inherited time constant. The only drawback on the voltage source controlled rectifier is mainly the offsetting by its virtually instantaneous response and high post-fault field forcing capability and recommended for interconnected power systems such as SAPP grid [81, 82]. Despite the voltage source controlled rectifier takes time to respond when regulating already high voltage.

4.5.1.5 **Compound-source rectifier system**

This type of static excitation can be taken as the self-excitation of the synchronous generator. The generator terminal provides the source of voltage to the exciter contrary to the rest of the excitation system that takes supply from the slip rings of the shaft. The basic feedback provision is controlled by saturable reactors that control both ac output and exciter values. This type of excitation system was originally designed for the smaller units of the generator[83] .

In cases where this type of self-excitation system is generating low ac output voltage and concurrently the exciter needs to correct the low voltage. The line drop compensation then regulates the voltage. The line drop compensation simulates the voltage drop through the current and voltage transformers in the grid. The current transformer is installed on neutral earth of the common stator windings of the synchronous generator.

This neutral current transformer provides also a continuous path to ground of the generator. If it is open then the main protection of the generator fails operation due to broken conduction to the ground. However in the case of faults then the current transformer will saturate such that any increase of voltage, current remains unchanged. This means that the line drop compensation provides the control of voltage for the generator. The current transformer is connected to the star points of the stator windings to the ground and outside the zones for differential protection.

4.5.1.6 **Compound –controlled rectifier excitation system**

This system functions with controlled rectifiers in the output of the exciter circuit. The voltage and the current derived sources from the excitation transformer are installed together with the generator stator to provide the source of supply to the excitation control system. This then results in a fast response on faults on the excitation to prevent causing damage to the stator.

The three phase supply from the generator stator windings provides a voltage supply to the excitation. The primary side of the excitation transformer also supplies the voltage transformer in the stator windings which is connected in the series linear reactor. The voltage supply through the slip rings supplies the excitation control composed of the rectifier and thyristors.

The voltage and current sources provide power to the rectifier and thyristors that regulate the voltage for the generator. Moreover, the linear reactor acts as in such manner as a compound the normal behaviour of the excitation system and also reduce fault current into the generator.

CHAPTER 5

5 SIMULATION OF RESULTS

5.1 Methodology and Simulation results of SAPP grid

The simulation of the SAPP grid was carried out to determine the power oscillation of the region from the synchronous generators hence the rotor speed has been used to obtain the frequency deviation of the network[84] **.** DIgSILENT Powerfactory uses the rotor equivalent circuits diagram on synchronous generator using electromagnetic transients and modal analysis to obtain the behaviour of the power oscillation and the frequency stability The required data and circuit are shown in Appendix B -1 and B-3.

5.1.1 Rotor angle and frequency behaviour on synchronous generators

In order to determine the rotor behaviour on change of sudden drop of load, load flow analysis was carried out on the transmission line to be switched off in order to transfer that particular load to alternative transmission line. The transfer of load helps customers to have supply at all times during the maintenance [84] . However the rotor behaviour under fault condition will be initiated with a fault without carrying out load transfers.

(a) **Initiated a sudden load drop to switch of the transmission line between T1_6 and sub 22**: This point was selected because the transmission line is a radial feeder and has no alternative transmission line to supply the north and east blocks. First of all, determined the normal load flow from the thermal plant to sub 22 .Then at sub 22, determined the branch load flow, a small load was supplying sub 21 and the rest was the inter power exchange to East block through sub 23.

The equivalent load that was supplying to the east block from sub 23 was transferred to increase the generation at T3-1 and T2-6 .Then switched off the 400kV line between sub 23 and T2_6 and thereafter switched the line between T1_6 and sub 22. It means that the only sub23 was affected with this simulation.

Figure 5-1 indicates that the load switching caused the change of frequency to oscillate between acceptable frequencies of 50.5 Hz and 49.957 Hz within 6.066 s on the first swing of frequency. The second swing of the frequency settled at 50.320 Hz before settling above 50.1 Hz. The first swing was the action being conducted in the speed governor temporary droop that was set at 0.5 s. The second swing is caused by the turbine control to increase mechanical power due to lack sufficient electrical power that was switched off on Sub 23 then the frequency settles above 50.01 Hz. Figure 5-1 was obtained on frequency vs time for synchronous generators in the modified SAPP grid.

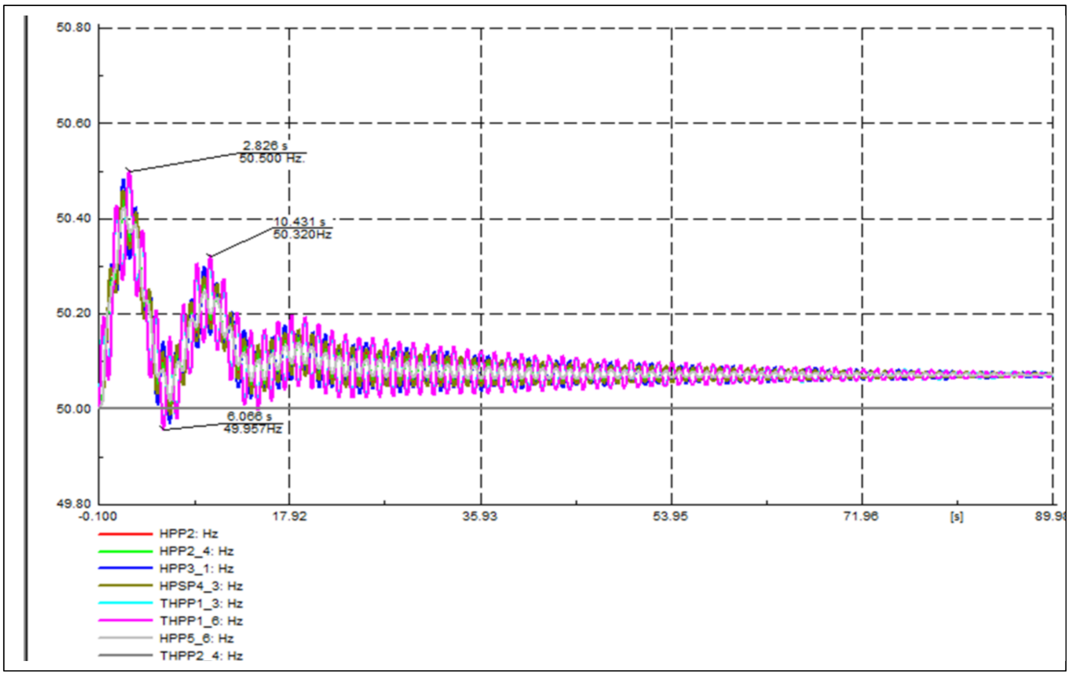

Figure 5-1: Frequency deviations after change of load in SAPP grid

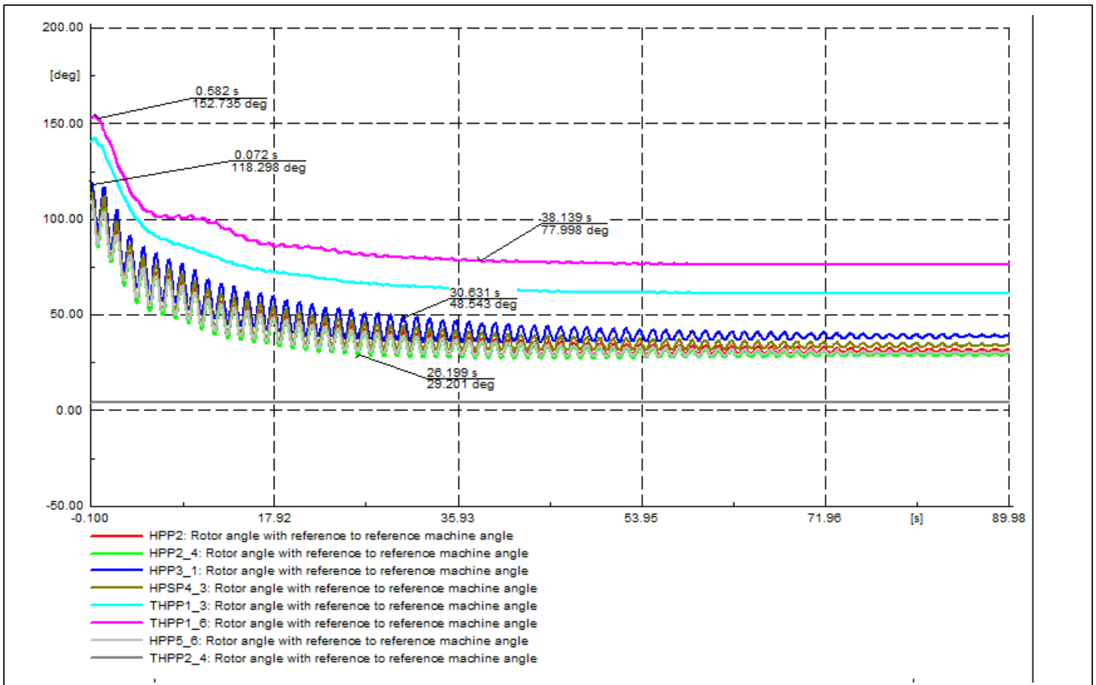

Figure 5-2: Rotor effects due to change of load in SAPP grid

Figure 5-2 represents rotor angle versus time. The two generators T1_6 and T1_3 had 152 degrees higher than the rest of the synchronous generator plotted in the figure. It can been seen from the figure that T1_6 had another swing at about 8s. It is at the same time the frequency had the second swing before settling at 77 degrees. The decrease of rotor angle has influenced the frequency of the system to increase due to turbine controls and when the rotor angle stabilized the frequency too becomes constant.

It is clear from the Figure 5-1 and Figure 5-2 that rotor angle influences the change of frequency and also the cause the system to operate within a band of frequency. It has been also observed that the change of load can influence the rotor behaviour to change too. The load change has caused unstable condition of synchronous generators to oscillate but remain in synchronism.

(b) Initiated a sudden switching on a hydro generation plant at H1_6

An equivalent load of 150 MW was switched off in west block of the modelled SAPP grid.

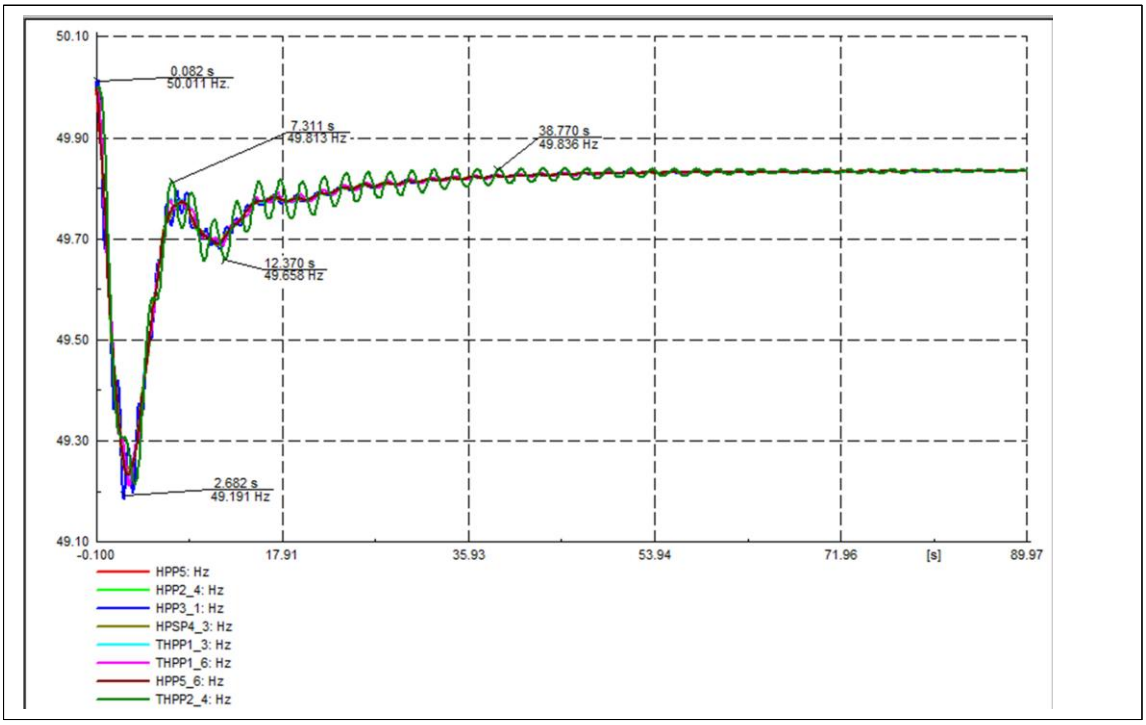

Figure 5-3: Frequency deviations of a general fault on generator H1_6

Figure 5-3 indicates that the frequency dropped in the synchronous generators modelled in SAPP grid due to switching off generator but remained in synchronism despite large machine oscillating within the frequency band. Even though the frequency in figure 5-3 dropped but remained within the acceptable band of 50.011 Hz and 49.191 Hz. The network also fails to settle back to 50 Hz but swings around 49.836 Hz. Unlike the results on the switching of the transmission line, the generating stations have uniformed dropped the frequency. The effect of 150 MW machine has caused 665 MW more damping than the rest of the generators.

Similarly to Figure 5-2, the rotor angle drops as shown in Figure 5-4 when one machine was switched off the circuit, the rotor angle drops tremendously, Figure 5-4 indicates rotor angle for the generators decreasing due to fault on H1_6 and the change has considerably changed the turbine power and also sudden drop of load for the system.

