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ZESCO POWER SYSTEM STABILITY STUDIES FOR THE YEAR 2011

Master of Science thesis in the Programme of Electric Power Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, November 2011

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In partial fulfillment for the award of Master of Science degree in Electric Power Engineering, in the Department of Environment and Energy, Division of Electric Power Engineering, Chalmers University of Technology, Goteborg, Sweden

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Abstract

The purpose of this work is to look at the short term stability studies on 330 kV, 220 kV and 88 kV transmission system of the whole ZESCO Power System in terms of voltage and rotor angle stability after being exposed to severe system disturbances. The work also considers the network expansions up to 2011. The initial conditions are considered critically for better analysis. As one of the initial conditions to do the stability studies, all system variables are within acceptable limits and the stability analysis is done at both off peak and peak loads for static simulations and at peak loads only for transient simulations.

The assumptions considered, on the other hand on this study, are that the Zambian system is connected via two 330 kV circuits to the Zimbabwe system to the south and to the 220 kV Congo DR system to the North but no power exchange between these two systems is considered. Studies in steady-state and transient states have been carried out with an expected peak load demand in 2011 amounting to 1670 MW (the losses on the transmission system are not included). An additional study in stead state has been carried out with an expected off-peak load demand in 2011 amounting to 1418 MW (the losses on the transmission system are not included). In any case the generation is to match the load demand values plus power system loses.

The methodology taken was to carry out Simulations in stead state to calculate the power flows over the transmission system, the voltage profile and the active and reactive generation of the generators. N-1 Contingency situations were examined. Whatever the situation, the Zambian system must be able to satisfy the load demand and operate within the acceptable limits. Simulations were also performed in transient state to verify that the System was able to recover un acceptable situation without loss of synchronism of any generator or sustained oscillations.The most severe faults being three phase faults near generating stations and major substations on various system components and analyse the results for a specific short period (10 seconds). The faults are cleared within 100 ms. Also considered in the simulations is the taking out of some major loads and the analysis of the effect.

The major findings are that in the stead studies the system is able to withstand any N-1 contingency without exceeding limits. And in the transient state studies the overall behaviour of the system is not beyond limits. Oscillations are dumped within the expected period of 4 to 10 seconds. All generators operate in synchronism.

Key words

Rotor angle stability, transient stability, inter-area oscillations, spinning or primary reserve.

Acknowledgement.

Firstly I would like to give thanks to Dr. Tuan A. Le and the course coordinator, Ola Carlson to give me the opportunity to do the thesis on our ZESCO power system.

My second gratitude goes to my classmate, Mr. Gustavo who guided me through the process of learning the Power Factory soft ware by Dig Silent that I used on my stability studies. There were no conditions attached, he was really helpful with his great knowledge in Power Factory software.

Many thanks go to all my lecturers and classmates who shared the knowledge with me during my Masters studies at Chalmers University of Technology. Class mates like Mr. Thinley, Kalid T., Selamu T. to mention but a few, gave me un conditional guidance in most of my Study work.

Not forgetting my workmates, from the department of Engineering Development, who guided me in the simulations of various stability scenarios, Mr. Kennedy Mwanza, as my supervisor who has great knowledge as well in Power Factory software, Mr. Julius Kampamba, Mr. C. Nthala, Mr. G. Musonda and Mr. A. Sikombe. They gave me a conducive working atmosphere. I worked freely with them.

The accomplishment of this project wouldn’t have been made possible without the data that I collected from various power stations and major substations. Therefore my sincere gratitude goes to the ZESCO Engineers and Technicians who helped me gather all the necessary data I needed.

To My Mother Silika Nakamba Singoyi

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Chapter 1: Introduction

ZESCO power system has in the past twenty years under gone several of system disturbances and the latest being early last year [1]. The most common disturbances are the ones to do with rotor angle and voltage instability following a severe system fault near generating stations or on lines to major load centres. It is in this regard that there is need to do some system stability studies to find a better solution to such disturbances. Therefore the stability studies should be based on 330 kV, 220 kV and 88 kV transmission system up to 2011. The highest voltage level is 330 kV in Zambia.

The Power system stability studies on the Zambian Power network are based on the fact that by 2011 the Power demand will have increased from 1500 MW to about 1670 [1]. Generation capacity also will have been up rated by 11%. Therefore the network studies are performed with the view that there will be this kind of Generation and demand by 2011 and hence the need to perform stability studies to ascertain the stability of the system.

Some severe situations have been examined to ascertain the stability of the Zambian network. The critical period for the study is the annual peak load demand. Some load flow simulations have also been done on 80% of the full peak load demand of the Zambian network to represent the off peak load demand. The unity commitment of the peak load is characterised as follows; all the six generating units at Kafue Gorge operate at almost full capacity seconded by the four units at Kariba North Bank Power station. The rest operate at almost full capacity as well.

All power plants are modelled as Hydro power plants (HPP) in Dig Silent software. This study reports the static and dynamic behavior of the Zambian power system with the view of the increased generation and load demand by 2011. For the transient study, the electromechanical transients are considered, few seconds after the disturbance occurrence, in order to detect a potential loss of synchronism on groups.

The description of the power system is detailed enough to simulate the electromechanical transients. The study is focused on the behavior of the generators in terms of rotor angle without any power exchange with the Zimbabwe or Congo DR system.

Currently the Zambian network is operated with the spinning reserve of 70 MW since it is always interconnected with ZESA to the south and SNEL of Congo to the North. But this spinning reserve is not enough if the Zambian system were to stand on its own. The recommended spinning reserve in this situation is 180 MW representing the capacity of one of the largest machines [1].

This report has the following details;

- A brief discussion on the Zambian network is highlighted to give a wide understanding of the network.
- The basic concepts on Power system stability is illustrated in chapter three where Equal Area Criterion is explained on how it helps to give the critical clearing angle or the critical clearing time and their importance.
- The methodology used to perform the Power System Stability study
- The different steps of the proposed work

- Stead state analysis covers the load flow and contingencies
- Transient state analysis which covers significant defaults to check the behavior of the rotor angle of all the interconnected machines to ascertain synchronism.
- The results of the study that consists of permanent state and transient state analysis

Chapter 2: Overview of the Zambian Power network

This chapter gives the overview of the Zambian power system with the consideration of the neighboring country interconnections.

The Zambian electrical power system is operated as part of an interconnected power system linking South Africa and Zimbabwe to the south and the Democratic Republic of Congo (DRC) to the north, through tie-lines as shown in Figure 1.

The Zambian Electricity Supply Industry (ESI) presently consists of three major market players namely ZESCO, CEC and LHPC involved in generation, transmission, distribution and supply. System operation is coordinated by the ZESCO National Control Center in conjunction with the various control centers.

2.1 ZESCO System

ZESCO owns and operates most of the power stations, transmission system, the distribution system and the National Control Center.

ZESCO produces almost all of its electric power from hydropower stations which account for 1668 MW, as at 31st May 2010 [1]. The remainder, about 1.6 MW is produced from isolated diesel power stations.

2.1.1 Kafue Gorge Power Station

This is the largest Power Station in Zambia. It is located on the Kafue River and has been in operation since 1971. The Station has an installed capacity of 990 MW with 6 generators of 165MW each. Two generators feed one transformer consisting of three single-phase generators. There are therefore ten single-phase generators, including a spare generator.

2.1.2 Kariba North Bank Power Station (KNBPS)

KNBC is the second largest power station after Kafue Gorge. It has a total capacity of 720 MW consisting of four generators of 180 MW each. Each generator feeds one three phase transformer. The power station is located on the north bank of Kariba dam on the Zambezi River. It has been in operation since 1977.Originary it had 4 by 150 generators but there has been an uprating exercise on all the four generators to 180 MW. Currently there are two more 180 MW generators being constructed to be completed in 2012. To the south of this power station is another power station of 600 MW belonging to ZESA of Zimbabwe. The two power stations are interconnected by two by 330 kV transmission lines of 1.5 km long.

2.1.3 Victoria Falls Power Station

The station is a run-of-river station located on the Zambezi River at Victoria Falls. It has an installed capacity of 108 MW and comprises three power stations namely stations A, B and C. Station A was commissioned in 1936. It has an installed capacity of 8 MW consisting of two generators of 1 MW each and another two of 3 MW each. Station B was commissioned in 1968 and has an installed capacity of 60 MW consisting of 6 generators of 10 MW each.

Station C was commissioned in 1968 and has an installed capacity of 40 MW consisting of 4 generators of 10 MW each.

2.1.4 Small Hydropower Stations

There are four (4) Small hydro power stations with a combined capacity of 23.75 MW. These are Lusiwasi (12 MW) in Central province, Musonda Falls (5 MW) in Luapula province, Chishimba Falls (6 MW) and Lunzua (750 kW) in Northern Province.

2.1.5 Diesel Power Stations

ZESCO operates several small Diesel Power Stations throughout the country. The stations are at Lukulu, Luangwa, Chama, Zambezi, Mufumbwe, Mwinilunga, Chavuma, Kabompo and Kaputa. [1]

2.1.6 Transmission System

The transmission system has a total of 4,638 km of transmission lines spread as follows: 2,008 km of 330 kV lines, 348 km of 220 kV, 85 km of 132 kV, 704 km of 88 kV, and 2,823 km of 66 kV lines. The total transformer installed capacity is about 3,000 MVA. [1]

Transmission systems transports power from generating stations to all bulk distributions end points, the ZESCO major customer, Copper belt Energy Corporation on the Copper belt and Imports or Exports to neighboring counties

2.1.7 Distribution and Supply

The distribution system comprises the main network from the national grid and isolated networks fed from stand-alone diesel power stations. Zambia imports power at distribution voltage level from ESCOM (Malawi) to Lundazi District and ZESA (Zimbabwe) to supply Siavonga District. [1]

2.2 Lunsemfwa Hydro Power Company

Lunsemfwa Hydro Power Company owns and operates two (2) hydropower stations namely Lunsemfwa and Mulungushi power stations with installed capacities of 18 MW and 20 MW respectively. These stations are connected to the ZESCO power network**.**

2.3 Copper belt Energy Corporation

The Copper belt Energy Corporation owns and operates part of the transmission and distribution infrastructure on the Copper belt. The infrastructure includes 208 km of 220 kV lines, 590 km of 66 kV lines, 3 bulk purchase points, 5 by 220 kV substations, 28 by 66 kV substations, and 1,275 MVA of 220/66 kV transformer capacity and 1,750 MVA of 66/33/11 kV transformer capacity. [2]

CEC also owns and operates Emergency Gas Turbine Alternators (GTAs) with an installed capacity of 80 MW. They also own the 40 km long 220 kV tie line to the DRC.

2.4 System Operation

The National Control Center (NCC) coordinates all the operations in the system, which includes transmission switching, generation dispatch and exports. The Control Center uses a SCADA (Supervisory, Control and Data Acquisition) system, which was commissioned in June 1996 and upgraded in 2005. The SCADA system covers 24 transmission stations, which include four (4) Power Stations and twenty (20) Substations.

CEC operates a regional control center for its system on the Copper belt. ZESCO and Lunsemfwa Hydro Power Company also operate control rooms at their stations.

System operation is the function of maintaining the power system in a stable operating condition. This involves:

a. Monitoring changes in demand and scheduling and dispatch of generating plant in accordance with expected requirements.

b. Monitoring and taking corrective action to maintain frequency and voltage in the system.

c. Monitoring transmission lines, to ensure that the electrical and thermal stability limits are not exceeded.

d. Ensuring an acceptable level of system security.

e. Being prepared to take appropriate action in the event of a failure of any equipment that may jeopardize the security position.

f. Having a contingency plan to recover the system in the event of a complete system failure i.e. a “black-start” capability.

2.5 Regional Interconnections

The Zambia power system is connected to the regional interconnected system via two 330 kV transmission tie-lines to Zimbabwe to the south, and one 220 kV line to Congo power system to the north as shown in Figure 1.

