NTNU
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Improvement of power supply reliability

Case Study: Zambia

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Problem Description

The reliability of the power supply system in Zambia is not satisfactory. Two recent power blackouts have been serious. The purpose of this Master Thesis is to investigate the system by means of stability analysis, contingency analysis and review of protection settings with the aim of improving the reliability of the system. The work includes data collection from ZESCO Ltd, Zambia

The following tasks are included:

1. Dynamic stability studies of Zesco generators by use of SIMPOW
2. Contingency analysis for critical components in the transmission grid by use of NETBAS.
3. Investigation of protection settings for transmission, generation and consumption.
4. Work out recommendations based on the above mentioned investigations.

Assignment given: 15. January 2009
Supervisor: Ivar Wangensteen, ELKRAFT

SUMMARY

This thesis studied reliability of power supply in Zambia following two major power blackouts that affected the whole country. The case study focussed on the generation and transmission network owned by Zambia's biggest utility company Zesco. Three methods of study were selected. The first method looked at the transient stability simulations of Zesco generators when subjected to a large disturbance after a three phase short circuit was applied at three selected buses which are considered critical to the system. The simulations were carried out in SIMPOW. The results show that with fault duration of less than 200 milliseconds, all generators regained synchronism after fault removal. However, extending the fault duration to 200 milliseconds resulted in loss of synchronism in generators at Victoria Falls power station. The second method studied the contingency of some critical components in the Zesco system. The contingency analysis was implemented using software called NETBAS. Study showed that the Zesco system is N-1 stable for contingencies involving transmission lines and transformers. However the system is vulnerable to contingencies involving major power stations such as Kafue gorge and Kariba North bank. The third study proposed modification to the distance protection system to include the effect of zero sequence mutual coupling resulting from parallel circuits following a fault involving earth on a protected line. Adaptive techniques were developed where the settings of the distance relay would change to suit the circuit configuration. This technique resulted in optimal performance of the distance relay under all conditions of parallel line operation.

The thesis concludes by making recommendations based on the findings from the studies carried out.

DEDICATION

To My Wife, Gift, My Daughter Fiona and My Parents for Their Love, Patience and Support

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor, Prof. Ivar Wangensteen, for his support and guidance throughout my project work. His knowledge and experience contributed greatly to this report.

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1 INTRODUCTION

1.1 Background

Major power blackouts usually occur as a result of the inability of a transmission system to support the demand for generation and transportation of power.

Fig 1 shows a typical power system

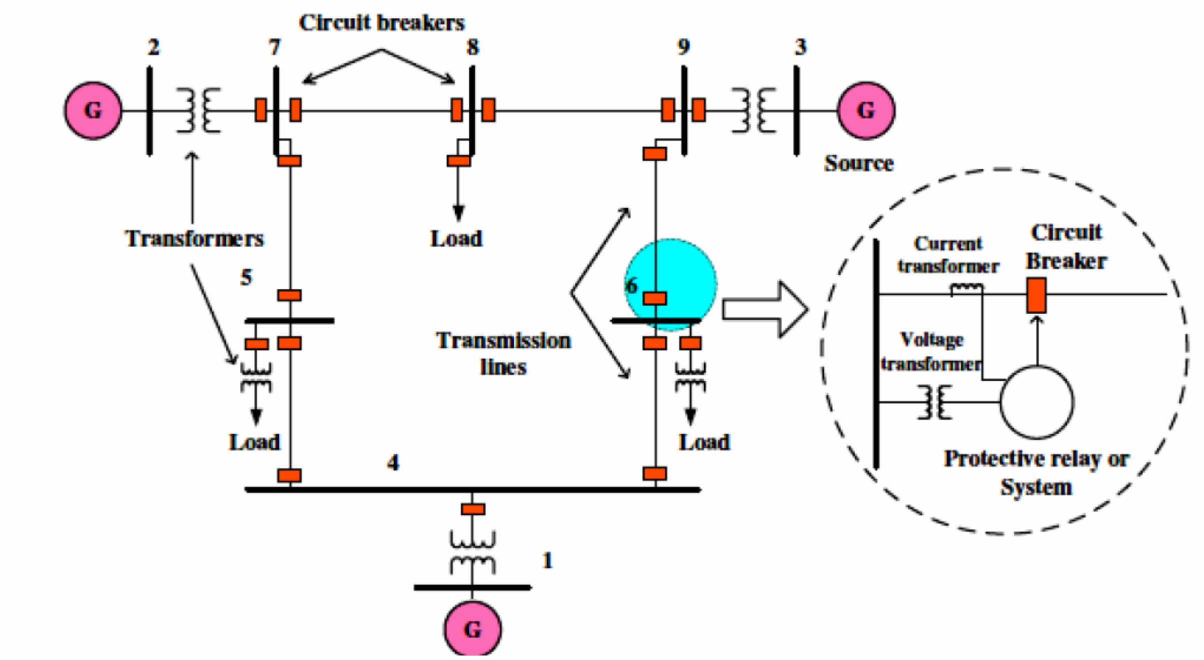

Fig 1 Example of a power system

In many cases, an initial incident results in the disconnection of a small amount of faulty primary plant. The incident may then escalate, either because the removal of primary plant item imposes additional stresses on the overall network, or because the initial incident cannot be contained and the consequences of the initial fault progressively spread into the rest of the power system. The role played by power system protection in power blackout situations is crucial. The protection is designed to detect specific types of primary plant fault and initiate rapid disconnection of the faulty components.

A blackout incident may be caused as a result of the following protection limitations [1]:

a) Failure to operate in the presence of an actual fault;

b) Failure to operate rapidly within the required design operating times;

c) Failure to provide a selective trip instruction to specific system circuit breakers, i.e. a non-discriminative trip;

d) Inadvertent operation during conditions where no system or plant fault is present;

Whilst the first three failure modes are self explanatory, an interesting and actual example of the forth failure mode was experienced in Zambia on the Zesco power network. In this case, the major transmission system voltage is 330 kV and, the network is interconnected. Protection of major transmission lines is via distance protection, used in a time-stepped mode with protection signalling. Backup protection is provided by over-current and earth fault relays with inverse-time characteristics.

Even when correct operation of the distance protection successfully isolates a faulty circuit, the resultant loss of the circuit results in re-distribution of load current via adjacent lines. Due to the high load factor and (potentially) low fault levels under minimum system conditions, selecting settings for time-delayed over-current relays which will allow operation under minimum fault conditions but prevent operation under high transient load conditions during load redistribution is difficult. A number of incidents of loss of several circuits following isolation of a faulty circuit have occurred.

No two blackouts appear identical according to the historical records [2]. But there is a common cascading process for different blackouts, which can be described as follows [3, 4]:

- **System state before the blackout**: Before the blackout, system parameters usually remain within their normal operating reliability ranges. At the same time, some noticeable deviations that could potentially weaken the system, such as high electricity demands, heavy power flows, depressed voltages, and frequency variations, etc, could be observed. Some scheduled maintenances on the nearby generators and/or transmission facilities may also happen before the blackouts.
- **Contingency conditions**: Before the blackouts, the system may be additionally weakened by unscheduled outages, such as several transmission line, transformer and generator outages due to the faults. Those conditions move the system to a more stressful stage.
- **Initiating events**: At a certain point of the blackout development, a triggering event happened. Triggering event is the point separating a period where multiple contributing but not direct factors for final blackout are accumulated, from the direct sequence of events with clear cause/effect relationships.
- **Steady state progression with slow succession**: The triggering event as well as the subsequent events in a blackout scenario may cause power flow surges, overloads, or voltage problems. The protection system may remove the equipment or a group of equipment from the rest of network if it detects the low voltage and high current even

though there may be no faults. Some load loss may accompany this process. This can result in more power flow surges, overloads, and voltage problems, and so on. In this initial stage, the cascading process can be relatively slow.

- **Transient state progression with fast succession**: In this stage, the system begins to lose major parts which results in bigger power swing, overload or low voltage. The components begin to trip one by one in a very short time. Uncontrollable system separation, angle instability, and voltage collapse may occur. As a result, a significant load loss may be inflicted. Final large-scale blackout is reached in a very short period.

From the above description, one can see that the cascading blackout is a result of accumulation of a chain of contingencies and system reactions.

1.2 Problem Definition

The reliability of the power supply system in Zambia is not satisfactory. Two recent power blackouts have been serious. The purpose of this Master Thesis is to investigate the system by means of stability analysis, contingency analysis and review of protection settings with the aim of improving the reliability of the system. The work includes data collection from Zesco Ltd, Zambia

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1.3 Methodology

The thesis involved data collection from Zesco in Zambia. This was done by site visitations to substations and power stations across the country. Data collection was achieved through existing reports as well as conducting oral interviews from the personnel involved.

1.4 Outline of the Thesis

The thesis is organized as follows:

- Chapter II describes the Zesco generation and transmission network and also gives a review of the power blackouts that occurred on the Zesco network in the recent past.
- A discussion of small signal and transient stability is given in chapter III which includes low frequency oscillations (local and inter-area), system Eigenvalues and their significance to the stability of the power system.

- Chapter IV discusses the results of both the static and dynamic simulations of the Zesco network carried out in SIMPOW.
- A contingency analysis for critical components in the transmission grid by use of NETBAS is presented in chapter V.
- Chapter VI investigates the protection settings for transmission, generation and consumption.
- Chapter VII concludes with recommendations based on the investigations carried out.
- References and Appendices are attached at the end.

2 REVIEW OF POWER SYSTEM IN ZAMBIA

2.1 Generation

In Zambia, [5] the bulk of the generation is from hydropower (1608 MW), generated by three main power stations, namely Kafue Gorge (900 MW), Kariba North Bank (600 MW) and Victoria Falls (108 MW).

Fig 2 is the map of Zambia showing the generation and transmission network at different voltage levels.

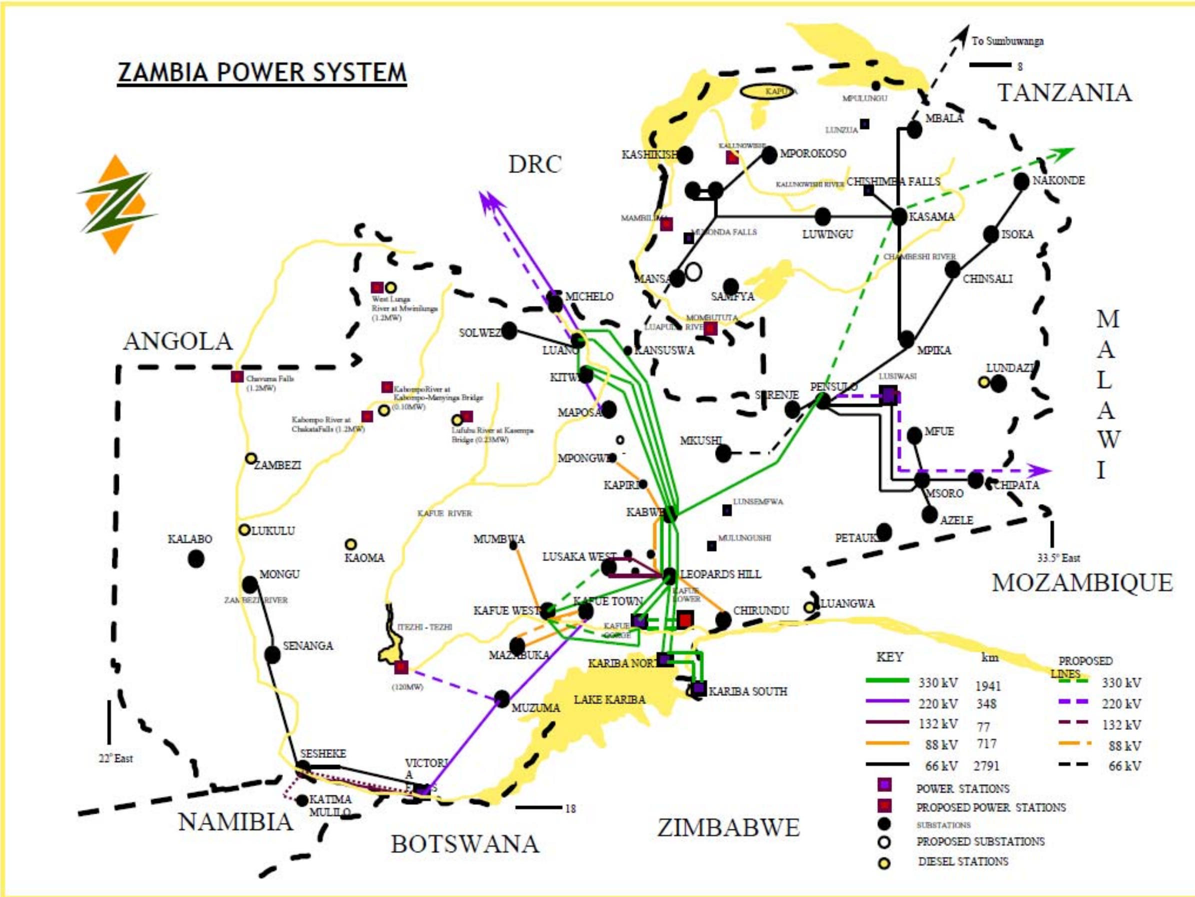


Fig 2 Map of Zambia showing the power grid at different voltage levels

These three plants are sufficient to support the power demand of Zambia but there is only some spare capacity available for export during the off peak period. Recently, the decision was made to rehabilitate these plants and upgrade the generating capacity of the units. There is also the possibility to increase by two the number of units installed in the Kariba North plant. In addition to these capacity extensions in progress, there are plans in Zambia to build two hydropower plants on the Kafue River to be located at Itezhi-Tezhi dam (120 MW) and Kafue Gorge Lower (600 MW). Following the completion of all these projects, Zambia will clearly have surplus power available for export for several years. The peak demand in Zambia is expected to grow from 1300 MW in 2004 to 2245 MW in 2025

2.2 Transmission

The transmission system has a total of 4,638 km of transmission lines spread as follows: 2,008 km of 330kV lines, 348 km of 220kV, 85 km of 132kV, 704 km of 88kV, and 2,823 km of 66kV lines (of which 2,180 km are under Zesco's Distribution and Supply Directorate).

Fig 3, Fig 4 and Fig 5 show pictorial view of part of the Zesco transmission network at 330kV level at Leopards Hill substation.

Fig 3 Kariba and Kafue gorge 330kV lines at Leopards Hill substation

Fig 4 330/132kV transformers at Leopards Hill substation

Fig 5 330kV SF6 circuit breakers type FXT15 at Leopards Hill substation

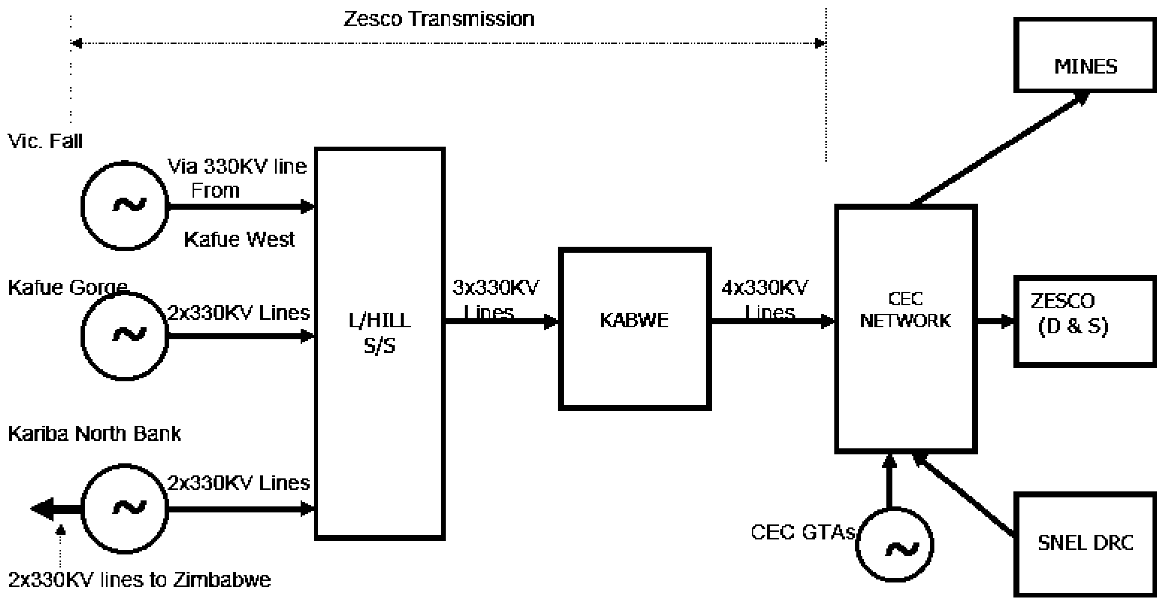


Fig 6 Schematic diagram of Zesco generation and transmission grid

The transmission network, whose schematic diagram is shown in Fig 6, serves as a means of power transport from the generating stations to the Distribution Bulk supply points throughout the country and also to the Copperbelt Energy Corporation and Export points. The transmission system refurbishment under Power Rehabilitation Project (PRP) was completed in 2004.

2.3 Southern African Power Pool (SAPP)

Like NordPool, the countries in southern Africa have formed a power sharing Pool called Southern African Power Pool (SAPP). Zambia is a member of this Power Pool. The Southern Africa Power Pool, [6] (SAPP) was formed in late 1995 and its operations have been guided by a memorandum of understanding, which was signed in December 1996. SAPP includes twelve southern African power utilities, namely: Angola, Botswana, Lesotho, Malawi, Mozambique, Namibia, South Africa, Swaziland, Tanzania, Zambia, Zimbabwe and Zaire (now DRC). The main objectives of setting up the power pool are to ensure that all member utilities co-operate and co-ordinate in the operation of their systems to minimize costs while maintaining reliability; fully recover costs; and share equitably in the resulting benefits. The member countries of SAPP are shown in Fig 7.

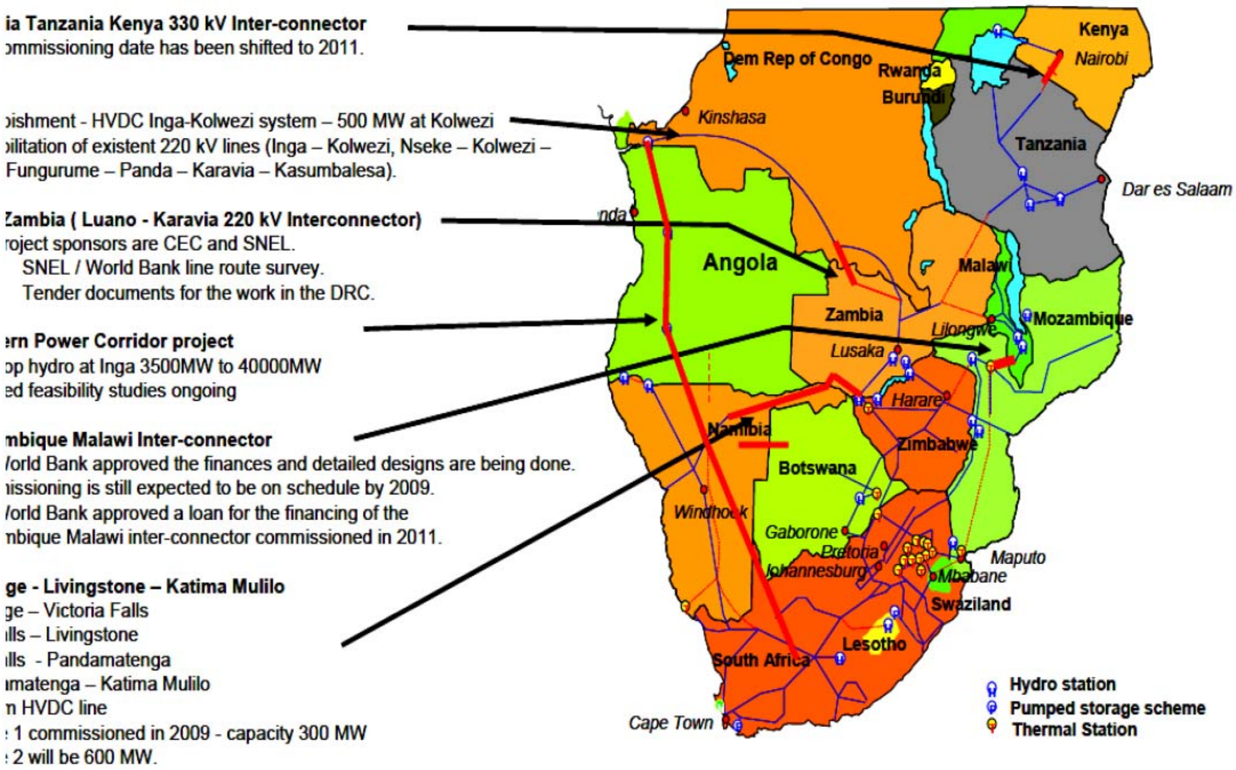


Fig 7 SAPP member countries

2.4 Recent Power Blackouts

2.4.1 Blackout of 19th January 2008

The blackout was initiated by a disturbance in the Zimbabwean grid which resulted in the loss of a major load and shut down of the Kariba North Bank power station. This caused overloading and subsequent tripping of the generators at Kafue Gorge and Victoria Falls power stations resulting in the blackout. The sequence of events leading to the blackout can be summarized as follows:

- At 19:38hrs a system disturbance was observed on the Zesco network attributed to an external fault on the ZESA (Zimbabwe) network which resulted in the tripping of the 400kV interconnector to ESKOM (South Africa)
- This subsequently caused tripping on over-current protection of the Kariba – Leopards hill 330kV line which connects the kariba North bank power station to the rest of the Zambian grid. The interconnection to the Zimbabwean network was also lost when under frequency protection operated.
- The rejected load could not be sustained by the two remaining power stations namely Kafue gorge and Victoria Falls so both stations tripped on overload protection.
- The ZESA network registered power swings on the transmission grid in the western region bordering Botswana Power Corporation (BPC) and ESKOM (South Africa)

resulting in the loss of 330kV Hwange – Sherwood and 420kV Insukamini – Phokoje lines.

- The lightly loaded grid of ZESA, Zesco, and SNEL (Congo DR) experienced over frequency and this resulted in instantaneous tripping of all the six generators at Kariba south bank and one unit at kariba North bank power stations.

2.4.2 Blackout of 21st January 2008

The blackout was initiated by a spurious tripping on the only 330 kV transmission line available at the time [line No.2] from Kariba North Bank power station to Leopards Hill substation. The failure of this line completely isolated Kariba North Bank Power Station from the national grid because on 30th December 2007, a tower on the only other line [Line No.1] had collapsed due to heavy rains making this line unavailable. This situation caused over loading of Kafue Gorge and Victoria Falls power stations and subsequent tripping on under frequency protection.

2.4.3 Blackout of 22nd January 2008

The blackout of 22nd January 2008 was caused by a collapse of the system voltage due to insufficient generation capacity. The Zambian system had been isolated from Zimbabwe and Kariba North Bank Power Station was not available on this day because both lines that transmit power from this station were out of service, as indicated in above. Kafue Gorge Power Station was operating at maximum available generation without any reserve margin at all and as the demand for power increased, the station tripped on under frequency protection.

3 SMALL SIGNAL AND TRANSIENT STABILITY

3.1 Stability Definition

In order to clearly determine the goals of this research, the concept of "stability" must be defined since this term represents different concepts to different persons involved with power system stability. A definition given is as follows:

> "Power system stability may be broadly defined as that property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance." [7]

From this general definition, two categories of stability are derived: small-signal and transient stability. *Small-signal stability* is the ability of the system to return to a normal operating state following a small disturbance. Investigations involving this stability concept usually involve the analysis of the linearized state space equations that define the power system dynamics. *Transient stability* is the ability of the system to return to a normal operating state following a severe disturbance, such as a single or multi-phase short-circuit or a generator loss. Under these conditions, the linearized power system model does not usually apply and the nonlinear equations must be used directly for the analysis.

3.2 Small Signal Stability

Since small signal stability involves perturbations around the operating point, analysis can therefore be done by linearizing a set of state equations that describe the power system.

3.2.1 State-Space Representation and Linearization

Every dynamic system can be described with a state vector **x**, an input vector **u**, and an output vector **y**, as in Fig 8. The state vector **x** contains the n state variables of the dynamic system.

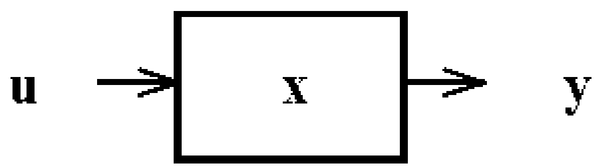


Fig 8 A dynamic system

A state variable is a variable in the system that has to be time-derived through a time simulation. If the derivatives of the state variables, $\dot{\mathbf{x}}$, and the output vector, **y**, are not explicit functions of time, the dynamic system in Fig 8 can be described with the two functions **f** and **g**:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}) \tag{3.1}$$

$$\mathbf{y} = \mathbf{g}(\mathbf{x}, \mathbf{u}) \tag{3.2}$$

By disturbing the system in Fig 8 with small deviations in both the state vector **x** and the input vector **u**, the linearized form of the dynamic system can be written as,

$$\Delta\dot{\mathbf{x}} = \mathbf{A}\Delta\mathbf{x} + \mathbf{B}\Delta\mathbf{u} \tag{3.3}$$

$$\Delta\mathbf{y} = \mathbf{C}\Delta\mathbf{x} + \mathbf{D}\Delta\mathbf{u} \tag{3.4}$$

The matrix **A** in equation (3.3) is the state matrix of size [*nxn*] and the poles of the dynamic system are the roots of the equation,

$$\det(s\mathbf{I} - \mathbf{A}) = 0 \tag{3.5}$$

where **I** is the identity matrix of dimension *n*.

3.2.2 Eigenvalues and Eigenvectors

The values of s which satisfy (3.5) are known as **eigenvalues** of matrix **A**, and equation (3.5) is referred to as the characteristic equation of matrix **A**, see [7], page 707.

The number of eigenvalues is always the same as the dimension of matrix **A**. Some of them can be multiple. The eigenvalues can be complex and therefore it is useful to depict them in the complex plane.

For every eigenvalue there exist two eigenvectors, **right** and **left eigenvector**. For any eigenvalue λ_i, the column vector of dimension n, $\mathbf{\Phi}_i$, which satisfies equation (3.6), is called the right eigenvector of **A**, see [7], page 707.

$$\mathbf{A\Phi}_i = \lambda_i \mathbf{\Phi}_i \tag{3.6}$$

The right eigenvector measures the activity of the state variables of mode i, see [15]. It shows how observable an eigenvalue is among the state variables. The right eigenvector can be calculated in SIMPOW.

For any eigenvalue λ_i, the row vector of dimension n, $\mathbf{\Psi}_i$, which satisfies equation (3.7), is called the left eigenvector of **A**.

$$\mathbf{\Psi}_i^T \mathbf{A} = \lambda_i \mathbf{\Psi}_i^T \tag{3.7}$$

The left eigenvector weighs the contribution of the activity of the state variables to mode i, see [15]. It shows how able a state variable is to influence an eigenvalue. The left eigenvector cannot be calculated in SIMPOW. The eigenvectors can be normalized so that the product of them in each case is,

$$\mathbf{\Psi}_i^T \mathbf{\Phi}_i = 1 \tag{3.8}$$

Note that the product of the left and right eigenvectors that belong to different eigenvalues is 0,

$$\mathbf{\Psi}_j^T \mathbf{\Phi}_i = 0 \text{ for i} \neq \text{j}$$

The eigenvalues may be real or complex, and are of the form $\sigma \pm j\omega$, where σ is the damping constant and ω is the frequency of oscillation in radians per second. (Note that SIMPOW calculates ω in Hertz). Complex eigenvalues always occur in conjugate pairs.