From the same figure 5-4, T2_6 has not been affected by the fault because the rotor angle is relatively at normal operation and this the reason why it was oscillating with the frequency of the rest of the generators in figure 5-3

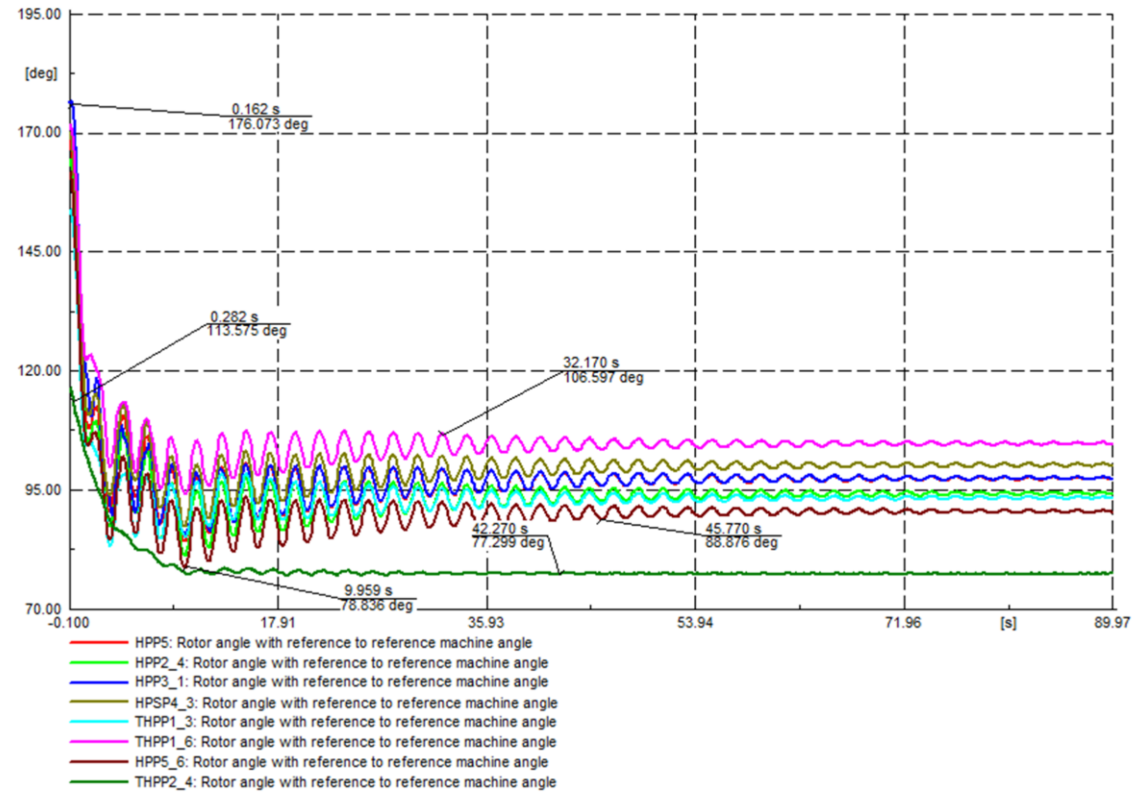

Figure 5-4: Rotor angle effects of a general fault on H1_6 generator

(c) Initiated fault between T2_6 and sub 31 in the eastern block

The substation is fed with the longest transmission from the generating station and also furthest point from the grid.

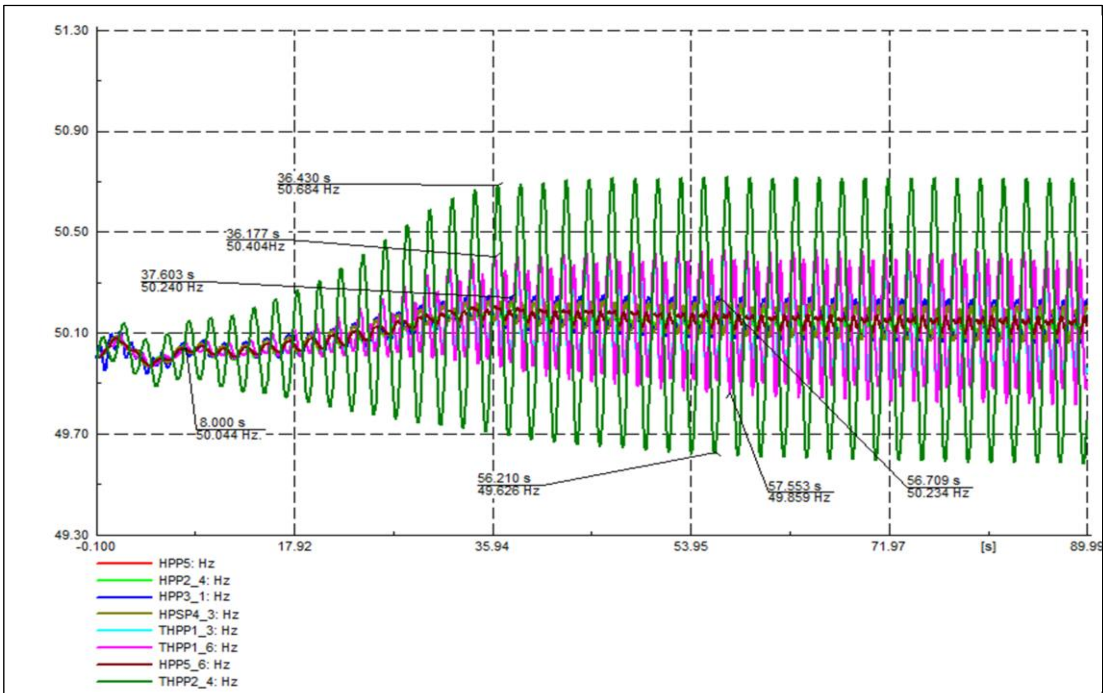

Figure 5-5: Frequency deviations of 3phase fault between T2_6 and Sub 31

Figure 5-5, indicates three bands of frequency deviations caused by the fault between T2_6 and sub 31 transmission line. T2_6 is oscillating between 50.680 Hz and 49.626 Hz from 36 s. T1_6 oscillates between 50.404 Hz and 49.859 Hz and also hydro generators within the 50 Hz. The overall frequency deviation for the grid due to fault on the transmission line has caused the increase of system frequency due to loss of load in the network. T2_6 oscillates highest frequency because it is directly affected with the fault.

Figure 5-6, depicts the rotor angle having three distinct operating angles affected by the fault due to fault on the transmission line between T2-6 and sub 31.

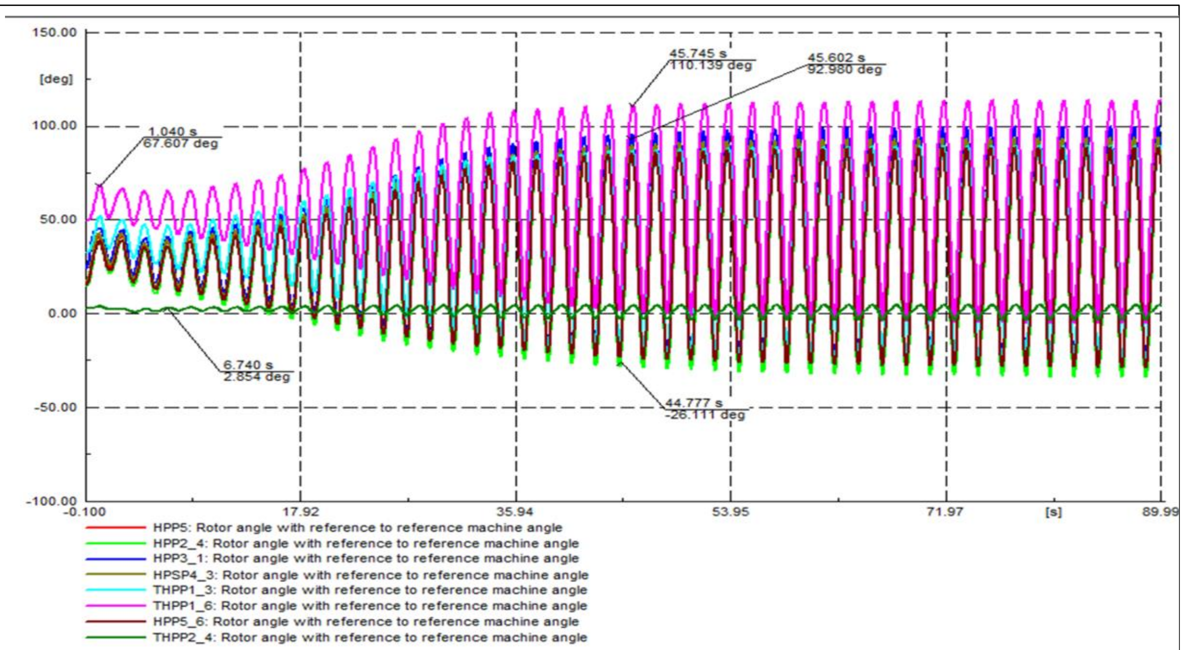

Figure 5-6: Rotor effects due to 3phase fault between T2_6 and Sub 31

The oscillation of the rotor angle has caused from the small generators to respond to unknown oscillations that have not affected their system. Form the various simulations T1_6 generators exceeds the rest of the generators in damping oscillations.

From Figure 5-1 to figure 5-6, they have depicted that the change of load angle affects the rotor movement and also responds to the turbine control to produce the required mechanical power. However, speed is the most essential component that the mechanical power should respond effectively due to changes on the electrical power. The change of electrical power vary due to load variation in the power system grid but at the same time the grid require to maintain the frequency. Primarily, the control of frequency is achieved by controlling the mechanical power through the speed – governor system and require precise measurement to achieve the required control of the generator.

5.1.2 Simulations of faults using electromagnetic transients of the turbine

(a) A three phase fault was initiated between T1_6 and Sub 22 on transmission line and without any load transfers:

This point was selected for initiation of a fault because most of the simulation results indicated high rotor angle and speed. The fault was initiated in the electromagnet transient analysis in the Powerfactory tool to check the turbine output.

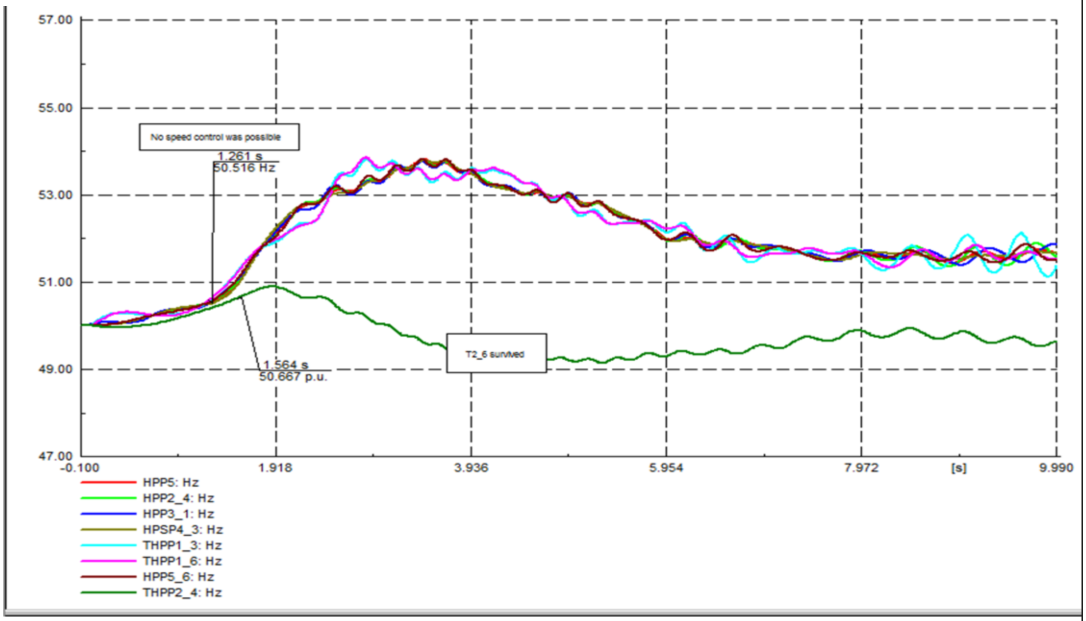

Figure 5-7: Frequency deviations of a 3phase fault between T1_6 and Sub 22

Figure 5-7 depicts two frequency bands, the higher frequency is over 53 Hz within 1.2 seconds from the small rated generators in the west and central blocks .and the large generators at T2_6 generating station controlled the frequency within the same time. The west block experiences a disturbance from external grid and the system operator will not realise the sudden over frequency that occurred in their network. The sudden change of frequency in the west and east will have no protection relay operations to indicate the nature of fault

The point of fault is the interconnecting point between the other blocks with the eastern block which has the largest machines for the network. From figure 5-7 it depicts that the whole of the generation plants in the west and central had tripped due to over frequency because the fault was operating beyond 51 Hz the statutory requirements.

The output power has been affected by the fault as shown in figure 5-8 and as a result of over frequency that has separated the grid into two isolated islands as shown in figure 5-7. This can be noted in figure 5-8 where only a single plot is flowing close to 1.00 pu when all the machines have collapsed in the system

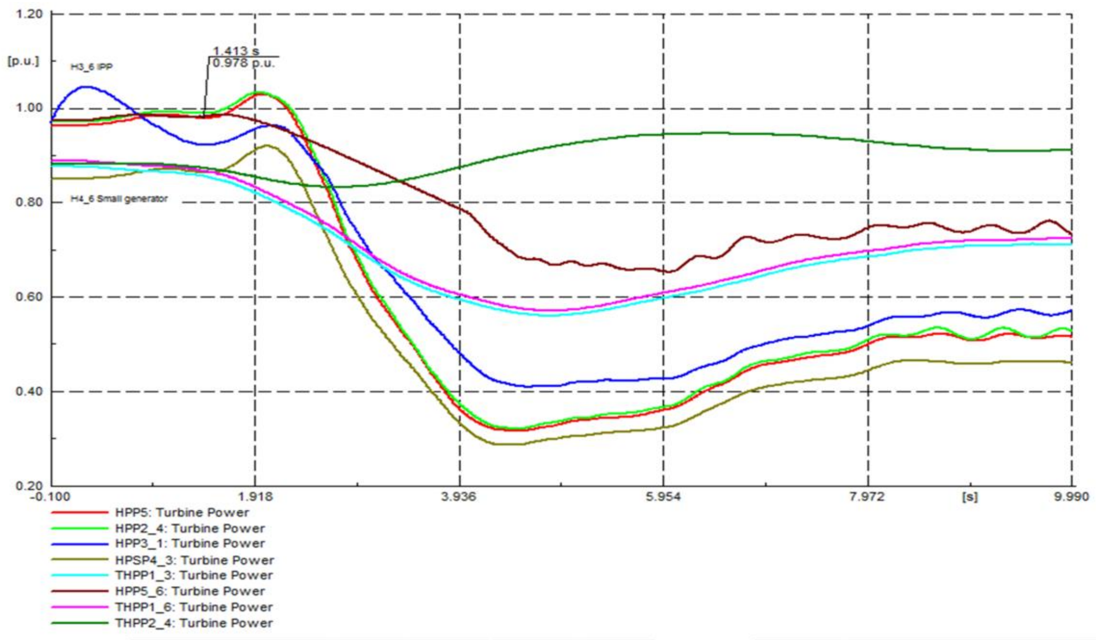

Figure 5-8: Turbine power fluctuations due to a 3phase fault between T1_6 and Sub22

The turbine power of each generating station differs due to design of the plant and also the share of power dispatch distributed amongst the generators. Therefore the large machine will be shared with the larger amount of power to generate than the machines with small capacity.