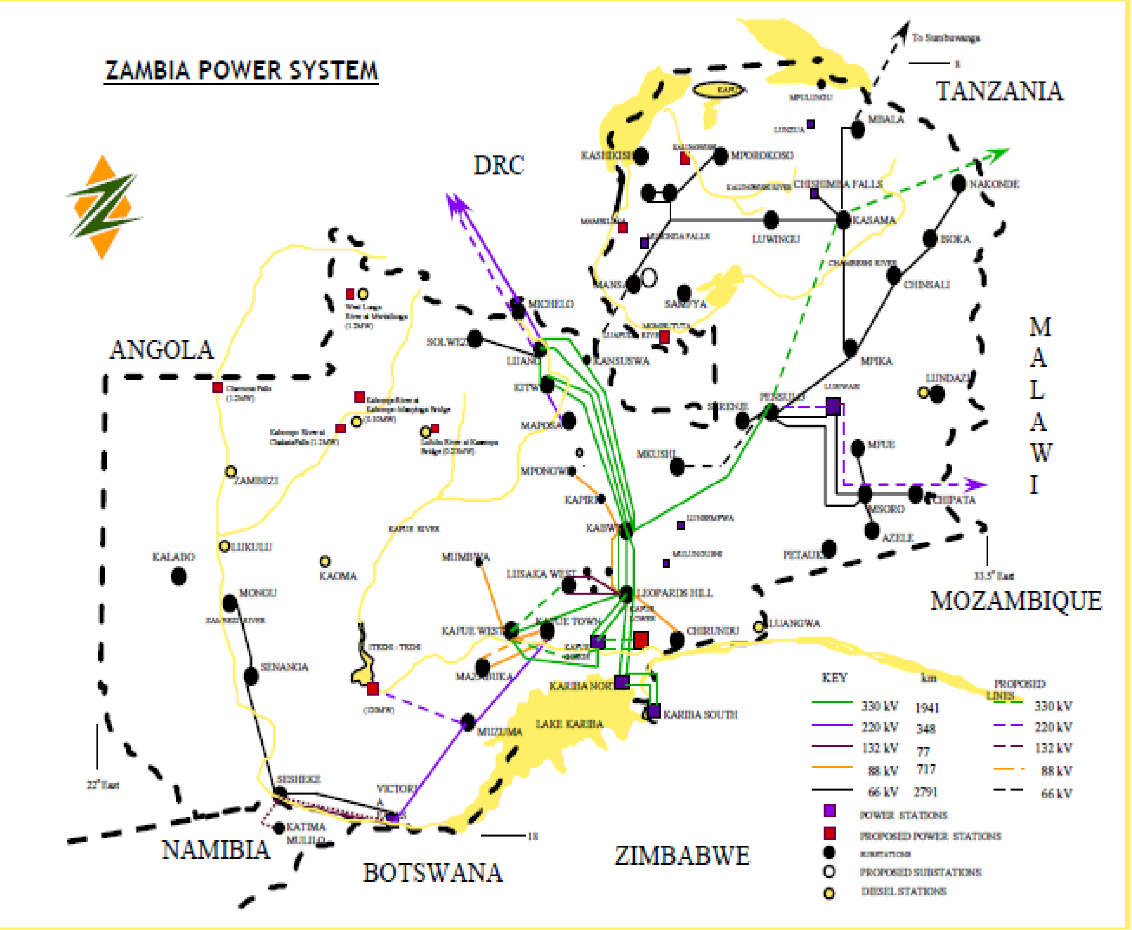


Figure 1: The Zambian Power System

The regional interconnected system is operated under the auspices of the Southern African Power Pool (SAPP), which falls under SADC. There are twelve (12) member utilities of SAPP of which nine are interconnected, including ZESCO. The SAPP objectives are to coordinate the planning and operation of member systems and to promote energy trading among members in the region. SAPP activities are coordinated by the SAPP Coordination Center based in Harare Zimbabwe.

Chapter 3: Basic concepts on Power System Stability.

The chapter describes the classification of the power system stability and its basic concepts. On the basic concepts, the chapter clearly explains various cases of system transient faults, their effects on the power network and how the system is brought back to the stead state with time.

3.1 Classification of Power System Stability.

Power system stability was first recognized as an important problem in the 1920s [l]. From the beginning, for convenience in analysis, gaining a better understanding of the nature of stability problems and developing solutions to the problems, it has been the usual practice to classify power system stability basing on the following consideration [2]:

- The physical nature of the resulting instability;
- The size of the disturbance considered;
- The devices, process, and time span that must be taken into consideration in order to determine stability; and
- The most appropriate method of calculation and prediction of stability.

The traditional large disturbance stability problem is related to the short term or transient period, which is usually limited to a few seconds following the disturbance. It is concerned with the system response to a severe disturbance, such as a transmission system fault. Much of the electric utility industry effort and interest related to system stability to date have been concentrated on the short-term response, and as a result the system is designed and operated so as to meet a set of reliability criteria concerning transient stability [3]. Well established analytical techniques and computer programs exist for the analysis of transient stability. In recent years, the need for studying the response of the system for longer periods has been recognized, and the terms mid-term and long-term stability have been introduced. Analytical tools for studying these aspects of system stability are evolving.

As power system have evolved through continuing growth in interconnections, use of new technologies and controls, and the increased operation in highly stressed conditions, different forms of system instability, frequency stability and inter-area oscillations have become greater concerns than in the past [4]. Voltage stability, frequency stability and inter-area oscillations have become greater concerns than in the past. Historically transient angle instability has been the dominant stability problem on most systems, and has been the focus of much of industry’s attention concerning system stability.

A typical modern power system is a high-order multivariable process whose dynamic response is influenced by a wide array of devices with different characteristics and response rates. Depending on the network topology, system operating condition and the form of disturbance different sets of opposing forces may experience sustained imbalance leading to different forms of instability. Below, in

Figure 2, is the summary of the classification of the system stability, giving the overall picture of the power system stability problem and identifying its categories and subcategories [4].

The classification of power system stability is for convenience case to identify causes of instability, applying suitable analysis tools, and developing corrective measures. In any given situation, however, any one form of instability may not occur in its pure form. This is particularly true in highly stressed systems and for cascading events; as systems fail one form of stability may lead to another form. However, distinguishing between different forms is important for understanding the underlying causes of the problem in order to develop appropriate design and operating procedures.

While classification of power system stability is an effective and convenient means to deal with the complexities of the problem, the overall stability of the system should always be kept in mind. Solutions to stability problems of one category should not be at the expense of another. It is essential to look at all aspects of the stability phenomena and at each aspect from more than one view point.

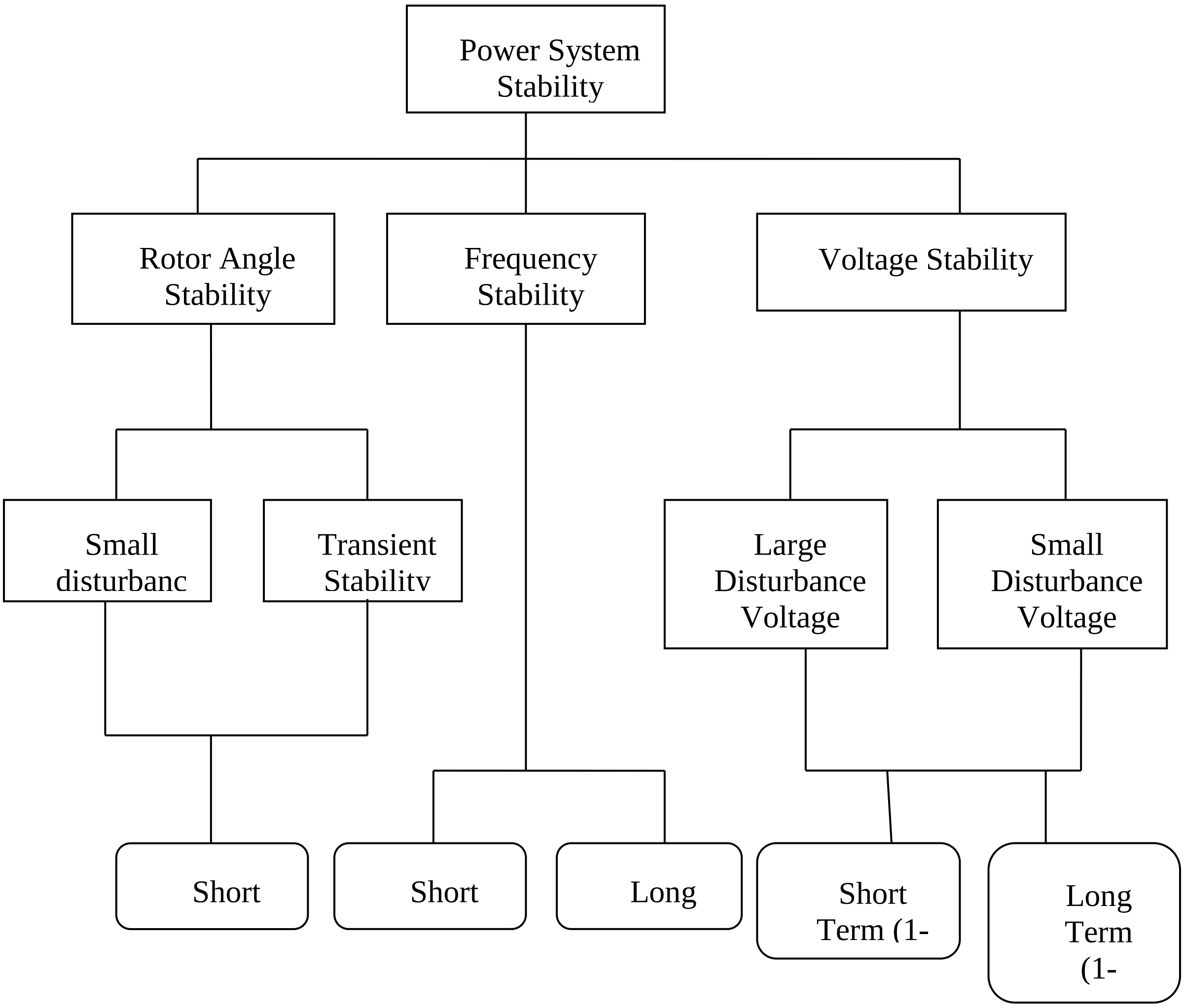


Figure 2: Classification of power system stability.

As already stated, transient angle instability has been the center of all forms of instability. In this thesis therefore we analyze further the rotor angle instability in response to short-circuit faults.

3.2 An Elementary View of Transient Stability.

Power system stability is the ability of an electric power system, for a given initial operating conditions, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact[3]. The system response to such disturbances involves large excursions of generator rotor angles, power flows, bus voltages, and other system variables.

The stability is influenced by the nonlinear characteristics of the power system. If the resulting angular separation between the machines in the system remains within certain bounds, the system maintains synchronism. Loss of synchronism because of transient instability, if it occurs, will usually be evident within 2 to 3 seconds of the initial disturbance [5] [6].

3.2.1 Loss of one Parallel Line

Consider Figure 3 below where the generator is delivering power to the infinite bus bar through two parallel lines. The infinite bus bar represents a voltage source of constant voltage magnitude and constant frequency;

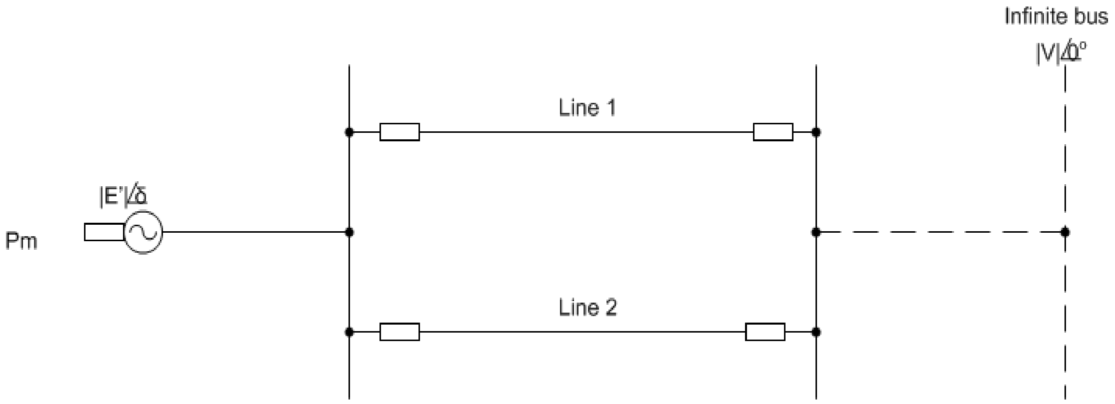


Figure 3: Generator connected to infinite bus bar through two parallel lines.

In Figure 4 below all resistances are neglected.

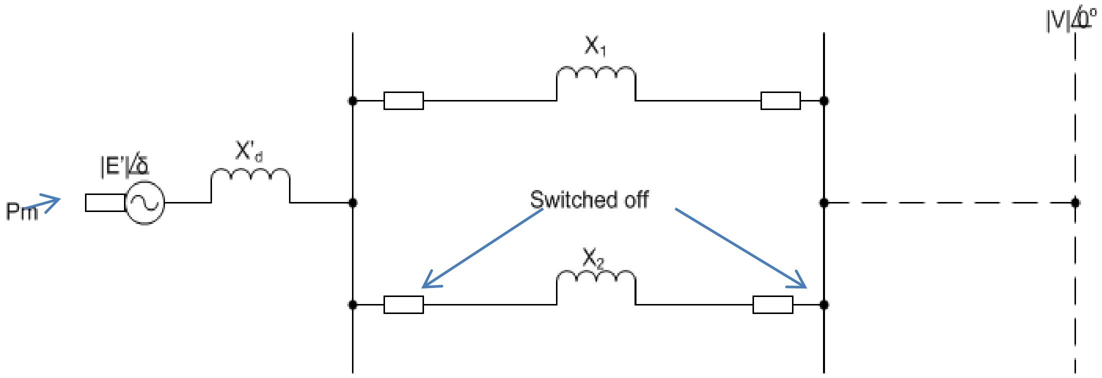


Figure 4: Electrical representation.

The electrical power transfer to the infinite bus before one line is isolated is given by

$$P_{elect} = \frac{|E'||V|}{X'_d + X_1//X_2} Sin\delta = P_{max1} Sin\delta \qquad (1)$$

Where δ is the angle between the internal voltage of the machine and that of the infinite bus.

E′ is the voltage behind the transient reactance X'_d.

V is the infinite bus voltage,

P_{elect} is the electrical power output and finally

P_m is the mechanical power in put.

After the line is isolated the electrical power transfer becomes

$$P_{elect} = \frac{|E'||V|}{X'_d + X_1} Sin\delta = P_{max2} Sin\delta \qquad (2)$$

$$P_{max} = \frac{|E'||V|}{X'_d + X_1//X_2} = \frac{|E'|X|V|}{Xt} \qquad (3)$$

If one of the circuits is out of service the effective reactance X_t in Figure 4 is higher and the corresponding maximum power is lower.