The stability of the operating point (δ_0, ω_0), where δ_0 is the power angle in radians, may be analyzed by studying the eigenvalues. The operating point is stable if all of the eigenvalues are on the left-hand side of the imaginary axis of the complex plane; otherwise it is unstable. If any of the eigenvalues appear on or to the right of this axis, the corresponding modes are said to be unstable, as is the system. This stability is confirmed by looking at the time dependent characteristic of the oscillatory modes corresponding to each eigenvalue λ_i, given by $e^{\lambda_i t}$. The latter shows that a real eigenvalue corresponds to a non-oscillatory mode. If the real eigenvalue is negative, the mode decays over time. The magnitude is related to the time of decay; the larger the magnitude, the quicker the decay. If the real eigenvalue is positive, the mode is said to have aperiodic instability.

On the other hand, the conjugate-pair complex eigenvalues $\sigma \pm j\omega$ each correspond to an oscillatory mode. A pair with a positive σ represents an unstable oscillatory mode since these eigenvalues yield an unstable time response of the system. In contrast a pair with a negative σ represent a desired stable oscillatory mode. Eigenvalues associated with an unstable or poorly damped oscillatory mode are also called dominant modes since their contribution dominates the time response of the system. It is quite obvious that the desired state of the system is for all of the eigenvalues to be in the left-hand side of the complex plane.

Other information that can be determined from the eigenvalues is the oscillatory frequency and the damping factor. The damped frequency of the oscillation in Hertz is given by

$$f = \frac{\omega}{2\pi} \tag{3.9}$$

And the damping factor (or damping ratio) is given by

$$\xi = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \tag{3.10}$$

3.3 Transient Stability

The real power system is a dynamic system and the normal operation condition may be altered by certain disturbances caused by faults, load rejection, line switching, and loss of excitation. Transient stability is defined as the ability of the power system to maintain synchronism when subjected to those disturbances [7, 8]. The protection system performance plays an important role to maintain the system transient stability after the fault. The basic idea of transient stability can be demonstrated using a simple two-machine system shown in Fig 9. For this system, if we neglect the resistance of the line, the active power P_e transferred between two generators can be expressed as,

$$P_e = \frac{E_S . E_R}{X} \sin \delta \tag{3.11}$$

and $X = X_S + X_L + X_R$.

Where

δ Angle difference between the two generators (power angle) in radians

E_S Thevenin equivalent generator voltage magnitude at the source end in kV

E_R Thevenin equivalent generator voltage magnitude at the receiving end in kV

X Combined reactance between the source and the receiving end generators in ohms

X_S Thevenin equivalent source reactance in ohms

X_L Equivalent transmission line reactance in ohms

X_R Thevenin equivalent reactance at the receiving end in ohms

If E_S, E_R and X are fixed, the relationship between P_e and δ can be described using the power angle curve shown in Fig 10, where the two power angle curves correspond to the normal state and the fault situation respectively. The differential equation to model the motion of the generator rotor angle is known as the swing equation [7, 8]:

$$\frac{2H}{\omega_o} \frac{d^2\delta}{dt^2} = P_m - P_e \tag{3.12}$$

H Inertia constant of the generator

ω_o Generator synchronous speed

P_m Generator input mechanical power

P_e Generator output electrical power

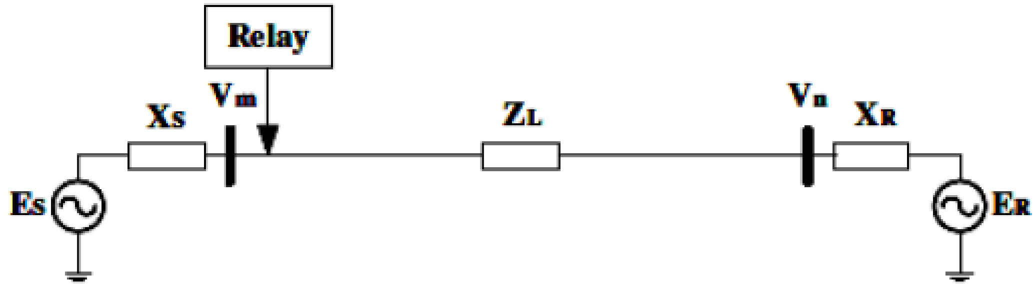


Fig 9 A two machine system

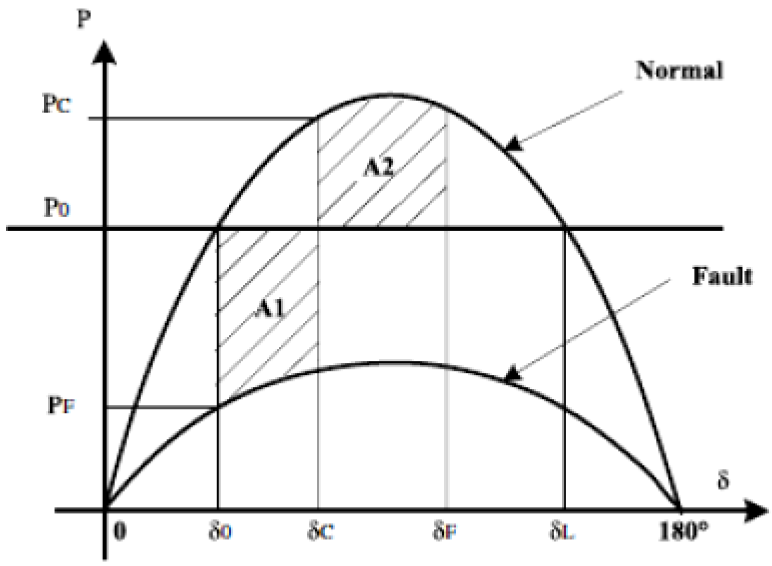


Fig 10 The power angle curve

As shown in Fig 10, during the normal state $P_m = P_e = P_0$. The generator rotor runs at a constant speed and the rotor angle difference between the generators is constant, at δ_0. When a fault occurs, the power transmission P_e is dropped to P_F from P_0. At the same time, the mechanical power P_m of generator can not be changed at once to match the change of P_e, resulting in the rotor acceleration and δ increasing. When the fault is cleared at the time δ reaches δ_C, the power transmission P_e returns to the P_C, which is larger than mechanical power $P_m = P_0$. That causes the rotor to decelerate and δ reaches δ_F due to the inertia of the rotor system. At δ_F, the deceleration area A2 is equal to the acceleration area A1. This is known as the equal-area criterion [7, 8]. If δ_F is smaller than δ_L, δ can eventually go back to the original balance point δ_0 with sufficient damping. The system is transient stable in this case. If area A1 is still larger than A2 at the time δ reaches δ_L, the rotor will accelerate again beyond recovery since $P_e < P_m$. The system is transient unstable and may cause big problem such as cascading blackouts. It is seen that the fault clearing time by the protection system will directly relate to the area of A1 and A2. The faster the fault is cleared, the more stable the system. Consider a large system; any disturbance such as fault, load rejection, line switching, loss of excitation; etc will cause similar behaviour of each system generator as demonstrated above, resulting in the oscillation of system bus voltages and angles. That will in turn have an impact on the relay operations, which will be explained in chapter 6.

There are several ways to enhance system transient stability, such as high-speed fault clearing, reduction of transmission system reactance, single-pole switching, generator tripping, controlled system separation and load shedding, etc [8]. It is obvious that the fast and accurate response of transmission line protection system, which can precisely recognize the disturbances and take correct actions, is the first and most important requirement.

3.4 Oscillations in Power Systems

Electro-mechanical oscillations between interconnected synchronous generators are phenomena inherent to power systems. These oscillations can be created by small disturbances in the system, such as changes in the load, and are normally analyzed through the small-signal stability (linear response) of the power system. These small disturbances lead to a steady increase or decrease in generator rotor angle caused by the lack of synchronizing torque, or to rotor oscillations of increasing amplitude due to a lack of sufficient damping torque. The most typical instability is the lack of a sufficient damping torque on the rotor's low frequency oscillations. Small-signal stability analytical tools aid in the identification and analysis of these oscillations. The stability of these oscillations is of vital concern, and is a prerequisite for secure system operation. For many years, the oscillations observed to be troublesome in power systems, were associated with a single generator, or a very closely connected group of units at a generating plant. Some low frequency unstable oscillations were also observed when large systems were connected by relatively weak tie lines, and special control methods were used to stabilize the interconnected system [9]. These low frequency modes were found to involve groups of generators, or generating plants, on one side of the tie oscillating against groups of generators on the other side of the tie.

Oscillations associated with a single generator or a single plant, are called **local modes**, or **plant modes**. Local modes normally have frequencies in the range 0.7 to 2.0 Hz. The characteristics of these oscillations are well understood. They may be studied adequately, and satisfactory solutions to stability problems developed, from a system which has detailed representation only in the vicinity of the plant [10].

Oscillations associated with groups of generators, or groups of plants, are called **inter-area modes**. Inter-area modes have frequencies in the range 0.1 to 0.8 Hz. When present in a power system, this type of oscillation limits the amount of power transfer on the tie-lines between the regions containing the groups of coherent generators. The characteristics of these modes of oscillation, and the factors influencing them, are not fully understood. They are far more complex to study, and to control. Generally, a detailed representation of the entire interconnected system is required to study inter-area modes [11].

In recent times, many instances of unstable oscillations, involving inter-area modes in large power systems, have been observed, both in studies and in practice [12, 13, and 14]**.** Such oscillations are increasingly becoming a cause of concern and the mitigation of these oscillations is commonly performed with power system stabilizers (PSS).

4 SIMULATIONS OF ZESCO NETWORK IN SIMPOW

4.1 Steady state analysis

Load flow analysis was carried out on the Zesco network to determine the steady state solution. The following assumptions were made:

- The load was modelled as constant power
- The interconnecting lines to neighbouring countries are disconnected
- The generators are operating with at least 30 percent stability margin
- There is spinning reserve on the generators

The network was created by writing a script in SIMPOW called an 'optpow' file. This file was used to generate the single line diagram shown in Fig 11. The detailed script is shown in appendix D.

The solved load flow case generated by SIMPOW is shown graphically on a single diagram in Fig 11. The detailed loadflow results are shown tabulated in appendix A.

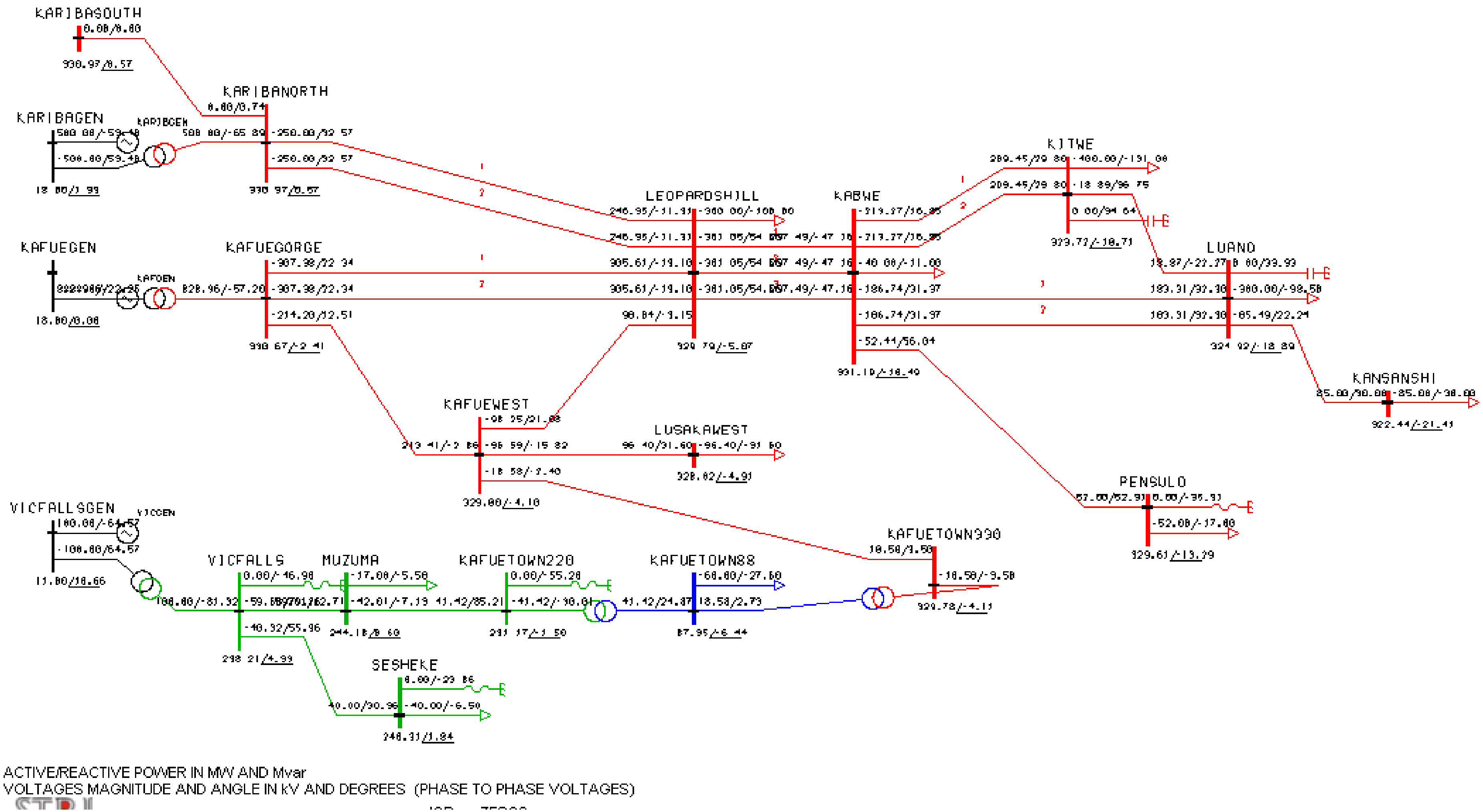
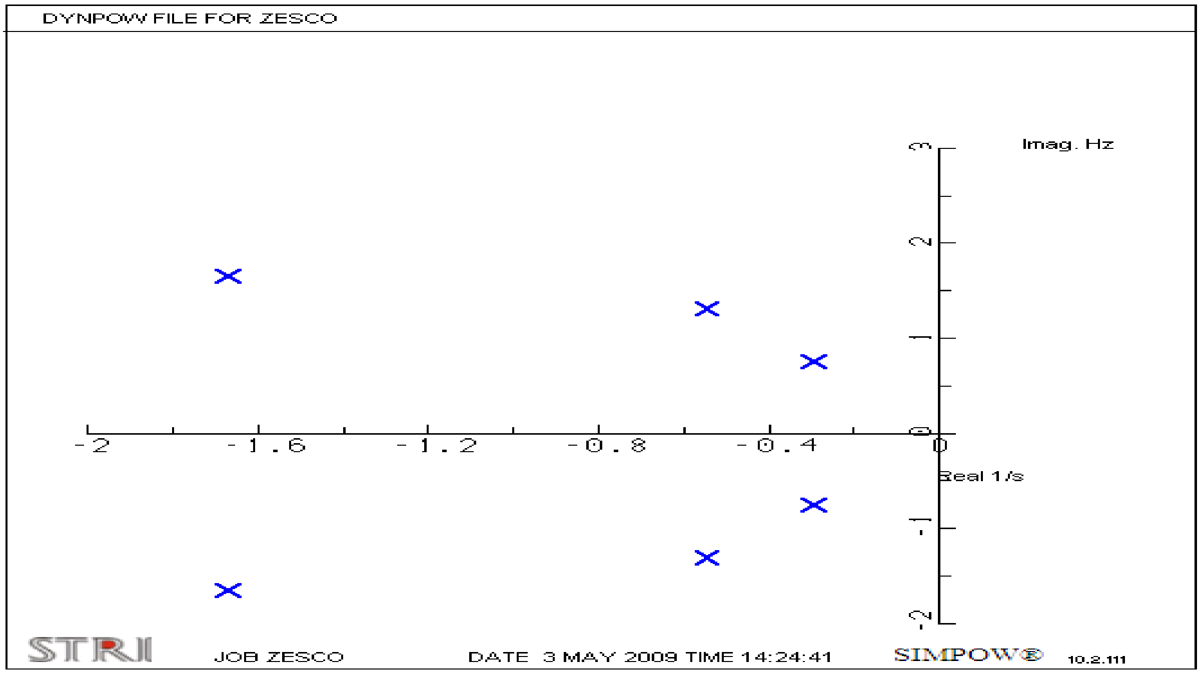


Fig 11 Zesco network showing voltages, currents, active and reactive powers

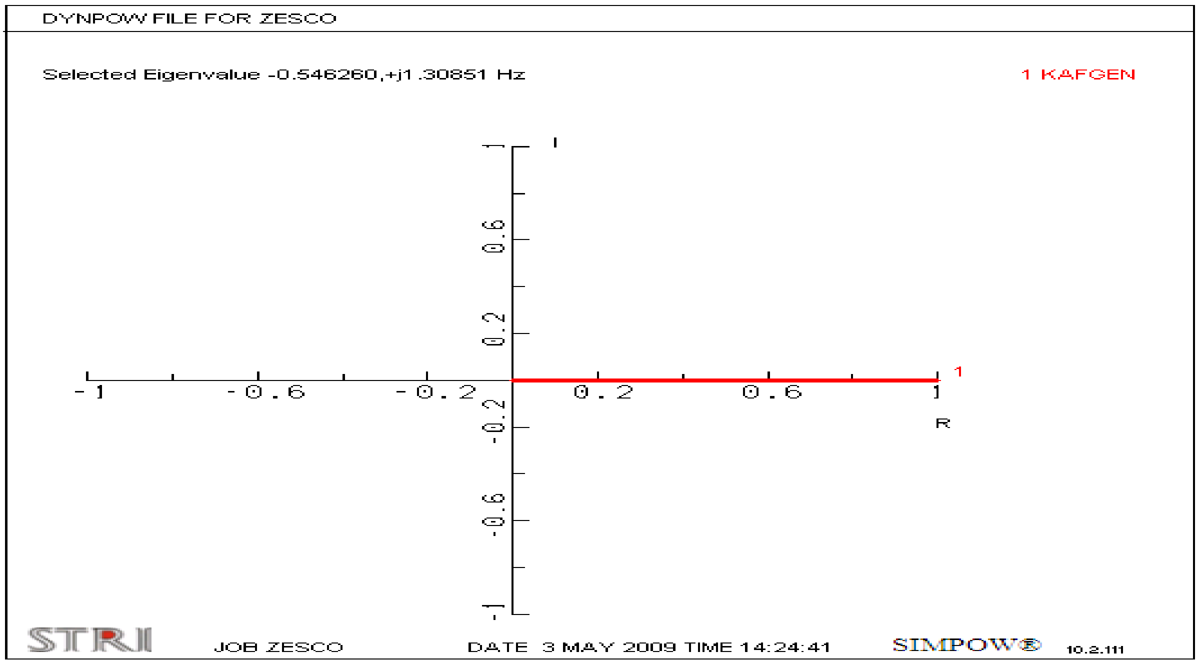
4.2 Dynamic Analysis

4.2.1 Eigenvalue and Modal Analysis

The Zesco transmission network shown in Fig 11 was analysed for eigenvalues at the operating point to determine the small signal stability at that point. Modal analysis which shows how synchronous generators feed a particular eigenvalue was also carried out. The results are shown in Fig 12 below.



(a)



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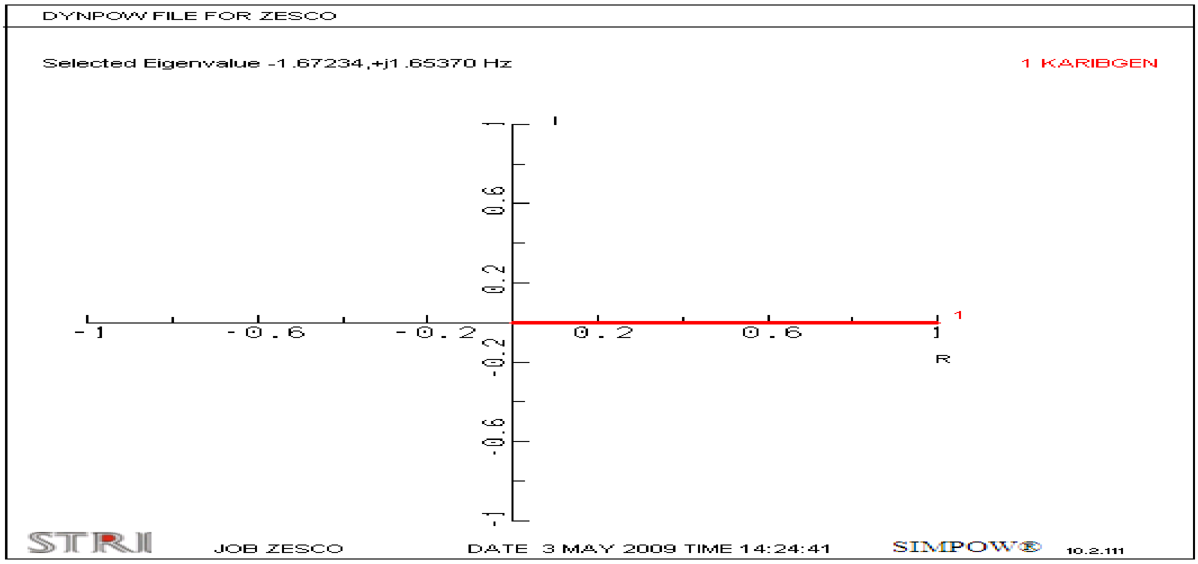
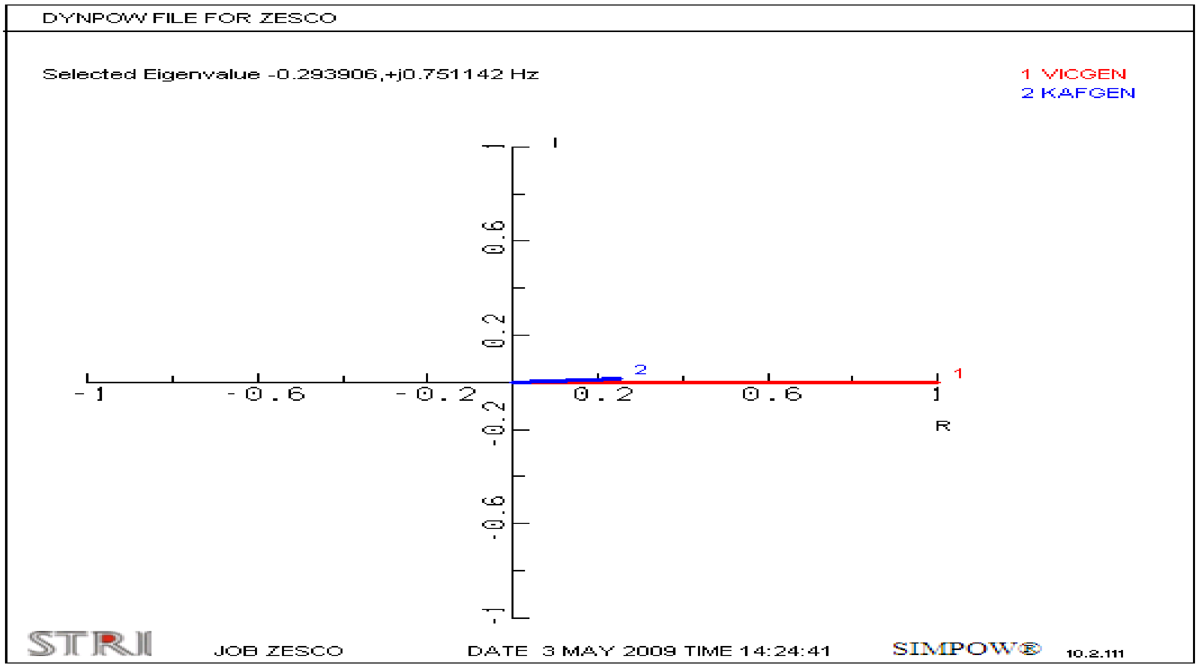


(c)



(d)

Fig 12 Plots of eigenvalues and mode shape

From Fig 12(a) we see that all the eigenvalues are located on the left hand side of the complex plane which is the requirement if the operating point is to be considered stable. It is clear from the figure that the operating point is stable against small perturbations. This means that when the system is subjected to a small disturbance the generators will oscillate with the following damped frequencies as shown in the table below

Table 1 Oscillation frequencies of generators

Generator name	Oscillation frequency(Hz)
Kafgen	1.30851
Karibgen	1.65370
Vicgen	0.751142

Next we consider the observability of the eigenvalues in relation to how the synchronous generators feed them. The table below summarizes the result.

Table 2 Observability of eigenvalues

Eigenvalue	Observability
-0.546260±j1.30851	Observed only in Kafue gorge generators (Kafgen)
-1.67234±j1.65370	Observed only in Kariba generators (Karibgen)
-0.293906±751142	Observed the most in Victoria Falls generators (Vicgen)

The results shown in the table can also be seen by looking at Fig 12 (b), (c) and (d). Note that in Fig 12 (d) the observability of Kafgen generators is very small.

4.2.2 Transient Stability

Transient stability analysis was carried out by simulating a three phase short circuit at selected buses which are considered critical to the Zesco system. The three selected critical buses are:

1) Kariba North
2) Leopards Hill
3) Kafue gorge

In each of these cases the duration of the fault was varied until stability was lost in some generators in the system. In some cases faulty components were disconnected and then reconnected. The transient behaviour of all the generators in the system as a result a fault at a particular bus was analysed. The interconnecting bus to neighbouring countries at Kariba South was selected as stiff bus and used as reference.

4.2.2.1 Case 1 : Three phase fault at Kariba North Bus without loss of stability

Using the 'dynpow' module in SIMPOW a three phase fault was applied at Kariba North bus at time t= 4.6seconds chosen arbitrarily. The fault was disconnected 0.1 seconds later together with one of the lines. The line was reconnected after a further 0.1 seconds. The transient behaviour of the generators as a result of this fault is depicted in the figures below.