(b) Initiated a fault on the transmission line between Sub 29 and 31

A simulation was initiated on the transmission line between Sub 29 and Sub 31 to determine the effects of fault at the furthest point of the SAPP grid can supply load and to represent the longest overhead line to Sub 31 in east block.

Figure 5-9 shows that the all synchronous generators are swinging above the normal frequency at about 50.1 Hz except TH 2_4 which is oscillating at high frequency and the damping is ever increasing as from 11 s. This fault has a direct effect on generation of T2_6 and the loss of 354 MW brings a high frequency deviation for the plant. Hence, the oscillation of the large machine has caused the other generators to oscillate due to the impact caused by the fault on the line. If the oscillations continues, the frequency control will start loading shedding other loads. The system operators from the central and west will not know the cause of the load shedding in their system

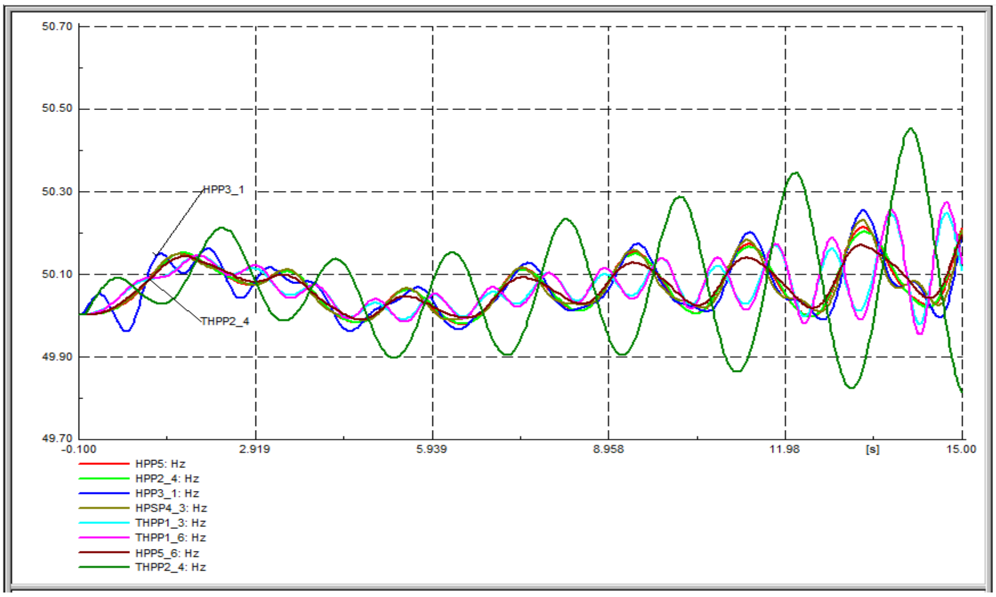

Figure 5-9: Frequency deviations of a 3phase fault between Sub 29 and sub 31

The generator HPP3-1 at H3-6 generating station in figure 5-9 and also in figure 5-10 started to separate from the system but then become synchronised in frequency with the other generator in central and west blocks. The generator HPSP4-3 is operating at considerably low power output as compared with the other generators and this is due to its contribution in power output in the grid.

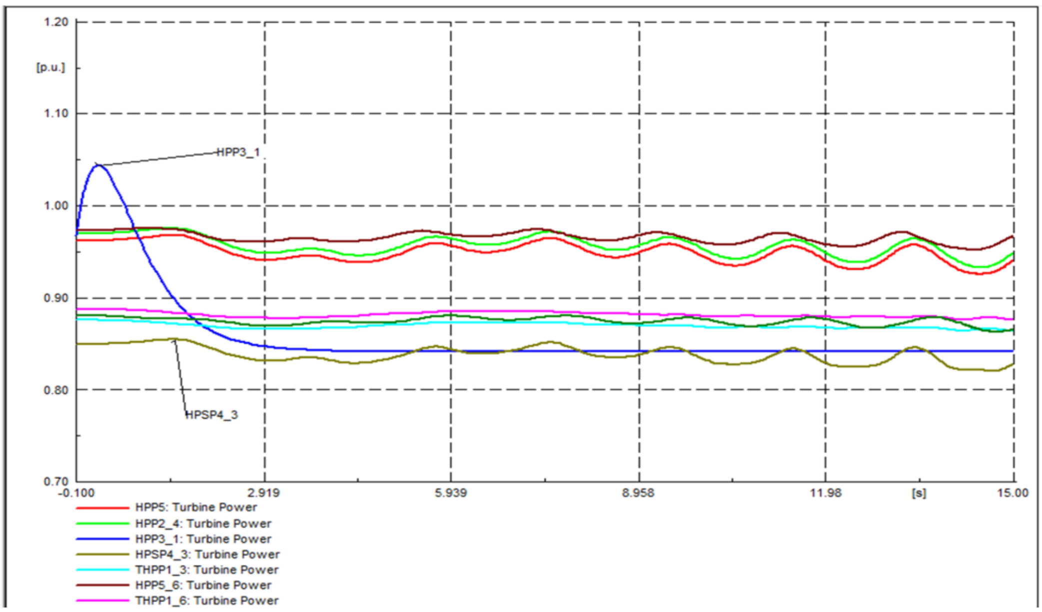

Figure 5-10: Turbine power fluctuations due to a 3phase fault between Sub 29 and Sub 31

The voltage output from generator T1-6 is showing higher values than the rest in the network from figure 5-11. The results has been caused by the high load angle emanating from the generation plant and was due to synchronizing coefficient power to sustain the electrical power

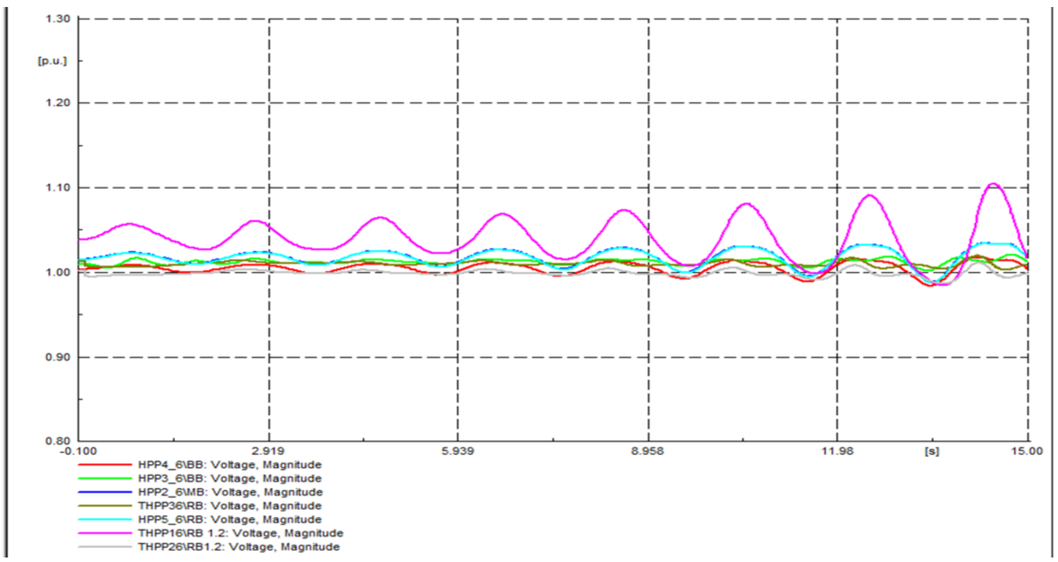

Figure 5-11: Voltage variations due to a 3 phase fault between Sub 29 and Sub 31

(c) Initiated a fault on the transmission line from the west block network**:**

The west block main transmission lines have been provided with adequate alternative transfer of power and hence have sufficient capacity of the transmission line. The fault was initiated from transmission line between sub 7 and sub 8.

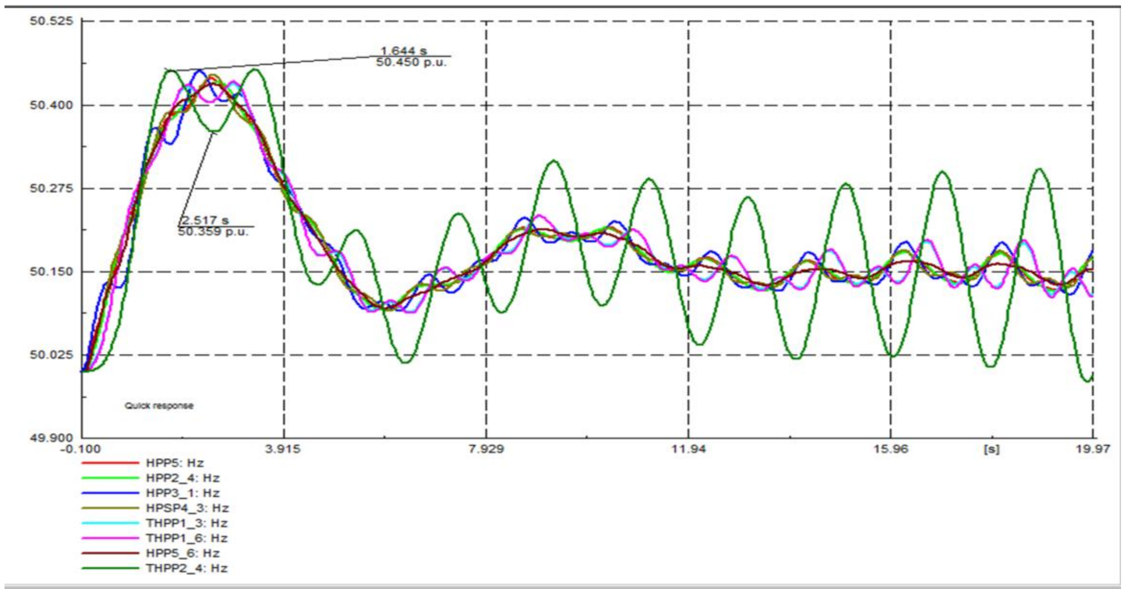

Figure 5-12: Frequency deviations due to a fault between Sub 7 and Sub 8

Figure 5-12 indicates that the frequency deviations on synchronous generators caused by a fault between Sub 7 and Sub 8 in the west block. The fault has caused the frequency to rise and the speed governor also controlled within 2 s but the oscillation for different generating station kept oscillating within the frequency band. The large machine has the high order of oscillation than the rest of the synchronous generator when affected by fault.

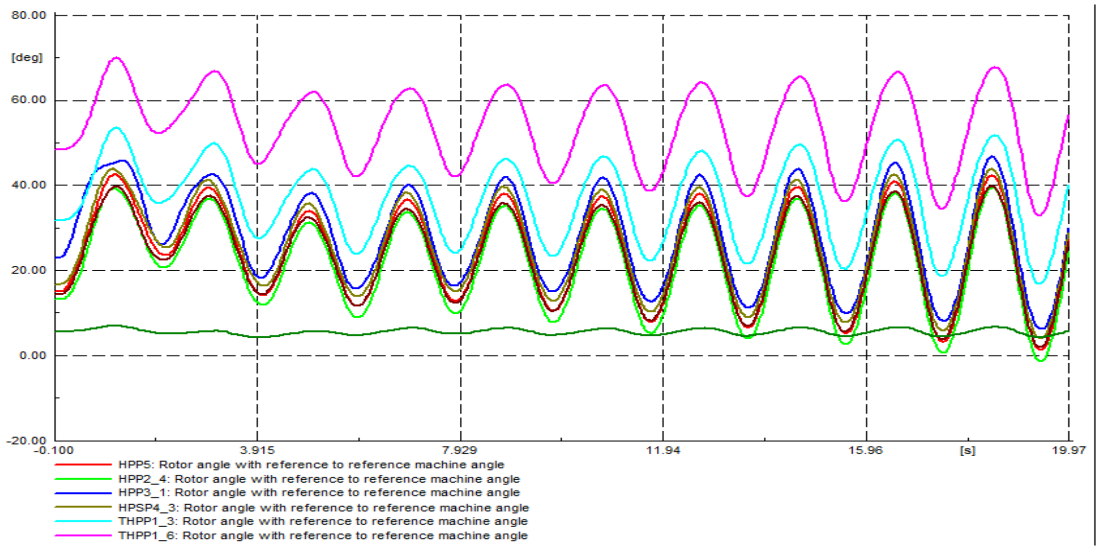

Figure 5-13: Rotor angle effects due to a 3 phase fault between Sub 7 and Sub 8

From figure 5-13, the rotor angle of THPP1_6 has dominated oscillating higher than the rest of the synchronous generators. The hydro generators seem to oscillate together when affected by a three phase fault between Sub 7 and Sub 8.

When a rotor has been operating at very low angle in the synchronised power system, it will cause high frequency oscillation and this has been observed with generators having large capacity in the network. This has been noted throughout the simulations on the rotor angle for the interconnected power system.

Figure 5-14 shows that the voltage are operating at high values at the generating plant at T1-6 whilst the rest busbar are operating with the acceptable limits.