Basically the two equations, equation (1) and (2) give the power angle curves as shown below in Figure 5 where P_{max1} and P_{max2} power curves are clearly shown.

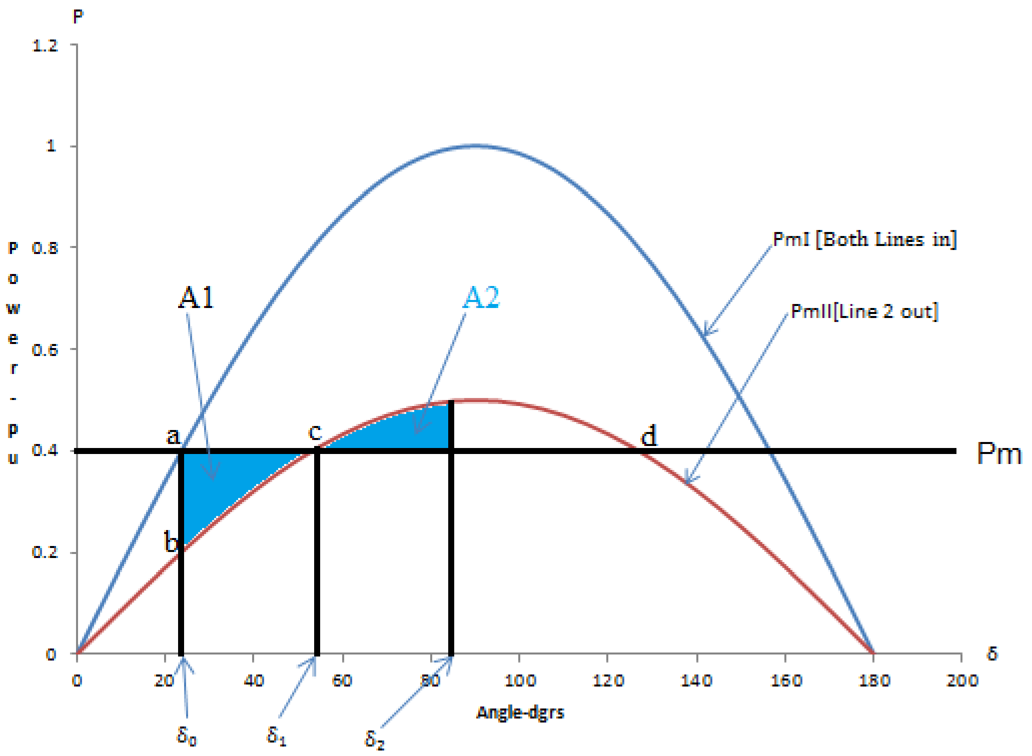


Figure 5: Equal area criterion for the loss of one parallel line

When the system is perturbed, the magnitude of E′ remains constant at its pre-disturbance value and δ changes as the generator rotor speed deviates from synchronous speed ω_o.

3.2.2 Equal Area Criterion;

The equation of motion or the swing equation may be written as

$$\frac{2Hd^2\delta}{\omega_o dt^2} = P_m - P_{max}Sin\delta \qquad (4)$$

Where P_m = mechanical power input, in Pu

P_{max} = maximum electrical power output, in Pu

H = inertia constant, in MW.s/MVA

δ = rotor angle in elect. rad

t = time, in s

From the equation (3) we have following relationship between the rotor angle and the accelerating power [2];

$$\frac{d^2\delta}{dt^2} = \frac{\omega_o}{2H}(P_m\text{-}P_e) \qquad (5)$$

Now P_e is a nonlinear function of δ, and therefore the above equation cannot be solved directly. If both sides are multiplied by 2dδ/dt, then

$$2\frac{d\delta}{dt}\frac{d^2\delta}{dt^2} = \frac{\omega_{o(P_m-P_e)}}{H}\frac{d\delta}{dt}$$

Or

$$\frac{d}{dt}\left[\frac{d\delta}{dt}\right]^2 = \frac{\omega_{o(Pm-Pe)}}{H}\frac{d\delta}{dt}$$

Integrating gives

$$\left[\frac{d\delta}{dt}\right]^2 = \int \frac{\omega_{o(Pm-Pe)}}{H} d\delta \qquad (6)$$

The speed deviation dδ is initially zero. It will change as a result of the disturbance. For stable operation, the deviation of angle δ must be bounded, reaching a maximum value (as at δ_2 on the line2 out- power curve on Figure 5 above) and then changing direction. This requires the speed deviation dδ/dt to become zero at some time after the disturbance. Therefore, from the equation(4), as a criterion for stability we may write;

$$\int_{\delta_0}^{\delta_2} \frac{\omega_0}{H}(P_m - P_e)d\delta = 0 \qquad (7)$$

Where δ_0 is the initial rotor angle and δ_2 is the maximum rotor angle. As illustrated in the last figure above. Thus, the area under the function P_m-P_e plotted against δ must be zero if the system is to be stable. In the last figure above this is satisfied when area A_1 $is\ equal\ to\ area\ A_2$. Kinetic energy is gained by the rotor during acceleration when δ changes from δ_0 to δ_1. The energy gained is

$$E_1 = \int_{\delta_0}^{\delta_1}(P_m - P_e)d\delta = \text{area } A_1 \qquad (8)$$

The energy lost during deceleration when δ changes from δ_1 to δ_2 is;

$$E_2 = \int_{\delta_1}^{\delta_2}(P_e - P_m)d\delta = \text{area } A_2 \qquad (9)$$

Since the losses are not considered the energy gained is equal to the energy lost which means that area A_1 in equation (8) is equal to areaA_2 in equation(9). And this forms the basis of equal area criterion.

The criterion enable us to determine the maximum swing of δ and hence the stability of the system without computing the time response through formal solution of the swing equation.

We now consider the loss of one parallel line. The initial operating point of the system would be at point a (from figure4) where the mechanical power Pm is equal to electrical power P_e. When the line is opened the operating point suddenly changes to point b because the transfer reactance has now changed. Because of the inertia angle δ cannot change instantly. The mechanical power is greater than the electrical power at this point hence there will be some accelerating power that will make the rotor angle shift from δ_0 to δ_1 at point c. At this point the mechanical power is equal to electrical power but because of the acceleration power which makes the speed of the rotor higher than the synchronous speed ω_0 and the rotor angle continues to rise until it reaches maximum value δ_2 where the rotor speed is now equal to synchronous speed and where the kinetic energy gained during this acceleration will have expended by transferring the energy to the system. That is area A_1 is equal to area $A_{2.}$ At this point the electrical power will be greater than mechanical power and consequently there will be some deceleration power and the rotor speed will be seen to be reducing. Eventually we see that there will be some oscillations about point c until these oscillations are damped.

If we now suddenly increase the mechanical power from the initial operating point shown in Figure 5, we see a situation where we need more decelerating power available because area A_1 has now increased. At this point we search for the critical point, a point at which the two areas will just be equal so that we don't lose stability of the system.

3.2.3 Fault at Either end of the Line

Another interesting situation is when we have a fault on one of the parallel lines but close to either end of that line. See the Figure 6 below.

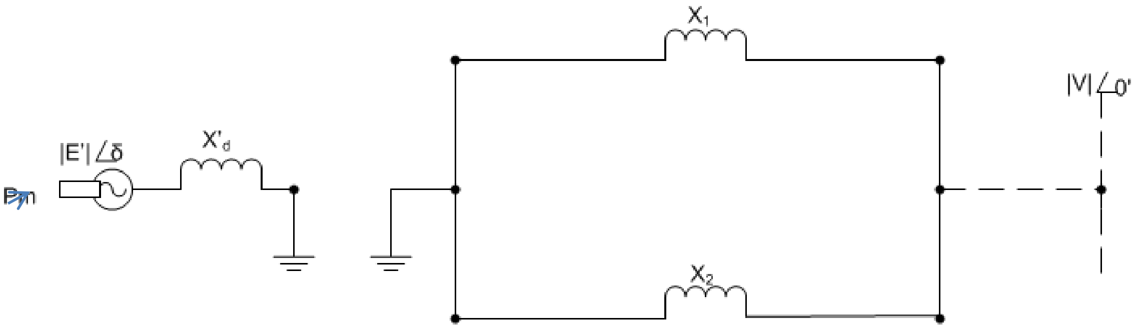


Figure 6: Short circuit at the end of the line

From the last figure above we see that there is no power transfers to the infinite bus because the voltage just after the machine reactance becomes zero. See Figure 7 below. During the fault the operating point is as shown in figure5 as P_{eII}

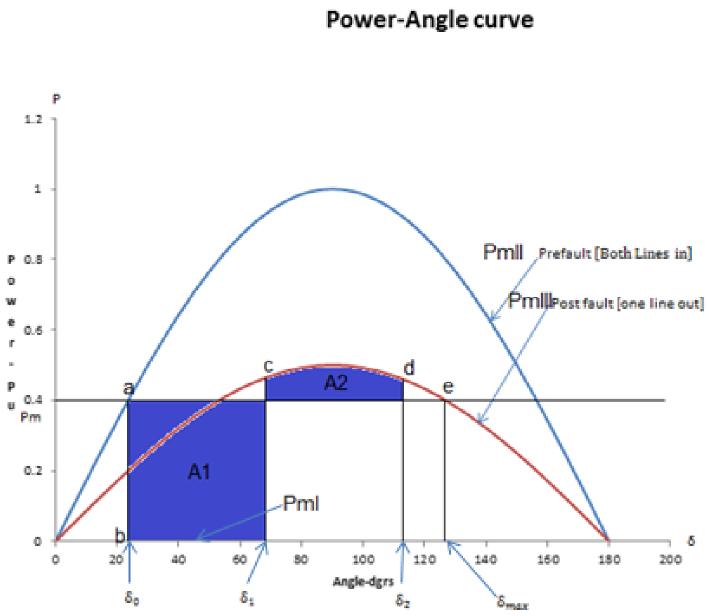


Figure 7: Power angle relationship after a fault at either end of the parallel line

In this case when a fault occurs the operating point suddenly shifts from point a to point b. Before the fault the power angle relationship is given by

$P_{elect} = P_{maxI}$ Sinδ and during the fault the power transfer is zero and after the fault is cleared by opening the faulted line the power transfer becomes; P_{maxII} Sinδ as shown in Figure 7 above.

The rotor angle won't change immediately owing to the inertia and it will move along the zero line to δ_1 when the fault is cleared. At this point the new operating point will be at c. and because rotor speed is greater than the synchronous speed the rotor continues to accelerate until point d where the rotor speed is equal to the synchronous speed. At this point the Electrical power is higher than the mechanical power hence the deceleration in the rotor speed which gives out some oscillations until the oscillations are dumped.

From the figure above we see that if we increase the clearing time the acceleration area becomes larger and this limits the deceleration area available to a critical clearing angleδ_1. Similary if we reduce the fault clearing angle the smaller is the accelerating area compared to the deceleration area available and hence more chance of the system remaining stable. And if the initial operating point is raised a similar situation occurs where the decelerating area available becomes smaller compared to the acceleration area.

We therefore conclude that the stability of the system is dependent on two things in this case, the initial operating angle and the fault clearing time.

3.2.4 Fault in the Middle of the Line

Now let us take another scenario where the fault occurs in the middle of the line. See Figure 8 below;

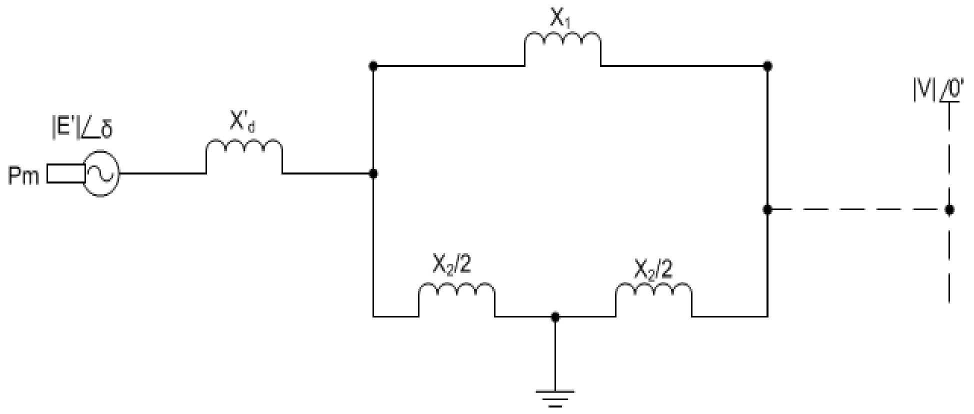


Figure 8: Fault in the middle of the line.