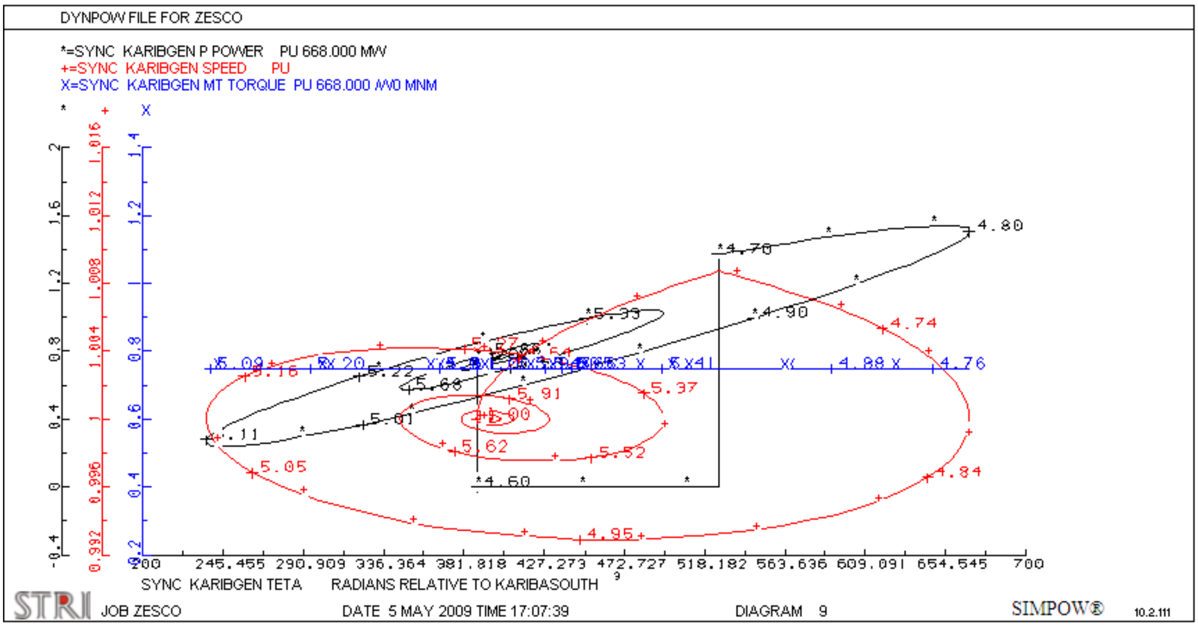


Fig 13 Variation of electrical power, mechanical torque and speed with power angle δ for generators at Kariba North

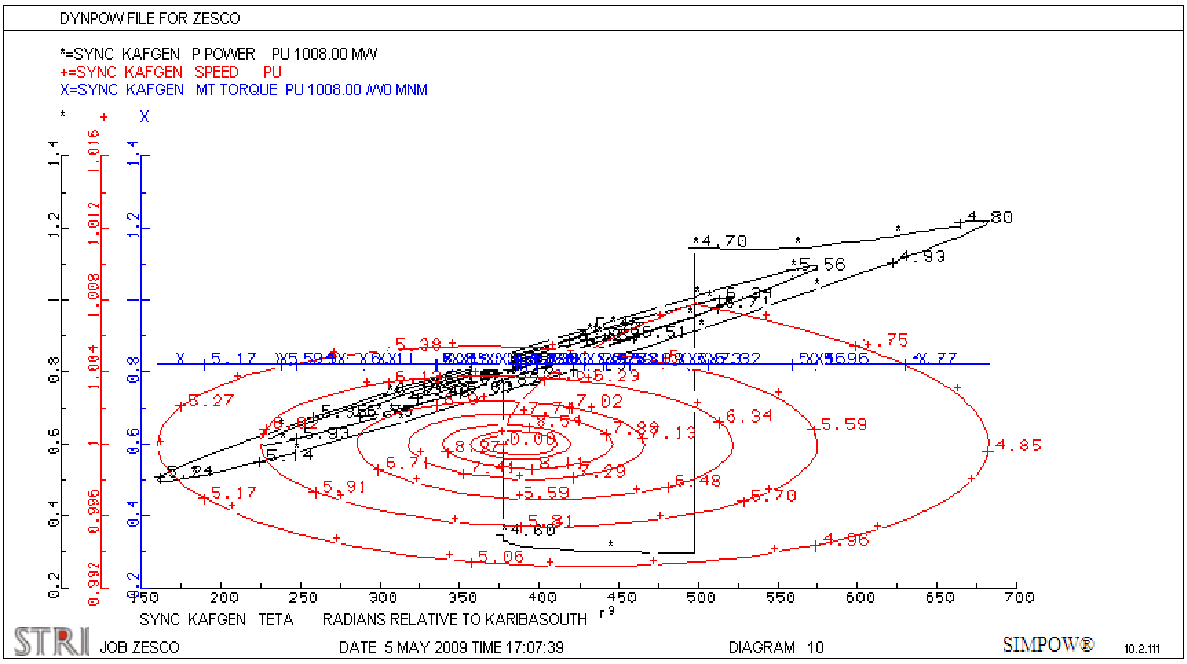


Fig 14 Variation of electrical power, mechanical torque and speed with power angle δ for generators at Kafue gorge

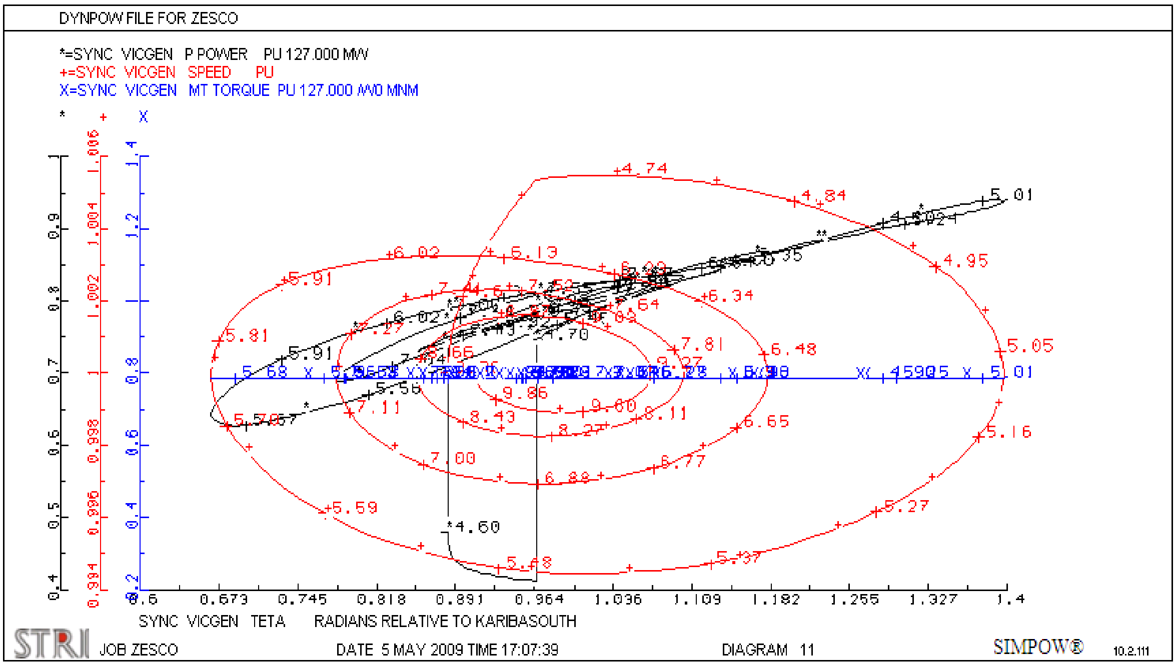


Fig 15 Variation of electrical power, mechanical torque and speed with power angle δ for generators at Victoria Falls

We see that with a three phase fault of duration 0.1 seconds all the generators regain synchronism and return to their original operating points after a fault is cleared and the line reconnected. We can therefore conclude that with a three phase fault lasting 0.1 seconds at Kariba North bus the generators are transiently stable. The mechanical torque is kept constant since the governors are assumed to be too slow act during this period.

The same behaviour can be viewed in the time domain as depicted in the figures below.

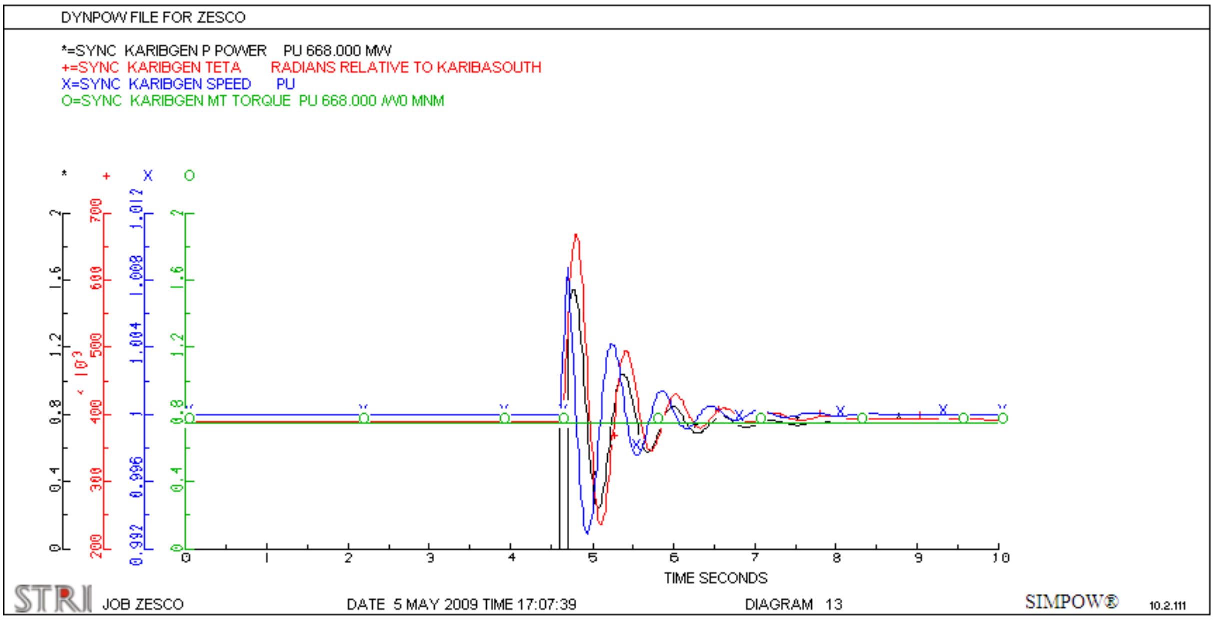


Fig 16 Variation of electrical power, mechanical torque, speed and power angle δ with time for generators at Kariba North

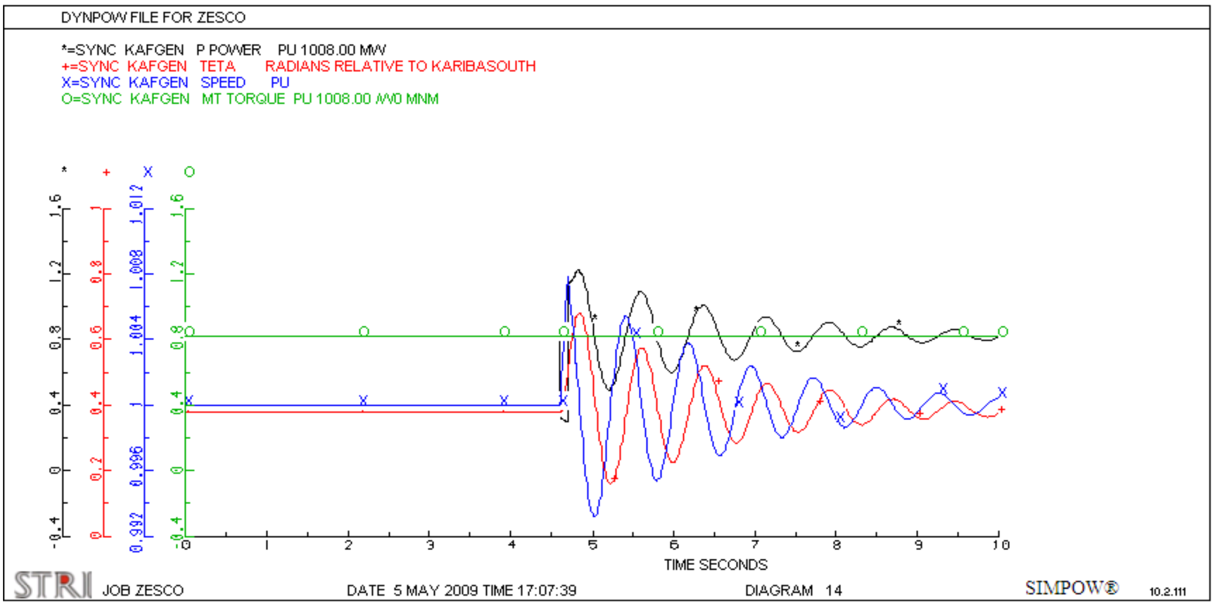


Fig 17 Variation of electrical power, mechanical torque, speed and power angle δ with time for generators at Kafue gorge

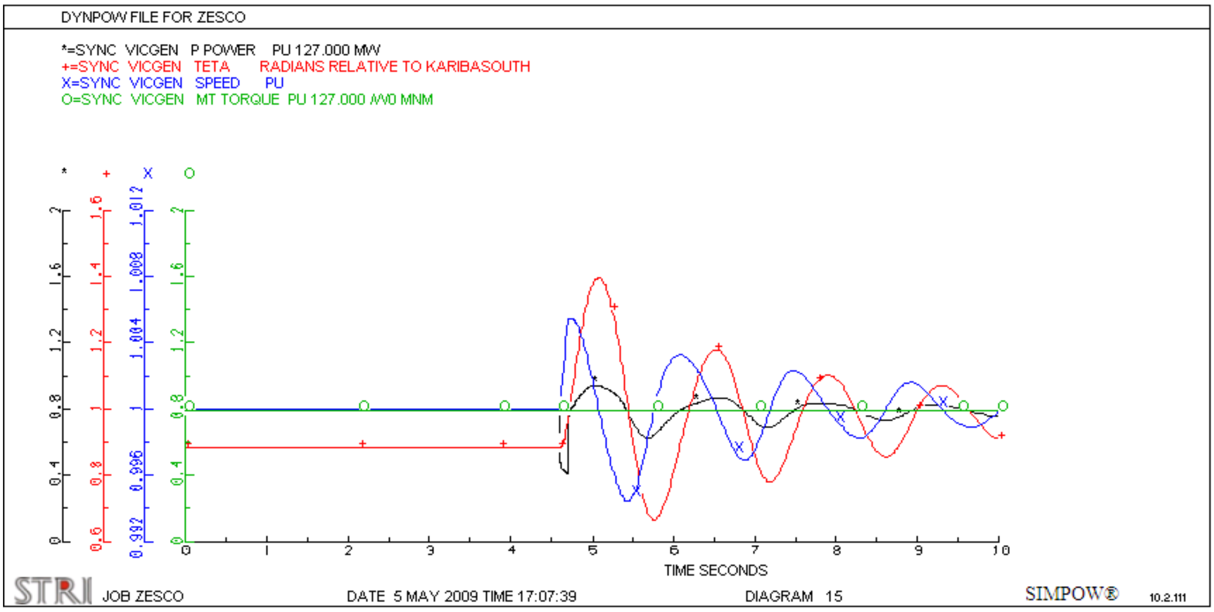


Fig 18 Variation of electrical power, mechanical torque, speed and power angle δ with time for generators at Victoria Falls

We observe that as time passes the electrical power tends to find a steady state value equal to the mechanical torque. Since the speed is in per unit the electrical power and the mechanical torque are the same when the speed is at 1pu. The results in the time domain are consistent with the fault scenario. Note that during the 0.1 seconds when the fault is present, electrical power is depressed to a smaller value and increases instantaneously to a higher value after the fault is cleared. In this particular situation it is important to note that the system topology is restored to its original state after occurrence of the fault. This means that the steady state values for electrical power, speed, and power angle will be the same as before.

4.2.2.2 Case 1A : Three phase fault at Kariba North Bus with loss of stability

The duration of the fault was extended to 200 milliseconds and a simulation repeated. From the results it is seen that the generators at Victoria Falls power station lost synchronism while those from Kariba North and Kafue gorge restored synchronism after the fault was cleared and line reconnected. The transient behaviour of the generators at Kariba North and Kafue gorge are almost the same as that shown in Fig 13 and Fig 14 above and will not be shown. However, for the generators at Victoria Falls power station the transient behaviour is depicted in the figures below.

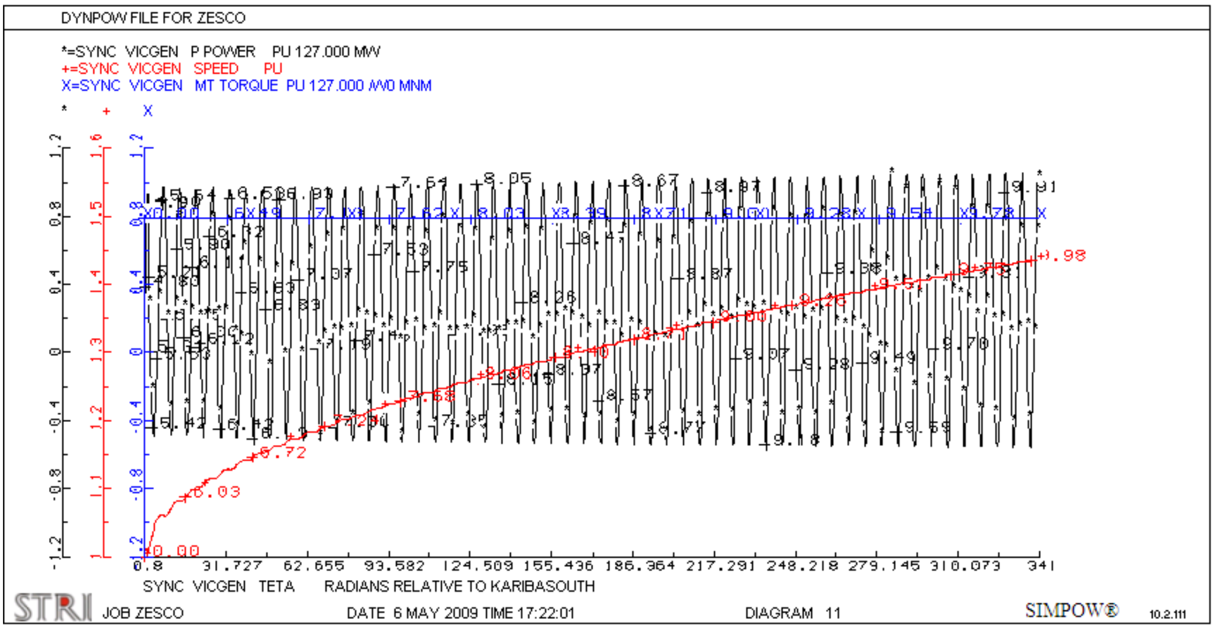


Fig 19 Transient behaviour of Victoria Falls generators as a function of power angle

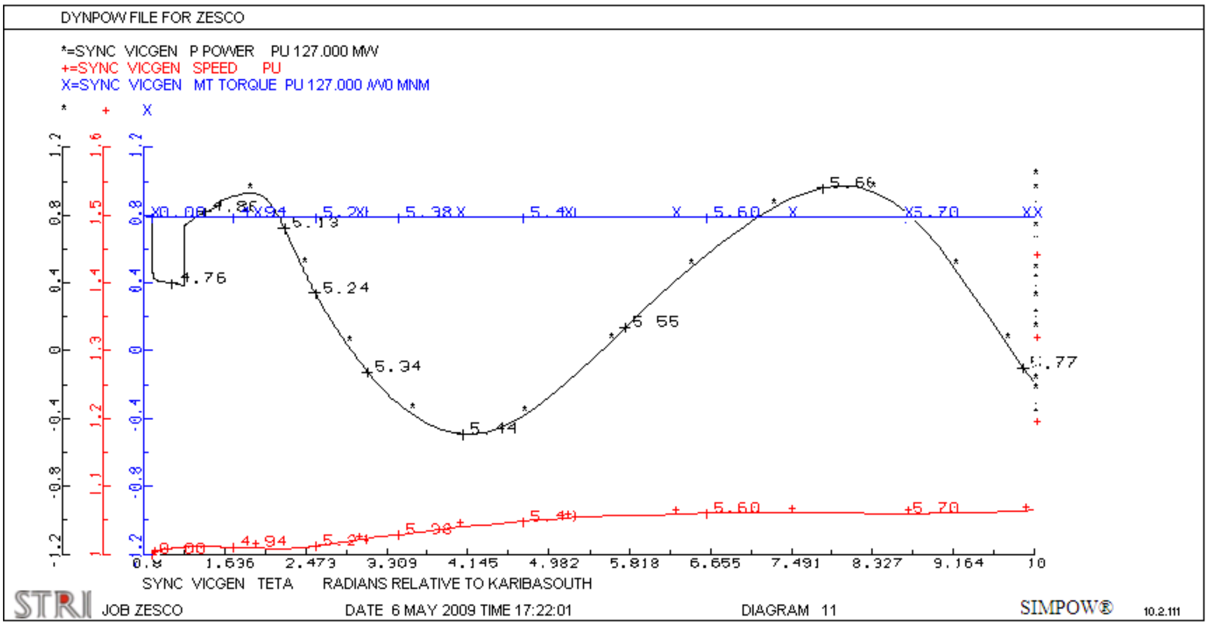


Fig 20 Detailed view of power/angle characteristic

From the Fig 20 above we see that at the time the fault was cleared the available electrical power was less than the mechanical power resulting in continued acceleration of the rotor. We also see from the plot that the acceleration area is greater than the available deceleration area and from the equal area criterion the generator will not find a stable point.

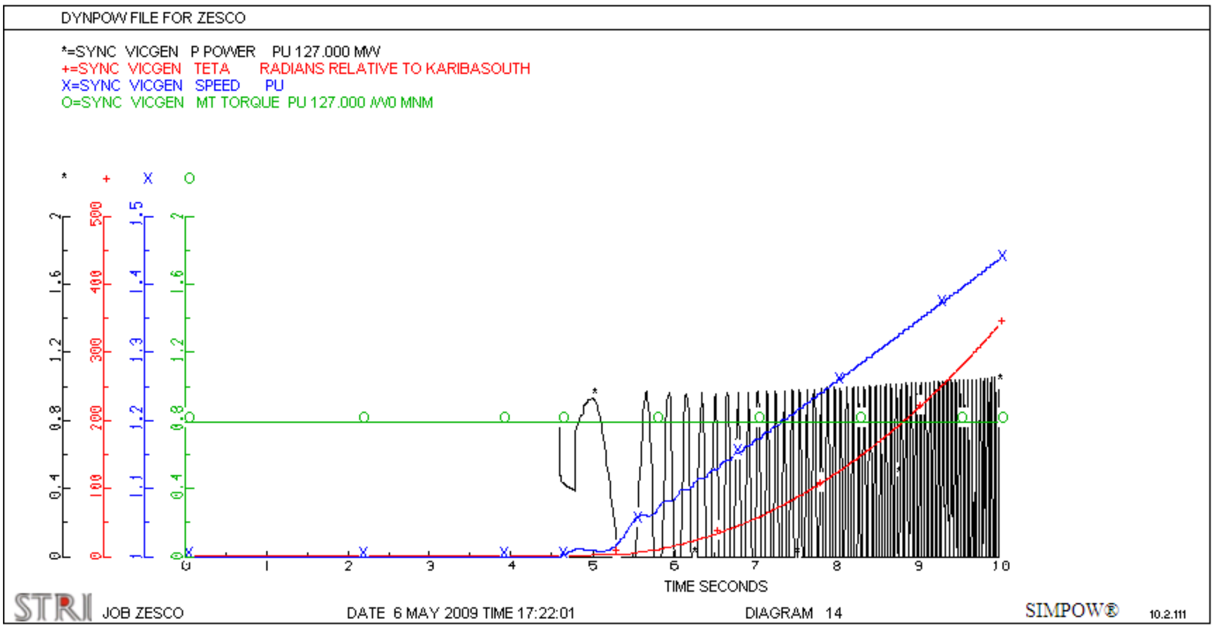


Fig 21 Transient behaviour in time domain

If we view the results in time domain from Fig 21 it is quite clear what is happening. Observe that at t=4.6 seconds when the fault is applied the electrical power is depressed and after 200 milliseconds when the fault is cleared the electrical power oscillates and cannot find a stable operating point. Correspondingly the power angle and speed also increase. This is an indication of loss of synchronism and unless protection acts quickly the generator can be damaged. Note that the mechanical torque is kept constant during the simulation.

It can be concluded from the simulation that for a three phase fault at Kariba North lasting 200 milliseconds or longer the generators at Victoria Falls power station will fall out of synchronism. So the critical clearing time for conditions described above should be less than 200 milliseconds. This guarantees that the generators remain in synchronism after an external fault. The exact critical clearing time depends largely on the system loading level; the nature of fault and the changes in network topology after the fault is cleared.

Next we move the fault to Leopards Hill and then Kafue gorge buses and apply the simulation as described in section 4.2.2. The results of the simulation are shown in appendix B

5 CONTINGENCY ANALYSIS

5.1 Introduction

Power systems are planned and operated so that the most probable and critical contingencies can be sustained without an interruption or a quality reduction. The power system should be able to continue its operation despite sudden outage of a production unit, transmission line, transformer, compensation device, etc. Outages of power system equipment are typically due to faults (short circuits and earth faults), overloads, malfunctions (false settings or operation actions) or breakdown of equipment. The occurrence of disturbances cannot be predicted, thus the security of the power system needs to be guaranteed beforehand.

The security of the power system is commonly defined based on (*n-1*) criteria i.e. the system should withstand any single contingency. A system consisting of *n* components should be able to operate with any combination of *n-1* components, thus for any single component outage. This criterion plays an important role in preventing major disturbances following severe contingencies. The use of criteria ensures that the system will at worst, transit from the normal state to the alert state. The probability of *n-2* contingency increases e.g. when the weather is bad and the two transmission circuits are placed on the same towers, or when a generator may be relayed out due to a line outage.

The security analysis is required to guarantee the power system's secure operation in all conditions and at all operation points. The purpose of power system planning is to ensure power system adequacy. The analysis is based on forecast cases. Online security assessment is needed in the power system operation to guarantee security momentarily, because not all possible future scenarios can be checked beforehand. The purpose of power system operation is to guarantee that a single disturbance cannot cause cascading outages and finally a total blackout.

5.2 Operating States of a Power System

The operating condition of a power system may be classified as: (i) normal, (ii) emergency and (iii) restorative. The normal state is one, in which the total demand on the system is met by satisfying all the operating constraints. Contingencies, such as the outage of a generating unit, short circuit and subsequent tripping of a line, loss of a transformer, etc. can lead to two types of emergency conditions [16], [17]. In the first type, the system remains stable but operates with the violation of some of the operating constraints. Thus, while the consumer's demand is met, an abnormal voltage and frequency condition may arise; loading limits of some lines and equipment may be violated, and so on. This type of emergency can be tolerated for a certain period. In the second type, the power system becomes unstable and hence the loads cannot be fully supplied. The second type of emergency thus causes a violation of both the loading and the operating constraints, and unless corrective action is taken immediately, the system faces the risk of a total shutdown. In the restorative state, corrective action is taken so that the system goes back either to new normal state or to the previous normal state. This state is characterized by the interruption of the consumer's demand, bringing into operation of rapid-start units. The above states and their mode of transition are shown in Fig 22.

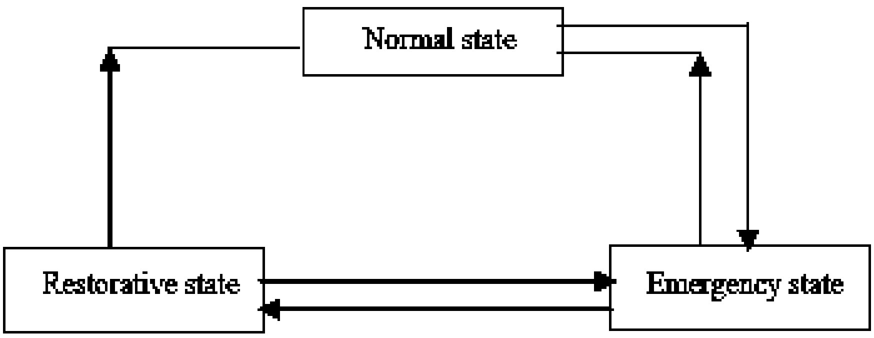


Fig 22 Three states of operation

5.3 System state at peak loading

The single line diagram of Zesco network is shown in Fig 23. Prior to implementing a contingency the load flow was run in NETBAS in order to determine the voltages and currents in the network at peak loading. A summary of the results is shown in the tables below.