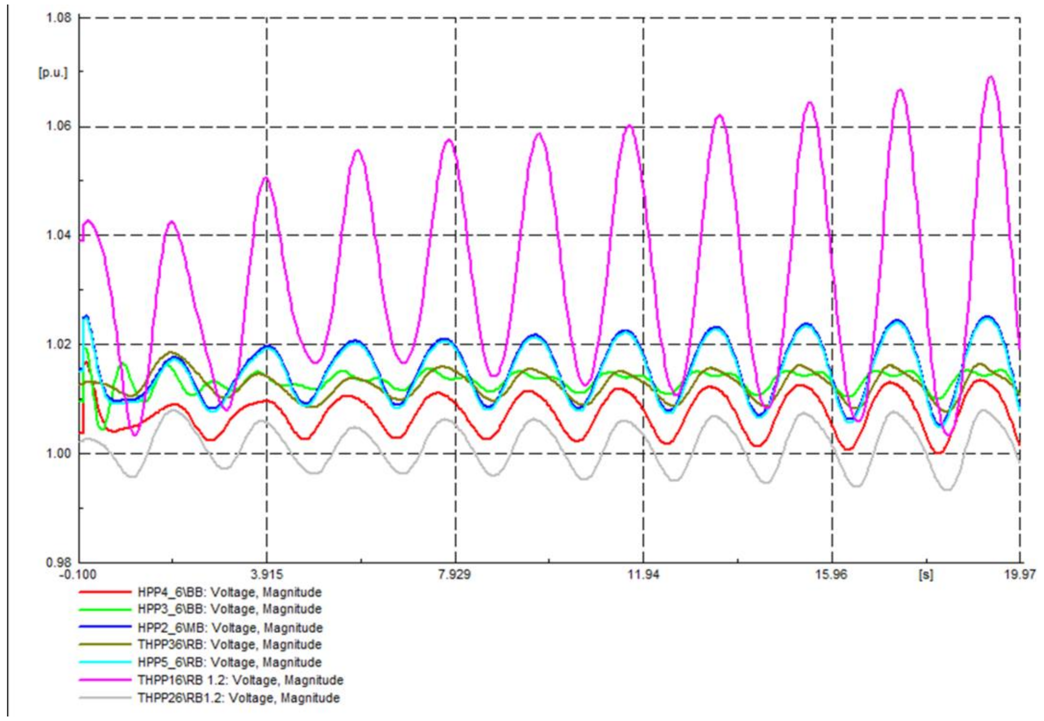

Figure 5-14: Voltage variations due to a fault between Sub 7 and Sub 8

5.1.3 Modal Analysis for SAPP grid

Modal analysis in the Powerfactory tool uses the eigenvalue and eigenvectors to determine the frequency oscillations.

In the figures 5-1 to 5-14, the plots have shown that the frequency and rotor angle for the synchronous generator oscillate when a fault and switching has occurred in the power system. The synchronous generators and the controllers such as automatic voltage regulator and governor have been used to determine the complex frequency of the system

(a) Initiated a calculation of eigenvalue using the Arnoldi/Lanczos method[7, 49]

The method has determined the natural critical system oscillation for the frequency at 1 Hz an equivalent of 6.28 radians per second.

Figure 5-14 has been tabulated with its details in Table 5-1. The coordinates in the complex plane denotes the stability of the grid because they are all in the left hand side and the real parts are all negative.

Table 5-1: Values for critical frequencies in the eigenvalue plot

Name	Real part	Imaginary	Magnitude	Angle	Damped Frequency	Period	Damping	Damping Ratio	Damping Time Const.	Ratio A1/A2
	1/s	rad/s	1/s	deg	Hz	s	1/s		s	
Mode 00001	-0.1136	5.8830	5.8841	91.1065	0.9363	1.0680	0.1136	0.0193	8.8004	1.1290
Mode 00002	-0.0353	6.8197	6.8198	90.2964	1.0854	0.9213	0.0353	0.0052	28.3470	1.0330
Mode 00003	-0.5708	7.0253	7.0484	94.6451	1.1181	0.8944	0.5708	0.0810	1.7519	1.6661
Mode 00004	-0.7842	7.4507	7.4919	96.0087	1.1858	0.8433	0.7842	0.1047	1.2751	1.9374
Mode 00005	-0.5487	8.0274	8.0462	93.9105	1.2776	0.7827	0.5487	0.0682	1.8224	1.5365
Mode 00006	-1.4560	8.6346	8.7565	99.5715	1.3742	0.7277	1.4560	0.1663	0.6868	2.8850
Mode 00007	-0.8590	8.9280	8.9692	95.4956	1.4209	0.7038	0.8590	0.0958	1.1642	1.8304
Mode 00008	-0.8590	8.9280	8.9692	95.4956	1.4209	0.7038	0.8590	0.0958	1.1642	1.8304

Table 5-1 shows the mode values and details obtained from the eigenvalue plot in figure 5-15 and it can be observed that the damping time constant on mode 00001 and mode 0002 have higher time constant than the rest of the modes. It is the obliged to work on the time constant in order to improve the stability of the grid. However it is required to analyse the two modes that can be termed as the interplant mode oscillations occurring in the SAPP grid. The two modes have been tagged as 0001 and 0002 in figure 5-15.

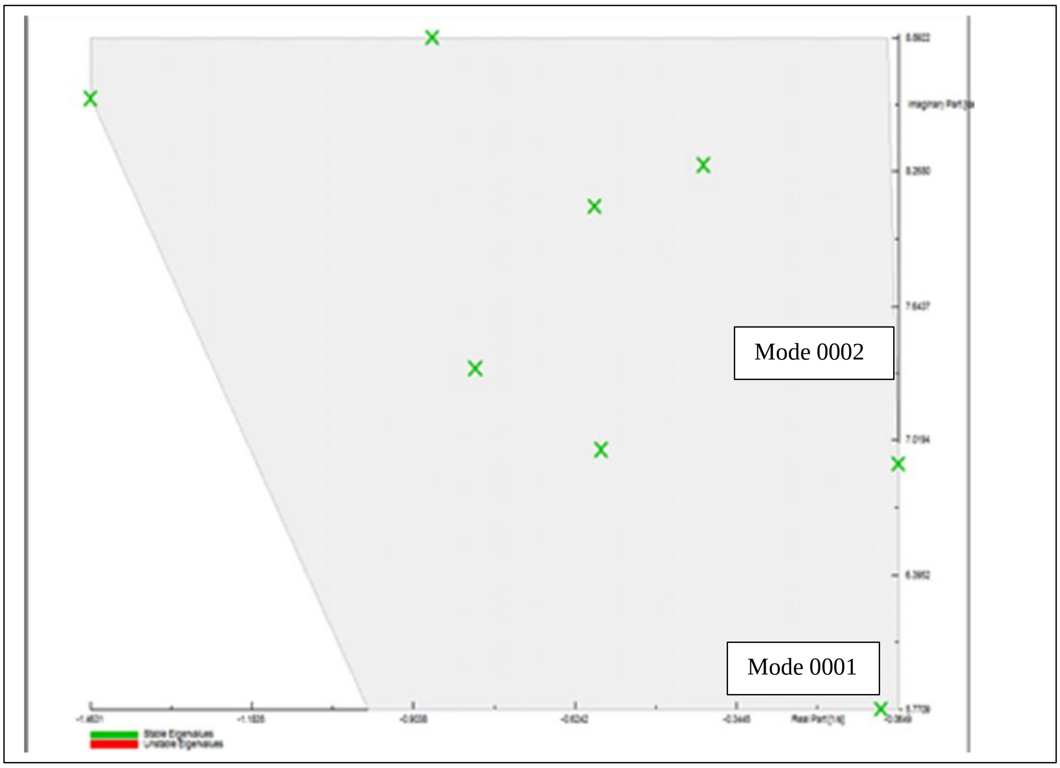

Figure 5-15: Critical frequencies obtained for the modelled SAPP grid

Each and every critical coordinates plotted in the eigenvalue have the controllability and observability of the modelled controllers in the synchronous generators. The controllers that are shown in figure 5-16 on the right hand side are termed as the controllability that will impact on the oscillations for SAPP grid. These are the synchronous speed controllers that are causing the instability during the simulations on the electromagnetic transients and require to be controlled for effective operation of the grid. It can be observed that the generator THPP 1_6 has a speed problem and showing a high value.

From figure 5-16, it indicates that the rotor speed is causing the instability of the system and it’s the thermal plant station problem

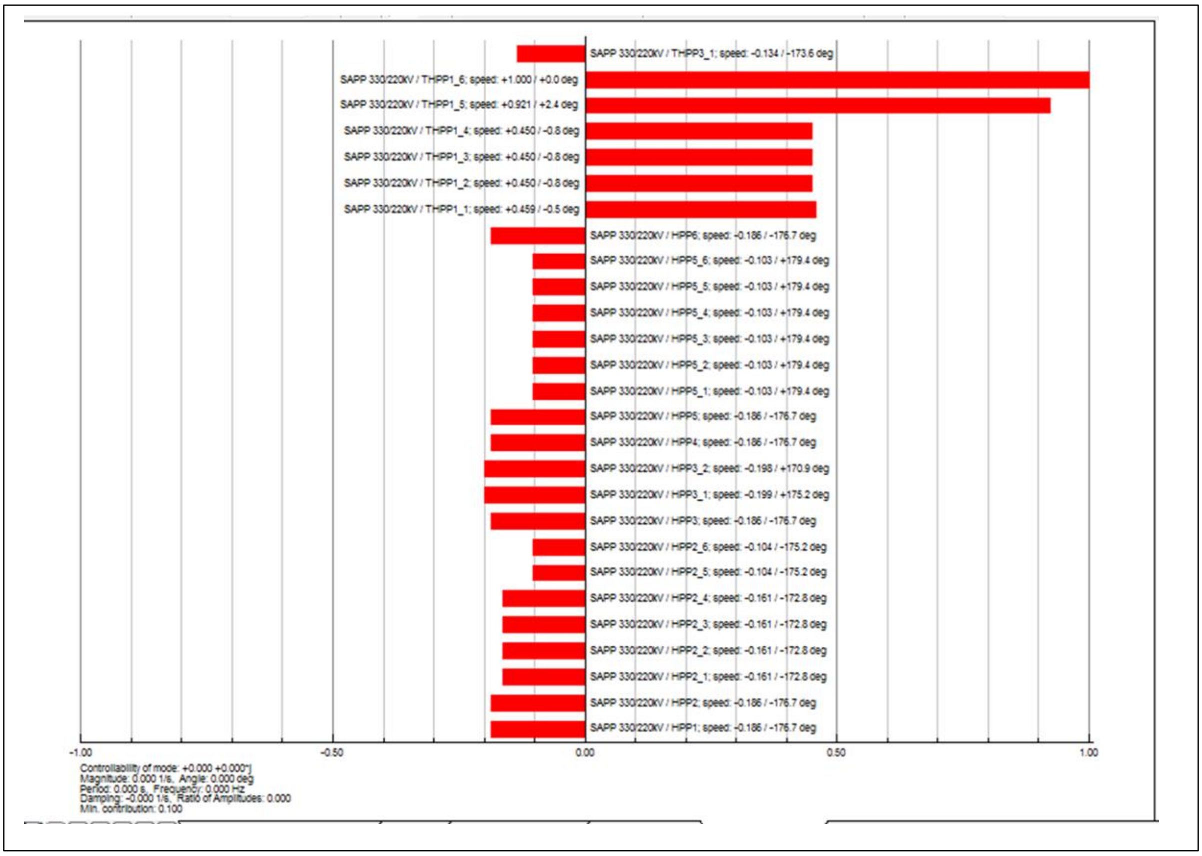

Figure 5-16: Controllability determined from mode 0001

From figure 5-17 shows that the voltage control requires further settings on gain and time constants for the automatic voltage controller in the excitation system than the available settings in the synchronous generator. The indication to plot the requirement of the settings in the eigenvalue plot is termed as the observability of the system. The settings on the gain of the automatic voltage regulator does not suffice the eigenvectors to control the voltage and this is the reason the generator was experiencing rapid changes of voltage in figure 5-14. In order to change the gain, it was required to under the behaviour of the type of excitation and the circuit components whether can withstand high amplification of the voltage. The observability acts the elements that have been noted during the control of the system to correct the instability experienced in the system

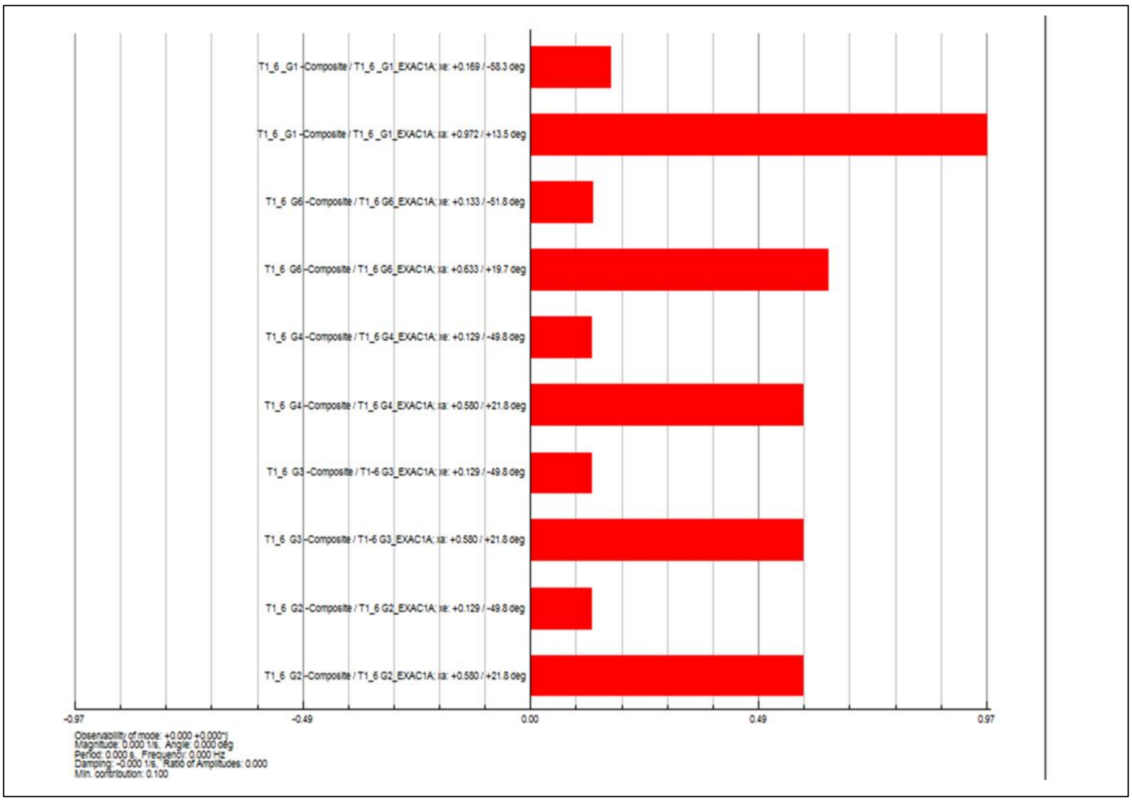

Figure 5-17: Observability determined from mode 0001

Figure 5-17 indicates two generators located at H3-6 generating station in west block that it is also affected with rotor speed and together two generator located at T1_6. These generators are the inter area generators of the modelled SAPP grid. The two generators H3_1 and H3_2 at HPP3_6 have caused the high acceleration of the rotor speed and also generator THPP1_5 and THPP 1_6 are also associated with the acceleration of the rotor speed. The generating plants are allocated 1150 km apart and associated to cause oscillations in the SAPP grid.