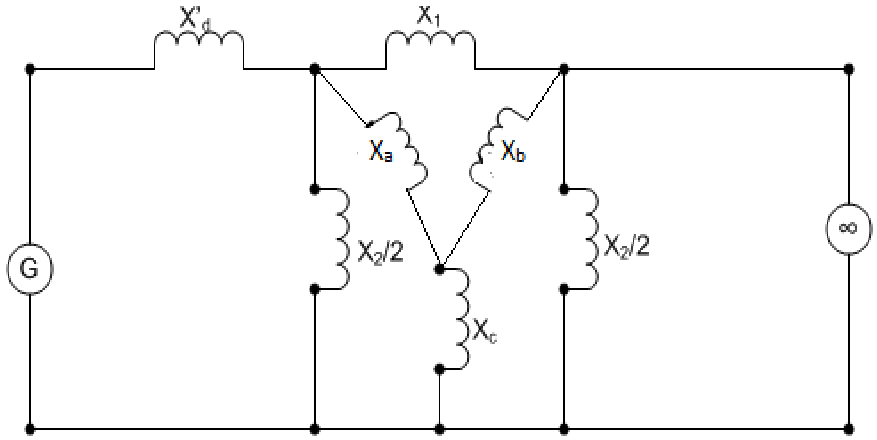


Figure 9: Circuit model for the fault in the middle of the line

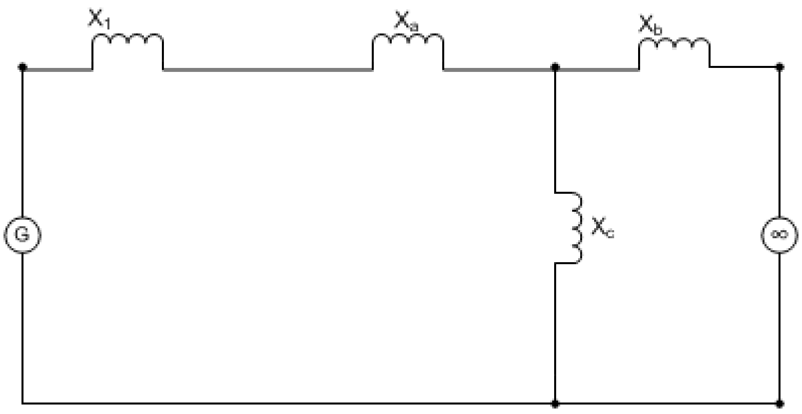


Figure 10: Star delta transformation

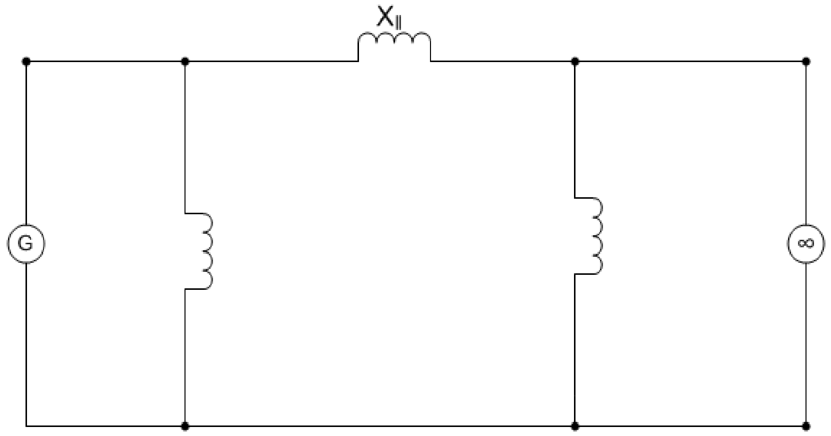


Figure 11: Final circuit representation where only X_{II} is considered as the transfer reactance

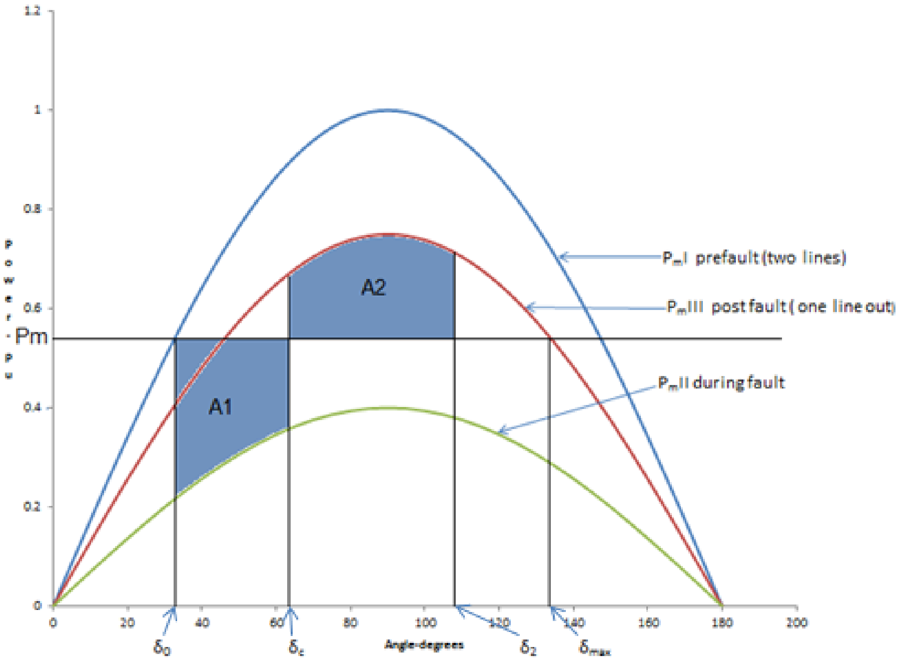


Figure 12: Equal Area criterion for the fault in the middle of the line

From the above figures, Figure 8, Figure 9, Figure 10, Figure 11 and Figure 12, we see that the only difference between the previous case and this one is that in this case where the fault is in the middle of the line the power transfer never goes to zero hence more chances of the system remaining stable unless the fault clearing time is increased in such a way that the accelerating area is larger than the decelerating area.

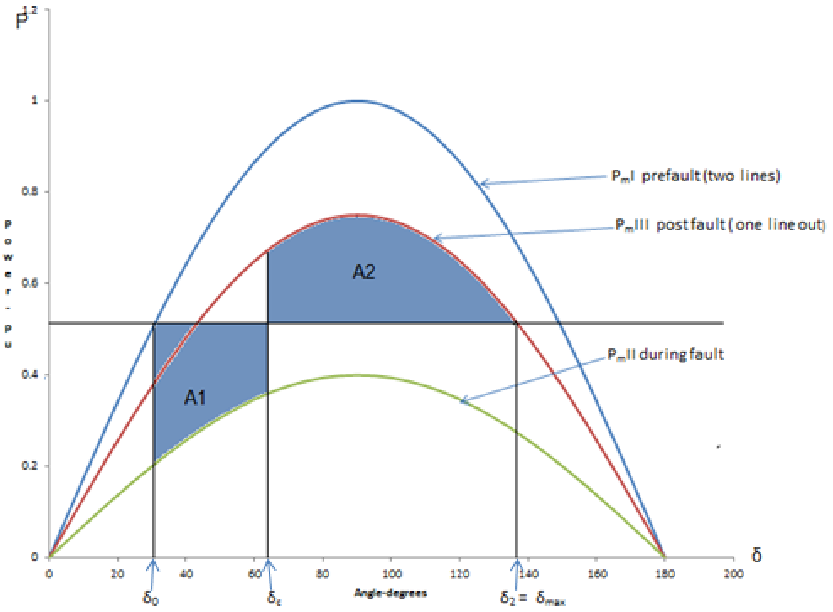


Figure 13: Critical clearing angle

The critical clearing angle is found at the point where the accelerating angle is just equal to the decelerating area as we increase the fault clearing time. See Figure 13 below;

3.2.5 Auto-reclosing on to Either Transient or Permanent Fault

Another interesting scenario is the case of auto-reclosing on to the transient fault or persistent fault. We consider the case where we have a fault in the middle of the line. See Figure 14 below

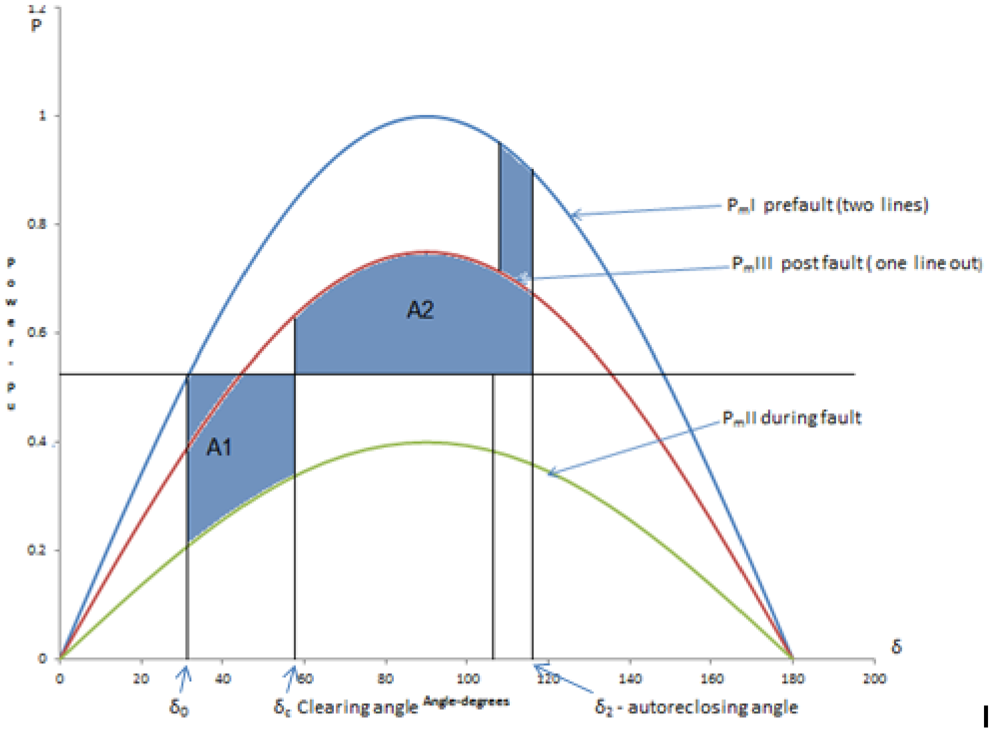


Figure 14: Auto reclosing to either transient or persistent fault

If we auto-reclose to a transient fault we see that the decelerating area becomes larger due to the fact that the new operating point goes back to the initial operating point. But if we auto reclose to a persistent fault the decelerating area reduces and we may go into a runaway situation because now the accelerating power is larger than the decelerating power available. This situation can be avoided if the auto-reclosing is only allowed once and more time set for the initiation of the auto-reclosing, say 10 seconds and by then the system will have been stabilized. Delayed auto reclosing only applies to three phase faults because this is when we have critical situation for the rotor stability.

Chapter 4: Power System Modeling

This chapter describes how various power system components are modeled in the Power Factory Software. On the generating end side voltage regulators and speed governors are modeled accordingly and finally the load side the load characteristics are modeled to give desired results in the power system simulations.

4.1 Voltage Regulations

On all the generators connected to the Zambian transmission system, the units are equipped with an Automatic Voltage Regulation (AVR) and a speed governor. Whatever the real regulations used to equip the future HPP, the behavior will be very close of the proposed models. The retained models are displayed hereafter. See Figure 15 and **Figure 16** for AVR models. Concerning the speed governor model, the IEEEG3 [13] model was proposed for all the generators connected to the Zambian transmission system. It is normally used for hydro generators. See Figure 17. The parameters of the regulations are displayed in Appendix 11, Table 15.