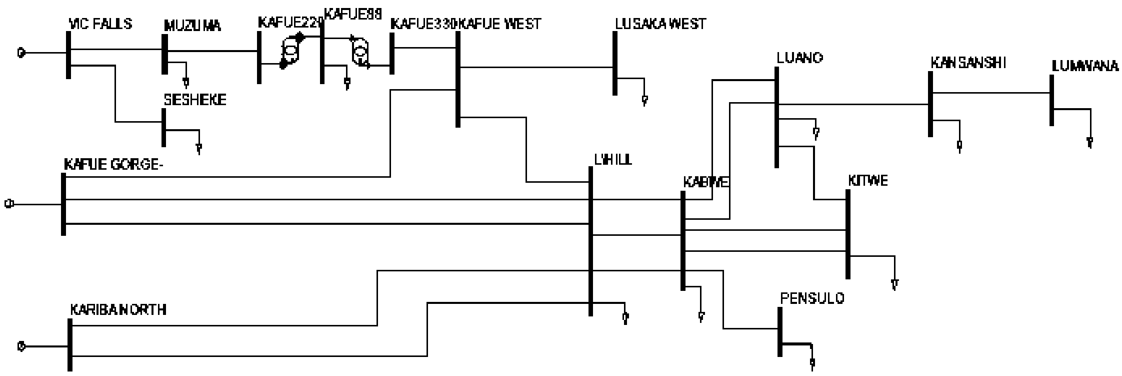


Fig 23 The 330kV Zesco network

Table 3 Voltage result of peak operating conditions 330kV system

Bus ID	Bus name	Bus operating voltage (kV)
1	Kafue Gorge	330
2	Leopards Hill	338.3
3	Kariba North	330
4	Kafue Town (330)	333.2
5	Kafue West	333.3
6	Kabwe	353.7
7	Kitwe	343.4
8	Luano	347.2
9	Pensulo	361.9
10	Kansanshi	362

Table 4 Voltage result of peak operating conditions 220kV system

Bus ID	Bus name	Bus operating voltage (kV)
1	Vic Falls	220
2	Muzuma	226
3	Sesheke	228.8
4	Kafue Town 220	219.5

Table 5 Current result of peak operating conditions

No	Bus name	Transmission operating current(A)
1	Kafue Gorge - Leopards Hill No1	519
2	Kafue Gorge - Leopards Hill No2	867
3	Kafue Gorge – Kafue West	545
4	Leopards Hill – Kabwe No1	675
5	Leopards Hill – Kabwe No 2	675
6	Leopards Hill – Kabwe No 3	675
7	Kariba North - Leopards Hill No1	437
8	Kariba North - Leopards Hill No2	437
9	Vic Falls - Muzuma	214
10	Muzuma – Kafue Town 220	128
11	Kafue West - Leopards Hill	359
12	Kabwe – Kitwe No1	400
13	Kabwe – Kitwe No2	400
14	Kitwe - Luano	193
15	Kabwe – Luano No1	379
16	Kabwe – Luano No 2	383

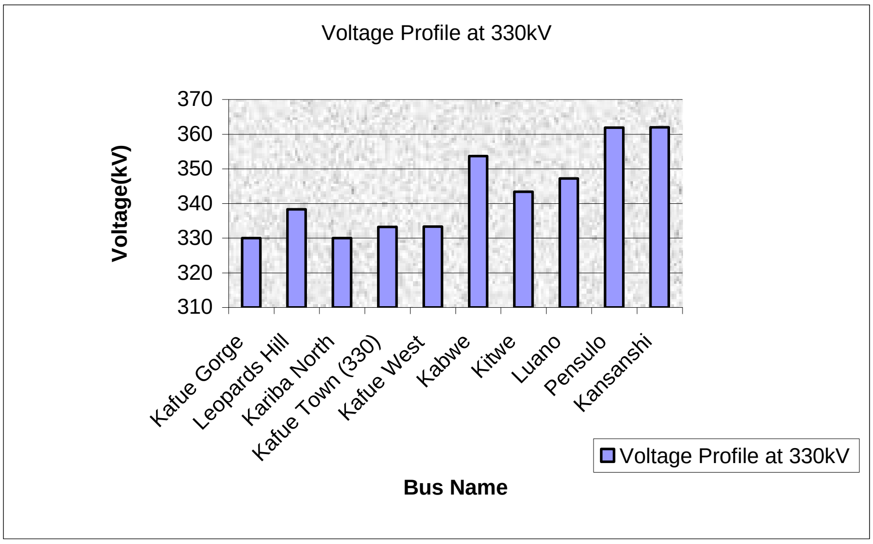


Fig 24 Voltage profile at 330kV

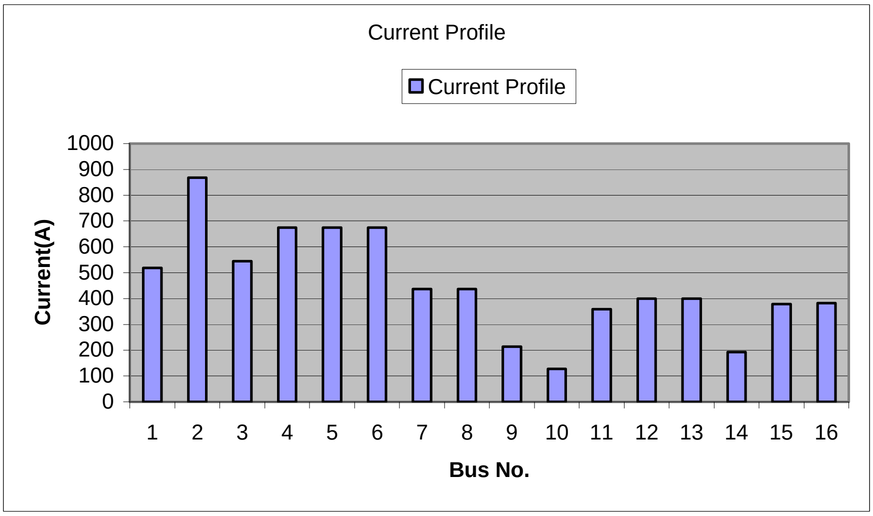


Fig 25 Profile of current distribution (Bus No. according to Table 5)

5.3.1 Implementation of contingencies in NETBAS

Contingency analysis means that the consequences of line sections and transformers sections falling out (not three winding transformers) are examined. All contingencies are simple contingencies, where the consequence of components falling out one by one (N-1) is examined. For every contingency, a load flow is run and voltage problems as well as overload are checked. A check is also carried out to see if the contingency results in the network being divided into two separate parts, i.e. islands. If this happens, NETBAS examines whether there is enough power available to operate the two different network parts separately. If there is not enough available power, NETBAS considers this part to be “lost”; i.e. it loses the supply. If the load flow does not converge for either the whole network or for one of the network islands, NETBAS also considers the network "lost". The situation where contingency in one section results in another contingency, is disregarded. If double contingencies is to be looked at, this can be carried out by taking out first one section and running a load flow with this section out, before starting contingency analysis.

5.3.2 Applying a contingency on Zesco Network

The Zesco network was uploaded in NETBAS so that contingency analysis could be carried out. Using a 'contingency analysis module' found in NETBAS, the program was able to identify all the possible contingencies and then applied a single contingency one at a time. The summary for the most critical ones are shown in the table below. A detailed report for all the contingencies is given in appendix C.

Table 6 Contingency ranking according to NETBAS

```
Data set : netbus. Year of calculation 2009.
 -------------------------------------------------------------


 No of contingencies :   23     0
 lines               :   21     0
 transformers        :    2     0

 Summary from Contingency Analysis


       Lines ranked after contingency problems
        ........ Name ...........       invalid   Volt.  Exceed    Interr.
        From       -  To        split  Mainpart.  diff.   load.     power
 -----------------------------------------------------------------------------
    1  VIC FALLS    - SESHEKE       X        ---     0     5
    2  KAFUE WEST   - LUSAKA WEST   X        ---     1     3
    3  KABWE        - PENSULO       X        ---     0     3
    4  LUANO        - KANSANSHI     X        ---     0     3
    5  KAFUE330     - KAFUE WEST    X        ***     7     1
    6  L\HILL       - KABWE                          0     5       5.806 *
    7  L\HILL       - KABWE                          0     5       5.806 *
    8  L\HILL       - KABWE                          0     5       5.806 *
    9  KAFUE GORGE- - L\HILL                         0     5       5.305 *
   10  KAFUE GORGE- - L\HILL                         7     4       4.465 *
   11  KABWE        - KITWE                          0     4      11.458 *
   12  KABWE        - KITWE                          0     4      11.458 *
   13  KARIBA NORTH - L\HILL                         0     4       4.027 *
   14  KARIBA NORTH - L\HILL                         0     4       4.027 *
   15  KAFUE GORGE- - KAFUE WEST                     0     4       3.326 *
   16  KABWE        - LUANO                          2     3       9.844 *
   17  KABWE        - LUANO                          0     3      10.337 *
   18  KAFUE WEST   - L\HILL                         0     3       0.960 *
   19  LUANO        - KITWE                          0     3       0.714 *
```

As seen from Table 6 the contingencies marked with X are considered 'lost' as outlined in section 5.3.1. These contingencies should be disregarded. NETBAS sorts the contingencies with the most critical ones coming first. We note from Table 6 that outage of Leopards Hill – Kabwe lines and Kafue gorge – Leopards Hill lines at peak load would result in 5 sections of the network being overloaded. This is followed by Kariba –Leopards Hill lines and Kabwe – Kitwe lines. Note that outage of power transformers have very little effect on the system. This is because they connect a smaller power station to the rest of the system. When this contingency occurs, it results in the network being split into two separate 'islands' each capable of supplying its own load.

Generators outages are not considered here for two main reasons

1) The contingency analysis module in NETBAS does not support generator outage. See section 5.3.1.
2) The occurrence of entire power station outage is rare. Only sections of it may be taken out for scheduled maintenance. Note that the generators shown in Fig 11 are lumped. This means a single equivalent generator representing a group of actual generators.

6 TRANSMISSION LINE PROTECTION

6.1 General

The protective relay system, which is shown in the zoomed area in Fig 1, is the most important component in the power system to preserve the reliability of system operation. It detects the faults using its fault diagnosis mechanism and removes the faulted component by its associated circuit breaker action in a short time to avoid damage of the system equipment. The protection system for transmission lines is very important since the transmission lines are mostly extended across large geographic area to carry the power from sources to loads. They can easily experience a fault due to the lightning that causes loss of insulation. The performance of protection system is measured by several criteria including reliability, selectivity, speed of operation, etc. [18, 22]. Reliability has two aspects: dependability and security [23]. Dependability is defined as *"the degree of certainty that a relay system will operate correctly when there is a fault on the system"*. Security, "*relates to the degree of certainty that a relay or relay system will not operate incorrectly when there is no fault on the system"* [22]. For a weakened system that already lost several components, loss of reliability due to the relay mal-operation will have a large impact on the system that may contribute to the cascading blackout. There are two kinds of relay unintended operations:

- Relay fails to operate. This situation is relative rare. But it is very harmful to the system stability when it happens. Even though the fault is cleared by the backup relays in a delayed time, there are healthy components removed from the system. This can result in more power flow surges, overloads, and voltage problems for a weakened system.
- Relay operates in a non-fault situation. This situation is more common in most of blackouts involving the distance relay's unintended operations. For example, the relays may observe a low voltage and a high current, at the time during the overload, power swing or low voltage. Trip of the healthy components will also result in more power flow surges, overloads, and voltage problems for a weakened system. The event may unfold and spread out.

Each transmission line protective relay (distance relay) has its own designated area known as primary zone, and usually it still has the opportunity to operate in overreached zones to provide backup protection to an adjacent transmission line section. To ensure the selectivity of transmission line protection systems, the relays need to be coordinated with the backup relays to operate only when the primary relay fails to clear the fault. Hence, selectivity is important to assure maximum service continuity and minimum system disconnection. The speed of operation indicates how fast the relay can isolate a faulted area. Usually for transmission line protection, the high-speed relay is one that operates in less than 20 milliseconds. Not in all situations the very high-speed operation is preferred. The relay must have the ability to differentiate fault and other tolerable transients very well before issuing high-speed operation. The most commonly used scheme for transmission line protection is the distance relay. The basic principle is shown in Fig 26. The voltage and current measured through voltage transformer (VT or PT) and current transformer (CT) are the inputs for protective relays. The distance relay algorithm is trying to extract the fundamental

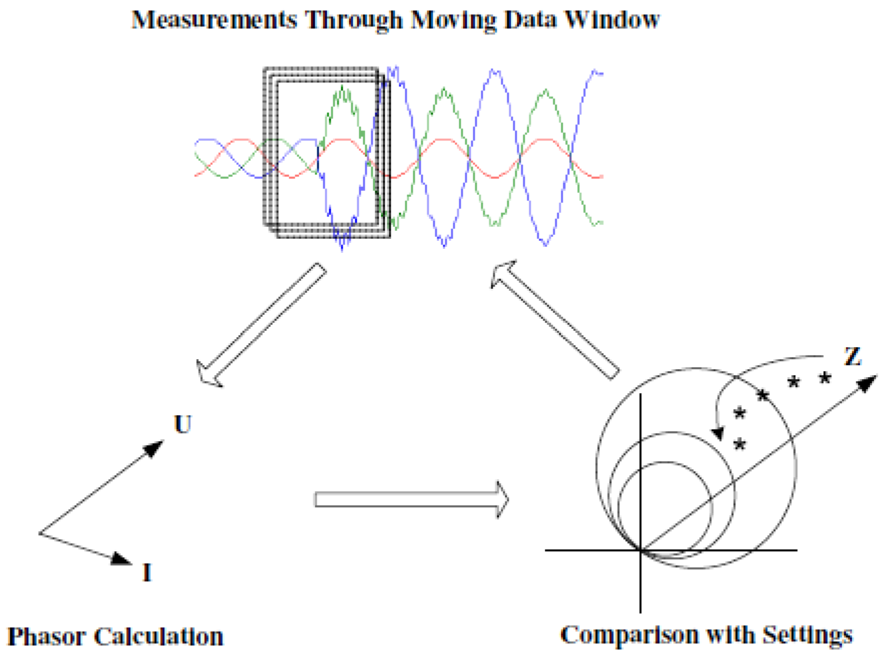


Fig 26 Basic principle of distance relay

frequency phasor of voltage and current signals. Then through the calculation of certain nonlinear ratio of voltage and current phasors, the apparent impedance seen by the relay is obtained and compared to the preset thresholds. If the impedance falls into the protected zones, the relay will assume a fault occurred and will send a trip signal to the circuit breaker on the transmission line to disconnect the faulted line. Once triggered, the impedance calculation is continuously iterated using the moving data window. The relay algorithm is fixed by design. When the relay is installed in the system, the most important task is to determine the thresholds (settings). The settings are obtained by comprehensive short-circuit system studies in a predefined system operating condition. To ensure the protection system maintains dependability when protecting the equipment as fast as possible, a backup scheme is provided for each relay.

The distance relay principle is straightforward and usually performs reliably. That is the reason why this principle is still dominantly used in the industry, although the relay hardware has advanced through the technologies of electromechanical, solid state, and microprocessor.

6.2 Types of Transmission Line Relays

In general, the transmission line faults are associated with increased currents and decreased voltages. Other changes of the AC quantities in one of the following parameters may also occur: phase angles of current and voltage phasors, harmonic components, active and reactive power, frequency of the power system, etc [18]. Those parameters can be the inputs of the relays to detect the faults. The operating principles of the relays in use on transmission lines may be classified as follows [18, 19]:

- **Magnitude Relays**: These relays are based on the comparison of the magnitude of one or more operating quantities to the threshold. For example, the over-current relay responds to the changes in the magnitude of the input current. The load-shedding relay responds to the changes of the system frequency.
- **Directional Relays**: These relays are based on the comparison of the phase angle between two AC inputs. The comparison can be based on current phasor and voltage phasor, and also on current phasor and another current phasor.
- **Ratio Relays**: These relays are based on the comparison of the ratio of two phasors to the thresholds. The ratio of two phasors are complex number, therefore the threshold should be set in a complex plane. A typical example of a ratio relay is the distance relay.
- **Differential Relays**: These relays are based on the algebraic sum of two or more inputs. In a general form, those inputs may be the currents entering (or leaving) a specific protection zone. According to the Kirchhoff's law, the algebraic sum should be close to zero when there is no internal fault and should be a big value when there is an internal fault.
- **Pilot Relays**: These relays are based on the communicated information obtained from the two ends of a transmission line. The decisions made by a local relay and by a remote end relay are combined to form the final decisions. The inside principle of each relay could be any of the four types described above.

When applied to the transmission line protection, the above principles can be further classified into two broad categories: a) non-unit protection scheme and b) unit protection scheme. The non-unit protection scheme uses data from one end of a transmission line while the unit protection scheme usually uses data from two or more ends. For non-unit schemes such as over-current relay and distance relay, they can not protect very accurately the entire length of the primary line because they can not differentiate the internal faults from external faults occurring around the line boundaries due to the imperfections caused by measuring errors, transformation errors, the inaccuracy of the line impedance, source and load changes, different fault parameters, etc. Backup protection needs to be introduced as a trade-off for protecting the entire length of the transmission line. Unit protection schemes such as differential relays and pilot relays can protect the entire length of the transmission line. They require a communication link to transmit the blocking or transfer tripping signals. Therefore, the reliability of the unit protection scheme highly depends on the reliability of the communication link. The cost of the communication link also needs to be taken into account.

The primary goal of transmission line protection, whatever the principle it uses, is to rapidly and precisely detect the fault and disconnect the faulted component. If possible, it should also differentiate the internal faults from external faults so that only the faulted line is removed; provide the exact fault type selection so that advanced tripping and reclosing schemes (single pole tripping and reclosing) can be applied; locate the precise fault position on the transmission line so that the line can be repaired and restored quickly.

6.3 Distance Relay

Distance relay protection is the most common type used for multi-terminal transmission lines [18, 20, and 21]. As implied by its name, it calculates the impedance between the relay location and the fault location. The impedance is calculated through the measured voltage and current signals at the relay location. If the measured fault impedance is smaller than the line impedance, the relay will assume that an internal fault has occurred on the transmission line. Since the impedance per kilometre of a transmission line is a relatively constant parameter, the distance relay hence responds to the computed impedance that corresponds to the distance between the relay location and the fault location.

6.3.1 Relay Coordination Scheme

Due to the imperfections in the distance relay measurement caused by measuring errors, transformation errors, the inaccuracy of the line impedance, source and load changes, different fault parameters, etc, the distance relay may not be able to always protect the entire line length using only one end of measured data. A coordinated protection scheme using distance relays is applied today. As shown in Fig 27, the scheme is described for the relay at position “1” (relay 1). For relay 1, the security margin of 10-15% should be selected from the remote end (Bus B) to be absolutely sure that the relay 1 will not overreach to the next line in some situations. Hence the first zone (Zone 1) of relay 1 is set to reach 85-90% of the line length A-B. If fault is found within Zone 1 of the distance relay, the trip signal will be sent to the circuit breaker instantaneously or with a very small time delay t1. The rest of the line A-B will be covered by an overreaching zone (Zone 2). The reach of the second zone is usually set at 120-150% of the line length A-B. If the adjacent line B-C has quite different impedance characteristics, Zone 2 can be also set as the line length of A-B plus 20-50% of the line length B-C [20]. A timer t2, usually 0.3-0.5 seconds, should

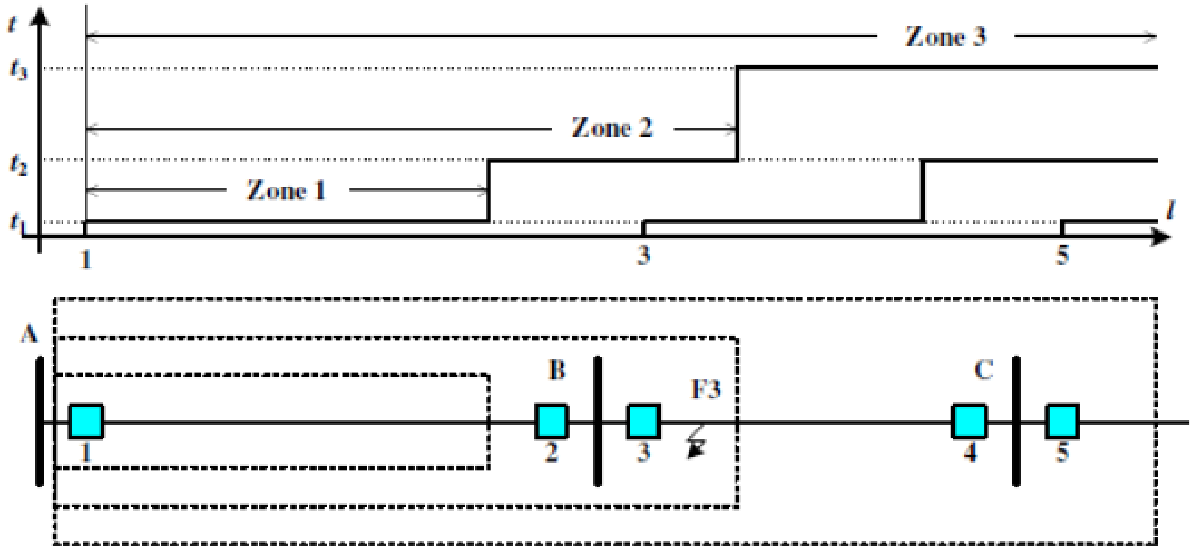


Fig 27 Relay coordination scheme

be set for Zone 2 to ensure that relay 1 is delayed to allow relay 3 to trip the fault at F3. Relay 1 must provide enough time for relay 3 to respond the fault in its Zone 1 before relay 1 sends the trip signal. The Zone 2 of relay 1 will also provide a backup function for the relay 3 since it overreaches to the line B-C. However, it is only true for part of the line B-C because Zone 2 of relay 1 can not reach beyond Zone 1 of relay 3 to ensure the similar selectivity mentioned above. Another zone (Zone 3) is used to provide the backup function for the entire line length of line B-C. Zone 3 of relay 1 is usually extended to the 250% of the line length of line A-B and the timer t3 for its delayed action is set for a delay in the order of 1 second. Similarly, the step distance settings for other relays in the system will follow the same principle. It should be noted that in this example only the typical system configuration is considered. In reality, the settings must be calculated and coordinated by a comprehensive short circuit study for more complicated network structures [20]. Such a tedious work may result in incorrect settings due to the human error or improper settings due to lack of consideration of unusual system operating conditions. The relay settings may play a significant role in different stages of cascading blackouts [2].

6.3.2 R-X Diagram

Since the distance relay respond to the impedance measurements, it is common to use an R-X diagram to analyze and demonstrate the behaviour of the distance relay. Consider an R-X diagram matching an ideal simple system shown in Fig 28. The origin of the R-X plane is the relay location. The axis R corresponds to the real part of the impedance Z, while the axis X corresponds to the imaginary part of the impedance Z. The apparent impedance at the relay location is calculated by the quotient of the measured secondary voltage and current phasors.

$$Z_a = \frac{V_s}{I_s} \tag{6.1}$$

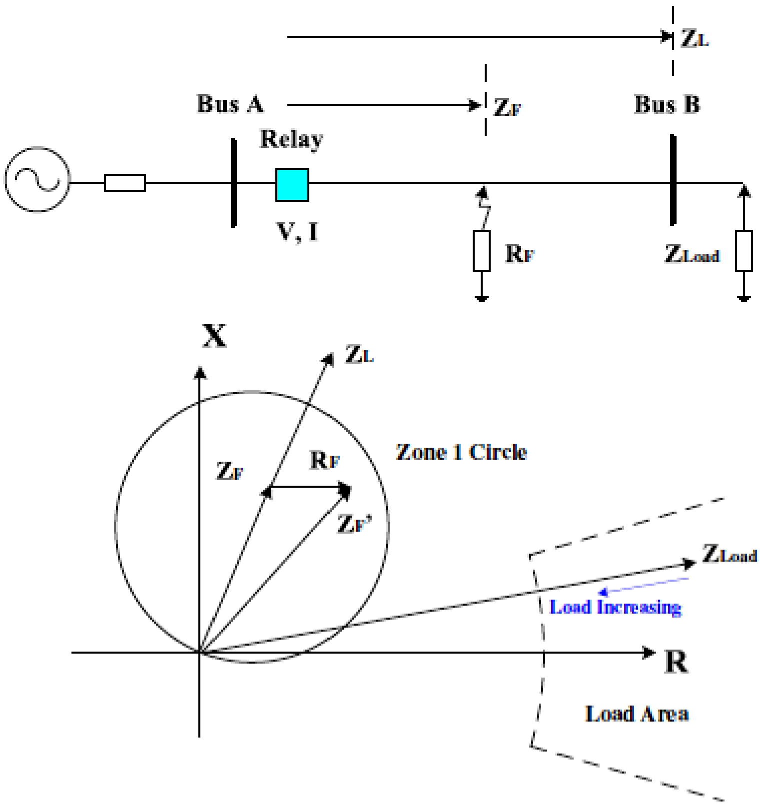


Fig 28 The R-X diagram

During the normal condition, the measured apparent impedance is close to the load impedance since $Z_L \ll Z_{Load}$. The load area shown in Fig 28 is far from the relay settings. When fault occurs, the apparent impedance seen by relay will change to $\vec{Z}_f^{'} = \vec{Z}_f + R_f$ where Z_f is the line impedance from the relay location to the fault location and R_f is the fault resistance. Since $R_f \ll Z_{Load}$, the line section behind the fault location as well as the load impedance can be neglected according to the circuit theory. As shown in Fig 26, the impedance during the fault will flow into the relay setting area. Due to the transient phenomenon during the fault, the impedance will not jump instantaneously from Z_{Load} to $Z_f^{'}$. In R-X plane, it will move step by step to $Z_f^{'}$ until the transient is gone after about one cycle. From the R-X diagram, it is not difficult to conclude that the performance of the distance relay will depend on the fault resistance. The fault resistance is a random value that may be influenced by the electrical arc between two phases of the transmission lines or between one phase and a grounded object. The magnitude varies with respect to the fault type, fault location, and fault inception time. Besides the fault resistance, the pre-fault load condition will also play a role for the distance relay performance. If the load is too high, it may float to the relay setting area, especially for the backup settings in Zone 2 and Zone 3. In that case, the relay may operate in the overload situation thinking that it is a real fault. When some of the healthy lines are removed from the system, the power flows in those lines are re-dispatched to the other lines. Similar overload situations will cause more healthy lines being tripped by the relays and unfolding cascades may start.