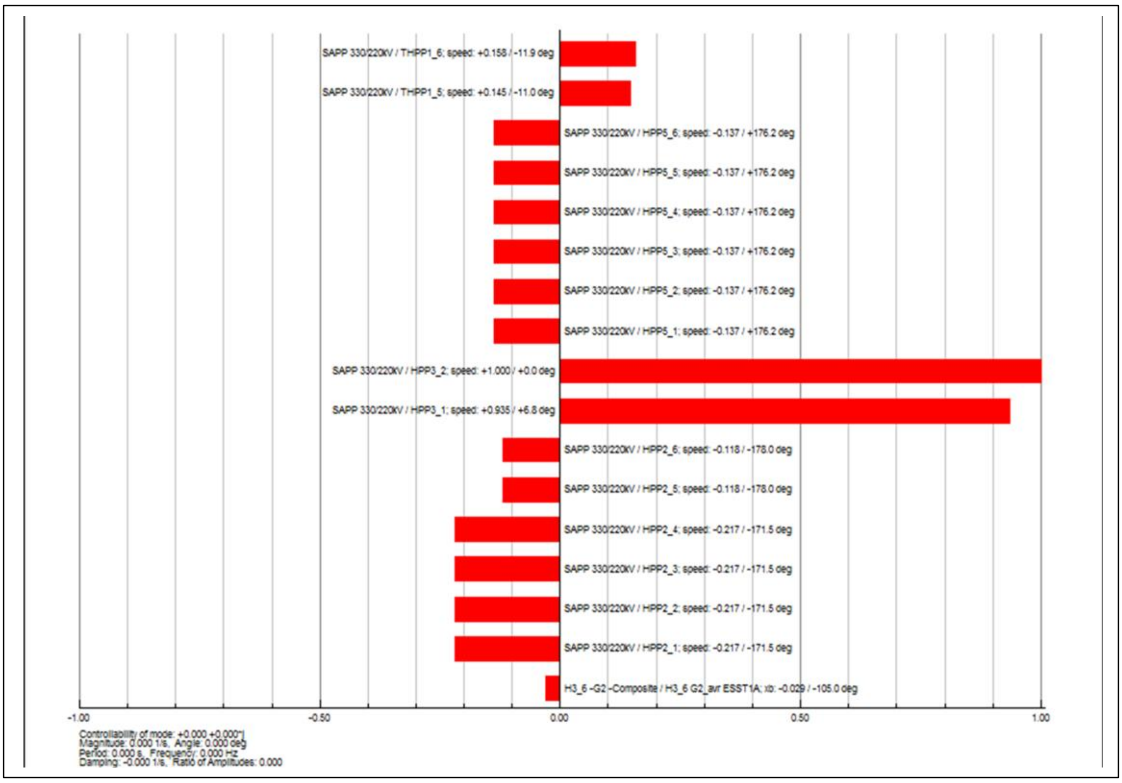

Figure 5-18: Controllability determined from mode 002

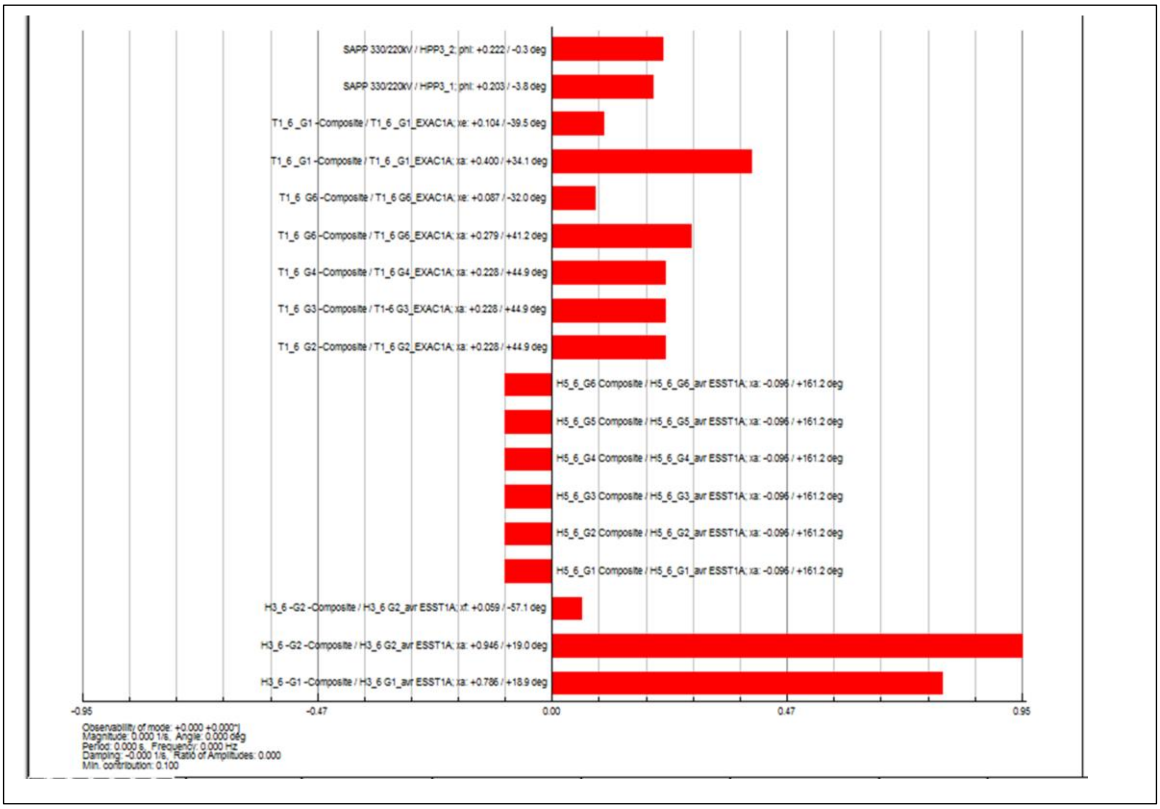

Figure 5-19: Observability determined from mode 0002

From the figures 5-15 to 5-19, it can be concluded that most of the generator will operate under steady state in SAPP grid but it is required to further improve on the gain of excitation system. This also means in practice that under fault conditions the oscillation will affect the Zambian and Zimbabwean power networks due the inter area oscillations between T1_6 in Zimbabwe and H3_6 an IPP in Zambia

5.1.4 Methods to improve rotor speed in synchronous generators

There are three ways to improve the speed of the machines at TH1_6 apart from the site location of the generating plant. It should be borne in mind that the plant is located at a site 355km away from the load centres and the transmission line should require voltage compensators at both ends. The two sides are from T1-6 to sub 22 and also from T1_6 to sub 17.The effects of speed has occurred due to the following:-

a) The speed in the model is derived from the flux of the generator on d and q axis of the synchronous machines and by changing the parameters of the inductance and resistance rotor speed will improve in simulation. The change of parameters would best suit when designing a newly generation plants and not on the already existing generation system.

b) Additional torque being applied to the generator to increase the moment of inertia and it will be appropriate on the simulation for the new design of the generator and on the existing generator requires increase of weight to the rotating parts of the generator. The additional torque can be applied to a large generators by installing a sub resonance on the busbar before transfer of loads to different substations so that the effects of the high damping oscillations caused by the large machine is eliminated in the oscillations

c) The change of gain and time constant in the excitation has changed the speed of the rotor on the existing generators like SAPP grid and it all depends on the circuitry technology and type of excitation system applied to the generator. Hence, the observability that have been noted in figures 5-17 and 5-19 have indicated the need to adequately tune the excitation system. There are different methods to tune the excitation in order to increase the gain such as the installation of power system stabiliser in the synchronous generator and static Var compensators that are determined in the contingency analysis study.

CHAPTER 6

6 DISCUSSIONS ON THE DYNAMIC PERFORMANCE OF SAPP GRID

The steady state analysis for the synchronous generators, transmission overhead lines, load behaviour and mathematical fundamentals are relative to the study of dynamic performance of the modelled SAPP grid. The exigencies explained in the steady state has led to various studies of power network to analyse performance and behaviour of the power system so that the reliability and quality of supply was continuously prevailing at all times. The simulation of any power networks are derived from the mathematical analysis and developed into a DIgSILENT Powerfactory software. It was for this reason the load flow of the SAPP was modelled to obtain the grid adequacy of power transfer and to be used for the evaluation of generated power to run for dynamic studies.

The dynamic analysis involves on the electromagnet transient analysis in the nodal equation and eigenvalue in the modal analysis to determine time based and frequency oscillations as the required character for the study. The study analyses the effects of synchronous generator and its associated speed governor and automatic voltage regulator on the system stability and performance on the interconnected power system. The synchronous generator plays an important role in the interconnected power system to provide supply unlike any other components in the power system network. It is for this reason that the undertaken study would want to understand the behaviour of the excitation and speed control in SAPP grid. The results of the electromagnet transient provide the behaviour of the network in a waveform and the modal analysis will provide details in the complex frequency mode. The eigenvalue plot provides the character of the frequency and how the mode was achieved by checking the elements of the speed controller and automatic voltage regulator. Presently, the details provided by the modal analysis are not monitored in the power system and such interactive indication can improve the performance of the power system.

In the simulated results, the figures 4-6 to 4-19 have been plotted to indicate the behaviour of the rotor angle, speed relative to frequency and voltage in damping oscillations. In the time based plots, it is very difficult to determine the actual frequency amplitude or actual measured frequency and only provides the kind of behaviour being experienced during the fault. The figure 4-20 provide the critical frequencies associated in the system performance and each stable cross will show the character and the corresponding equipment as shown in figures 4-21 to 4-24.

6.1 Discussions on simulated results

The plots obtained during simulations have shown that the faults and switchings in the interconnected power system respond to the effects of the fault and have returned after controls to remains in synchronism hence creating another operating value. When the synchronous generators have been affected by a disturbance, the frequency of the system was oscillating due to changes of the operating rotor angle in the synchronous machines. The SAPP grid simulated is affected by the rotor angle speed at TH1_6 and H3_6 and every simulation the rotor speeds were higher than expected operations.

The SAPP grid in figures 4-12 and 4-13 after initiating a fault between T1_6 and sub 22 ,the simulation showed two distinct separations of the system due to interaction of large generators located at T2_6 and the rest of the generators located in the central and west blocks. The effects of the separated system has likely been caused the generators in the west and central block to initiate frequency change and cause load shedding due to frequency increase or decrease beyond the acceptable regulatory requirements. The large generators in SAPP has a higher control area frequency bias at a rated MW/0.1 Hz than the rest of the generators. This frequency bias causes also the damping oscillation between the large and small generators where the former would possibly control to match with the rest of the generators to remain separated.

The simulation of eigenvalue plot, the Arnoldi/Lanczos method was selected in the Powerfactory tool to identify the most critical modes of interarea oscillations in the SAPP grid[49]. The critical frequencies are normally located in the range of 0.2 to 1.0 Hz because the low frequency is rated at such rate. It has been shown that there is an inter area oscillations between T1_6 and H3_6 as shown in the observability of mode 0001 and mode 002 in respect to speed and voltage control. The generating stations are located in different countries and over thousand kilometres away.

It should also be known that in a large network such as the modelled SAPP grid more especially when run on the electromagnetic transient analysis, there shall be two separate interarea oscillations [7] that may occur such as

(a) A very low frequency (0.1 to 0.2 Hz) that has occured on all generators in the power system. It has been identified in the plots that the large generators from South Africa have been swinging against the rest of the generators connected in the system.
(b) A high frequency in the range (0.4 to 0.7 Hz) the generators also swinging amongst each other within the same frequency just like figure 4-14

The nature of separation into two area oscillations just like that has occurred in figures 4-12 and 4-14, the system operators on the west block will experience a sudden frequency rise and the effects of automatic load shedding will be initiated to cause trip without realising that the fault is beyond their own control area and east block will too realise abrupt rise of frequency and stabilising without actually knowing the cause of such incidents.

The power monitoring instruments do not provide an immediate indication to show oscillation of frequency due to slow sampling rate of SCADA by use of transducer. The values shown in Table 4-2 for the critical frequencies in the modelled SAPP may not be obtained from SCADA because it has a slow response to data acquisition at 1 sample per 4-10 seconds. From the NERSA grid code requirements, the allowable time for the full operation of the governor is 10 seconds and due to slowness of data acquired from the monitoring device the effects of change of speed could not be noticed by the system operators.

There is a disparity of error on measurement that occurs between the input supply of the excitation system and speed governor on the generator. The difference can affect the rotor angle in practice, the excitation obtains the input source of voltage direct from the secondary output of voltage transformer and the speed governor obtains the load input from the output of power transducer both from the grid. This means that the requirement to change the voltage has depended on the instantaneous value of the grid and the same voltage becomes one of the input to the power transducer. The change of voltage to the power transducer has not effectively changed its output for the speed governor signal because of the due process to convert the inputs to dc current and caused a delay to control the speed. Therefore, the excitation require to improve its control of voltage to improve stability of the power system.

The SAPP grid was intended for the supply of own use by the participating members and it can be visibly seen from the modelled network that the synchronous generators supply the electricity in an adequately designed transmission lines. The west block is meant to be the network of Zambia and the generation plants are located in the south of the country to supply the load centres the mining centres in the north of the country. The central block is the network for Zimbabwe. The thermal generating plant T1_6 is located in Zimbabwe and the site runs very long transmission line to load centres over 355km. The behaviour of the rotor speed noted during simulation befits on the character to suffice the synchronising coefficient power due to the line capacitance and reactance required for the load.

CHAPTER 6

7 CONCLUSIONS AND RECOMMENDATIONS

The dynamic analysis of SAPP grid has produced the power oscillation that has been characterised with low frequency caused by synchronous generator in an interconnected power system. The behaviour of the generator depends on the nature of disturbance and magnitude of the disturbance to remain in synchronism. The character of the excitation system to regulate voltage limits and the speed governor to control the rotor shaft speed initiated the power oscillation in the interconnected power system. When the voltage was being controlled, changed the rotor speed to match the grid frequency.