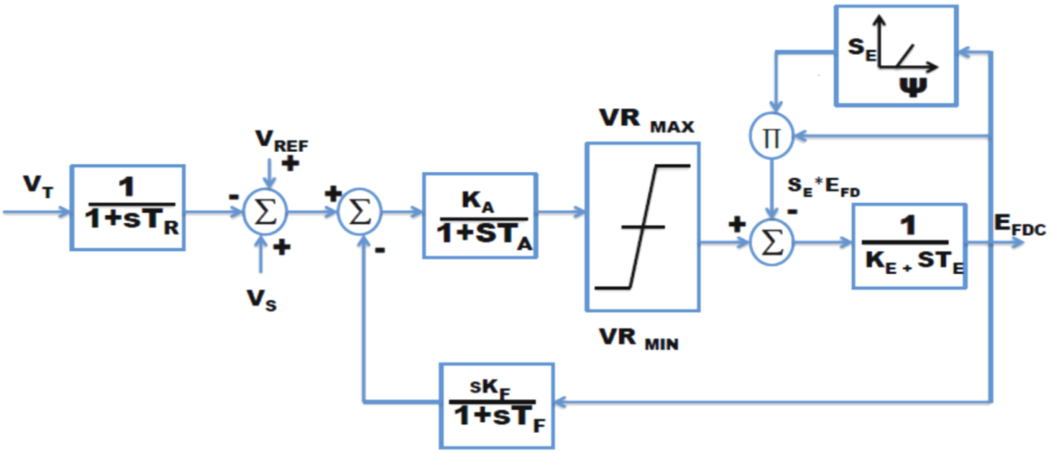


Figure 15: AVR Model IEEET1A

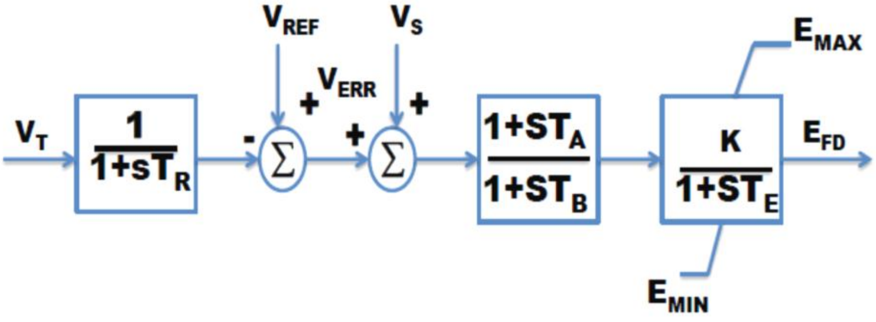


Figure 16: AVR Model SCRX/SEXS

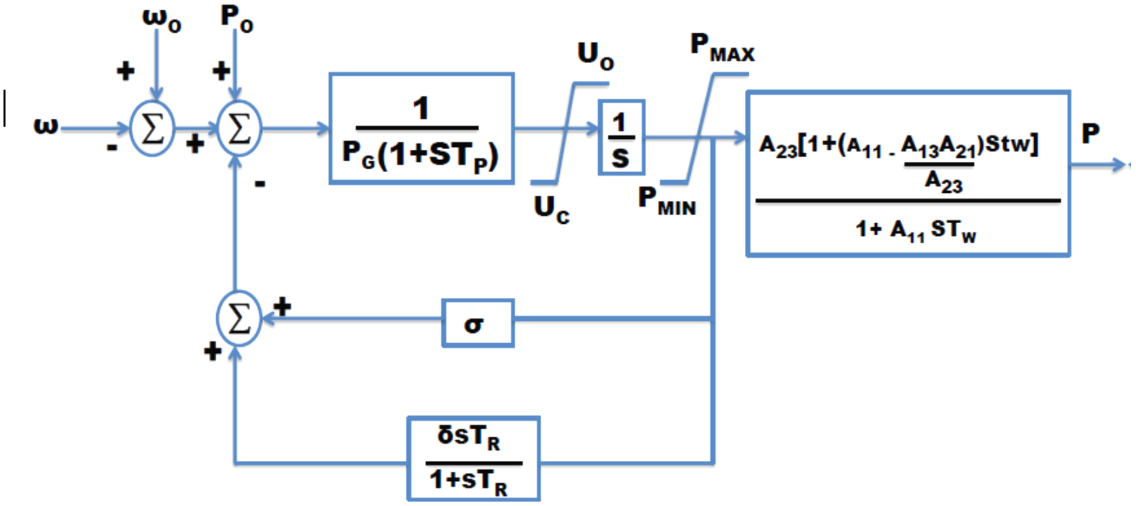


Figure 17: Speed Governor Model IEEEG3

4.2 Load Modeling

4.2.1 General Description

Load characteristics have long been known to have a significant effect on system performance, and transient stability results are known to be highly dependent upon the load characteristics assumed [7]. Because of the uncertainty of the actual load characteristics utilities have attempted to use characteristics that would lead to conservative designs. It has been shown, however, that there is no single load characteristic that leads to a conservative design for all system configurations [8].

Dynamic load models are of growing importance to the studies of power system dynamics [9]. If the load representation is not of sufficient accuracy, the simulation results will not correspond to the actual response of the load. This will affect the assessment of system stability limit [10]. Frequently, both power industry engineers and academic researchers study system stability and planning by utilizing static load models (i.e. constant impedance, constant current, constant power, and combinations of these models) to represent the relationship between power and voltage. Because these load models are static and time invariant, they are not sufficiently accurate to describe the load behaviors under various operation conditions. The uncertainty regarding load composition and the sufficiency of these static load models have been questioned in some publications [11]. However, the load behavior is mostly dynamic, with the real and reactive powers being changed at any instant of time [12]. For this reason, dynamic load models are considered.

In power systems, electrical load consists of various different types of electrical devices, from incandescent lamps and heaters to large arc furnaces and motors. It is often very difficult to identify the exact composition of static and dynamic loads in the network. This load composition can also vary depending on factors such as the season, time of day etc. [7].

Additionally, the term load can be used for entire MV-feeders in case of an HV-system or LV-feeders if an MV system is in the center of interest.

4.2.2 Load Modeling in Power Factory Software.

In Power Factory, most of the loads are modeled as General loads where they represents:
- A complete feeder
- A combination of dynamic and static loads

The general load model representation is shown in Figure 18 below;

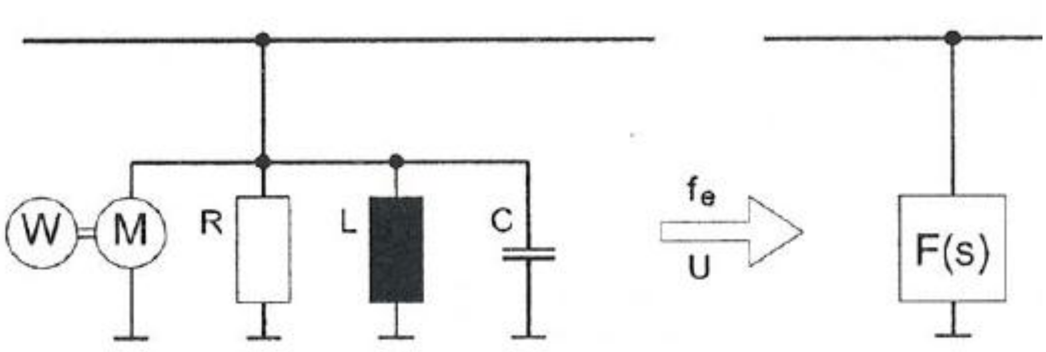
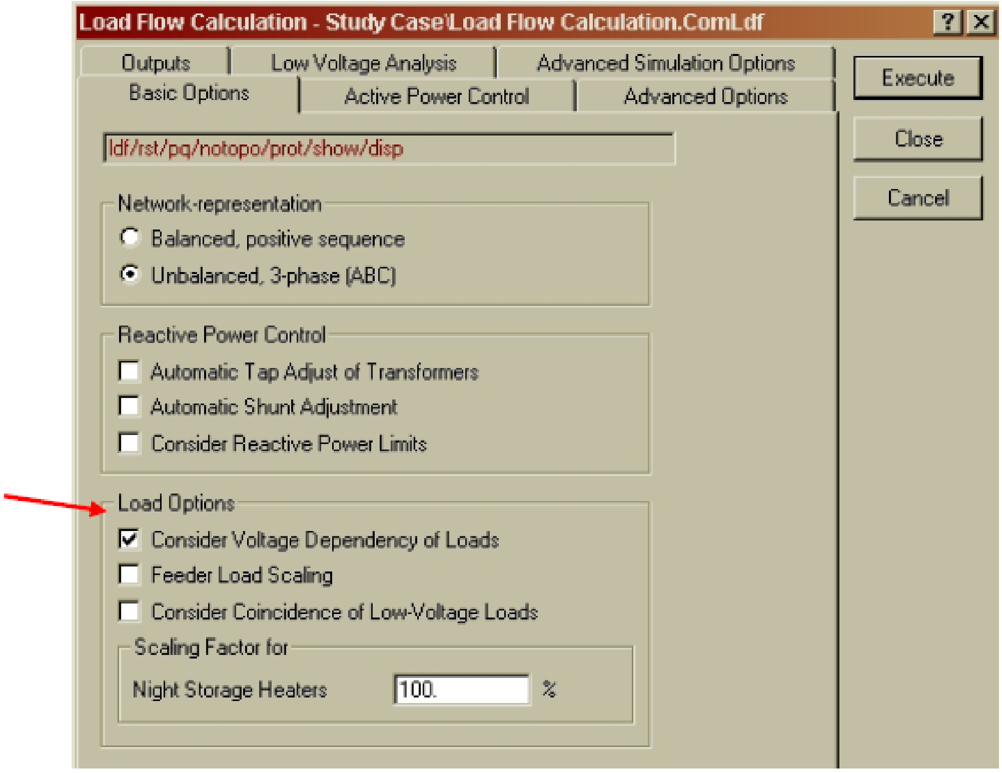


Figure 18: Power Factory general load model

For load flow analysis, in Power Factory software [13], there is an option to specify for balanced or unbalanced loads. Furthermore the user can specify the input parameters for the load. Based on the available data, the user can select the relevant combination of parameters from S (apparent power), P (real power), Q (reactive power), cos(phi) (power factor) and I (current). The other parameters such as voltage dependence loads and the number of phases used are specified in Load type as shown in the window below in Figure 19.



ldf/rst/pq/notopo/prot/show/disp

Network-representation

○ Balanced, positive sequence
● Unbalanced, 3-phase (ABC)

Reactive Power Control

☐ Automatic Tap Adjust of Transformers
☐ Automatic Shunt Adjustment
☐ Consider Reactive Power Limits

Load Options

☑ Consider Voltage Dependency of Loads
☐ Feeder Load Scaling
☐ Consider Coincidence of Low-Voltage Loads

Scaling Factor for

Night Storage Heaters 100. %

Figure 19: Load flow calculation window indicating the voltage dependence terms for load flow calculations in Power Factory software.

4.2.3 Three phase load modeling for transient Stability Simulations.

For transient simulations a three-phase load can be modeled as a percentage of static and dynamic load. The static portion is modeled as constant impedance whereas the dynamic load can be modeled as either a linear load or a non-linear load [13].

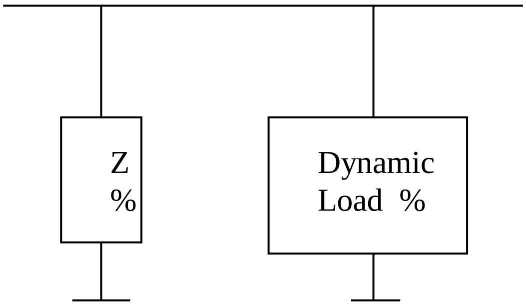


Figure 20: Diagram indicating the mixture of static and dynamic load model used for stability studies.

According to [13] the models used to approximate the behavior of linear and non-linear dynamic loads are given in Figure 21 and **Error! Reference source not found.** respectively.

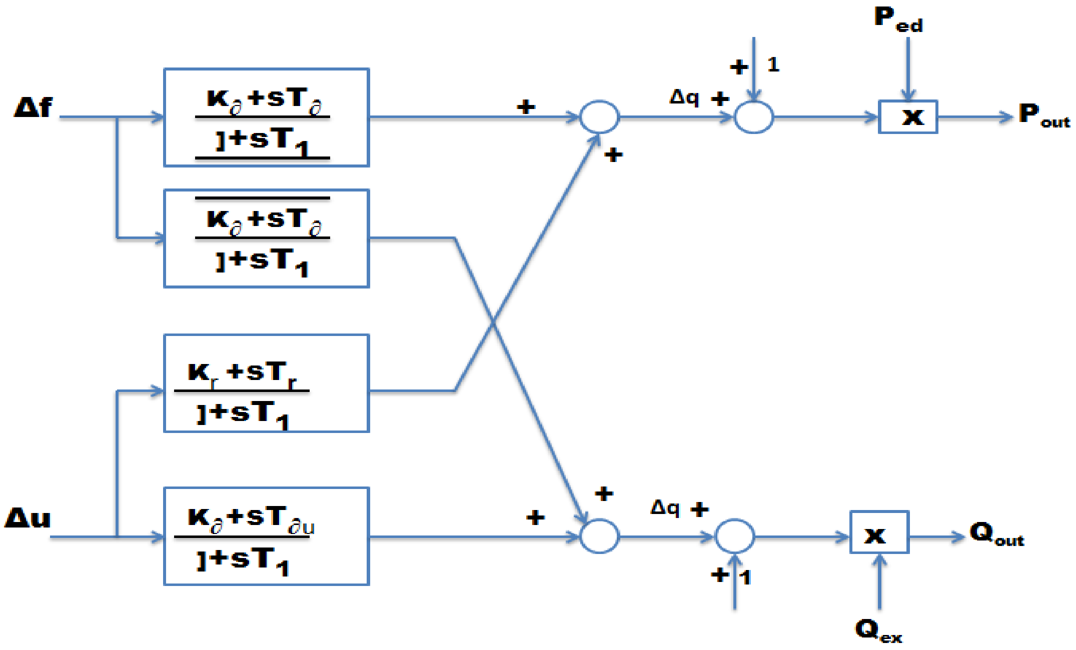


Figure 21: Model used to approximate the behavior of the linear dynamic load.

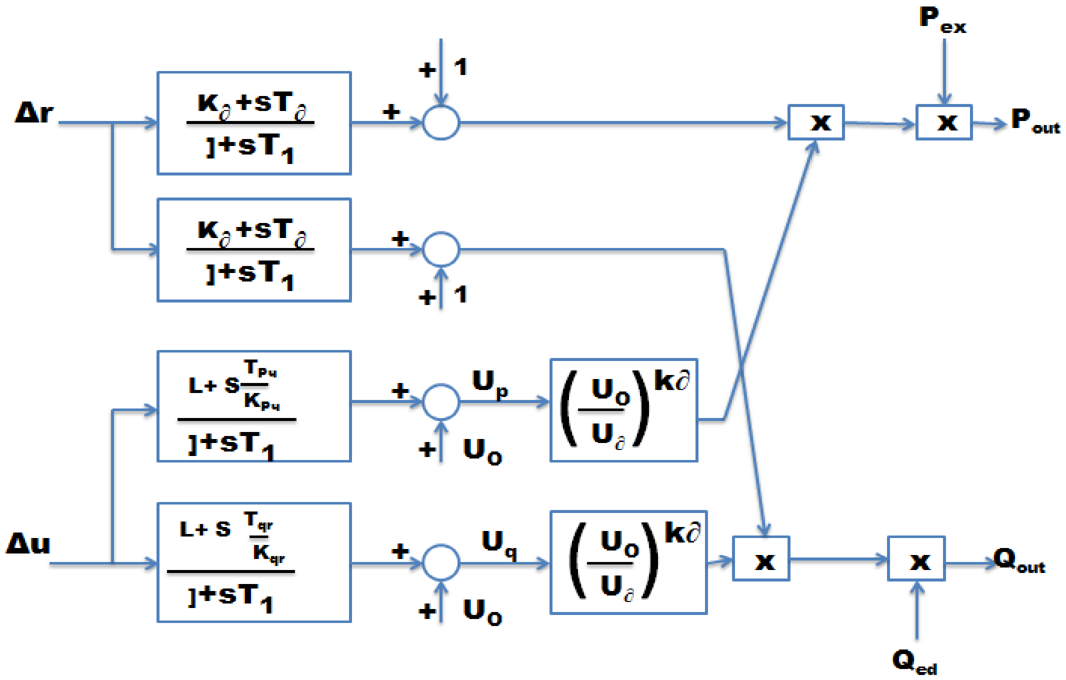


Figure 22: Model used to approximate the behavior of the non-linear dynamic load.