6.3.3 Three Phase Distance Relay

The previous illustration is based on a single phase system. On a three-phase power system, the apparent impedance can not be calculated using (6.1) directly. There are 11 different fault types in three-phase systems, which are single-phase-to-ground faults (A-G, B-G, C-G), phase-to-phase faults (A-B, B-C, C-A), phase-to-phase-to-ground faults (A-B-G, B-C-G, C-A-G), three-phase fault (ABC) and three-phase-to-ground fault (ABC-G) [18]. For different fault type, a symmetrical component analysis may be used to obtain the relationship between voltages and currents measured at the relay location [21, 24]. It is known that regardless of the fault type, distance relay is able to measure the positive sequence impedance from relay location and fault location in a three phase system [18]. Therefore, the relay settings can be calculated based on the total positive sequence impedance of the transmission line regardless of the fault type.

Consider the system shown in Fig 28 as a three-phase system and the fault as a B-C fault. The symmetrical network connection for this fault is shown in Fig 29, where the subscript “1” corresponds to positive network components and subscript “2” corresponds to negative network components. We can observe that

$$\vec{V}_{1F} = \vec{V}_{2F} = \vec{V}_1 - \vec{Z}_{1F}\vec{I}_1 = \vec{V}_2 - \vec{Z}_{2F}\vec{I}_2 \tag{6.2}$$

since $Z_{1F} = Z_{2F}$ for a transmission line, we further get

$$\frac{\vec{V}_1 - \vec{V}_2}{\vec{I}_1 - \vec{I}_2} = \vec{Z}_{1F} \tag{6.3}$$

The relationship between phase value and sequence value can be expressed as:

$$a = e^{j\frac{2\pi}{3}} \tag{6.4}$$

$$\begin{bmatrix} \vec{V}_a \\ \vec{V}_b \\ \vec{V}_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} \vec{V}_0 \\ \vec{V}_1 \\ \vec{V}_2 \end{bmatrix} \tag{6.5}$$

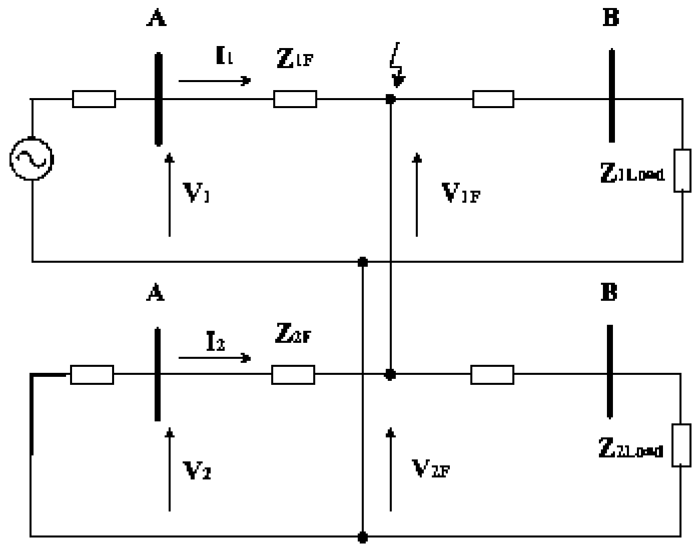


Fig 29 Symmetrical network connection for B-C fault

Subtract the third row from the second row, we have

$$\vec{V}_b - \vec{V}_c = (a^2 - a)(\vec{V}_1 - \vec{V}_2) \tag{6.6}$$

Similarly, we can also get

$$\vec{I}_b - \vec{I}_c = (a^2 - a)(\vec{I}_1 - \vec{I}_2) \tag{6.7}$$

Substituting (6.6) and (6.7) in (6.3), we get

$$\frac{\vec{V}_b - \vec{V}_c}{\vec{I}_b - \vec{I}_c} = \frac{\vec{V}_1 - \vec{V}_2}{\vec{I}_1 - \vec{I}_2} = \vec{Z}_{1F} \tag{6.8}$$

It relates the phasor measurements at relay location to the positive impedance measured from relay location to the fault location. For other fault types, we can also use different symmetrical component networks to get the voltage and current used to calculate the positive impedance. The result is shown in Table 7, where it can be seen that in order to detect a three-phase fault, a pair of voltage and current may be used for phase fault detection or for ground fault detection since they are required to calculate the exact positive impedance in a three-phase fault. For traditional electromechanical relays and solid-state relays, we need six elements to respond to all eleven fault types. In a digital relay, the different voltage and current pairs shown in Table 7 can be organized by the relay software as long as the three-phase voltage and

Table 7 Voltages and currents used to calculate apparent impedance for each fault type

	AB/ABG	BC/BCG	CA/CAG	AG	BG	CG	ABC/ABCG
V	$\vec{V}_a - \vec{V}_b$	$\vec{V}_b - \vec{V}_c$	$\vec{V}_c - \vec{V}_a$	$\vec{V}_a$	$\vec{V}_b$	$\vec{V}_c$	Any of the six V on the left
I	$\vec{I}_a - \vec{I}_b$	$\vec{I}_b - \vec{I}_c$	$\vec{I}_c - \vec{I}_a$	$\vec{I}_a + \vec{k}_0\vec{I}_0$	$\vec{I}_b + \vec{k}_0\vec{I}_0$	$\vec{I}_c + \vec{k}_0\vec{I}_0$	Corresponding I

$$\vec{k}_0 = \frac{\vec{Z}_0 - \vec{Z}_1}{\vec{Z}_1}$$

current inputs are available

6.3.4 Specific applications

The above introductions of distance relay principles are based on the very simple system configuration. In real practice, the distance relay needs to be tuned to face specific system configurations [26, 27]. Four typical system configurations are shown in Fig 30. For parallel lines that are on the same tower or share the same right-of-way, the mutual coupling between these lines must be taken into account for the relay schemes. For the multi-terminal lines, the infeed current from the tapped terminal plays a role in the fault detection. For a weak electrical system in which the source impedance is high, one should notice relative low values of fault current and relatively flat voltage profile along the line seen by the relay. For the series compensated line in which the series reactor or series capacitor is installed, the relay scheme must take into account the change of the line impedance due to the on/off switching of the compensation devices.

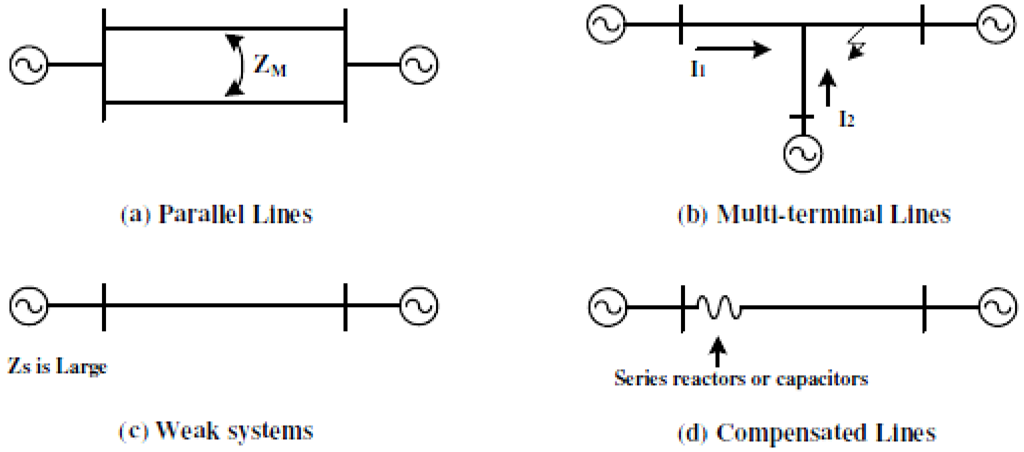


Fig 30 Specific system configurations for distance relay applications

6.3.5 Power Swing

The associated phenomenon with the transient stability issue is power swing, which is defined as *"a variation in three phase power flow which occurs when the generator rotor angles are advancing or retarding to each other in response to changes in load magnitude and direction, line switching, loss of generation, faults and other system disturbances.* [25]" The power swing is stable if the generator does not experience pole slipping and unstable (out-of-step) if one or a group of generators experience pole slipping.

Distance relay for transmission line protection is designed to isolate faults occurring within the desired zone only. It is not supposed to trip the line during the power swing caused by the disturbances outside the protected zones. Even for the out-of-step conditions, the preferred operation is to separate the system with an out-of-step tripping (OST) protection at pre-selected network locations and blocking other distance relays by out-of-step blocking (OSB) protection [25, 28]. Power swing, either stable or unstable, may have impacts on distance relay judgment. During the emergency state, such kind of relay unintended operation may cause more healthy lines removed from the system, resulting in the system becoming even more stressful. The reason is given below.

For the two machine system shown in Fig 9, for steady state, assume the two sources have the terminal voltages as $E_{SO}\angle\delta_0$ and $E_{R0}\angle 0$ respectively, where the phase angle of the receiving end generator is always used as the angle reference. As for the two-machine system, the power swing appears to a relay as an oscillation of magnitudes and the angles of two generators. At certain time during the power swing, assume the voltages are $E_S\angle\delta$ and $E_R\angle 0$.

Then we have

$$\vec{I} = \frac{E_S\angle\delta - E_R\angle 0}{\vec{Z}} \tag{6.9}$$

where $\vec{Z} = \vec{X}_S + \vec{Z}_L + \vec{X}_R$

From Fig 9, we have

$$\vec{V}_m = E_S\angle\delta - jX_S\vec{I} \tag{6.10}$$

Therefore the apparent impedance seen by the relay at bus m can be expressed as

$$\vec{Z}_m = \frac{\vec{V}_m}{\vec{I}} = -jX_S + jZ\frac{E_S\angle\delta}{E_S\angle\delta - E_R} \tag{6.11}$$

The trajectory of $\vec{Z}_m$ with respect to $\vec{E}_S$ and $\vec{E}_R$ can be found in [25, 28]. When the angle difference δ becomes large enough, the trajectory of $\vec{Z}_m$ will float into the relay setting area and cause relay unintended operation.

Now, let us extend the idea to regular multi-machine systems. Still look at Fig 9. Consider the line in the middle as one of the transmission lines in the system with the terminal voltages of $V_m\angle\theta_m$ and $V_n\angle\theta_n$. The other parts outside the line represent the rest of the system. If there is no fault on the line, the impedance seen by relay at bus m is,

$$\vec{Z}_C = \frac{\vec{V}_m}{\vec{I}_m} = \frac{\vec{V}_m}{(\vec{V}_m - \vec{V}_n)/\vec{Z}_L} = \vec{Z}_L\left(\frac{1}{1-\left|\frac{V_n}{V_m}\right|\angle\theta_{nm}}\right) \tag{6.12}$$

According to (6.12), Z_C is only related to the magnitude ratio $\left(|V_n|/|V_m|\right)$ and angle difference $(\theta_{nm} = \theta_n - \theta_m)$ of the bus voltages at the two ends. When power swing occurs in the system, $V_m\angle\theta_m$ and $V_n\angle\theta_n$ will oscillate during the time.

If power swings causes θ_{nm} large enough, the impedance seen by relay will reach the zone settings and relay will mal-operate. The right side of Fig 31 gives an example of typical actual impedance trajectories during a stable power swing and an unstable power swing.

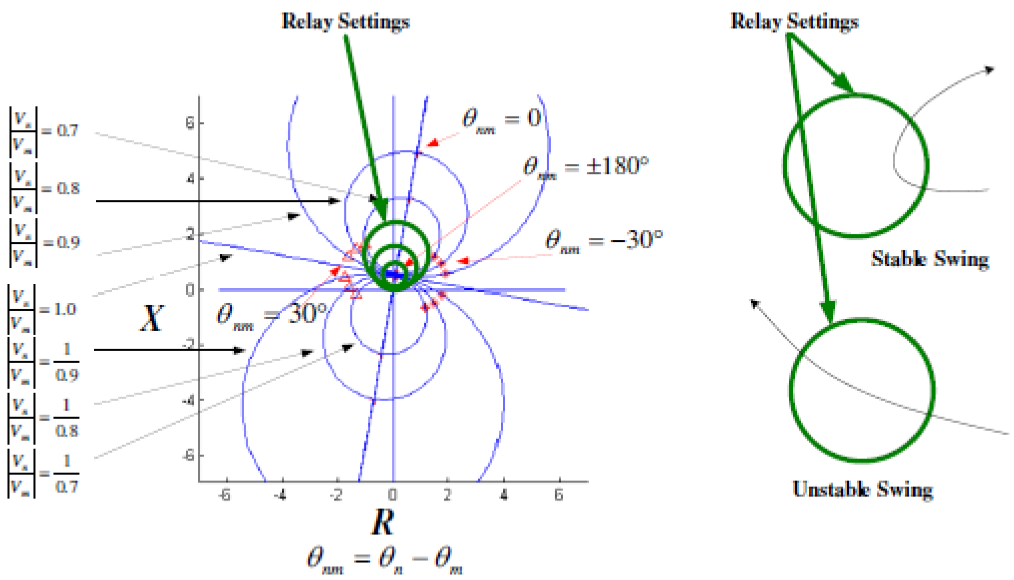


Fig 31 Zc trajectory in the R-X diagram in different terminal conditions

6.4 Zesco Transmission Protection Philosophy

Prior to commencement of the Power Rehabilitation Project (PRP), the ZESCO 330 kV system consisting of transmission lines, power transformers, generators and bus-bars, were protected using old electromechanical relays. However, these old relays became obsolete due to changes in technology. This meant that there were no longer spare parts to repair broken down equipment as manufacturers had moved to new numerical technology. This made maintenance of relays and control equipment very difficulty and the system was at risk of becoming unsafe due to inadequate protection as some equipment became inoperable. The main purpose of the rehabilitation project was to enhance system security by replacing old equipment that had become obsolete with the introduction of modern protection equipment.

Therefore, Zesco decided to replace all old relays with new numerical ones. In 2004 Zesco Limited completed the transmission system rehabilitation in which the main focus was on the upgrade and rehabilitation of the 330kv protection, control, metering and primary equipment such as circuit breakers.

To enhance the protection system further, the old bulk oil and air blast circuit were replaced with faster and more reliable SF6 gas breakers, shown in Fig 5, with two trip coils for increased reliability.

The DC system at the major substations, that consisted of battery sets and charger were also replaced. To increase the reliability two sets of batteries and chargers are each used to supply one of the two trip coils.

6.4.1 Old Protection Philosophy

Before the transmission rehabilitation was implemented, the protection philosophy was based on the following:

(a) Main 1 Electro-mechanical Distance relay type TS and H were used on the 330 kV transmission lines and the scheme used was Permissive Under-reach based on mho characteristics for fault loops

(b) Backup Protection Electro-mechanical Over-current and Earth Fault relay with IDMT Characteristics

(c) Analogue Substation Control

6.4.2 New Protection Philosophy

As part of the preparation for the transmission rehabilitation project, A Norwegian firm Norconsult was hired to carry out an intensive review of the state of all the plant on the transmission system. This work was carried out over a period of one year. One of the main recommendations of the study was on the need for adopting a new protection philosophy. Norconsult and Zesco formulated the new protection philosophy jointly.

The main principles of the philosophy are:

(a) Main 1 protection: Numerical Differential

(b) Main 2 protection: Numerical Distance

(c) Breaker failure protection

(d) Backup protection: Directional earth fault (DEF) with direction comparison feature. Over-current and earth fault with IDMT characteristics.

(e) Generator protection for bus bars with two zones: main and check. Primary function is to protect bus-bars

(f) Two tripping Supply system

6.4.3 General Advantages of Numerical Relays

(a) Numerical line differential relays provide high speed current differential generator protection for transmission lines and transformers.

(b) Optimal selectivity is assured as the scheme measures the current entering and leaving the protected generator. Both solid and resistive faults are detected and instantaneously cleared. Most stable to out of zone faults than electromechanical because of internal vector group and current transformer matching.

(c) Power up and continuous self monitoring and checking enhance reliability of relays.

(d) Numerical distance relays are far superior to electromechanical relay in detection of resistive faults because more accurate characteristics based on the quadrilateral and new algorithms used in fault detection.

(e) They have faster tripping times hence making the system more stable by clearing faults quicker than electromechanical relays.

(f) The new relays have inbuilt post fault analysis tools.

(g) They also have management functions like fault locators, disturbance recorders and event recorders to help in fault analyses

(h) Transformer protection relays have better algorithms for protecting power transformers against over fluxing and restricted earth fault protection and also inrush current detection uses more advanced and accurate algorithms.

(i) They come with integrated software for interrogating relays and easier relay programming and fault analysis.

(j) User friendly and modular design for easier maintenance and installation.

(k) Programmable digital outputs and inputs for easier and customized protection schemes.

6.5 Review of Transmission and Generation Protection Settings

6.5.1 Transmission Protection Settings

The existing distance protection on Zesco transmission lines does not take into consideration the effect of zero sequence mutual coupling although the transmission lines share a common way leave. This introduces errors in distance measurement for earth faults and may further cause the distance relay to either underreach or overreach depending on the direction of the zero sequence current in the adjacent parallel line. In single line applications, the measured fault impedance is proportional to the distance between the relay and the fault location. The measured impedance in faulted phase with zero fault impedance is

$$Z_{measure\_a} = \frac{V_{sfa}}{I_{sfa} + k_0 I_{sf0}} = mZ_{L1} \tag{6.13}$$

Where

$k_0 = \dfrac{Z_{L0} - Z_{L1}}{Z_{L1}}$ is the line zero sequence current compensation factor; Z_{L0} and Z_{L1} are respectively the zero and positive sequence impedance of the line. V_{sfa} and I_{sfa} are the faulted phase (assuming fault on phase a) post-fault phase voltage and current at the relay location,

m is the per-unit distance between the relay and the fault location of the protected line and I_{sf0} the post-fault zero sequence current at the relay location.

The same distance relay, when applied to protect a parallel line as shown in Fig 32 will encounter errors in distance measurement due to the mutual coupling effect.

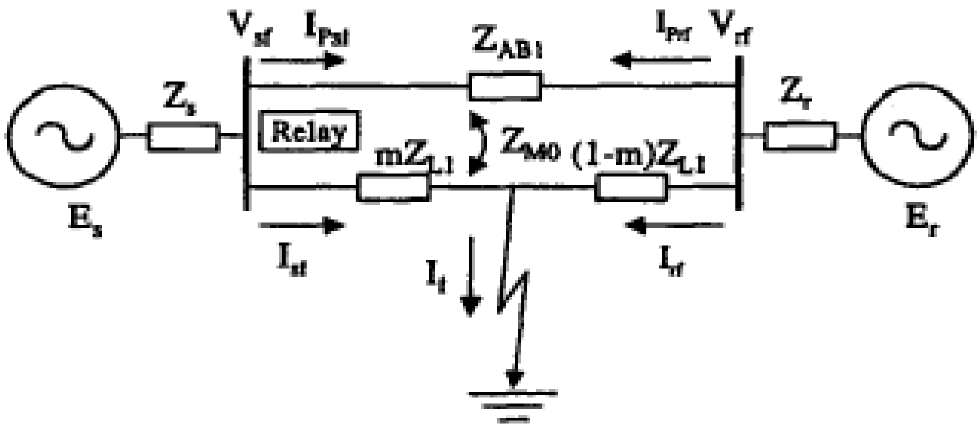


Fig 32 Typical parallel line system

The measured fault impedance of a conventional distance relay using zero sequence current compensation on a parallel line as shown in Fig 32 is,

$$
\begin{aligned}
Z_{measure\_a} &= \frac{V_{sfa}}{I_{sfa} + k_0 I_{sf0}} = mZ_{L1} \\
&= \frac{mZ_{L1}(I_{sfa} + k_0 I_{sf0}) + mZ_{M0} I_{psf0}}{I_{sfa} + k_0 I_{sf0}} \\
&= mZ_{L1} + \beta Z_{L1}
\end{aligned}
\tag{6.14}
$$

which contains an error βZ_{L1} because of the additional voltage drop $mZ_{M0}I_{psf0}$ resulting from the coupling effect of the parallel line's zero sequence current (the positive and negative sequence current mutual coupling effects are very small and thus generally are negligible). The per unit error β in terms of Z_{L1} is

$$
\beta = \frac{m(Z_{M0} / Z_{L1}) I_{psf0}}{I_{sfa} + k_0 I_{sf0}} \tag{6.15}
$$

In equation (6.14) and (6.15), Z_{M0} is the total zero sequence mutual coupling line impedance and I_{psf0} is the parallel line's zero sequence current.

The error may cause the relay either to overreach or underreach depending upon the relative direction of the parallel line's zero sequence current I_{psf0} verses the compensated current $I_{sfa} + k_0 I_{sf0}$. The relay will overreach if they are in the opposite direction. The relay will underreach if they are in the same direction. In view of the problems outlined above the following adaptive techniques are proposed.

6.5.1.1 Proposed Solutions

A. Using line operating status

When parallel line operating status is known, a distance relay could adjust its zone reach settings and/or zero sequence current compensation factor to take into account the mutual coupling effect corresponding to the prevalent line operating status. Properly selected zone reach settings and/or zero sequence current compensation factor would allow the distance relay to provide a better zone coverage and prevent possible overreach or underreach at each prevalent line operating condition. It may be preferred that either zone reach setting or zero sequence current compensation factor may be changed when line operating status is changed, since changing both of them at the same time may unnecessary complicate the application of the method. In distance relays where one zero sequence compensation factor setting is shared by different protection zones, changing zone reach settings may be the only choice. In a numerical distance relay, changing zero sequence compensation factor may be preferred, as it would allow the same zone reach setting (e.g., 80% to 85% for zone 1) to be used for different line operating status, which may be easier to understand.

B. Using parallel line's zero sequence current

On faulted line, the error in distance measurement of a conventional relay caused by zero sequence mutual coupling effect could be fully compensated by using parallel line's zero sequence current. Use of the parallel line's zero sequence current provides a simple way to adapt distance measurement on the faulted line to the mutual coupling effect under different line operating conditions and/or bus configurations. For a phase-a-to-ground fault on the protected line the equation shown below could be used to calculate correct fault impedance on the faulted line

$$Z_{measure\_a} = \frac{V_{sfa}}{I_{sfa} + k_0 I_{sf0} + k_{M0} I_{psf0}} = mZ_{L1} \qquad (6.16)$$

where $k_{M0} = Z_{M0} / Z_{L1}$. The distance measurement on the faulted line will always be correct under any line operating condition and/or bus configuration, since errors in distance measurement caused by the mutual coupling effect of I_{psf0} is fully compensated. Normal 80% to 85% zone coverage for zone 1 thus can be used, which will provide consistent zone coverage under all conditions for parallel lines. This method has a drawback if not implemented properly in that the distance relay may trip a healthy line in an event of a close-in fault on a parallel line. To prevent this false trip the method called earth fault balance is implemented. It compares the earth currents of the two lines and blocks the parallel line compensation (coupled current), when the earth current of the parallel line exceeds the earth current on the protected line by a settable percentage margin. This principle is based on the fact that the earth current in the faulted line is always at least as large (fault at the end of the line) or greater than the earth current of the healthy parallel line.

6.5.2 Generation Protection Settings

The generation protection settings are based on recommendations and tests carried out by a team of experts that was tasked to investigate the causes of the nationwide power blackout. This thesis attempts to reproduce the review of the settings proposed by the team of experts. Most of these results are based on real time testing and monitoring and cannot be simulated using the available tools in SIMPOW and NETBAS. A summary of the proposed settings are given below.

- **Frequency Protection review**: The frequency protection on the Zambia – Zimbabwe tie lines should be implemented as follows
    - In case of Zesco or ZESA inadvertently losing a load of at least 450MW and if the frequency is sustained at 52Hz for 3 seconds then Zesco should trip the interconnector line circuit breakers.
    - Zesco should trip the interconnector lines if the frequency is sustained at 47.75Hz for 1 second.
    - Zesco should trip the interconnector lines if a power swing detected in the ZESA network is sustained for more than 3 seconds.
- **Main and Backup Protection on the Zesco – ZESA (Zimbabwe) tie lines**:
    - Existing line differential protection on the tie lines should remain in service.
    - Existing directional over-current and earth protection should remain in operation.
    - Zesco should trip the tie lines if the directional over-current and earth fault protection on the Zesco end detects a fault in the ZESA network sustained for 1 second.

- **Under Frequency Protection On Zesco – SNEL (Congo DR) Interconnector**:

In an event that SNEL loses generation, Zesco should, according to SAPP regulations, supply power to SNEL for 30 minutes. Thereafter Zesco should open the 220kV interconnector lines if the frequency is sustained below 48Hz.

- **Frequency Protection Settings for Kariba North Power Station**

The Kariba North bank generators are initially set at 47Hz with 5 seconds delay but this should be adjusted to 46Hz for 3 seconds. The droop characteristic for Zesco is 150MW/Hz in the absence of interconnection.

7 CONCLUSIONS

7.1 Transient Stability Study

Transient stability of the generators in the Zesco system was studied. The system was modelled in SIMPOW by writing a script called an 'optpow file' for load flow simulations and the 'dynpow file' for transient stability simulations (see appendix D). In order to study the dynamic behaviour of the generators when subjected to a large disturbance, the generators were modelled as type 2A (i.e. model with one field winding, one damper winding in d-axis and one damper winding in q-axis. Saturation excluded). Generator parameters obtained from the Zesco catalogue were used. The simulations focussed on the dynamic behaviour of Zesco generators when subjected to a three phase short circuit applied at three selected buses namely Kariba North, Leopards Hill and Kafue gorge. These buses were selected because they are considered critical to the system. The duration of the short circuit in each case was varied until stability in at least one set of generators was lost. Results show that with the fault duration of 100 milliseconds, all generators in the system were able to regain synchronism after the fault was cleared but with the duration extended to 200 milliseconds the generators at Victoria Falls power station, which is the smallest of the three, were the first to lose synchronism. The simulations were carried out at peak load condition. It can therefore be concluded that at the current loading level, the critical clearing time should be less than 200 milliseconds. This guarantees that no generator will lose synchronism.

7.2 Contingency Study

This study was implemented using software called NETBAS. Results show that although certain constraints are violated when a contingency is applied (because the analysis is done at peak load condition), the Zesco system can operate under (N-1) criteria. The violated constraints can be corrected by load-shedding. The power blackout of 21st January 2008 (see section 2.4.2) was caused by an N-2 contingency. Appendix C gives the details of the consequences of each contingency.

7.3 Protection System

The study proposed that when calculating the distance relay protection settings, the effect of zero sequence mutual coupling that exists between parallel circuits should be considered. As seen in section 6.5.1 the performance of conventional distance relays on parallel lines is negatively impacted by the zero sequence mutual coupling effect between lines. Using settings based upon the worst case scenario results in sub-optimal performance of the relays under other operating conditions. It has been shown that it is feasible to achieve an optimal distance relay performance on parallel lines by accessing multiple additional locally available signals and adapt relay operation based on the signals availability and the line status. The adaptive protection scheme could provide an enhanced distance protection for parallel lines as no remote signals are required for the scheme. The adaptation to the signal availability provides a built-in fallback scheme, which ensures the reliable operation of the relay under all conditions. The application of the new adaptive scheme would enhance the performance of distance protection on parallel lines.

The settings for under/over frequency protection should be implemented as described in section 6.5.2.

7.4 Other Considerations

7.4.1 Automatic Under Frequency Load Shedding

The absence of an effective automatic under-frequency load-shedding scheme contributed significantly to the failure to contain the disturbances. Implementation of such a scheme would enable Zesco respond to the loss of generation by automatically switching off appropriate loads, thereby balancing demand with the available generation. Zesco should consider implementing such a scheme to improve reliability of power supply.

7.4.2 System Capacity and Spinning Reserve

The other most important factor for the building up of faults into total blackouts has to do with the failure to maintain a generation spinning reserve (spare capacity at generation). While it's understood that Zesco is currently under pressure to minimize load-shedding, the absence of a spinning reserve contributes to the inability of the system to contain the large disturbances. Zesco should review system operation and ensure that a reasonable reserve capacity is always maintained.