The SAPP grid was modelled in the DIgSILENT Powerfactory to simulate different types of power system analysis amongst the load power flow and the modal analysis The SAPP grid modelled consists of the transmission line from Zambia, Zimbabwe, Botswana and part of South Africa and the associated synchronous generators that has been used to demonstrate the low frequency oscillation in the Dynamic Analysis of SAPP network. The modal together with electromagnetic transients (EMT) analysis were used to simulate in the software to generate the frequency oscillation and time based plots to determine the required dynamic behaviour of the SAPP grid. The modal analysis produced the bar graph and the modes to be evaluated for the power oscillations .The left eigenvectors in the bar graph demonstrated the parameters that have provided stable variables during simulation on load flow and the right eigenvectors provided the parameters that were unstable during operation. It was from the electromagnet transient analysis that provided the damping oscillations of the rotor and frequency relative to rotor speed. However, the behaviour of the modelled synchronous generators have shown the interarea damping oscillation from different area of operations. The Arnoldi/Lanczos method was used to identify the critical oscillations in SAPP grid in the complex frequency of the eigenvalue plot. The inter area oscillation was identified based on the results that indicated very high time constant of the eigenvalue plot from the calculation of Arnoldi/Lanczos method in Powerfactory tool.

In the electromagnetic transient analysis, it has been observed the frequency of the synchronous generators decouples between large and small generators in the SAPP grid under the fault conditions. If the fault was located in the area of large machines the small machines would over accelerate and cause over frequency then an eminent to load shedding of the part of the system to remain in synchronism. If the fault occurs in the area of the small machines, the large machine has been oscillating conspicuous within the same frequency band.

It was therefore to noteworthy to understand that the critical oscillation that was demonstrated in simulation can be re-tuned to increase the excitation gain incorporated with a separate controlling unit of power system stabilise to the synchronous generator. The power system stabiliser has reduced the damping oscillation considerably and improve reliability of the power network. The originality of power stability is based at the generating plant and during the study of the dynamic analysis the line compensators are neglected.

Further to the power system stabiliser, the modern power system monitoring measurements is based on the synchro phasors measuring unit to be installed at strategic substations in order to

(a) Improve system monitoring due to sampling rate of data to be analysed by the instrument
(b) Provide valid system parameters on-line for the system operators to be aware of the dynamic changes of the system
(c) Provide technical audit data required for regulatory performance indices on transmission and generation plant.
(d) Provide event record due to disturbance and switching
(e) Provide the effective planning actual data from the network

Presently the synchro phasors are not available in SAPP network, but if they are available are not being fully utilised for the effectiveness and usefulness in providing the necessary requirements of power system. The availability of such instruments would be used to verify the simulation results with the actual results of the system under study in SAPP grid.

The dynamic performance in the modelled SAPP grid has been affected by the performance of the synchronous generators when under any disturbance due to:-

(a) **The behaviour of large generators towards the small generating plants**:
It has been observed that under any disturbance the large generator has a high oscillations within the system synchronism. However, depending on the severity of the oscillations and location of the system may collapse.

(b) The existence of the natural transmission line link:
SAPP network has a natural transmission weak link that connects between Zimbabwe and South Africa. There is no alternative route of transmission line to transfer power from Zambia and Zimbabwe to supply South Africa or vice versa. Therefore the bottleneck situation impedes the power trading between the mentioned countries. It

has observed in the simulations to be the epic of inter area oscillation around the generating station connect the link.

(c) Hydro speed governor effects on the impact of environmental impact:

In case of hydro generators where its speed governor depends on the restricted water canal movement, any natural changes in the flow of water to run the machine would affect the performance of the generators. It is imperative for such countries to constantly study the behaviour of its source of energy.

It has been then required for the SAPP members to undertake the study of power oscillations in their perspective countries and also the whole network. This will depend on acquiring performance data at points of common connection and also invest in acquiring the wide area monitoring system. The instruments provide adequate real time data for planning and system operations to likely monitor the dynamic performances of the power system network. The mitigation factors for power oscillations require adequate data on power parameters at the point of connection that has been monitored continuously.

The electricity regulatory body require to encourage the power utilities company to provide own telecommunication link to strengthen the acquiring of power system data and quick response on operations of equipment in SAPP network. The high speed data transfer will effectively provide smart grid operation and includes monitoring systems. The electricity regulatory body need also to enforce the harmonisation of standards and operations of SAPP with emerging technology for optimal technical and economic performances.

7.1 Recommendations

After identifying that the focal points of power oscillations in SAPP, it would be required to verify with real time measurements of the load flow and behaviour of the voltages under normal operations of the power network. Hence, the need for phase measurement unit to ably measure the voltage angles at the strategic substation. Then the measured data will assist to re-tune the control system of the automatic voltage regulator of synchronous generators to provide high gain and adequately control damping oscillations in SAPP grid.

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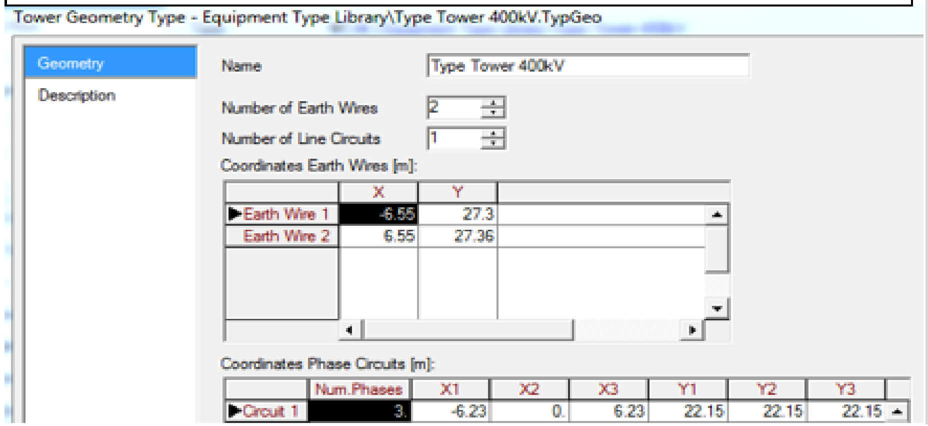
APPENDIX A DETAILS OF TRANSMISSION LINE PARAMETERS

A.1 CALCULATION OF REACTANCE ON BUNDLED CONDUCTOR

Based on from equation 18

- $X_L = 2\pi f x 2x10^{-7} x10^3 \ln\frac{D_{eq}}{D_s} = X_L = 0.0628 \ln \frac{D_{eq}}{D_s}$
- $D_s = 1.091\sqrt[2]{r_{gmr}} d_{bs}^3 = 1.091\sqrt[4]{0.011682x}\, 0.38^3 = 0.1735961$
-
- $D_{eq} = \sqrt[3]{D_{X1X2} D_{X2X3} D_{X3X1}}$ - distances from the transmission tower on the right hand side and equal to
-
- $D_{eq} = \sqrt[3]{6.23x6.23x12.46} = 7.849$;
  $\therefore X_L = 0.0628 \ln \frac{D_{eq}}{D_s} = \mathbf{0.2393\Omega}$


Tower Geometry Type - Equipment Type Library\Type Tower 400kV.TypGeo

Geometry

Description

Name: Type Tower 400kV

Number of Earth Wires: 2

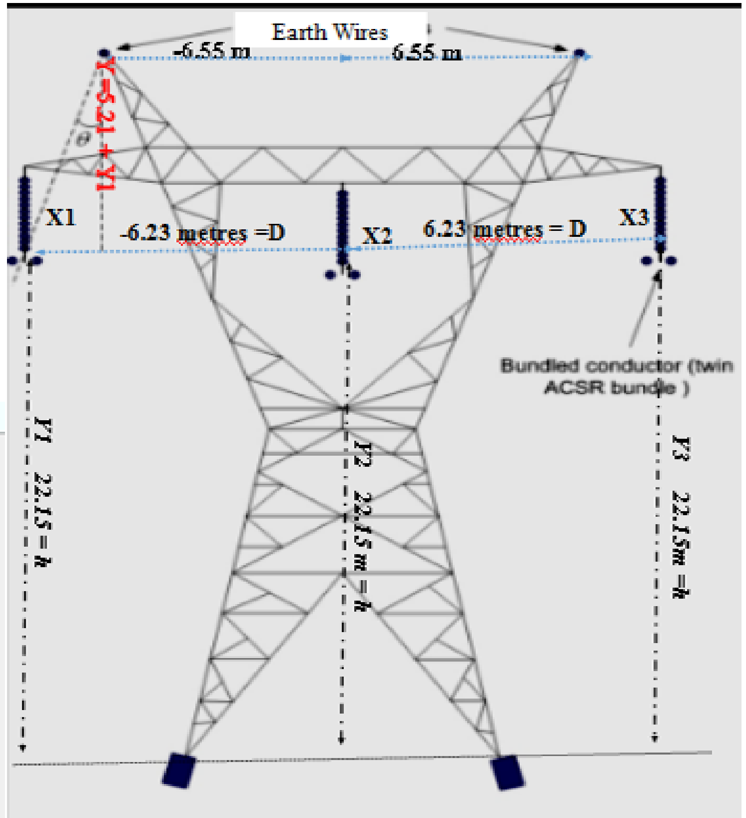
Number of Line Circuits: 1

Coordinates Earth Wires [m]:

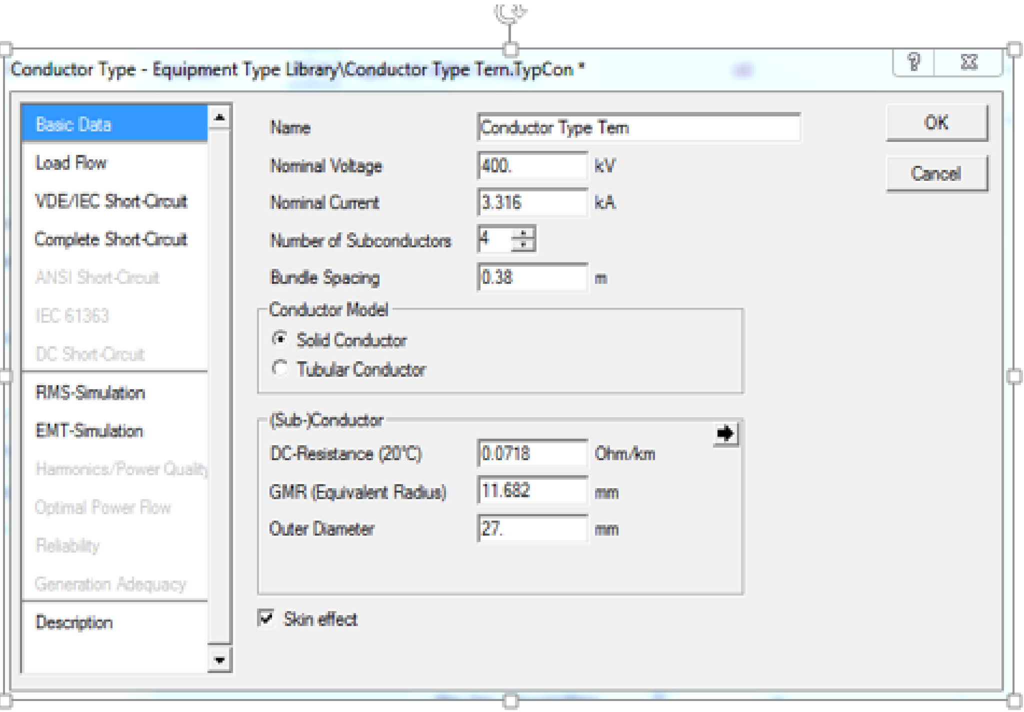
	X	Y
Earth Wire 1	-6.55	27.3
Earth Wire 2	6.55	27.36

Coordinates Phase Circuits [m]:

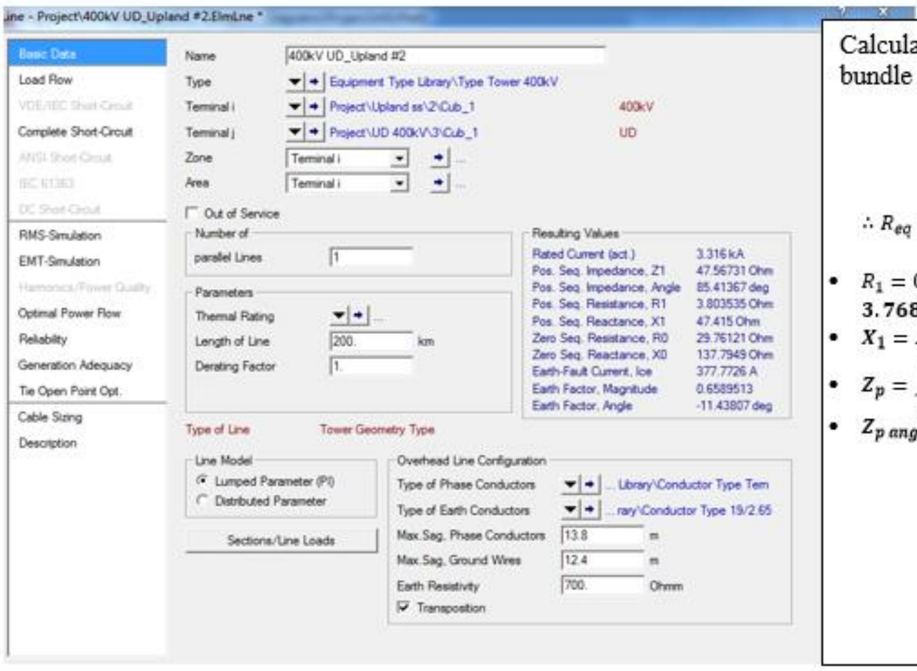
	Num.Phases	X1	X2	X3	Y1	Y2	Y3
Circuit 1	3.	-6.23	0.	6.23	22.15	22.15	22.15



Input Data A- 1: specification and tower type of 400kV



Input Data A- 2: specifications of a conductor Tern



Calculation of Resistance on bundle conductor

$$R_{eq} = \frac{R_{dc\,20^\circ}}{\ln D_{eq}/D_s}$$

$$\therefore R_{eq} = \frac{0.0718}{3.811} = 0.01884\Omega/km$$

- $R_1 = 0.01884\ x\ 200km = \mathbf{3.76805\Omega}$
- $\boldsymbol{X_1 = X_L x 200km = 47.86\Omega}$
- $\boldsymbol{Z_p = \sqrt{R_1^{\,2} + X_1^{\,2}} = 48\ \Omega}$
- $\boldsymbol{Z_{p\,angle} = \tan^{-1}\frac{X_1}{R_1} = 85.9^\circ}$