Figure 21 and Figure 22 represent small signal model and are valid in limited voltage range. This voltage range is defined as U_{min} and U_{max}. and outside this range the power is adjusted as shown in Figure 23 below [13].

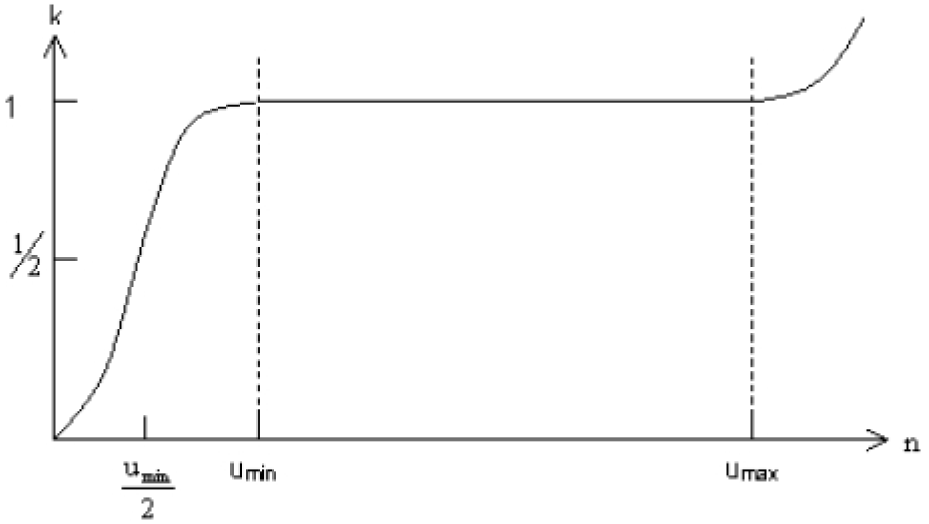


Figure 23: Low/High voltage approximations used in the non-linear dynamic load model.

Chapter Five: Power System Simulations

Here the chapter describes the power system simulations in a detailed manner. The chapter starts with the planning criteria to show some limits which are considered in the simulation results followed by the methodology to show in which state the system is considered in a particular simulation and finally the analysis of the various simulation results of different cases.

5.1 Planning Criteria

The Zambia transmission system must satisfy the N-1 criteria, where it is meshed. So, following the tripping of any network component (overhead lines, transformers, generators) no overload must appear on the remaining components. Thermal ratings of equipment should not be exceeded during the outage. The operational limits must be respected whatever the situation.

The operational limits, in normal and emergency situations, are described hereafter. In normal conditions the flows must be kept below the thermal rating of each network element. The voltage at each bus bar must be kept within 95% and 105% of its nominal value. The generators must operate within their reactive capabilities (generation and absorption).

In emergency situation (outage of one element), the thermal rating of any equipment should not be exceeded. The voltage should be kept within 95% and 105% of its nominal value. A 15% over-voltage will be acceptable during 5 s and a 20 % over-voltage will be acceptable during 1s or 2s. This is according to IEEE 1453-2004 standard.

In transient state, the power system must remain stable following a three-phase fault cleared within 100 ms. This time includes the current transformer errors, protection relay response and the breaker operating time.

Transient stability is that ability of the power system to maintain synchronism when subjected to a severe transient disturbance such as a fault on transmission facilities, loss of generation, or loss of large load [14]. The generators must operate in synchronism without inter-area oscillations. Power and voltage oscillations must be damped.

Inter-area oscillations can appear on the power system if the power exchange between two parts of the power system (areas) is close to the maximum transmitted power [14]. They can also appear between one power plant and the transmission system.

Spinning or primary reserve corresponds to the power delivered by generators due to the action of their speed governor following a decline of the system frequency. All the units may participate to the primary reserve. For the purpose of the load flow calculations, it has been assumed that each unit can participate to the primary reserve up to 10% of its net output. The primary reserve of the Zambian system alone will amount to 180 MW by 2011, corresponding to loss of one large unit at Kariba North Bank or Kafue Gorge power stations.

5.2 Methodology

The operation of the Zambian power system was simulated to analyze its behavior and its ability to operate within its capacity in stead state and in transient state.

In permanent-state the electrical parameters that characterize the behavior of the system, currents, voltages, generation, angles of the machine, position of the automatic on-load tap-change, are assumed to be constant. The load flow calculation is used to simulate the behavior of the power system in permanent state and to calculate its electrical parameters. The behavior of the power system is satisfactory if, and only if [14]:

- The currents in the lines are below their rating;
- The flows through the transformers are below their rating
- The voltage profile is within the acceptable limits;
- The reactive power output of the generators respects their capability curve.

All load flow calculations were carried out for the peak and the off-peak load demands.

In transient-state the system is affected by a fault, such as a short-circuit, a tripping of a unit or a disconnection of a load, all these parameters evolve very quickly during a brief period until the system recovers a new permanent state situation. If the system fails to do it, a loss of synchronism between some units and other units of the system may occur [14].

The transient-state analysis determines if the up rating of the machines can improve the control of the voltage and the frequency of the system. The electromechanical behavior of the power system is analyzed versus time for few seconds. The generators and their control system are represented in detail, taking into account their inertia, their turbine with the speed governor, the electrical parameters of their alternator with their excitation system and voltage regulator. Moreover, the voltage and frequency dependent characteristics of loads are represented. A fault is applied on a line connected to Hydro Power Plant and then is cleared by permanent tripping of the faulted element following a normal operation of the protections. The dynamic behavior of the Machines connecting to the system is satisfactory if [14]:

- No loss of synchronism of units occurs;
- No sustained voltage oscillations are detected on substations;
- No sustained oscillations of the rotor angle appeared on the machines;
- Voltage profile and currents remain within the acceptable limits.

5.3 Analysis in Stead State

5.3.1 Presentation

The simulations were performed for the year 2011 with the 10% uprated generation capacity as indicated in Appendix1. They were performed in normal conditions, with all the network elements in operation. Kafue Gorge Power plant operates at almost maximum output minus the primary reserve. They were also performed in N-1 conditions. The following N -1 cases were examined:

- Tripping of one of the two 330 kV circuits connecting Kariba North to the Zambian system.
- Tripping of one of the two 330 kV circuits between Kafue Gorge and LHill substation.
- Tripping of 330 kV Kafue Gorge-Kafue west line.
- Tripping of 220 kV Vic.Falls-Muzuma line
- Tripping of one of the three 330kV circuits between Leopards Hill and Kabwe.
- Tripping of one of the two circuits between Kabwe and Luano and between Kabwe and Kitwe.
- Tripping of the 330 kV Luano-Kansanshi Mine.
- Tripping of the 330 kV Kabwe-Pensulo Line.

The generation had been adjusted to the Zambian load in order to have no transit on the two
circuits interconnecting the Zambian and the Zimbabwe systems, i.e. between Kariba North Bank and Kariba South Bank substations. The power system must operate within the limits defined by the Zambian grid code. If it does not, improvements (such as capacitor banks) will be proposed to allow a satisfactory operation.

The load flow calculations were performed in normal and in N-1 conditions for the peak and the off-peak.

5.4 Load flow Calculations at Peak Period

Load flow gives us the analysis of the power system in terms of power flow, real and reactive power, on various lines and the voltage magnitudes and respective angles at various bus bars at a particular time instant for given condition of Generation and loads [13].

The power system operation is considered as Quasi-static, the static analysis of power network. The real power balance, reactive power balance, transmission flow limits and bus voltage limits is studied.

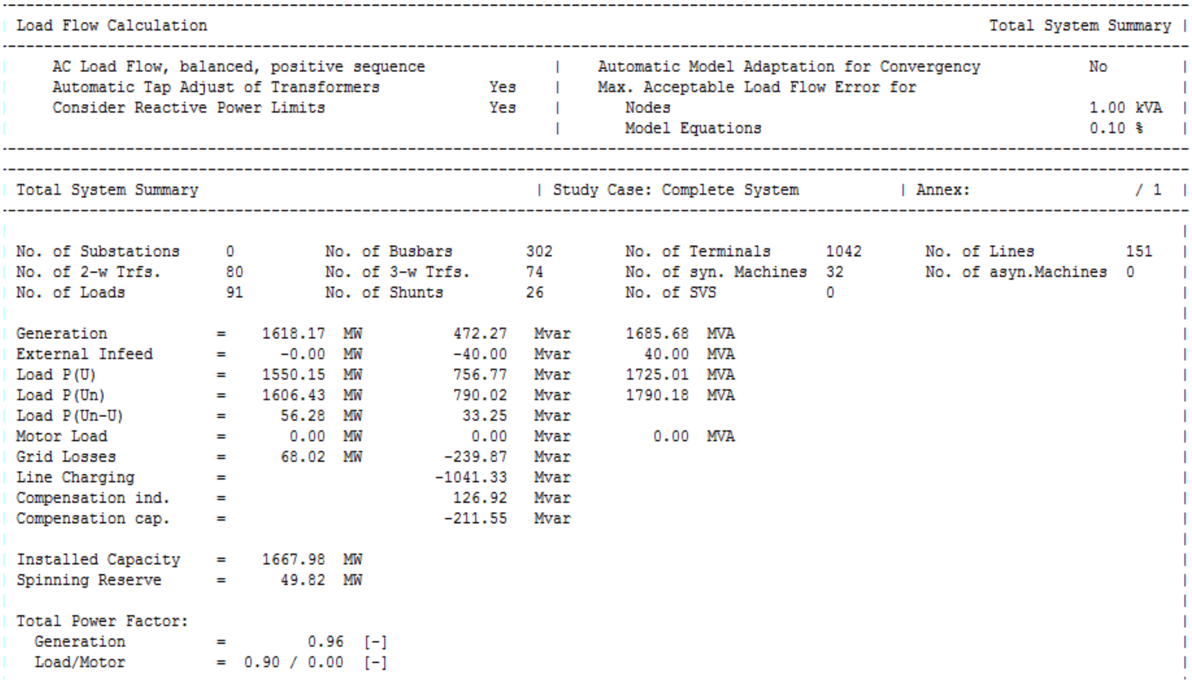
In Power Factory software the following is specified: the generating bus bars as PV buses simply because at these buses the voltage magnitude is maintained by the excitation of the generators. The Kafue Gorge bus bar has been selected as slack bus bar. This is a reference bus bar where voltage magnitude and angle are specified. This means that all loses are assigned to this bus bar. The real and reactive power is allowed to vary at this bus bar.

5.4.1 Analysis in Normal Conditions

The simulation was performed in normal conditions; all the network elements were in operation. The generation is located in the south of the transmission system and about 45% of the total demand is located in the north of the system (Copper belt area).See Figure 24 and Figure 25 below. The North of the system is then supplied from the South through four 330 kV lines between Kabwe and Luano substations of which two are direct lines ,then one goes via Kitwe substation to Luano the fourth one goes via Kitwe and Chambishi substations. See Figure 1. Kariba North substation is linked to Kariba south substation through two 330kV circuits. These two border systems are balanced in order to have no load on these two circuits. The unit commitment of the Zambian network is displayed in Table 2. Figure 24 below shows the Generated power, loses and the installed capacity

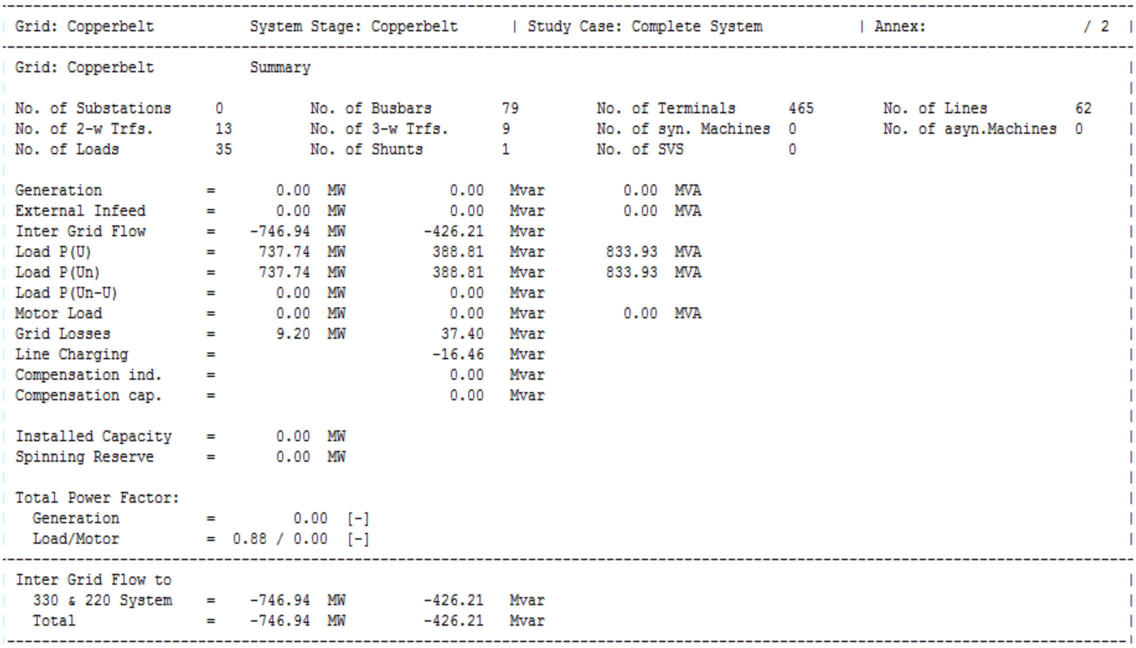
As can be seen Figure 24,the system is operating at almost full capacity hence the spinning reserve cannot hold system stability in case of loss of one generator in Kafue Gorge or Kariba unless the interconnections from other mentioned countries are considered as it is shown in the N-1 analysis below.