7.4.3 New Generation Capacity

Until significant new generation capacity is developed, there will be difficulties and compromises in running the Zambian system. However plans are currently underway to build a new power station at Itezhi tezhi and Kafue lower. This will greatly improve power supply reliability and reduce load shedding.

7.4.4 System Monitoring

It is currently difficult to reconstruct some of the events that occur during the disturbances because the recorders and protective relays on the system are not time-synchronized. It is therefore, recommended that Zesco takes immediate steps to acquire equipment that is needed to synchronise the so-called 'time stamping' on all event recorders.

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APPENDIX A

A.1. Load flow results from SIMPOW

Job Ident:ZESCO

DATE 3 MAY 2009 TIME 14:04:19

OPTPOW FILE FOR ZESCO SYSTEM

Table A 1 Load flow results

KAFUEGORGE (1)	1.00202 P.U.	330.666 KV	-2.40994 DEGREES	
POWER FROM			MW	MVAR
LINE KAFUEGORGE LEOPARDSHILL 1			-307.379	22.3434
LINE KAFUEGORGE LEOPARDSHILL 2			-307.379	22.3434
LINE KAFUEGORGE KAFUEWEST 0			-214.199	12.5117
TR2 KAFUEGENKAFUEGORGE 0			828.957	-57.1985

LEOPARDSHILL (1)	0.999373 P.U.	329.793KV	-5.06948 DEGREES	
POWER FROM			MW	MVAR
LINE KAFUEGORGE LEOPARDSHILL 1			305.607	-19.0999
LINE KAFUEGORGE LEOPARDSHILL 2			305.607	-19.0999
LINE KARIBANORTH LEOPARDSHILL 1			246.948	-11.3099
LINE KARIBANORTH LEOPARDSHILL 2			246.948	-11.3099
LINE KAFUEWEST LEOPARDSHILL 0			98.0404	-3.14714
LINE LEOPARDSHILLKABWE 1			-301.051	54.6556
LINE LEOPARDSHILLKABWE 2			-301.051	54.6556
LINE LEOPARDSHILLKABWE 3			-301.051	54.6556
LOAD LEOPARDSHILL 0			-300.000	-100.000

KAFUEWEST (1)	0.999399 P.U.	329.802 KV		-4.10036	DEGREES
POWER FROM				MW	MVAR
LINE KAFUEGORGE KAFUEWEST			0	213.413	-2.86466
LINE KAFUETOWN330KAFUEWEST			0	-18.5776	-2.39876
LINE KAFUEWEST LUSAKAWEST			0	-96.5872	-15.8153
LINE KAFUEWEST LEOPARDSHILL			0	-98.2484	21.0787

KAFUETOWN330 (1)	0.999348 P.U. 329.785 KV			-4.11039	DEGREES
POWER FROM				MW	MVAR
LINE KAFUETOWN330KAFUEWEST 0				18.5771	3.50396
TR2 KAFUETOWN330KAFUETOWN88			0	-18.5771	-3.50396

LUSAKAWEST (1)	0.993997 P.U.	328.019 KV		-4.91133	DEGREES
POWER FROM				MW	MVAR
LINE KAFUEWEST LUSAKAWEST			0	96.4000	31.6000
LOAD LUSAKAWEST 0				-96.4000	-31.6000

KARIBANORTH (1)	1.00294 P.U.	330.971 KV	0.574901	DEGREES
POWER FROM			MW	MVAR
LINE KARIBANORTH LEOPARDSHILL 1			-250.000	32.5742
LINE KARIBANORTH LEOPARDSHILL 2			-250.000	32.5742
LINE KARIBANORTH KARIBASOUTH 0			0.307133E-04	0.744360
TR2 KARIBAGEN KARIBANORTH 0			500.000	-65.8927

KARIBASOUTH (1)	1.00294 P.U.	330.972 KV		0.574884	DEGREES
POWER FROM				MW	MVAR
LINE KARIBANORTH KARIBASOUTH			0	-0.406500E-18	0.254307E-16

KABWE (1)	1.00359 P.U.	331.186 KV	-10.4871	DEGREES
POWER FROM			MW	MVAR

LINE LEOPARDSHILLKABWE 1	297.486	-47.1590
LINE LEOPARDSHILLKABWE 2	297.486	-47.1590
LINE LEOPARDSHILLKABWE 3	297.486	-47.1590
LINE KABWE KITWE 1	-213.274	16.8535
LINE KABWE KITWE 2	-213.274	16.8535
LINE KABWE LUANO 1	-186.737	31.3663
LINE KABWE LUANO 2	-186.737	31.3663
LINE KABWE PENSULO 0	-52.4370	56.0374
LOAD KABWE 0	-40.0000	-11.0000

KITWE (1) 0.980971 P.U. 323.720 KV	-18.7136	DEGREES
POWER FROM	MW	MVAR
SHUN KITWE 0	0.152712E-06	34.6429
LINE KABWE KITWE 1	209.445	29.8020
LINE KABWE KITWE 2	209.445	29.8020
LINE KITWE LUANO 0	-18.8901	36.7531
LOAD KITWE 0	-400.000	-131.000

LUANO (1) 0.984598 P.U. 324.917 KV	-18.8892	DEGREES
POWER FROM	MW	MVAR
SHUN LUANO 0	-0.496729E-06	33.9302
LINE KABWE LUANO 1	183.310	32.2992
LINE KABWE LUANO 2	183.310	32.2992
LINE KITWE LUANO 0	18.8689	-22.2653
LINE LUANO KANSANSHI 0	-85.4881	22.2367
LOAD LUANO 0	-300.000	-98.5000

PENSULO (1) 0.998806 P.U. 329.606 KV	-13.2941	DEGREES
POWER FROM	MW	MVAR
SHUN PENSULO 0	-0.386136E-06	-35.9141
LINE KABWE PENSULO 0	52.0000	52.9141
LOAD PENSULO 0	-52.0000	-17.0000

KANSANSHI (1) 0.977105 P.U. 322.445 KV	-21.4132	DEGREES
POWER FROM	MW	MVAR
LINE LUANO KANSANSHI 0	85.0000	30.0000
LOAD KANSANSHI 0	-85.0000	-30.0000

KAFUEGEN (1) 1.00000 P.U. SWING BUS 18.0000 KV	0.00000	DEGREES
POWER FROM	MW	MVAR
TR2 KAFUEGENKAFUEGORGE 0	-828.957	22.2463
PROD KAFGEN	828.957	-22.2463

KARIBAGEN (1) 1.00000 P.U. 18.0000 KV	1.98613	DEGREES
POWER FROM	MW	MVAR
TR2 KARIBAGEN KARIBANORTH 0	-500.000	53.4015
PROD KARIBGEN	500.000	-53.4015

APPENDIX B

B.1 Transient Stability Simulations in SIMPOW

B.1.1 Cases

In this section the effect of the three phase short circuit applied at Leopards Hill and Kafue gorge bus will be studied. In particular the transient behaviour of the generators in response to the fault will be analysed. As described in section 4.2.2 each case will be simulated starting with a stable scenario and then gradually increasing the fault duration until stability is lost in one of the generators. The explanation of the various curves follows the one given in chapter 4. Here an illustration and brief explanation is given.

B.1.1.1 Case 1: Three phase fault at Leopards Hill without loss of stability

The transient response of the generators to this fault is shown below.

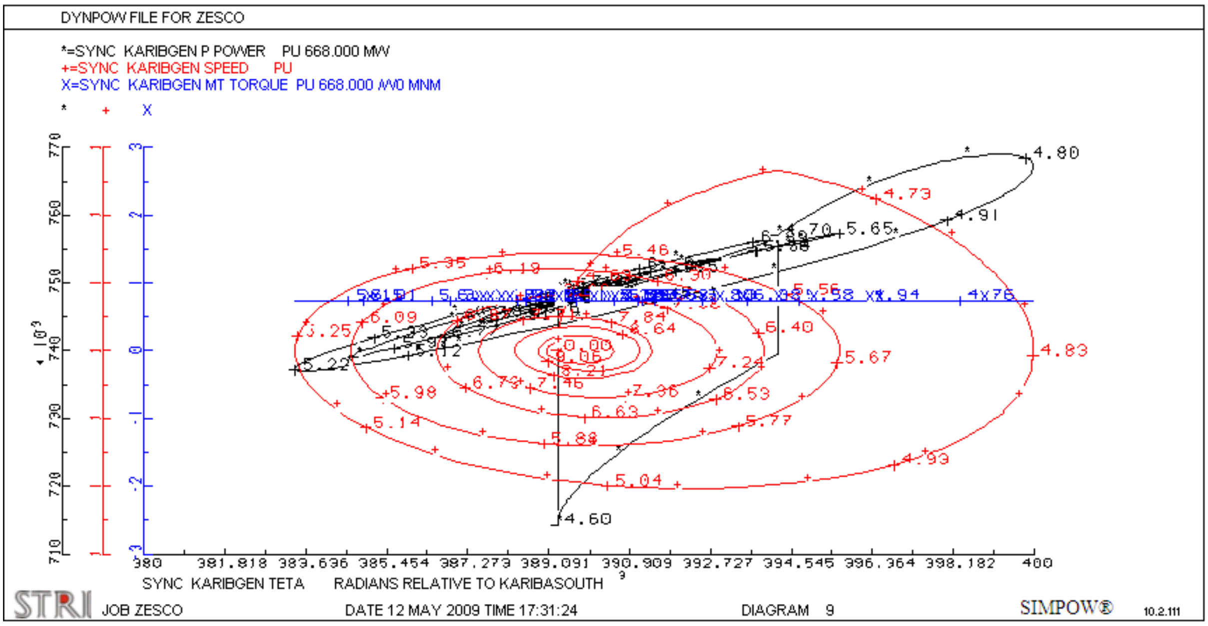

Fig B 1 Transient response of Kariba North generators to a fault at Leopards Hill

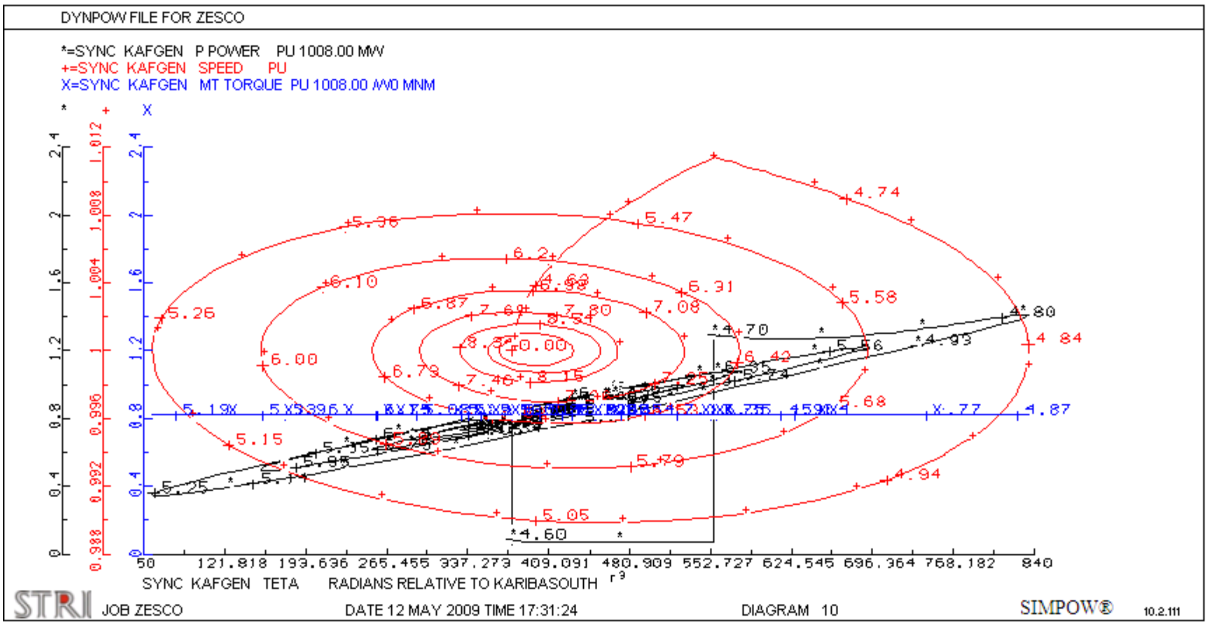

Fig B 2 Transient response of Kafue gorge generators to fault at Leopards Hill

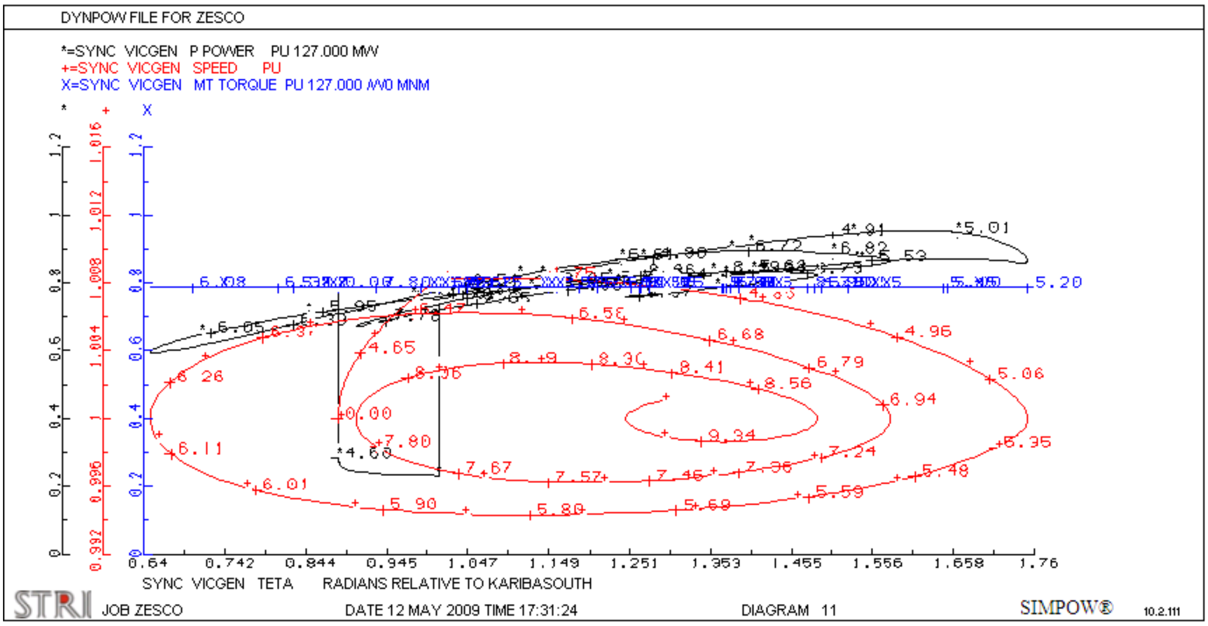

Fig B 3 Transient response of Victoria Falls generators to a fault at Leopards Hill

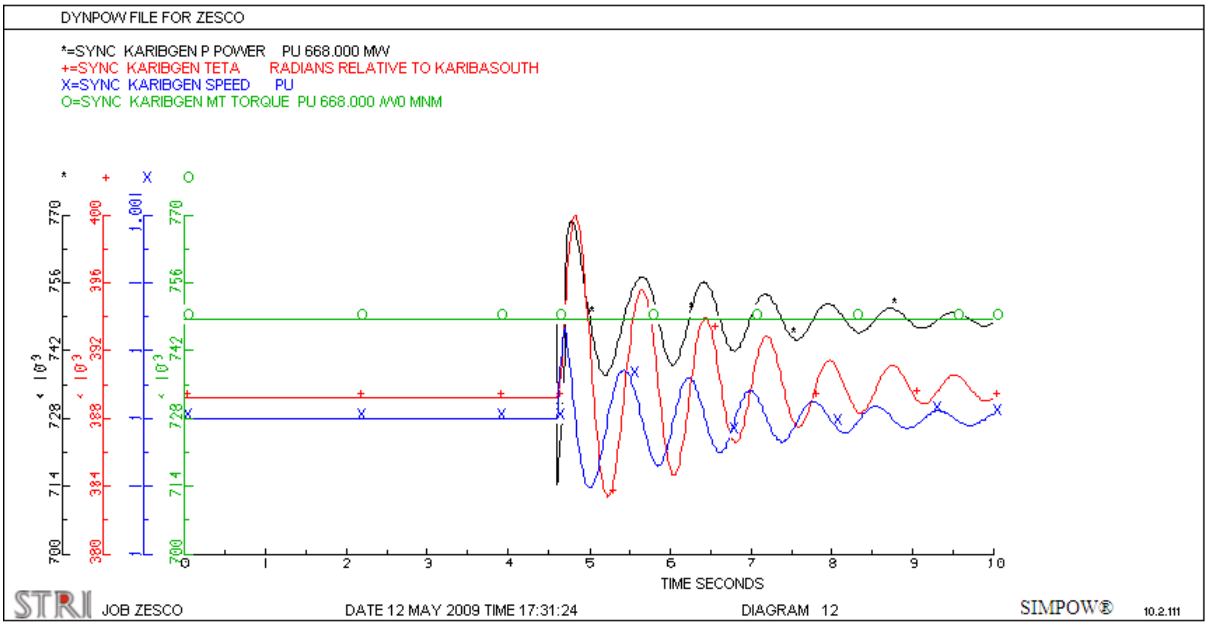

Fig B 4 Transient response of Kariba North generators in time domain

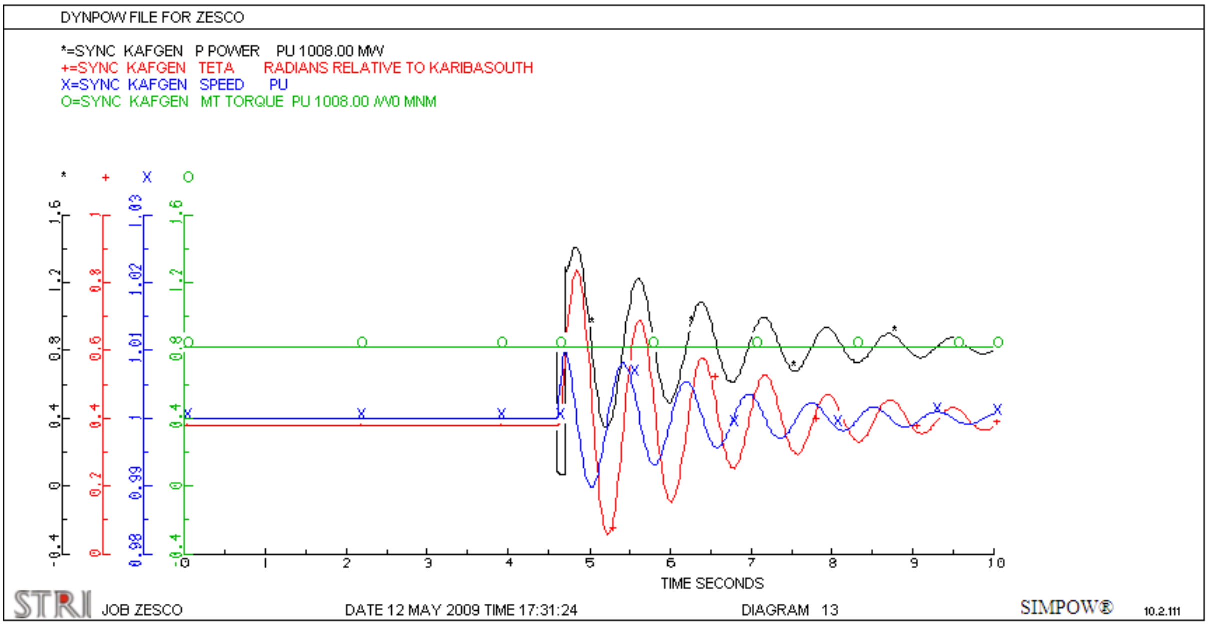

Fig B 5 Transient response of Kafue gorge generators in time domain

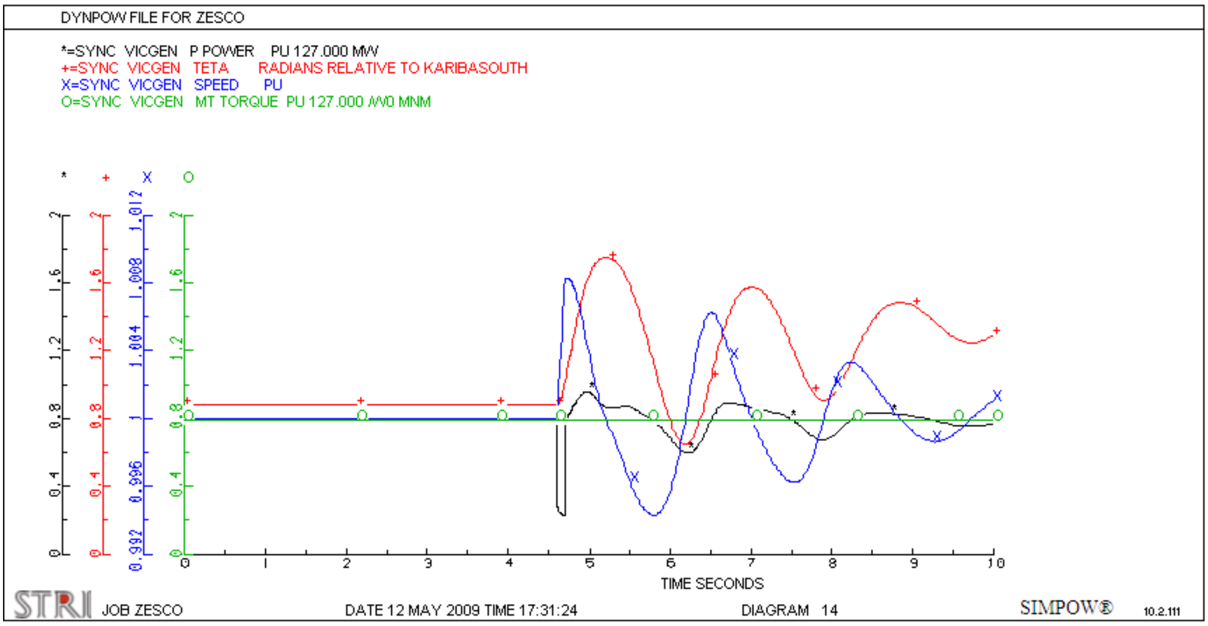

Fig B 6 Transient response of Victoria Falls generators in time domain

B.1.1.2 Case 2: Three phase fault at Leopards Hill with loss of stability of Victoria Falls generators

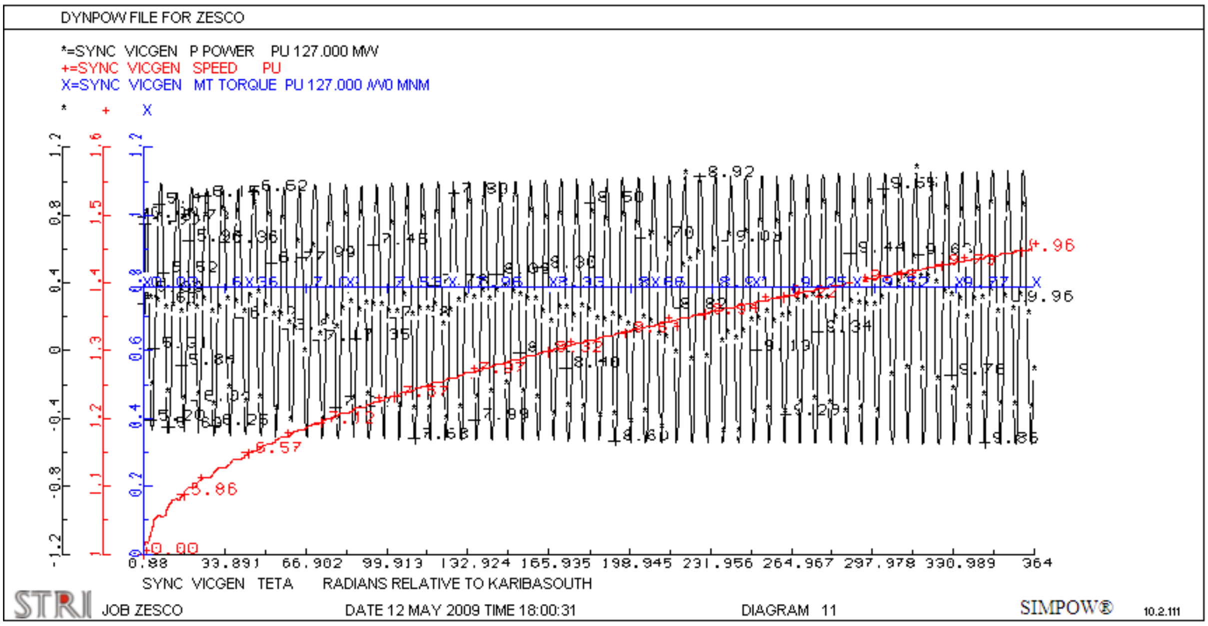

Fig B 7 Transient response of Victoria Falls generators showing loss of synchronism