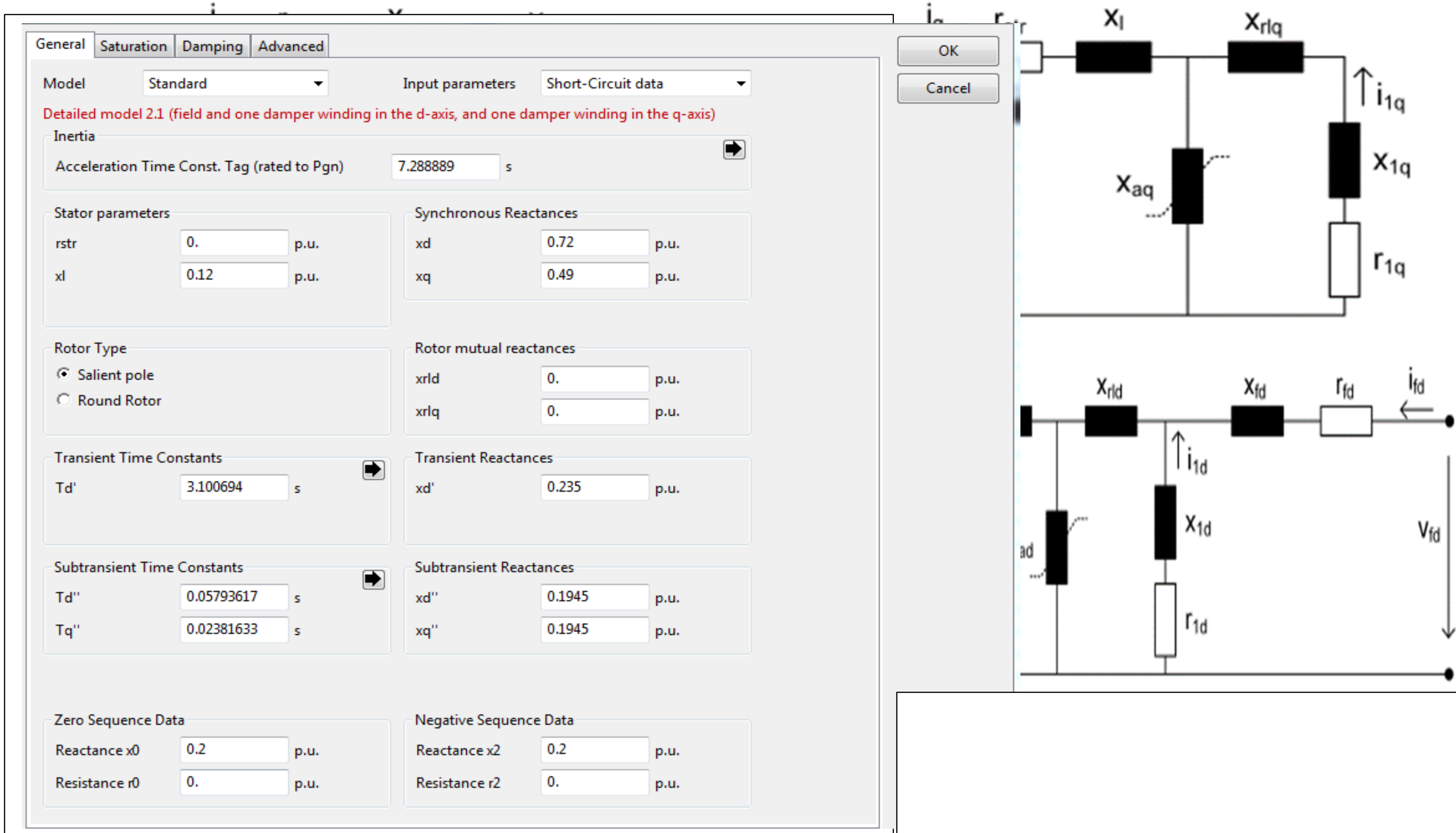
Input Data A- 3: Calculated Impedances for Tern Conductor

Table A- 1: Transmission line Data obtained in the network of SAPP

Name	Type	Length	Type of Phase Conductors	Type of Earth Conductors	Max.Sag Phase Conductors	Max.Sag Ear	Earth Resistivity	Irated(act.)	Irated	Positive sequence Impedance Z1	Positive sequence impedance,Angle phiz1	Positive sequence resistance, R1	Positive sequence reactance,X1	Negative sequence resistance,R0	Negative sequence reactance,X0	Earth factor magnitude ,k0	Earth factor angle,phik0
	TypLne,TypTow,TypGeo,TypCabsys	km	TypCon	TypCon	m	m	Ohm*m	kA	kA	Ohm	deg	Ohm	Ohm	Ohm	Ohm		deg
HPP1_6_Sub 4 #1	Type F_Std(3)	47	2x Bison_330kV	19/2.65_22kV	15.08	5.03	700	1.224	1.224	16.11372	83.58598	1.800099	16.01286	16.24176	49.74771	0.7591059	-16.76141
HPP1_6_Sub 4 #2	Type F_Std(3)	47	2x Bison_330kV	19/2.65_22kV	15.08	5.03	700	1.224	1.224	16.11372	83.58598	1.800099	16.01286	16.24176	49.74771	0.7591059	-16.76141
HPP2_6_HPP5_6#1	330kV TWIN BISON	1.3			0	0	100	1.306	1.306	0.418045	82.3353	0.055757	0.41431	0.42406	1.4742	0.8946867	-11.49722
HPP2_6_HPP5_6#2	330kV TWIN BISON	1.3			0	0	100	1.306	1.306	0.418045	82.3353	0.055757	0.41431	0.42406	1.4742	0.8946867	-11.49722
HPP2_6_Sub 1	330kV Tower F_STD (W)	135	2xBison	19/2.65	15.08	5.03	700	1.224	1.224	46.2841	83.58598	5.170498	45.99439	46.65186	142.8923	0.7591059	-16.76141
HPP2_6_Sub 4 #1	330kV Tower F_STD (W)	123	2xBison	19/2.65	15.08	5.03	700	1.224	1.224	42.16996	83.58598	4.710898	41.906	42.50503	130.1908	0.7591059	-16.76141
HPP2_6_Sub 4 #2	330kV Tower F_STD (W)	123	2xBison	19/2.65	15.08	5.03	700	1.224	1.224	42.16996	83.58598	4.710898	41.906	42.50503	130.1908	0.7591059	-16.76141
HPP3_6_Sub 3a	Tower Type A_220KV	146	1x Bison_220kV	7/2.65	11.79	3.93	700	0.8	0.8	64.64405	80.06203	11.15638	63.67408	53.06262	196.6411	0.7188818	-7.554947
HPP5_6_Sub 11 #1	2x Bison_330kV	169.4			0	0	100	1.306	1.306	53.99266	89.22897	0.7265565	53.98777	55.25828	192.0996	0.9167149	-20.77494
HPP5_6_Sub 11 #2	2x Bison_330kV	169			0	0	100	1.306	1.306	53.86518	89.22897	0.724841	53.8603	55.1278	191.646	0.916715	-20.77494
HPP5_6_Sub 11 #3	2x Bison_330kV	169.4			0	0	100	1.306	1.306	53.99266	89.22897	0.7265565	53.98777	55.25828	192.0996	0.9167149	-20.77494
Sub 22_Sub 23	Type 524	200	3 Tern 60_ 400kV	1.04E52	11	9.9	700	2.352	2.352	56.59935	84.92687	5.004914	56.37763	72.37791	208.7168	0.9810028	-18.7846
Sub 11_Sub 12 #1	2x Bison_330kV	109			0	0	100	1.306	1.306	34.74145	89.22897	0.467501	34.7383	35.5558	123.606	0.9167148	-20.77494
Sub 11_Sub 12 #2	2x Bison_330kV	112.2			0	0	100	1.306	1.306	35.76138	89.22897	0.4812258	35.75814	36.59964	127.2348	0.9167149	-20.77494
Sub 11_Sub 17	2x Bison_330kV	156.6			0	0	100	1.306	1.306	49.91294	89.22897	0.6716574	49.90842	51.08292	177.5844	0.9167149	-20.77494
Sub 12_Sub 15	2x Bison_330kV	20			0	0	100	1.306	1.306	6.374577	89.22897	0.08577999	6.374	6.524	22.68	0.9167149	-20.77494
Sub 13 A_Sub 14	2x Bison_330kV	251.4			0	0	100	1.306	1.306	80.12843	89.22897	1.078255	80.12118	82.00668	285.0876	0.9167149	-20.77494
Sub 13A_Sub13	2x Bison_330kV	50			0	0	100	1.306	1.306	15.93644	89.22897	0.21445	15.935	16.31	56.7	0.9167149	-20.77494
Sub 13_ Sub 12	2x Bison_330kV	50			0	0	100	1.306	1.306	15.93644	89.22897	0.21445	15.935	16.31	56.7	0.9167149	-20.77494
Sub 15_Sub 16	2x Bison_330kV	70.1			0	0	100	1.306	1.306	22.34289	89.22897	0.3006589	22.34087	22.86662	79.49339	0.916715	-20.77494
Sub 16_Sub 17	2x Bison_330kV	70.1			0	0	100	1.306	1.306	22.34289	89.22897	0.3006589	22.34087	22.86662	79.49339	0.916715	-20.77494
Sub 17_Sub 18	2x Bison_330kV	20			0	0	100	1.306	1.306	6.374577	89.22897	0.08577999	6.374	6.524	22.68	0.9167149	-20.77494
Sub 17_Sub 19	2x Bison_330kV	80.5			0	0	100	1.306	1.306	25.65767	89.22897	0.3452645	25.65535	26.2591	91.28699	0.9167148	-20.77494
Sub 18_Sub 19	2x Bison_330kV	123			0	0	100	1.306	1.306	39.20365	89.22897	0.527547	39.2001	40.1226	139.482	0.9167149	-20.77494
Sub 18_Sub 21	2x Bison_330kV	183.5			0	0	100	1.306	1.306	58.48674	89.22897	0.7870315	58.48145	59.8577	208.089	0.9167149	-20.77494
Sub 1_HPP1_6	Type F_Std(W) 330kV	43	2x Bison_330kV	19/2.65_22kV	15.08	5.03	700	1.224	1.224	14.74234	83.58598	1.646899	14.65006	14.85948	45.51386	0.7591059	-16.76141
Sub 1_Sub 4	Type F_Std(3)	53	2x Bison_330kV	19/2.65_22kV	15.08	5.03	700	1.224	1.224	18.17079	83.58598	2.029899	18.05706	18.31517	56.09848	0.7591059	-16.76141
Sub 20_Sub 19	2x Bison_330kV	130			0	0	100	1.306	1.306	41.43475	89.22897	0.55757	41.431	42.406	147.42	0.9167149	-20.77494