In case of voltage profile, on the Copper belt area, the voltage can be controlled in a satisfactory way with two Static Var compensator units, which have been implemented in two main 330kV substations (i.e. one in Kitwe and one in Luano). To operate the system within the voltage limits, the reactive compensation means were connected as shown in Appendix7 Table 3. Despite heavy loads on the copper belt, which accounts for 45% of the total load, the voltage profile is within the limits. The power factor is still ok with this compensation despite the high inductive load on the copper belt.



```
-------------------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                                                   Total System Summary |
-------------------------------------------------------------------------------------------------------------------------------
|     AC Load Flow, balanced, positive sequence                |    Automatic Model Adaptation for Convergency            No        |
|     Automatic Tap Adjust of Transformers             Yes     |    Max. Acceptable Load Flow Error for                             |
|     Consider Reactive Power Limits                   Yes     |       Nodes                                             1.00 kVA  |
|                                                              |       Model Equations                                   0.10 %    |
-------------------------------------------------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------------------------------------------------
| Total System Summary                                       | Study Case: Complete System          | Annex:                / 1  |
-------------------------------------------------------------------------------------------------------------------------------
|                                                                                                                               |
| No. of Substations     0         No. of Busbars        302       No. of Terminals     1042       No. of Lines           151   |
| No. of 2-w Trfs.       80        No. of 3-w Trfs.      74        No. of syn. Machines  32        No. of asyn.Machines   0     |
| No. of Loads           91        No. of Shunts         26        No. of SVS            0                                     |
|                                                                                                                               |
| Generation           =    1618.17  MW         472.27   Mvar      1685.68  MVA                                                |
| External Infeed      =      -0.00  MW         -40.00   Mvar        40.00  MVA                                                |
| Load P(U)            =    1550.15  MW         756.77   Mvar      1725.01  MVA                                                |
| Load P(Un)           =    1606.43  MW         790.02   Mvar      1790.18  MVA                                                |
| Load P(Un-U)         =      56.28  MW          33.25   Mvar                                                                   |
| Motor Load           =       0.00  MW           0.00   Mvar         0.00  MVA                                                |
| Grid Losses          =      68.02  MW        -239.87   Mvar                                                                   |
| Line Charging        =                      -1041.33   Mvar                                                                   |
| Compensation ind.    =                        126.92   Mvar                                                                   |
| Compensation cap.    =                       -211.55   Mvar                                                                   |
|                                                                                                                               |
| Installed Capacity   =    1667.98  MW                                                                                         |
| Spinning Reserve     =      49.82  MW                                                                                         |
|                                                                                                                               |
| Total Power Factor:                                                                                                           |
|   Generation         =         0.96  [-]                                                                                      |
|   Load/Motor         =  0.90 / 0.00  [-]                                                                                      |
```

Figure 24: Calculated load flow at peak period



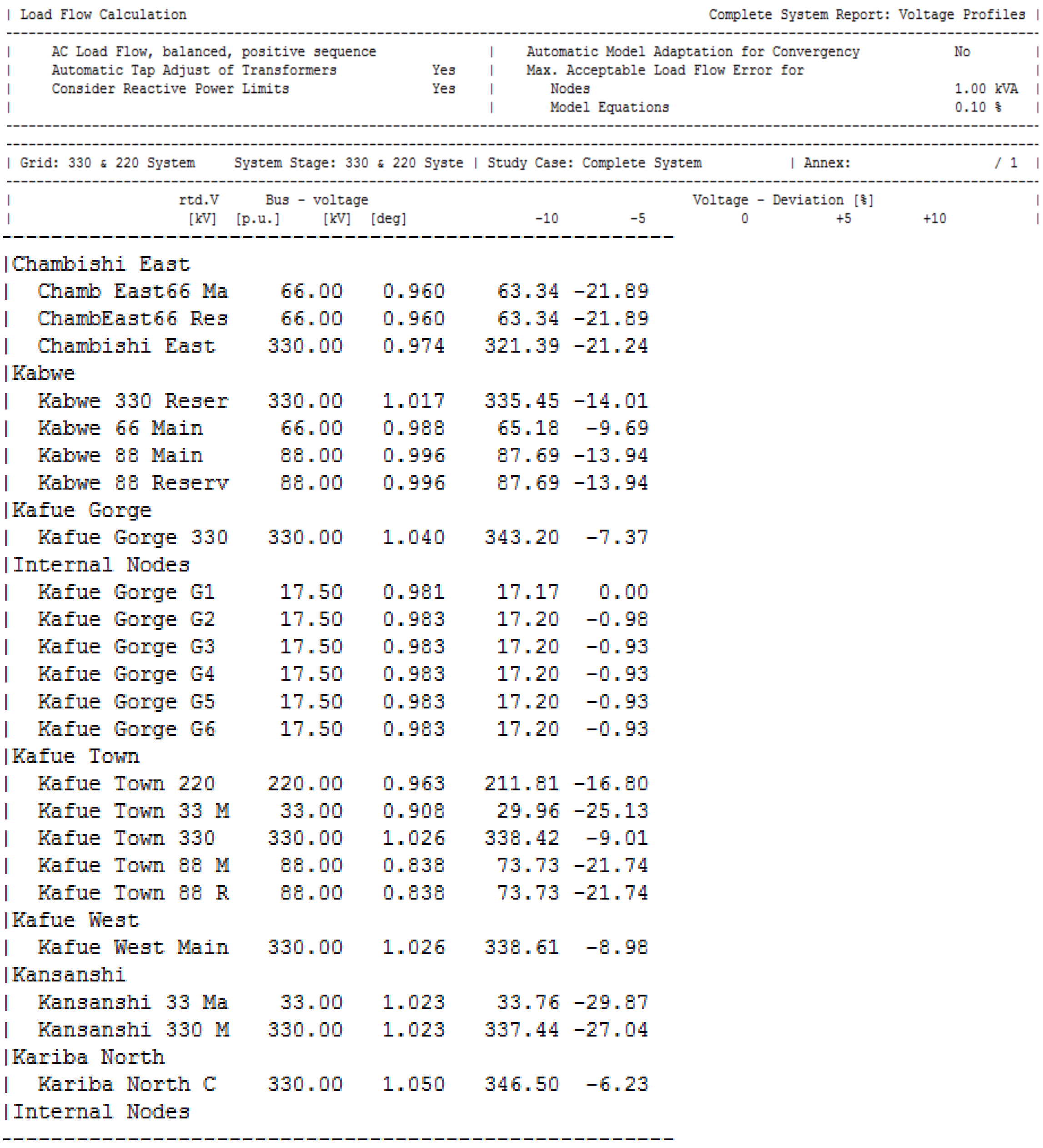
```
-----------------------------------------------------------------------------------------------------------------------------------
| Grid: Copperbelt           System Stage: Copperbelt       | Study Case: Complete System           | Annex:                 / 2   |
-----------------------------------------------------------------------------------------------------------------------------------
| Grid: Copperbelt           Summary                                                                                               |
|                                                                                                                                  |
| No. of Substations      0         No. of Busbars        79         No. of Terminals      465        No. of Lines          62     |
| No. of 2-w Trfs.        13        No. of 3-w Trfs.      9          No. of syn. Machines  0          No. of asyn.Machines  0      |
| No. of Loads            35        No. of Shunts         1          No. of SVS            0                                       |
|                                                                                                                                  |
| Generation             =      0.00  MW            0.00   Mvar         0.00  MVA                                                  |
| External Infeed        =      0.00  MW            0.00   Mvar         0.00  MVA                                                  |
| Inter Grid Flow        =   -746.94  MW         -426.21   Mvar                                                                    |
| Load P(U)              =    737.74  MW          388.81   Mvar       833.93  MVA                                                  |
| Load P(Un)             =    737.74  MW          388.81   Mvar       833.93  MVA                                                  |
| Load P(Un-U)           =      0.00  MW            0.00   Mvar                                                                    |
| Motor Load             =      0.00  MW            0.00   Mvar         0.00  MVA                                                  |
| Grid Losses            =      9.20  MW           37.40   Mvar                                                                    |
| Line Charging          =                        -16.46   Mvar                                                                    |
| Compensation ind.      =                          0.00   Mvar                                                                    |
| Compensation cap.      =                          0.00   Mvar                                                                    |
|                                                                                                                                  |
| Installed Capacity     =      0.00  MW                                                                                           |
| Spinning Reserve       =      0.00  MW                                                                                           |
|                                                                                                                                  |
| Total Power Factor:                                                                                                              |
|   Generation           =        0.00  [-]                                                                                        |
|   Load/Motor           = 0.88 / 0.00  [-]                                                                                        |
-----------------------------------------------------------------------------------------------------------------------------------
| Inter Grid Flow to                                                                                                               |
|   330 & 220 System     =   -746.94  MW         -426.21   Mvar                                                                    |
|   Total                =   -746.94  MW         -426.21   Mvar                                                                    |
|----------------------------------------------------------------------------------------------------------------------------------|
```

Figure 25: Copper belt load under calculated load flow.

The loading on Copper belt lines are within limits. As at now the lines are only loaded 25% to 36% of the capacity as shown in Table 4. Therefore for N-1 criterion the lines will still be safe in terms of their loading capacity.

With these capacitor banks on the copper belt main load centers and two Static Var Compensators, the behavior of the Zambian transmission system was generally satisfactory.

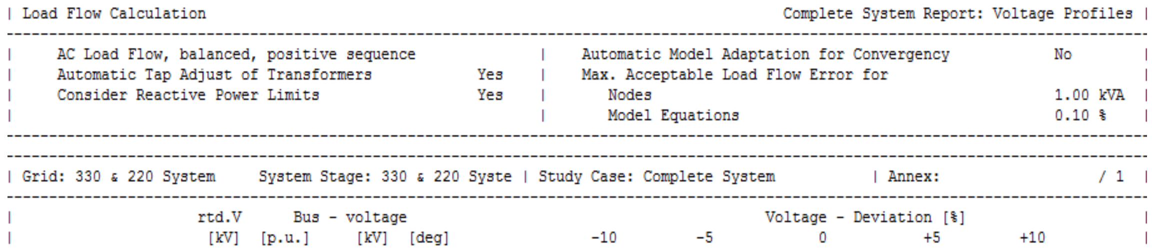
The voltage profile of Kafue town 88 kV substation exceeded the lowest limit (0.95 p.u.), see Figure 26 below. This is because the reactor which prevents high voltages during light loads is on, but this is normally out during heavy loads and the voltage profile in this earlier improves.