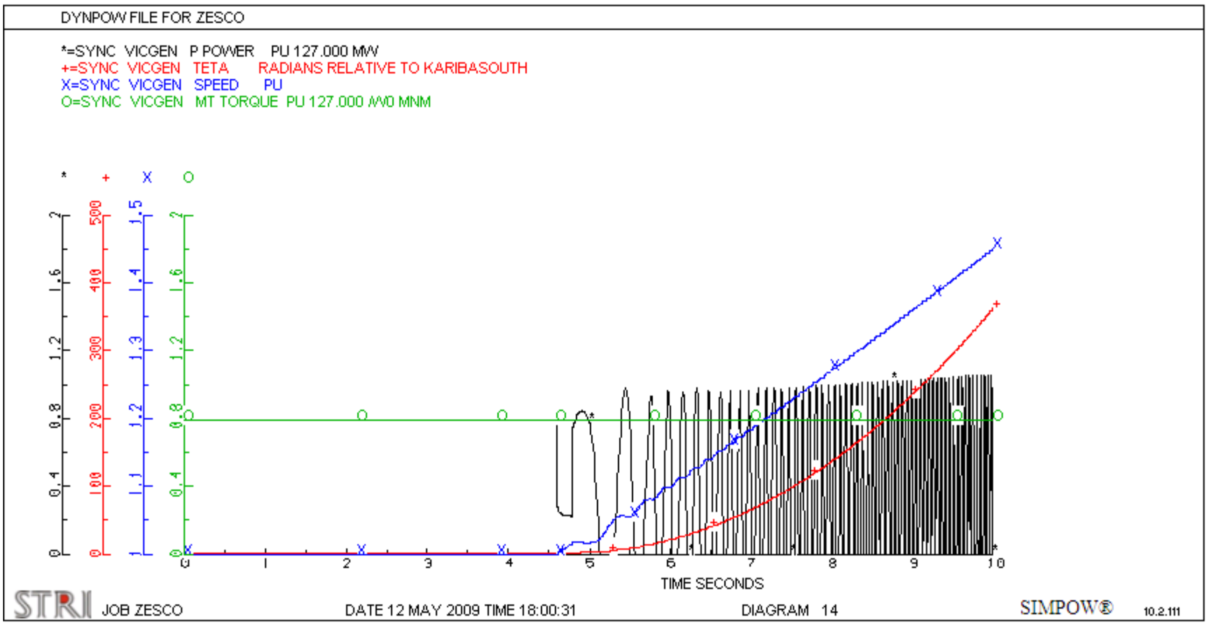

Fig B 8 Transient response of Victoria Falls generators observed in time domain

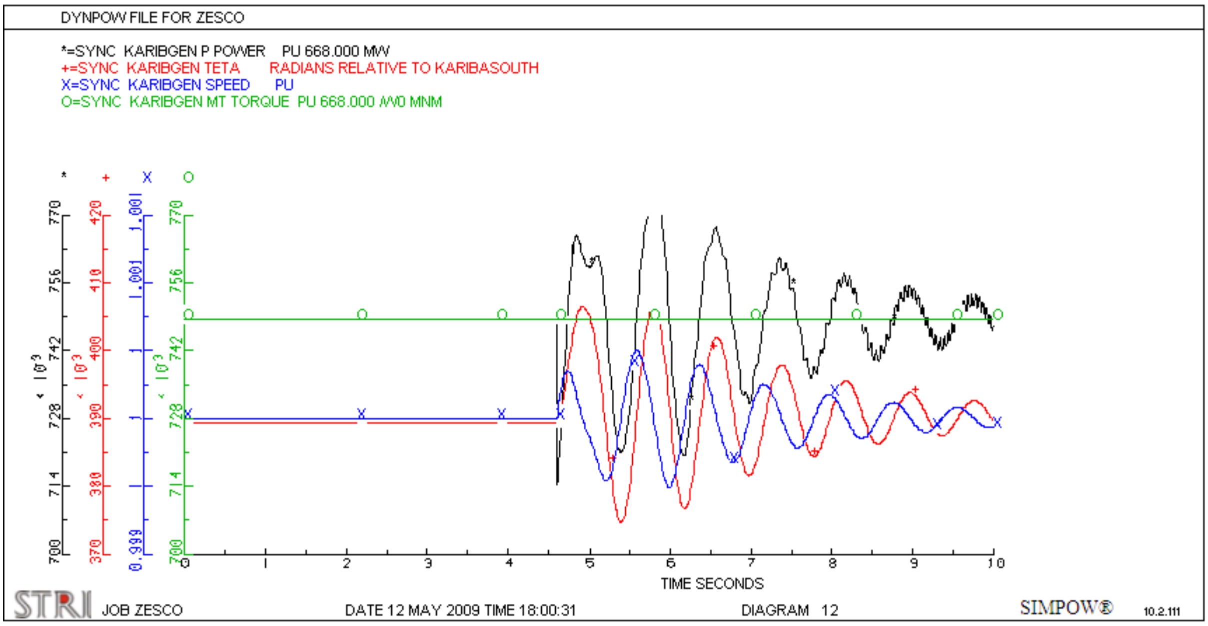

Fig B 9 Transient response of Kariba North generators observed in time domain

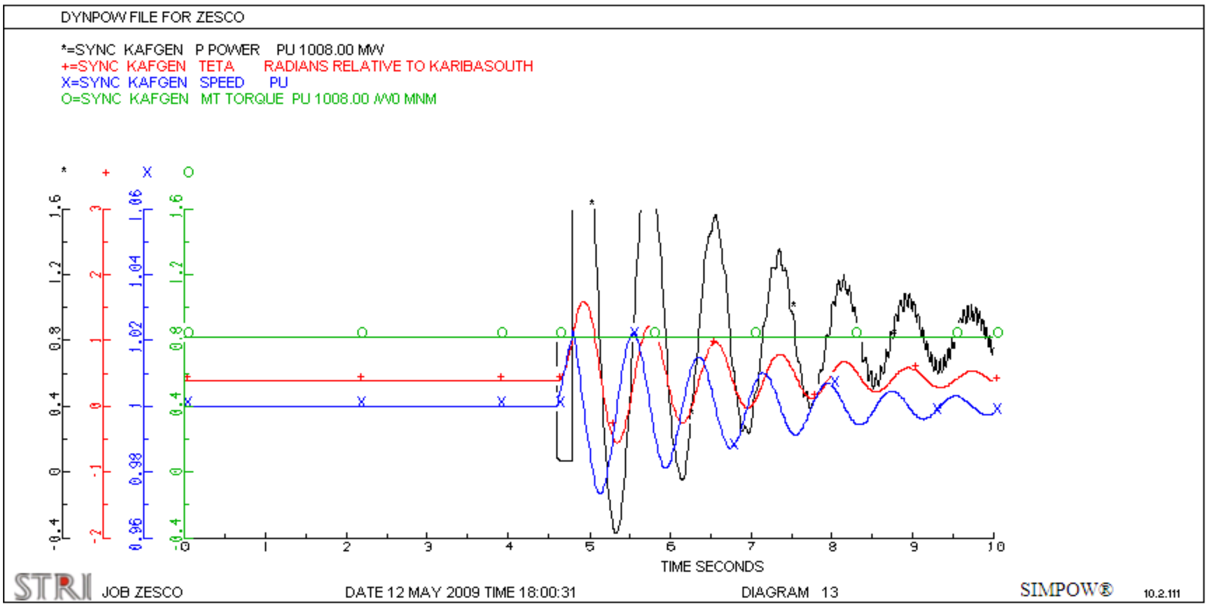

Fig B 10 Transient response of Kafue gorge generators observed in time domain

B.1 Case 3: Fault at Kafue gorge with loss of stability of generators at Victoria Falls

In this case the fault was applied at Kafue gorge bus and the duration varied until the generators in one of the power stations lost synchronism. The generators to first lose synchronism were those at Victoria Falls power station. Synchronism was lost when the fault duration was set at 100 milliseconds. The results are shown graphically below.

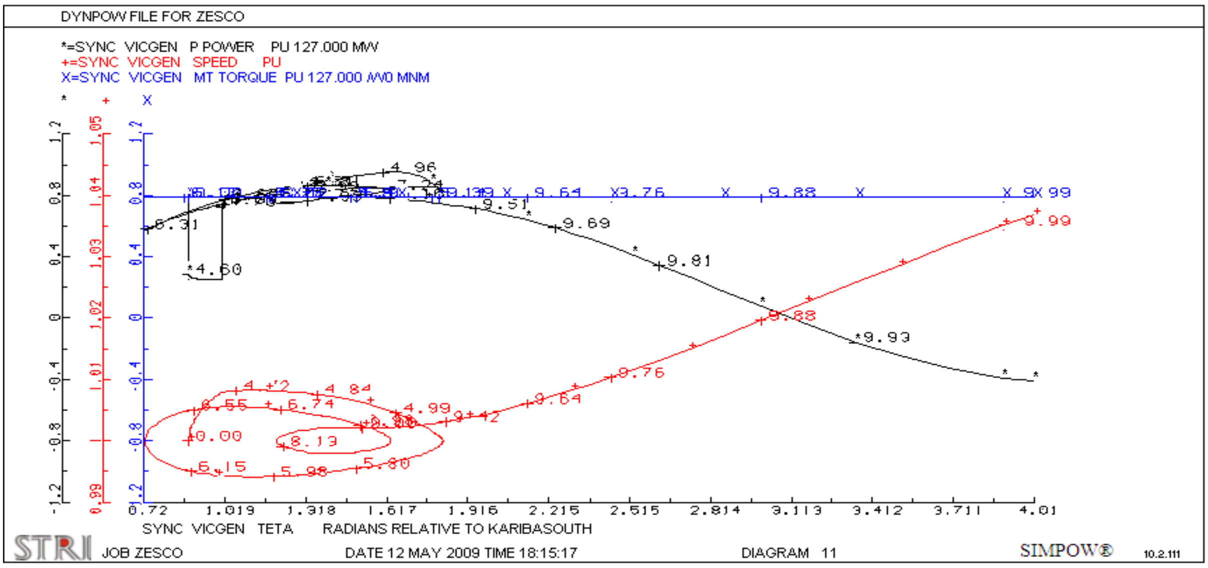

Fig B 11 Loss of synchronism at Victoria Falls

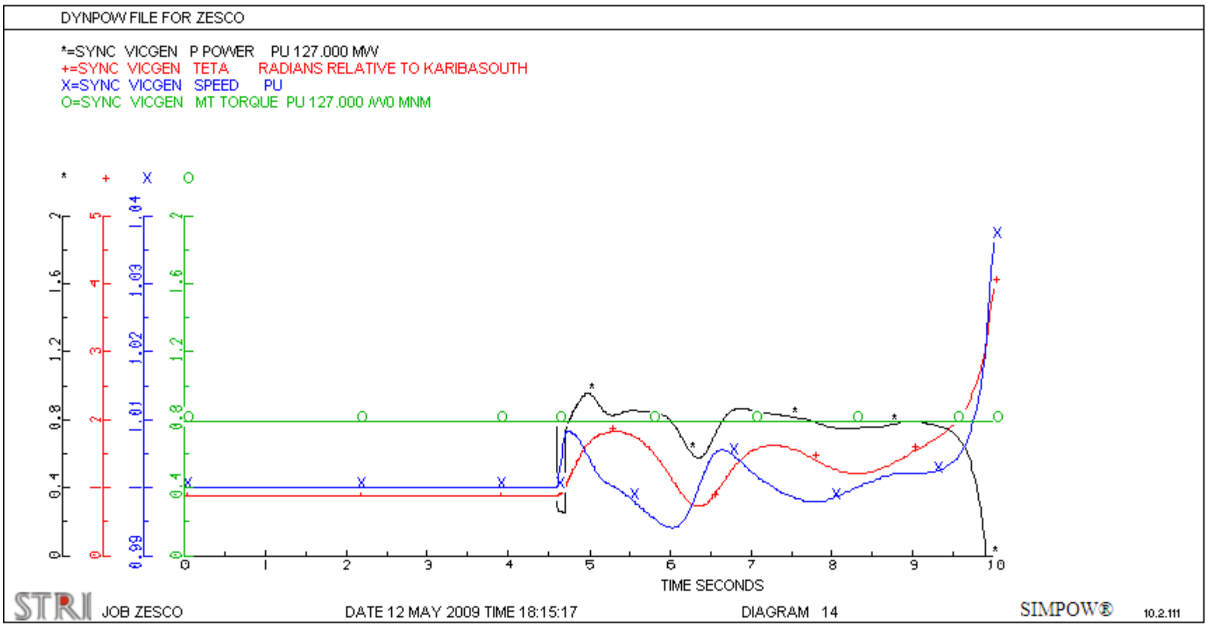

Fig B 12 Loss of synchronism at Victoria Falls seen in time domain

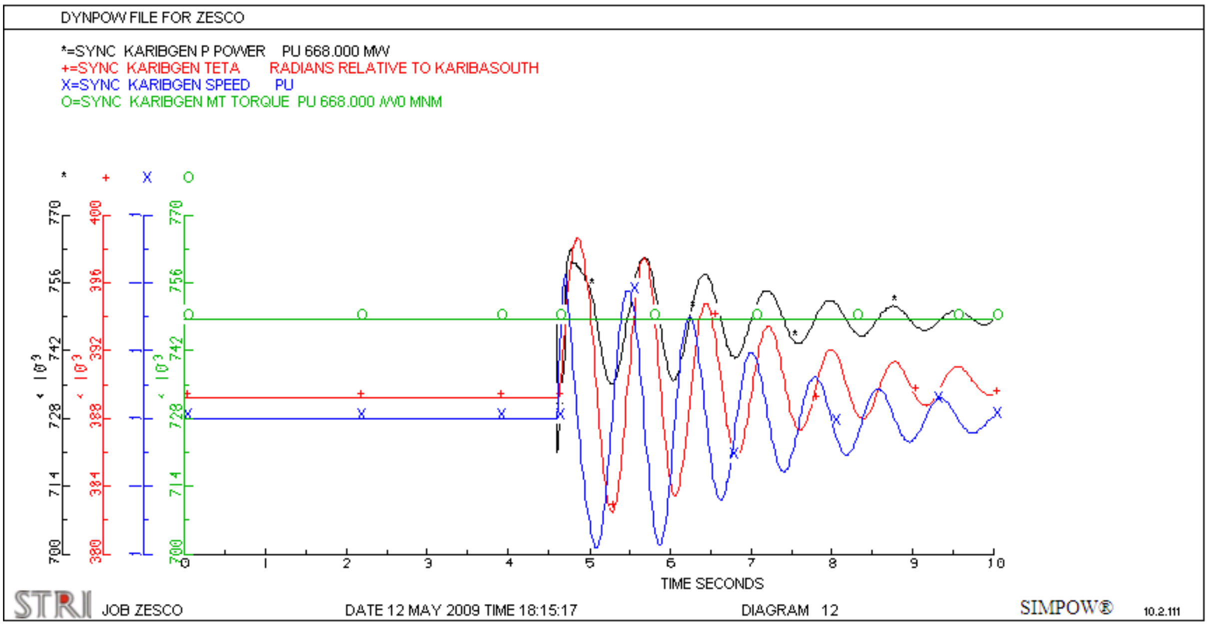

Fig B 13 Response of generators at Kariba North

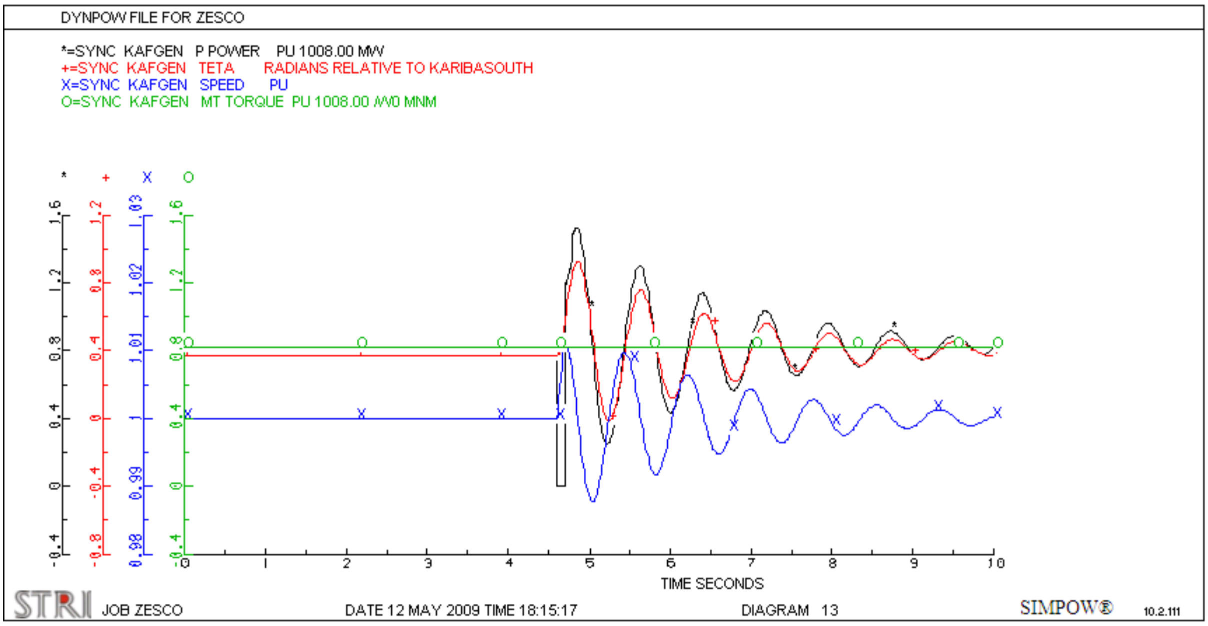

Fig B 14 Response of generators at Kafue gorge

APPENDIX C

C.1 Detailed results of contingency analysis

```
% ***************************************************************************
% ***** File name : studadm-utfall.lis         2009-05-13 18:49:39     *****
% ***************************************************************************


 Contingency analysis with KAFUE GORGE- as swingbus


% ***************************************************************************
% ****  Contingency no.   1  line   KAFUE GORGE- - L\HILL       SPG : 330.000 ****
% ***************************************************************************


       Node voltages and power flows
                                                .......... Load  ..........
   Node         Voltage       Generation       Vol.indep.       Vol.dep
     Name          kV        MW      MVAr       MW      MVAr     MW      MVAr
 --------------------------------------------------------------------------------
 KAFUE GORGE-    330.000   1000.807 -412.655 <
 KARIBA NORTH    330.000    420.000 -294.914 <
 VIC FALLS       220.000 -   76.000 -103.814 <
 PENSULO         364.096 >                          60.000  29.059            85.212
 KANSANSHI       364.789 >                          70.000  33.903
 #12             219.817 <
 KAFUE220        219.817 <                                                    19.967
 --------------------------------------------------------------------------------



        Power flow in line sections

 Node          Node                 Loadflow         Powerloss    Curr.  Load
 From           To                MW       MVAr     kW      kVAr     A   (%)
 -------------------------------------------------------------------------------
 KAFUE GORGE-- L\HILL           625.773 -271.177  8529.6 26192.3   1193  170
 KAFUE GORGE-- KAFUE WEST       375.034 -141.478  2674.4  -15830    701  100
 KAFUE88     - #14              -34.735  -27.805     0.3     0.3    297  531
 KAFUE88     - #13              -45.265  -10.941     0.3     0.3    311  555


% ***************************************************************************
% ****  Contingency no.   2  line   KARIBA NORTH - L\HILL       SPG : 330.000 ****
% ***************************************************************************

        Power flow in line sections

 Node          Node                 Loadflow         Powerloss    Curr.  Load
 From           To                MW       MVAr     kW      kVAr     A   (%)
 -------------------------------------------------------------------------------
 KARIBA NORTH- L\HILL           420.000 -135.429  8999.5  -36266    772  110
 KAFUE GORGE-- L\HILL           445.937 -229.957  4557.6 -4952.0    878  125
 KAFUE88     - #14              -34.734  -27.503     0.3     0.3    297  529
 KAFUE88     - #13              -45.266  -11.242     0.3     0.3    312  557


% ***************************************************************************
% ****  Contingency no.   3  line   KARIBA NORTH - L\HILL       SPG : 330.000 ****
% ***************************************************************************

        Power flow in line sections

 Node          Node                 Loadflow         Powerloss    Curr.  Load
 From           To                MW       MVAr     kW      kVAr     A   (%)
 -------------------------------------------------------------------------------
 KARIBA NORTH- L\HILL           420.000 -135.429  8999.5  -36266    772  110
 KAFUE GORGE-- L\HILL           445.937 -229.957  4557.6 -4952.0    878  125
 KAFUE88     - #14              -34.734  -27.503     0.3     0.3    297  529
 KAFUE88     - #13              -45.266  -11.242     0.3     0.3    312  557
```

```
% ***************************************************************************
% ****  Contingency no.   4  line   KAFUE GORGE- - L\HILL       SPG : 330.000 ****
% ***************************************************************************

       Power flow in line sections

 Node          Node                Loadflow          Powerloss    Curr.  Load
 From           To                MW        MVAr     kW      kVAr     A   (%)
 ----------------------------------------------------------------------------
 KAFUE GORGE-- L\HILL           512.646 -184.911  5440.3 32100.7    953  136
 KAFUE GORGE-- KAFUE WEST       489.001 -177.431  4538.7 -1261.0    910  130
 KAFUE WEST  - L\HILL           358.829 -211.287  3366.6  -21008    717  102
 KAFUE88     - #14              -34.736  -28.506     0.3     0.3    299  534
 KAFUE88     - #13              -45.264  -10.240     0.3     0.3    309  552


% ***************************************************************************
% ****  Contingency no.   5  line   KAFUE GORGE- - KAFUE WEST   SPG : 330.000 ****
% ***************************************************************************

       Power flow in line sections

 Node          Node                Loadflow          Powerloss    Curr.  Load
 From           To                MW        MVAr     kW      kVAr     A   (%)
 ----------------------------------------------------------------------------
 KAFUE GORGE-- L\HILL           373.732 -144.377  2910.5 -1675.3    701  100
 KAFUE GORGE-- L\HILL           625.936 -265.403  8479.6 25833.3   1189  169
 KAFUE88     - #14              -34.743  -30.129     0.3     0.3    304  542
 KAFUE88     - #13              -45.257   -8.617     0.3     0.3    304  543


% ***************************************************************************
% ****  Contingency no.   6  line   KAFUE WEST   - L\HILL       SPG : 330.000 ****
% ***************************************************************************

       Power flow in line sections

 Node          Node                Loadflow          Powerloss    Curr.  Load
 From           To                MW        MVAr     kW      kVAr     A   (%)
 ----------------------------------------------------------------------------
 KAFUE GORGE-- L\HILL           544.909 -270.838  6750.6 12136.0   1065  152
 KAFUE88     - #14              -34.739  -24.964     0.3     0.3    290  517
 KAFUE88     - #13              -45.261  -13.782     0.3     0.3    321  572


% ***************************************************************************
% ****  Contingency no.   7  line   L\HILL       - KABWE        SPG : 330.000 ****
% ***************************************************************************

       Power flow in line sections

 Node          Node                Loadflow          Powerloss    Curr.  Load
 From           To                MW        MVAr     kW      kVAr     A   (%)
 ----------------------------------------------------------------------------
 KAFUE GORGE-- L\HILL           447.265 -192.625  4311.9 -6664.2    852  121
 L\HILL      - KABWE            491.843 -278.189 11073.0 -3827.1    970  138
 L\HILL      - KABWE            491.843 -278.189 11073.0 -3827.1    970  138
 KAFUE88     - #14              -34.734  -27.056     0.3     0.3    295  527
 KAFUE88     - #13              -45.266  -11.689     0.3     0.3    314  560


% ***************************************************************************
% ****  Contingency no.   8  line   L\HILL       - KABWE        SPG : 330.000 ****
% ***************************************************************************

       Power flow in line sections

 Node          Node                Loadflow          Powerloss    Curr.  Load
 From           To                MW        MVAr     kW      kVAr     A   (%)
 ----------------------------------------------------------------------------
```

KAFUE GORGE--	L\HILL	447.265	-192.625	4311.9	-6664.2	852	121
L\HILL	- KABWE	491.843	-278.189	11073.0	-3827.1	970	138
L\HILL	- KABWE	491.843	-278.189	11073.0	-3827.1	970	138
KAFUE88	- #14	-34.734	-27.056	0.3	0.3	295	527
KAFUE88	- #13	-45.266	-11.689	0.3	0.3	314	560

```
% ****************************************************************************
% ****  Contingency no.   9  line   L\HILL       - KABWE        SPG : 330.000 ****
% ****************************************************************************
```

Power flow in line sections

Node From	Node To	Loadflow MW	MVAr	Powerloss kW	kVAr	Curr. A	Load (%)
KAFUE GORGE--	L\HILL	447.265	-192.625	4311.9	-6664.2	852	121
L\HILL	- KABWE	491.843	-278.189	11073.0	-3827.1	970	138
L\HILL	- KABWE	491.843	-278.189	11073.0	-3827.1	970	138
KAFUE88	- #14	-34.734	-27.056	0.3	0.3	295	527
KAFUE88	- #13	-45.266	-11.689	0.3	0.3	314	560

```
% ****************************************************************************
% ****  Contingency no.  10  line   KABWE        - PENSULO      SPG : 330.000 ****
% ****************************************************************************

------------------------------------------------
     * Total gen. :    1492.342 ->  1430.214 MW
     * Total load :                 1383.400 MW
```

Power flow in line sections

Node From	Node To	Loadflow MW	MVAr	Powerloss kW	kVAr	Curr. A	Load (%)
KAFUE GORGE--	L\HILL	398.729	-150.801	3303.5	-14387	746	106
KAFUE88	- #14	-29.912	-28.455	0.2	0.2	278	496
KAFUE88	- #13	-50.088	-10.291	0.4	0.4	344	614

No new swingbus isolated area   60.000 MW load

```
% ****************************************************************************
% ****  Contingency no.  11  line   KABWE        - LUANO        SPG : 330.000 ****
% ****************************************************************************
```

Node voltages and power flows

Node Name	Voltage kV	Generation MW	MVAr	Load Vol.indep. MW	MVAr	Vol.dep MW	MVAr
LUANO	292.031 <			350.000	169.513		70.481
KITWE	293.170 <			450.000	217.945		71.032

Power flow in line sections

Node From	Node To	Loadflow MW	MVAr	Powerloss kW	kVAr	Curr. A	Load (%)
KAFUE GORGE--	L\HILL	451.030	-47.630	3830.4	-9593.2	793	113
KAFUE88	- #14	-34.738	-25.342	0.3	0.3	291	519
KAFUE88	- #13	-45.262	-13.404	0.3	0.3	319	570

```
% ****************************************************************************
% ****  Contingency no.  12  line   KABWE        - LUANO        SPG : 330.000 ****
% ****************************************************************************
```

```
       Power flow in line sections

 Node          Node                 Loadflow         Powerloss    Curr.  Load
 From           To                 MW       MVAr     kW      kVAr     A   (%)
 ------------------------------------------------------------------------------
 KAFUE GORGE-- L\HILL            451.348  -41.209  3829.9 -9559.1    793  113
 KAFUE88     - #14               -34.738  -25.266     0.3     0.3    291  519
 KAFUE88     - #13               -45.262  -13.479     0.3     0.3    320  570


% ***************************************************************************
% ****  Contingency no.  13  line   KABWE        - KITWE        SPG : 330.000 ****
% ***************************************************************************

       Power flow in line sections

 Node          Node                 Loadflow         Powerloss    Curr.  Load
 From           To                 MW       MVAr     kW      kVAr     A   (%)
 ------------------------------------------------------------------------------
 KAFUE GORGE-- L\HILL            451.695  -56.614  3852.5 -9471.9    796  113
 KABWE       - KITWE             344.331   89.020 12752.9  -57690    725  103
 KAFUE88     - #14               -34.737  -25.446     0.3     0.3    291  520
 KAFUE88     - #13               -45.263  -13.300     0.3     0.3    319  569


% ***************************************************************************
% ****  Contingency no.  14  line   KABWE        - KITWE        SPG : 330.000 ****
% ***************************************************************************

       Power flow in line sections

 Node          Node                 Loadflow         Powerloss    Curr.  Load
 From           To                 MW       MVAr     kW      kVAr     A   (%)
 ------------------------------------------------------------------------------
 KAFUE GORGE-- L\HILL            451.695  -56.614  3852.5 -9471.9    796  113
 KABWE       - KITWE             344.331   89.020 12752.9  -57690    725  103
 KAFUE88     - #14               -34.737  -25.446     0.3     0.3    291  520
 KAFUE88     - #13               -45.263  -13.300     0.3     0.3    319  569


% ***************************************************************************
% ****  Contingency no.  15  line   LUANO        - KITWE        SPG : 330.000 ****
% ***************************************************************************

       Power flow in line sections

 Node          Node                 Loadflow         Powerloss    Curr.  Load
 From           To                 MW       MVAr     kW      kVAr     A   (%)
 ------------------------------------------------------------------------------
 KAFUE GORGE-- L\HILL            444.541 -214.027  4413.5 -5992.6    863  123
 KAFUE88     - #14               -34.734  -27.315     0.3     0.3    296  528
 KAFUE88     - #13               -45.266  -11.431     0.3     0.3    313  558


% ***************************************************************************
% ****  Contingency no.  16  line   LUANO        - KANSANSHI    SPG : 330.000 ****
% ***************************************************************************

 ------------------------------------------------
      * Total gen. :    1492.342 ->  1419.828 MW
      * Total load :                 1373.400 MW

       Power flow in line sections

 Node          Node                 Loadflow         Powerloss    Curr.  Load
 From           To                 MW       MVAr     kW      kVAr     A   (%)
 ------------------------------------------------------------------------------
 KAFUE GORGE-- L\HILL            397.321 -176.565  3421.4  -13613    761  108
 KAFUE88     - #14               -31.371  -28.195     0.2     0.2    283  505
 KAFUE88     - #13               -48.629  -10.551     0.3     0.3    334  596
```

```
 No new swingbus isolated area   70.000 MW load


% ***************************************************************************
% ****  Contingency no.  17  line   KAFUE330     - KAFUE WEST   SPG : 330.000 ****
% ***************************************************************************

 ------------------------------------------------
      * Total gen. :    1416.342 ->  1380.544 MW
      * Total load :                 1335.400 MW


 ** No nodes selected

        Power flow in line sections

 Node          Node                Loadflow         Powerloss    Curr.  Load
 From           To               MW       MVAr     kW      kVAr     A   (%)
 -------------------------------------------------------------------------------
 KAFUE GORGE-- L\HILL           407.019 -234.950  3974.7 -9597.2    822  117


 New swingbus isolated area    ....: VIC FALLS
 ------------------------------------------------
      * Total gen. :      76.000 ->   108.000 MW
      * Total load :                  108.000 MW


 No convergence in loadflow .....: VIC FALLS


% ***************************************************************************
% ****  Contingency no.  18  line   KAFUE WEST   - LUSAKA WEST  SPG : 330.000 ****
% ***************************************************************************

 ------------------------------------------------
      * Total gen. :    1492.342 ->  1398.759 MW
      * Total load :                 1353.000 MW


 ** No nodes selected

        Power flow in line sections

 Node          Node                Loadflow         Powerloss    Curr.  Load
 From           To               MW       MVAr     kW      kVAr     A   (%)
 -------------------------------------------------------------------------------
 KAFUE GORGE-- L\HILL           422.547 -234.830  4215.4 -7691.2    846  120
 KAFUE88     - #14              -34.344  -27.996     0.3     0.3    296  528
 KAFUE88     - #13              -45.656  -10.749     0.3     0.3    313  559


 No new swingbus isolated area   90.400 MW load


% ***************************************************************************
% ****  Contingency no.  19  line   MUZUMA       - KAFUE220     SPG : 220.000 ****
% ***************************************************************************

 ------------------------------------------------
      * Total gen. :    1416.342 ->  1463.278 MW
      * Total load :                 1415.400 MW

        Power flow in line sections

 Node          Node                Loadflow         Powerloss    Curr.  Load
 From           To               MW       MVAr     kW      kVAr     A   (%)
 -------------------------------------------------------------------------------
 KAFUE GORGE-- L\HILL           386.426 -216.913  3528.8  -13014    775  110
 KAFUE88     - #14              -80.057  -56.119     1.4     1.4    683 1218
 KAFUE88     - #13                0.057   17.373     0.0     0.0    121  216

        Power flow in two-winding transformers

 Node          Node              Loadflow           Powerloss  No-ld.l  TD.  Load
 From           Til               MW      MVAr      kW    kVAr    kW   (%)  (%)
 -------------------------------------------------------------------------------
```