Sub 21_Sub 22	2x Bison_330kV	62			0	0	100	1.306	1.306	19.76119	89.22897	0.265918	19.7594	20.2244	70.308	0.9167149	-20.77494
Sub 23_Sub 23A	Type 524	100	3 Tern 60	S7-Check (1)	11.7	10.5	700	2.352	2.352	28.31952	85.00504	2.465726	28.21198	32.0621	119.6869	1.131653	-12.93384
Sub 24_Sub 26	Type 510A	94.171	2 Dinasaurs50_400kV	S19_(19/0.104 1	11.4	10.3	700	1.704	1.704	30.04022	85.6487	2.279196	29.95363	37.3599	102.8855	0.8980213	-21.33657
Sub 26_Sub 27	Type 510A	42.13	2 Dinasaurs50_400kV	S19_(19/0.104 1	11.4	10.3	700	1.704	1.704	13.43932	85.6487	1.019661	13.40059	16.71399	46.02866	0.8980213	-21.33657
Sub 29_Sub 31	Type 520B	190	3 Tern 60_ 400kV	S19_(19/0.104 1	11	9.9	700	2.352	2.352	54.21647	84.98465	4.739747	54.0089	73.1979	206.5234	1.027819	-19.15821
Sub 29_Sub30	Type 524	22.37	ACSR_C 3 Tern 60	S19_(19/0.104 1	11	9.9	700	2.352	2.352	6.333401	84.96483	0.5558655	6.30896	7.92534	25.07423	1.061066	-16.40569
Sub 2A_Sub 2B	Type F_Std(3)	145	2x Bison_330kV	19/2.65_22kV	15.08	5.03	700	1.224	1.224	49.71255	83.58598	5.553498	49.40138	50.10755	153.477	0.7591059	-16.76141
Sub 2_Sub 2B	Type F_Std(3)	159	2x Bison_330kV	19/2.65_22kV	15.08	5.03	700	1.224	1.224	54.51238	83.58598	6.089698	54.17117	54.94552	168.2954	0.7591059	-16.76141
Sub 30_Sub 28	Type 524	87.45	ACSR_C 3 Tern 60	S7-Check (7/0.1	11	9.9	700	2.352	2.352	24.76538	85.00421	2.156633	24.6713	28.0512	104.6632	1.13167	-12.94175
Sub 4_Sub 5 #2	330kV Tower F_STD (W)	97	2xBison	19/2.65	15.08	5.03	700	1.224	1.224	33.25598	83.58598	3.715099	33.04782	33.52023	102.6708	0.7591059	-16.76141
Sub 4_Sub 5 #3	330kV Tower F_STD (W)	97	2xBison	19/2.65	15.08	5.03	700	1.224	1.224	33.25598	83.58598	3.715099	33.04782	33.52023	102.6708	0.7591059	-16.76141
Sub 5_Sub 6 #1	330kV Tower F_STD (W)	211	2xBison	19/2.65	15.08	5.03	700	1.224	1.224	72.34033	83.58598	8.081298	71.88753	72.91512	223.3354	0.7591059	-16.76141
Sub 5_Sub 6 #2	330kV Tower F_STD (W)	211	2xBison	19/2.65	15.08	5.03	700	1.224	1.224	72.34033	83.58598	8.081298	71.88753	72.91512	223.3354	0.7591059	-16.76141
Sub 5_Sub 8 #1	330kV Tower F_STD (W)	247	2xBison	19/2.65	15.08	5.03	700	1.224	1.224	84.68276	83.58598	9.460097	84.15269	85.35562	261.4401	0.7591059	-16.76141
Sub 5_Sub 8 #2	330kV Tower F_STD (W)	247	2xBison	19/2.65	15.08	5.03	700	1.224	1.224	84.68276	83.58598	9.460097	84.15269	85.35562	261.4401	0.7591059	-16.76141
Sub 6_Sub 7	330kV Tower F_STD (W)	25	2xBison	19/2.65	15.08	5.03	700	1.224	1.224	8.57113	83.58598	0.9574997	8.517479	8.639233	26.46155	0.7591059	-16.76141
Sub 7_Sub 8	330kV Tower F_STD (W)	16	2xBison	19/2.65	15.08	5.03	700	1.224	1.224	5.485523	83.58598	0.6127998	5.451187	5.529109	16.93539	0.7591059	-16.76141
Sub 8A_Sub 9	330kV Tower F_STD (W)	72	2xBison	19/2.65	15.08	5.03	700	1.224	1.224	24.68485	83.58598	2.757599	24.53034	24.88099	76.20925	0.7591059	-16.76141
Sub 8_Sub 10	220kV Type O	52	HDCu 900 A	7/3.25	9.49	3.16	700	0.9	0.9	19.07633	74.5932	5.068021	18.3908	21.99083	64.61101	0.8600677	-4.702611
Sub 8_Sub 8A	330kV Tower F_STD (W)	197	2xBison	19/2.65	15.08	5.03	700	1.224	1.224	67.5405	83.58598	7.545098	67.11774	68.07716	208.517	0.7591059	-16.76141
Sub1_Sub3A	330kV Tower F_STD (W)	145	2xBison	19/2.65	15.08	5.03	700	1.224	1.224	49.71255	83.58598	5.553498	49.40138	50.10755	153.477	0.7591059	-16.76141
Sub24_Sub 25	Type433	150	4 Tern 60 380	S7-Check (7/0.1	13.8	12.4	700	3.136	3.136	36.21744	85.56834	2.798518	36.10915	53.03493	177.267	1.378992	-15.15839
Sub2A_Sub1	Type F_Std(3)	43	2x Bison_330kV	19/2.65_22kV	15.08	5.03	700	1.224	1.224	14.74234	83.58598	1.646899	14.65006	14.85948	45.51386	0.7591059	-16.76141
Sub30_Sub 31	Type 524	52.9602	ACSR_C 3 Tern 60	S7-Check (7/0.1	11	9.9	700	2.352	2.352	14.99805	85.00421	1.306069	14.94108	16.98796	63.38462	1.13167	-12.94175
Sub3_Sub3A	330kV Tower F_STD (W)	43	2xBison	19/2.65	15.08	5.03	700	1.224	1.224	14.74234	83.58598	1.646899	14.65006	14.85948	45.51386	0.7591059	-16.76141
Sub4_Sub 5 #1	330kV Tower F_STD (W)	97	2xBison	19/2.65	15.08	5.03	700	1.224	1.224	33.25598	83.58598	3.715099	33.04782	33.52023	102.6708	0.7591059	-16.76141
THPP1_6_Sub 17 #1	2x Bison_330kV	355			0	0	100	1.306	1.306	113.1487	89.22897	1.522595	113.1385	115.801	402.57	0.9167149	-20.77494
THPP1_6_Sub 17 #2	2x Bison_330kV	355			0	0	100	1.306	1.306	113.1487	89.22897	1.522595	113.1385	115.801	402.57	0.9167149	-20.77494
THPP1_6_Sub 22	2x Bison_330kV	307.2			0	0	100	1.306	1.306	97.91351	89.22897	1.317581	97.90464	100.2086	348.3648	0.916715	-20.77494
THPP2_6_SUB 28 #1	Type433	158	ACSR 3 Dinosaur50	S19_(19/0.104 1	16.2	14.6	700	2.556	2.556	40.89537	86.5301	2.475162	40.8204	61.67764	174.8771	1.19449	-20.35744
THPP2_6_Sub 23A	Type 524	100	3 Tern 60	S7-Check (1)	11.7	10.5	700	2.352	2.352	28.31952	85.00504	2.465726	28.21198	32.0621	119.6869	1.131653	-12.93384
THPP2_6_Sub 24 #1	Type 516A	98.045	2 Dinasaurs50_400kV	S19_(19/0.104 1	11.3	10.1	700	1.704	1.704	31.30925	85.67817	2.359422	31.22022	38.87251	107.0405	0.8959453	-21.39244
THPP2_6_Sub 24 #2	Type 524	199.09	3 Tern 60_ 400kV	S19_(19/0.104 1	11	9.9	700	2.352	2.352	56.36641	84.96483	4.947128	56.1489	70.53445	223.1573	1.061066	-16.40569
THPP2_6_Sub 28 #2	Type433	158	ACSR 3 Dinosaur50	S19_(19/0.104 1	16.2	14.6	700	2.556	2.556	40.89537	86.5301	2.475162	40.8204	61.67764	174.8771	1.19449	-20.35744
THPP2_6_Sub 29	Type 520B(1)	267.8997	4 Zebra 80_400kV	S19_(19/0.104 1	16.2	14.6	700	4.32	4.32	69.54871	86.0881	4.744782	69.38667	100.7214	284.7746	1.130162	-20.1058
THPP2_6_Sub 31	Type 520B	342	4 Zebra 80_400kV	S19_(19/0.104 1	16.2	14.6	700	4.32	4.32	88.78567	86.0881	6.057174	88.57881	128.5806	363.5424	1.130162	-20.1058
THPP3_6_Sub 28 #1	Type433	200	4 Tern 60 380	19/2.65_22kV	13.8	12.4	700	3.136	3.136	48.24706	85.46033	3.818725	48.0957	80.60478	198.5165	1.166815	-22.5035
THPP3_6_Sub 28 #2	Type433	200	4 Tern 60 380	19/2.65_22kV	13.8	12.4	700	3.136	3.136	48.24706	85.46033	3.818725	48.0957	80.60478	198.5165	1.166815	-22.5035

APPENDIX B DATA FOR SYNCHRONOUS GENERATORS



B- 1: Required data for dynamic parameters and synchronous generators equivalent circuits d and q axis

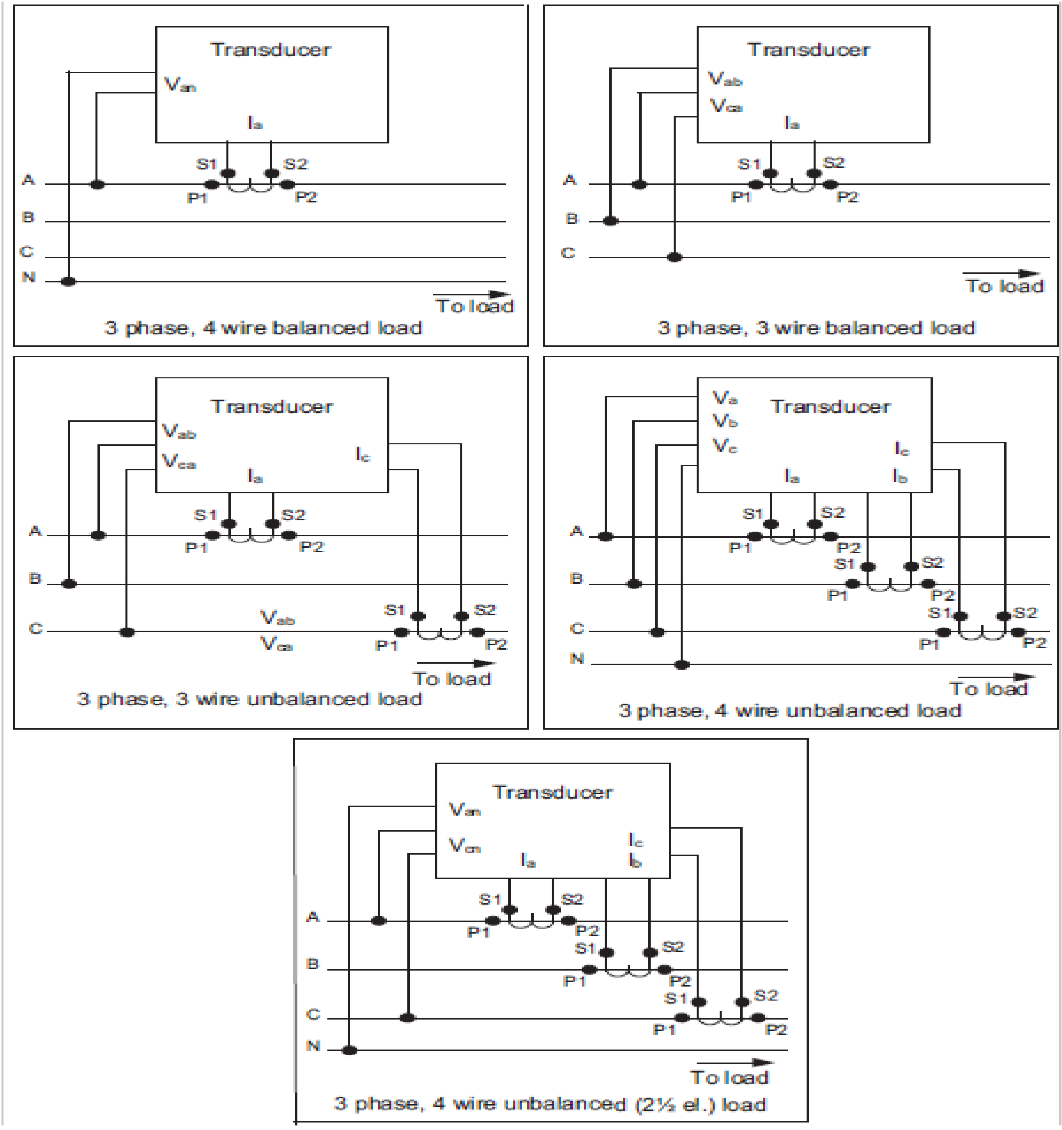
B- 33: Synchronous data used for SAPP grid

Name	Act.Pow .(act.) MW	React.Pow.(act.) Mvar	App.Pow.(act.) MVA	Pow.Fact.(act.)	Max.Active Power Limit MW
HPP1	145.488	32.59176	149.0936	0.9758147	150
HPP2	145.488	32.59176	149.0936	0.9758147	150
HPP2_1	145.488	32.59176	149.0936	0.9758147	150
HPP2_2	145.488	32.59176	149.0936	0.9758147	180
HPP2_3	145.488	32.59176	149.0936	0.9758147	180
HPP2_4	145.488	32.59176	149.0936	0.9758147	180
HPP2_5	150	32.59176	153.4999	0.9771993	180
HPP2_6	150	32.59176	153.4999	0.9771993	180
HPP3	145.488	32.59176	149.0936	0.9758147	150
HPP3_1	58.1951	9.770236	59.00954	0.9861979	60.3
HPP3_2	58.1951	9.770236	59.00954	0.9861979	60
HPP4	145.488	32.59176	149.0936	0.9758147	150
HPP5	145.488	32.59176	149.0936	0.9758147	150
HPP5_1	107.966	24.91842	110.8044	0.9743849	111
HPP5_2	107.966	24.91842	110.8044	0.9743849	111
HPP5_3	107.966	24.91842	110.8044	0.9743849	110
HPP5_4	107.966	24.91842	110.8044	0.9743849	110
HPP5_5	107.966	24.91842	110.8044	0.9743849	110
HPP5_6	107.966	24.91842	110.8044	0.974385	110
HPP6	145.488	32.59176	149.0936	0.9758147	150
HPSP4_1	9	1.775684	9.173497	0.9810871	10.5
HPSP4_2	9	1.775684	9.173497	0.9810871	10.5
HPSP4_3	9	1.775684	9.173497	0.9810871	10.5
HPSP4_4	9	1.775684	9.173497	0.9810871	10.5
THPP1_1	105.048	16.15253	106.2827	0.988384	120
THPP1_2	105.048	16.15253	106.2827	0.988384	108
THPP1_3	105.048	16.15253	106.2827	0.988384	108
THPP1_4	105.048	16.15253	106.2827	0.988384	108
THPP1_5	195.217	34.19847	198.1896	0.985	219
THPP1_6	195.217	29.613	197.4501	0.9886895	198
THPP2_1	585	112.2312	595.6684	0.9820901	665
THPP2_2	585	112.4693	595.7133	0.982016	665
THPP2_3	585	102.4816	593.9086	0.985	665
THPP2_4	585	112.241	595.6702	0.982087	665
THPP2_5	585	112.241	595.6702	0.982087	665
THPP2_6	585	116.0899	596.4075	0.980873	665
THPP3_1	700	128.0824	711.6215	0.983669	700

B- 34: Data acquired for the synchronous generators in modelled SAPP grid

		DATA INPUT FOR THE SYNCHRONOUS GENERATORS FOR SAPP GRID											
Name		**Tag[Pgn]**	**rstr**	**xl**	**Td''**	**Tq''**	**xd**	**xq**	**xrld**	**xrlq**	**xd'**	**xd''**	**xq''**
		s (M)	**p.u.**	**p.u.**	**s**	**s**	**p.u.**	**p.u.**	**p.u.**	**p.u.**	**p.u.**	**p.u.**	**p.u.**
HPP1_6	G1_G6	7.288889	0	0.12	0.057936	0.023816	0.72	0.49	0	0	0.235	0.1945	0.1945
HPP2_6	G1_G4	9.574706	0	0.16	0.080903	0.104612	0.8	0.49	0	0	0.288	0.233	0.233
	G5_G6	7.298620	0	0.12	0.048696	0.023816	0.79	0.49	0	0	0.23	0.16	0.1945
HPP3_6	G1	10	0.0024	0.1	0.05	0.05	0.72	0.49	0	0	0.235	0.18	0.2
	G2	10	0.0024	0.1	0.05	0.05	0.72	0.49	0	0	0.3	0.235	0.2
HPP5_6	G1_G6	10	0	0.1	0.05	0.05	0.88	0.53	0	0	0.3	0.2	0.2
H4_6	G1_G2	7.768361	0	0.17	0.045	0.025714	1.1	0.7	0	0	0.4	0.3	0.3
	G3_G4	7.768361	0	0.17	0.042	0.024	1.1	0.7	0	0	0.4	0.28	0.28
T1_6	G1_G4	8	0	0.1	0.05	0.045	2.31	2.26	0	0	0.3	0.2	0.2
T1_6	G5_G6	8	0	0.1	0.05	0.05	2.15	2.02	0	0	0.3	0.2	0.2
T2_6	G1_G6	4.622222	0	0.22	0.0336	0.034269	2.68	2.49	0	0	0.41	0.287	0.287
T3_1	G1	6.711111	0	0.25	0.028929	0.128571	2.23	2.12	0	0	0.28	0.27	0.27

APPENDIX C TYPES OF POWER TRANSDUCERS CONNECTION IN POWER SYSTEM



C- 1: Types of transducer connection for power measurement