#14	- #15	-80.058	-56.120	1803.9	9019.5	0	0.0	173

New swingbus isolated area ....: VIC FALLS

----

* Total gen. : 76.000 -> 28.949 MW
* Total load : 28.000 MW

** No nodes selected

% ***
% **** Contingency no. 20 line VIC FALLS - MUZUMA SPG : 220.000 ****
% ***

----

* Total gen. : 1416.342 -> 1480.862 MW
* Total load : 1432.400 MW

Power flow in line sections

Node From	Node To	Loadflow MW	MVAr	Powerloss kW	kVAr	Curr. A	Load (%)
KAFUE GORGE-	- L\HILL	381.567	-223.878	3511.2	-13197	774	110
KAFUE88	- #14	-97.383	-13.674	1.3	1.3	660	1177
KAFUE88	- #13	17.383	-25.072	0.1	0.1	205	365

Power flow in two-winding transformers

Node From	Node Til	Loadflow MW	MVAr	Powerloss kW	kVAr	No-ld.l kW	TD. (%)	Load (%)
#14	- #15	-97.384	-13.675	1684.9	8424.6	0	0.0	167

New swingbus isolated area ....: VIC FALLS

----

* Total gen. : 76.000 -> 11.373 MW
* Total load : 11.000 MW

% ***
% **** Contingency no. 21 line VIC FALLS - SESHEKE SPG : 220.000 ****
% ***

----

* Total gen. : 1492.342 -> 1480.871 MW
* Total load : 1432.400 MW

Power flow in line sections

Node From	Node To	Loadflow MW	MVAr	Powerloss kW	kVAr	Curr. A	Load (%)
KAFUE GORGE-	- L\HILL	404.822	-227.336	3880.9	-10291	812	116
KAFUE88	- #14	-12.740	-36.724	0.2	0.2	261	466
KAFUE88	- #13	-67.260	-2.021	0.6	0.6	452	807
VIC FALLS	- MUZUMA	89.004	-45.967	2375.5	-33659	263	114

Power flow in two-winding transformers

Node From	Node Til	Loadflow MW	MVAr	Powerloss kW	kVAr	No-ld.l kW	TD. (%)	Load (%)
#12	- #13	68.054	5.986	792.7	3963.7	0	0.0	114

No new swingbus isolated area 11.000 MW load

% ***
% **** Contingency no. 22 trans #15 - #14 SN : 60.000 ****
% ***

```
 ------------------------------------------------
      * Total gen. :    1416.342 ->  1380.544 MW
      * Total load :                 1335.400 MW

        Power flow in line sections

 Node          Node                 Loadflow         Powerloss    Curr.  Load
 From           To                MW       MVAr     kW      kVAr     A   (%)
 -------------------------------------------------------------------------------
 KAFUE GORGE-- L\HILL           406.996 -235.452  3978.4 -9571.0    823  117


 New swingbus isolated area    ....: VIC FALLS
 ------------------------------------------------
      * Total gen. :      76.000 ->   108.000 MW
      * Total load :                  108.000 MW


 No convergence in loadflow .....: VIC FALLS


% ***************************************************************************
% ****  Contingency no.  23  trans  #12          - #13          SN  :  60.000 ****
% ***************************************************************************

 ------------------------------------------------
      * Total gen. :    1416.342 ->  1463.278 MW
      * Total load :                 1415.400 MW

        Power flow in line sections

 Node          Node                 Loadflow         Powerloss    Curr.  Load
 From           To                MW       MVAr     kW      kVAr     A   (%)
 -------------------------------------------------------------------------------
 KAFUE GORGE-- L\HILL           386.171 -220.656  3553.1  -12846    778  111
 KAFUE88     - #14              -80.000  -38.746     1.1     1.1    609 1087

        Power flow in two-winding transformers

 Node          Node                Loadflow          Powerloss  No-ld.l  TD.  Load
 From           Til                 MW      MVAr      kW    kVAr    kW   (%)  (%)
 -------------------------------------------------------------------------------
 #14         - #15             -80.001  -38.747  1435.3  7176.4    0   0.0  154


 New swingbus isolated area    ....: VIC FALLS
 ------------------------------------------------
      * Total gen. :      76.000 ->    28.949 MW
      * Total load :                   28.000 MW

********************************************************************************

  Data set : netbus. Year of calculation 2009.
 -------------------------------------------------------------


 No of contingencies :   23     0
 lines               :   21     0
 transformers        :    2     0

 Summary from Contingency Analysis

       Lines ranked after contingency problems
        ........ Name ...........       invalid     Volt.  Exceed Interr.
        From       -  To        split  Mainpart.  diff. load.  power
 ------------------------------------------------------------------------------
    1  VIC FALLS    - SESHEKE       X        ---     0     5
    2  KAFUE WEST   - LUSAKA WEST   X        ---     1     3
    3  KABWE        - PENSULO       X        ---     0     3
    4  LUANO        - KANSANSHI     X        ---     0     3
    5  KAFUE330     - KAFUE WEST    X        ***     7     1
    6  L\HILL       - KABWE                          0     5       5.806 *
    7  L\HILL       - KABWE                          0     5       5.806 *
    8  L\HILL       - KABWE                          0     5       5.806 *
    9  KAFUE GORGE- - L\HILL                         0     5       5.305 *
   10  KAFUE GORGE- - L\HILL                         7     4       4.465 *
```

11	KABWE - KITWE	0	4	11.458	*
12	KABWE - KITWE	0	4	11.458	*
13	KARIBA NORTH - L\HILL	0	4	4.027	*
14	KARIBA NORTH - L\HILL	0	4	4.027	*
15	KAFUE GORGE- - KAFUE WEST	0	4	3.326	*
16	KABWE - LUANO	2	3	9.844	*
17	KABWE - LUANO	0	3	10.337	*
18	KAFUE WEST - L\HILL	0	3	0.960	*
19	LUANO - KITWE	0	3	0.714	*

APPENDIX D

D.1 A script in Simpow for the Zesco network (optpow file)

```
OPTPOW FILE FOR ZESCO
*****
GENERAL
SN=100
LBASE=100
END

NODES
KAFUEGORGE UB=330 AREA=1
LEOPARDSHILL UB=330 AREA=1
KAFUEWEST UB=330 AREA=1
KAFUETOWN330 UB=330 AREA=1
KAFUETOWN220 UB=220 AREA=2
KAFUETOWN88 UB=88 AREA=2
VICFALLS UB=220 AREA=2
SESHEKE UB=220 AREA=2
MUZUMA UB=220 AREA=2
LUSAKAWEST UB=330 AREA=1
KARIBANORTH UB=330 AREA=1
KARIBASOUTH UB=330 AREA=1
KABWE UB=330 AREA=1
KITWE UB=330 AREA=1
LUANO UB=330 AREA=1
PENSULO UB=330 AREA=1
KANSANSHI UB=330 AREA=1
KAFUEGEN UB=18 AREA=1
VICFALLSGEN UB=11 AREA=2
KARIBAGEN UB=18 AREA=1
END

TRANSFORMERS
KAFUETOWN220 KAFUETOWN88 SN=60 UN1=220 UN2=88 ER12=0 EX12=0.13
KAFUETOWN330 KAFUETOWN88 SN=60 UN1=330 UN2=88 ER12=0 EX12=0.13
VICFALLSGEN VICFALLS SN=110 UN1=11 UN2=220 ER12=0 EX12=0.13
KAFUEGEN KAFUEGORGE SN=846 UN1=18 UN2=330 ER12=0 EX12=0.043
KARIBAGEN KARIBANORTH SN=668 UN1=18 UN2=330 ER12=0 EX12=0.033
END

LINES
KAFUEGORGE LEOPARDSHILL NO=1 TYPE=12 R=0.00004 X=0.00032 B=0.0037 L=47
KAFUEGORGE LEOPARDSHILL NO=2 TYPE=12 R=0.00004 X=0.00032 B=0.0037 L=47
KAFUEGORGE KAFUEWEST TYPE=12 R=0.00004 X=0.00032 B=0.0037 L=43
KARIBANORTH LEOPARDSHILL NO=1 TYPE=12 R=0.00004 X=0.00032 B=0.0037 L=123
KARIBANORTH LEOPARDSHILL NO=2 TYPE=12 R=0.00004 X=0.00032 B=0.0037 L=123
KARIBANORTH KARIBASOUTH  TYPE=12 R=0.00004 X=0.00032 B=0.0037 L=2
VICFALLS MUZUMA TYPE=12 R=0.00008 X=0.00064 B=0.0037 L=200
VICFALLS SESHEKE TYPE=12 R=0.00008 X=0.00064 B=0.0037 L=200
MUZUMA KAFUETOWN220 TYPE=12 R=0.00008 X=0.00064 B=0.0037 L=189
KAFUETOWN330 KAFUEWEST TYPE=12 R=0.00004 X=0.00032 B=0.0037 L=3
KAFUEWEST LUSAKAWEST TYPE=12 R=0.00004 X=0.00032 B=0.0037 L=47
KAFUEWEST LEOPARDSHILL TYPE=12 R=0.00004 X=0.00032 B=0.0037 L=53
LEOPARDSHILL KABWE NO=1 TYPE=12 R=0.00004 X=0.00032 B=0.0037 L=97
LEOPARDSHILL KABWE NO=2 TYPE=12 R=0.00004 X=0.00032 B=0.0037 L=97
LEOPARDSHILL KABWE NO=3 TYPE=12 R=0.00004 X=0.00032 B=0.0037 L=97
KABWE KITWE NO=1 TYPE=12 R=0.00004 X=0.00032 B=0.0037 L=211
KABWE KITWE NO=2 TYPE=12 R=0.00004 X=0.00032 B=0.0037 L=211
KABWE LUANO NO=1 TYPE=12 R=0.00004 X=0.00032 B=0.0037 L=247
KABWE LUANO NO=2 TYPE=12 R=0.00004 X=0.00032 B=0.0037 L=247
```

```
KABWE PENSULO TYPE=12 R=0.00004 X=0.00032 B=0.0037 L=298
KITWE LUANO TYPE=12 R=0.00004 X=0.00032 B=0.0037 L=41
LUANO KANSANSHI TYPE=12 R=0.00004 X=0.00032 B=0.0037 L=157
END

SHUNT IMPEDANCES
PENSULO Q=36
KAFUETOWN220 Q=50
LUANO Q=-35
SESHEKE Q=20
KITWE Q=-36
VICFALLS Q=40
END

LOADS
LEOPARDSHILL P=300 Q=100 MP=0 MQ=0
SESHEKE P=40 Q=6.5 MP=0 MQ=0
KAFUETOWN88 P=60 Q=27.6 MP=0 MQ=0
MUZUMA P=17 Q=5.58 MP=0 MQ=0
LUSAKAWEST P=96.4 Q=31.6 MP=0 MQ=0
KABWE P=40 Q=11 MP=0 MQ=0
KITWE P=400 Q=131 MP=0 MQ=0
LUANO P=300 Q=98.5 MP=0 MQ=0
PENSULO P=52 Q=17 MP=0 MQ=0
KANSANSHI P=85 Q=30 MP=0 MQ=0
END

POWER
VICFALLSGEN TYPE=NODE RTYP=UP U=11 P=100 NAME=VICGEN
KARIBAGEN TYPE=NODE RTYP=UP U=18 P=500 NAME=KARIBGEN
KAFUEGEN TYPE=NODE RTYP=SW U=18 FI=0 NAME=KAFGEN
END
END
```

D.1 A dynamic simulation file (Dynpow file)

```
DYNPOW FILE FOR ZESCO
**
CONTROL DATA
TEND=10
TETL=10E6
END

GENERAL
FN=50
END

NODES
KARIBASOUTH TYPE=1
END

SYNCHRONOUS MACHINES
VICGEN VICFALLSGEN TYPE=2A SN=127 UN=11
                  XA=0.17
                  XD=1.1 XQ=0.70
                  XDP=0.4
                  XDB=0.3 XQB=0.3
                  TD0P=6
                  TD0B=0.06 TQ0B=0.06
                  H=3.3
KARIBGEN KARIBAGEN TYPE=2A SN=668 UN=18
                  XA=0.16
                  XD=0.8 XQ=0.49
                  XDP=0.288
                  XDB=0.233 XQB=0.233
                  TD0P=8.0
                  TD0B=0.1 TQ0B=0.2
                  H=4.3
KAFGEN KAFUEGEN TYPE=2A SN=1008 UN=18
                  XA=0.12
                  XD=0.72 XQ=0.49
                  XDP=0.235
                  XDB=0.1945 XQB=0.1945
                  TD0P=9.5
                  TD0B=0.07 TQ0B=0.06
                  H=3.28
END

FAULTS
MYFAULT TYPE=3PSG NODE=KAFUEGORGE
END

RUN INSTRUCTIONS
 AT 4.600 INST CONNECT FAULT MYFAULT
 AT 4.70 INST DISCONNECT FAULT MYFAULT
 AT 4.70 INST DISCONNECT LINE KAFUEGORGE LEOPARDSHILL NO=1
 AT 4.800 INST CONNECT LINE KAFUEGORGE LEOPARDSHILL NO=1
END

END
```

APPENDIX E

E.1 System Parameters

E.1.1 Transmission line parameters

SORTCODE	LINE NAME	Date In	Date Out	Bus A	Bus B	Crt	Rpos	Xpos	Bpos	Rzero	Xzero	Bzero	Rate A	Km	Config	A
ZBL9475	IRWIN66-MCLRN66 66-kV	1994	3000	5388	5389	1	0.008152	0.018196	0.000254	0.01825	0.070700	0.00015	46	2	AK3	3
ZBL9473	IRWIN66-ROAN66 66-kV	1994	3000	5388	5384	1	0.026733	0.067256	0.000833	0.06209	0.251020	0.00051	43	7	AK2	3
ZBL9425	ISOKA66-NAKND66 66-kV	1994	3000	5409	5408	1	0.521371	0.982966	0.013394	1.05355	3.776503	0.00805	42	107	AK1	3
ZBL9462	KABND66-LUANO66 66-kV	1994	3000	5363	5372	1	0.029358	0.093044	0.002436	0.11969	0.437220	0.00146	80	14	AT2	3
ZBL9470	KABND66-STADM66 66-kV	1994	3000	5363	5364	1	0.012573	0.027651	0.000378	0.03312	0.105150	0.00025	41	3	AU1	3
ZBL9320	KABWE3-KITWE3 330-kV	1994	3000	5240	5241	1	0.008294	0.065900	0.785797	0.05558	0.211407	0.59866	700	211	W1	3
ZBL9318	KABWE3-KITWE3 330-kV	1994	3000	5240	5241	2	0.008294	0.065900	0.785797	0.05558	0.211407	0.59866	700	211	W1	3
ZBL9319	KABWE3-LEPRD3 330-kV	1994	3000	5240	5243	1	0.003866	0.030500	0.360006	0.02644	0.098721	0.27289	700	97	W1	3
ZBL9327	KABWE3-LEPRD3 330-kV	1994	3000	5240	5243	2	0.003866	0.030500	0.360006	0.02644	0.098721	0.27289	700	97	W1	3
ZBL9317	KABWE3-LEPRD3 330-kV	1994	3000	5240	5243	3	0.003866	0.030500	0.360006	0.02644	0.098721	0.27289	700	97	W1	3
ZBL9312	KABWE3-LUANO3 330-kV	1994	3000	5240	5244	1	0.009647	0.076899	0.921354	0.06401	0.245654	0.70361	700	247	W1	3
ZBL9314	KABWE3-LUANO3 330-kV	1994	3000	5240	5244	2	0.009405	0.076898	0.921354	0.06401	0.245414	0.70436	700	247	AP1	3
ZBL9326	KABWE3-PENSL3 330-kV	1994	3000	5240	5246	1	0.011511	0.092281	1.114635	0.07512	0.292689	0.85467	700	298	W1	3
ZBL9334	KABWE66-MLNGS66 66-kV	1993	3000	5474	5472	1	0.229140	0.576480	0.007140	0.53220	2.151600	0.00438	43	60	AK2	3
ZBL9444	KABWE88-KAPIR88 88-kV	1994	3000	5426	5425	1	0.263403	0.496110	0.021337	0.53297	1.908070	0.01270	56	96	AL1	3
ZBL9324	KAFGR3-KAFWT3 330-kV	1994	3000	5247	5248	1	0.001677	0.013545	0.159444	0.01183	0.043903	0.12083	700	43	AP1	3
ZBL0201	KAFGR3-KARIB_N3 330-kV	2002	3000	5247	5116	1	0.003984	0.031440	0.371162	0.02724	0.101747	0.28137	700	100	W1	2
ZBL9322	KAFGR3-LEPRD3 330-kV	1994	3000	5247	5243	1	0.001880	0.014805	0.174276	0.01293	0.048034	0.13193	700	47	W1	3
ZBL9305	KAFGR3-LEPRD3 330-kV	1994	3000	5247	5243	2	0.001880	0.014805	0.174276	0.01293	0.048034	0.13193	700	47	W1	3
ZBL9325	KAFTN2-MUZUM2 220-kV	1994	3000	5250	5251	1	0.033361	0.176844	0.235560	0.12962	0.472098	0.19063	230	189	W2	3
ZBL9315	KAFTN3-KAFWT3 330-kV	1994	3000	5249	5248	1	0.000120	0.000945	0.011124	0.00083	0.003066	0.00842	700	3	W1	3
ZBL9438	KAFTN88-LEPRD88 88-kV	1994	3000	5433	5430	1	0.170748	0.320912	0.013764	0.34701	1.236900	0.00818	56	62	AL1	3
ZBL9340	KAFTN88-MAPEP88 88-kV	1993	3000	5433	5545	1	0.090882	0.170808	0.007326	0.18470	0.658350	0.00436	56	33	AL1	3

AGP Information System d:\AgpPsse\Psse 22-Sep-98	TRANSMISSION LINES ZAMBIA (ZESCO)	Page 3 of 7

Fig E 1 Transmission line parameters

E.1.2 Generator Parameters

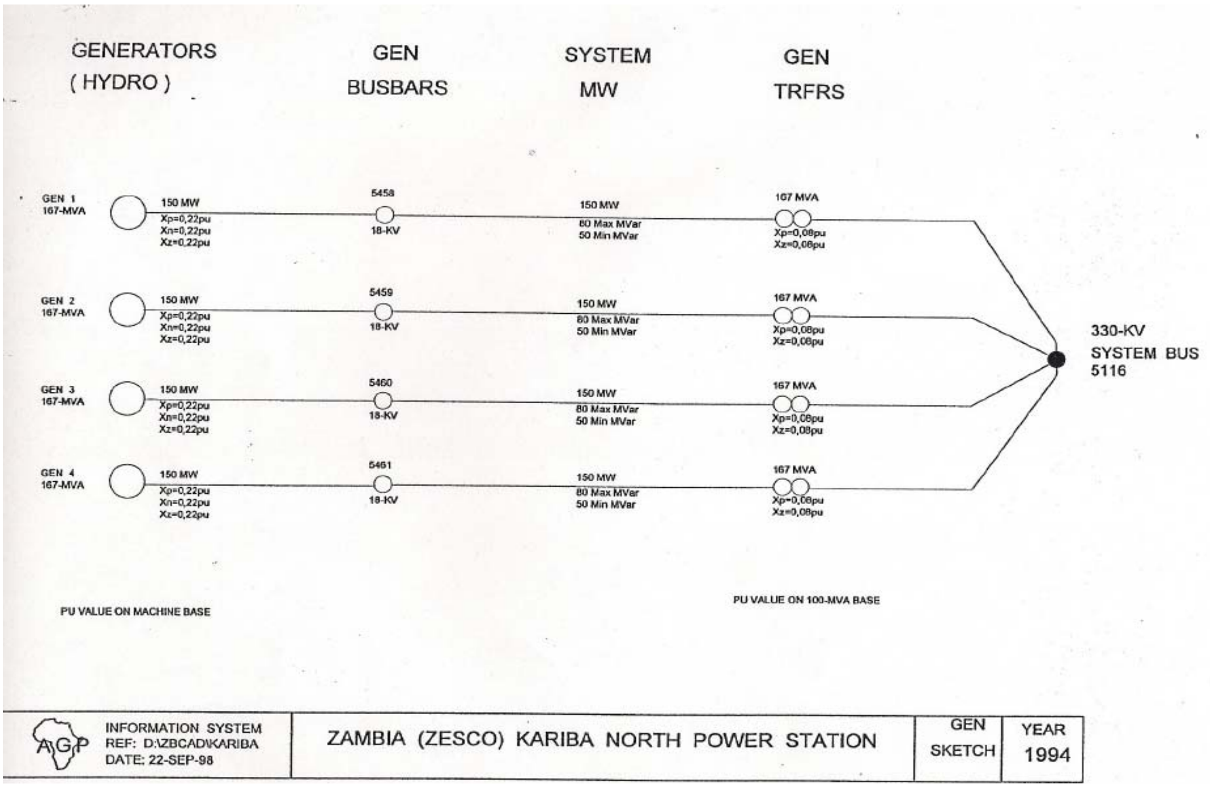

Fig E 2 Kariba North generator parameters

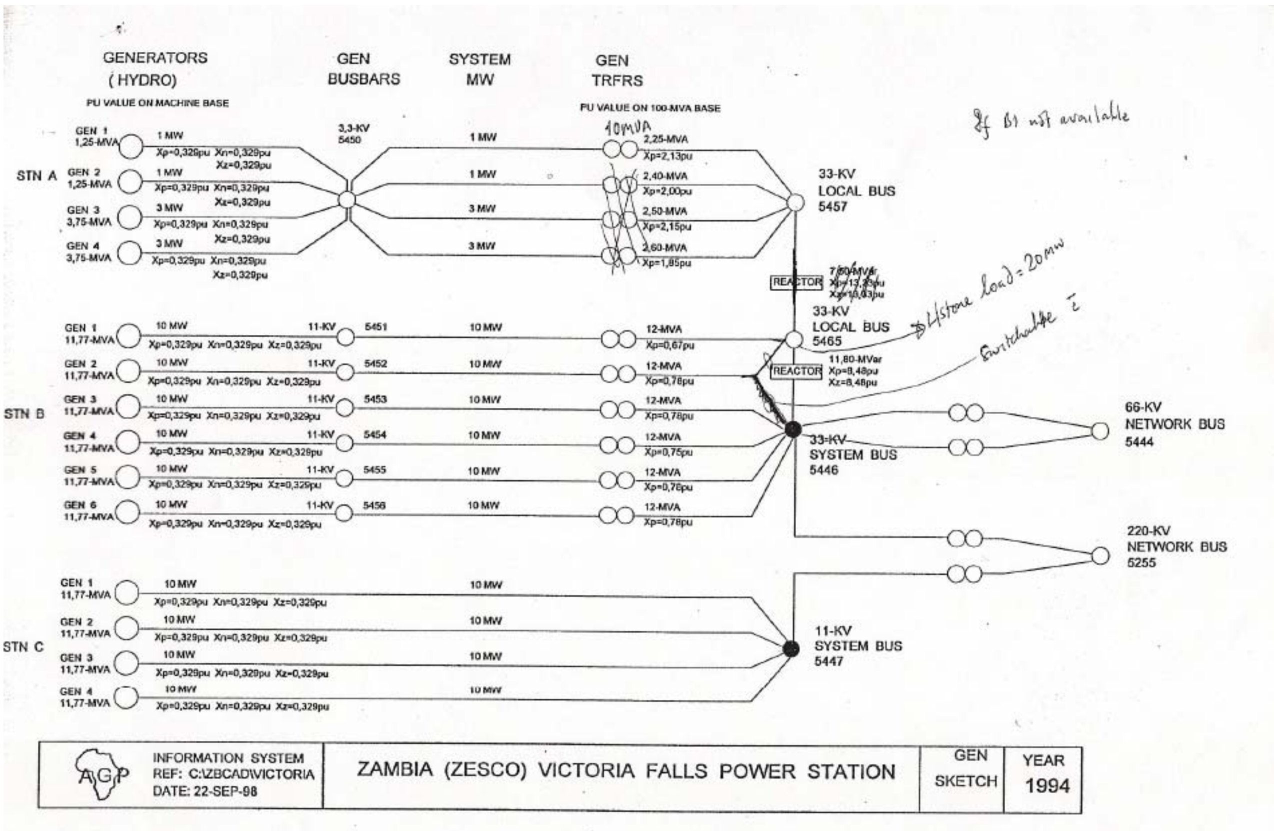

Fig E 3 Victoria Falls generator parameters