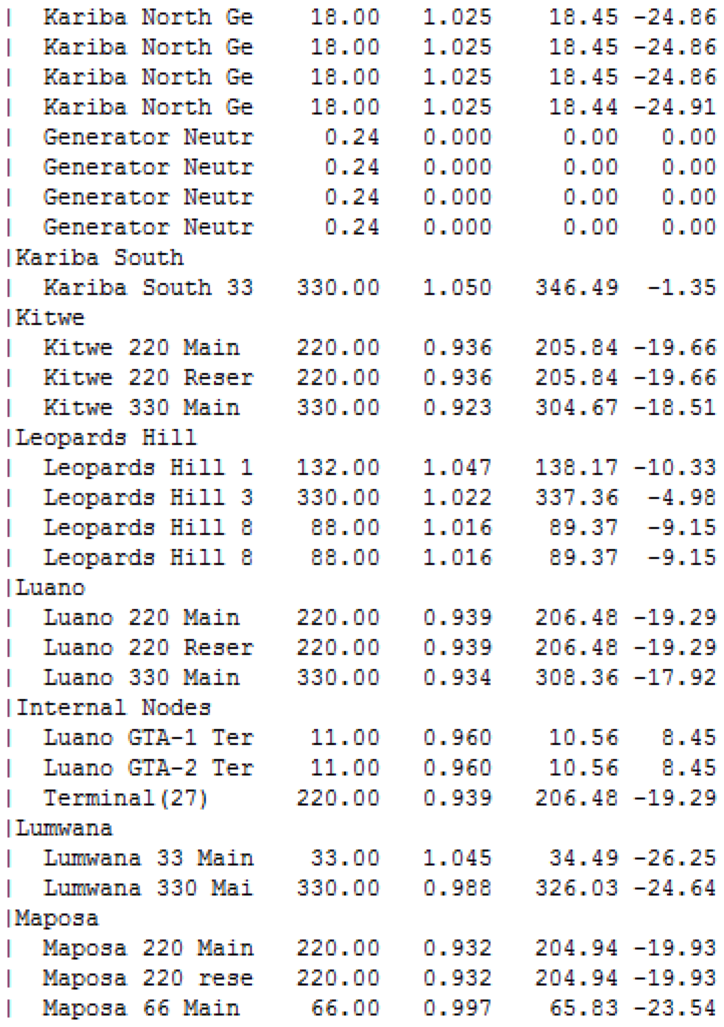
```
| Load Flow Calculation                                                                       Complete System Report: Voltage Profiles |
--------------------------------------------------------------------------------------------------------------------------------------
|     AC Load Flow, balanced, positive sequence                  |    Automatic Model Adaptation for Convergency           No          |
|     Automatic Tap Adjust of Transformers               Yes     |    Max. Acceptable Load Flow Error for                              |
|     Consider Reactive Power Limits                     Yes     |       Nodes                                            1.00 kVA    |
|                                                                |       Model Equations                                  0.10 %      |
--------------------------------------------------------------------------------------------------------------------------------------
--------------------------------------------------------------------------------------------------------------------------------------
| Grid: 330 & 220 System     System Stage: 330 & 220 Syste | Study Case: Complete System          | Annex:                    / 1  |
--------------------------------------------------------------------------------------------------------------------------------------
|                   rtd.V      Bus - voltage                                     Voltage - Deviation [%]                             |
|                    [kV]  [p.u.]     [kV]  [deg]              -10         -5          0          +5         +10                     |
-----------------------------------------------------
|Chambishi East
|  Chamb East66 Ma    66.00   0.960   63.34 -21.89
|  ChambEast66 Res    66.00   0.960   63.34 -21.89
|  Chambishi East    330.00   0.974  321.39 -21.24
|Kabwe
|  Kabwe 330 Reser   330.00   1.017  335.45 -14.01
|  Kabwe 66 Main      66.00   0.988   65.18  -9.69
|  Kabwe 88 Main      88.00   0.996   87.69 -13.94
|  Kabwe 88 Reserv    88.00   0.996   87.69 -13.94
|Kafue Gorge
|  Kafue Gorge 330   330.00   1.040  343.20  -7.37
|Internal Nodes
|  Kafue Gorge G1     17.50   0.981   17.17   0.00
|  Kafue Gorge G2     17.50   0.983   17.20  -0.98
|  Kafue Gorge G3     17.50   0.983   17.20  -0.93
|  Kafue Gorge G4     17.50   0.983   17.20  -0.93
|  Kafue Gorge G5     17.50   0.983   17.20  -0.93
|  Kafue Gorge G6     17.50   0.983   17.20  -0.93
|Kafue Town
|  Kafue Town 220    220.00   0.963  211.81 -16.80
|  Kafue Town 33 M    33.00   0.908   29.96 -25.13
|  Kafue Town 330    330.00   1.026  338.42  -9.01
|  Kafue Town 88 M    88.00   0.838   73.73 -21.74
|  Kafue Town 88 R    88.00   0.838   73.73 -21.74
|Kafue West
|  Kafue West Main   330.00   1.026  338.61  -8.98
|Kansanshi
|  Kansanshi 33 Ma    33.00   1.023   33.76 -29.87
|  Kansanshi 330 M   330.00   1.023  337.44 -27.04
|Kariba North
|  Kariba North C    330.00   1.050  346.50  -6.23
|Internal Nodes
-----------------------------------------------------
```

Figure 26: voltage profile for the calculated load flow.

The voltage profile of Leopard Hill 88 kV and Kabwe 330 kV substations (1.036 p.u) was the closest to the upper limit. Luano recorded the lowest voltage on the copper belt about 0.94 p.u as seen from Figure 26. This is because of the increased load on the two new mine Kansanshi and Lumwana connected to this bus bar. At Lumwana we have capacitor banks that improve the voltage profile in this area. See Figure 27 below,



```
| Load Flow Calculation                                                                       Complete System Report: Voltage Profiles |
--------------------------------------------------------------------------------------------------------------------------------------
|     AC Load Flow, balanced, positive sequence                  |    Automatic Model Adaptation for Convergency           No          |
|     Automatic Tap Adjust of Transformers               Yes     |    Max. Acceptable Load Flow Error for                              |
|     Consider Reactive Power Limits                     Yes     |       Nodes                                            1.00 kVA    |
|                                                                |       Model Equations                                  0.10 %      |
--------------------------------------------------------------------------------------------------------------------------------------
--------------------------------------------------------------------------------------------------------------------------------------
| Grid: 330 & 220 System     System Stage: 330 & 220 Syste | Study Case: Complete System          | Annex:                    / 1  |
--------------------------------------------------------------------------------------------------------------------------------------
|                   rtd.V      Bus - voltage                                     Voltage - Deviation [%]                             |
|                    [kV]  [p.u.]     [kV]  [deg]              -10         -5          0          +5         +10                     |
```



```
|  Kariba North Ge    18.00   1.025    18.45 -24.86
|  Kariba North Ge    18.00   1.025    18.45 -24.86
|  Kariba North Ge    18.00   1.025    18.45 -24.86
|  Kariba North Ge    18.00   1.025    18.44 -24.91
|  Generator Neutr     0.24   0.000     0.00   0.00
|  Generator Neutr     0.24   0.000     0.00   0.00
|  Generator Neutr     0.24   0.000     0.00   0.00
|  Generator Neutr     0.24   0.000     0.00   0.00
|Kariba South
|  Kariba South 33   330.00   1.050   346.49  -1.35
|Kitwe
|  Kitwe 220 Main    220.00   0.936   205.84 -19.66
|  Kitwe 220 Reser   220.00   0.936   205.84 -19.66
|  Kitwe 330 Main    330.00   0.923   304.67 -18.51
|Leopards Hill
|  Leopards Hill 1   132.00   1.047   138.17 -10.33
|  Leopards Hill 3   330.00   1.022   337.36  -4.98
|  Leopards Hill 8    88.00   1.016    89.37  -9.15
|  Leopards Hill 8    88.00   1.016    89.37  -9.15
|Luano
|  Luano 220 Main    220.00   0.939   206.48 -19.29
|  Luano 220 Reser   220.00   0.939   206.48 -19.29
|  Luano 330 Main    330.00   0.934   308.36 -17.92
|Internal Nodes
|  Luano GTA-1 Ter    11.00   0.960    10.56   8.45
|  Luano GTA-2 Ter    11.00   0.960    10.56   8.45
|  Terminal(27)      220.00   0.939   206.48 -19.29
|Lumwana
|  Lumwana 33 Main    33.00   1.045    34.49 -26.25
|  Lumwana 330 Mai   330.00   0.988   326.03 -24.64
|Maposa
|  Maposa 220 Main   220.00   0.932   204.94 -19.93
|  Maposa 220 rese   220.00   0.932   204.94 -19.93
|  Maposa 66 Main     66.00   0.997    65.83 -23.54
```

Figure 27: Voltage profile for the calculated load flow under normal system condition

5.5 Analysis in N-1 Conditions at Peak Load

Tripping of lines between Major Hydro Power Plants and the Copper belt area were analyzed at peak load:

- One of the three 330 kV circuits between Kariba North and Leopards Hill
- One of the three 330 kV circuits between Leopards Hill and Kabwe
- One of the two 330 kV circuits between Kabwe and Luano
- One of the two 330 kV circuits between Kabwe and Kitwe
- Pensulo line from Kabwe

After each tripping, the Zambian network impedance is increased and so the losses. Then, the flow over the two circuits between Kariba North Bank substation and Kariba South Bank substation will correspond to the additional losses.

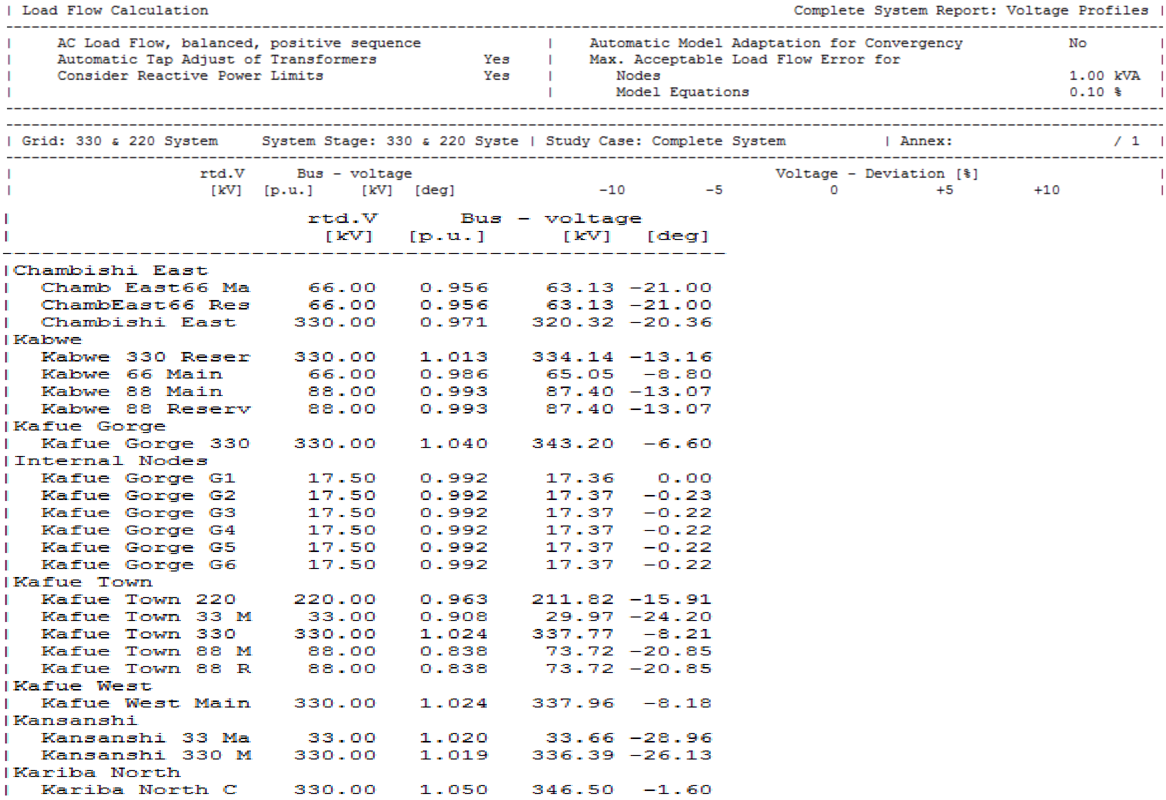
5.5.1 Tripping of one of the two 330 kV circuits between Kariba North and Leopards Hill

Following the tripping of the circuit, the behavior of the system was satisfactory, no overload

Occurred on the transmission system. The initial power flowing through the tripped circuit Kariba North - Lhill 1A was the same as that of the other parallel circuit. See appendix8. The tripped line was loaded to 27% of its capacity. Therefore the remaining line was loaded to 54% after a tripping.

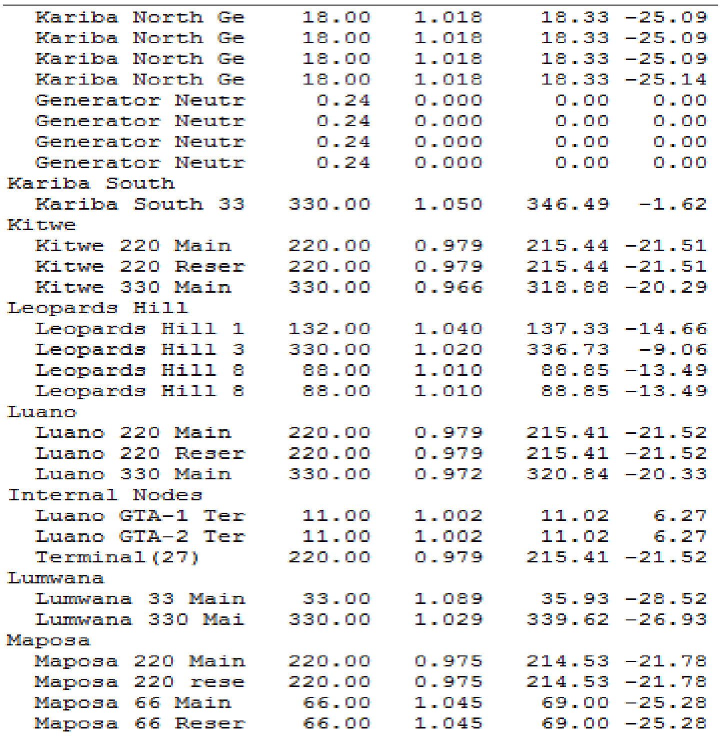
The voltage profile of the Copper belt area kept to almost its initial value thanks to the SVC of Kitwe and Luano. The reactive power on Kitwe SVC bank was raised from 2 Mvar to 18 Mvar and from 3 Mvar to 24 Mvar for Luano substation. See Table 3 in appendix 7.

The most significant voltage drop is at Leopards Hill substation with a dip of 1% (i.e. from 340 kV to 336.5 kV). See Figure 28 below.



```
| Load Flow Calculation                                                           Complete System Report: Voltage Profiles |
----------------------------------------------------------------------------------------------------------------------------
|     AC Load Flow, balanced, positive sequence                |   Automatic Model Adaptation for Convergency           No   |
|     Automatic Tap Adjust of Transformers            Yes      |   Max. Acceptable Load Flow Error for                       |
|     Consider Reactive Power Limits                  Yes      |     Nodes                                        1.00 kVA   |
|                                                              |     Model Equations                              0.10 %     |
----------------------------------------------------------------------------------------------------------------------------
----------------------------------------------------------------------------------------------------------------------------
| Grid: 330 & 220 System     System Stage: 330 & 220 Syste | Study Case: Complete System          | Annex:              / 1 |
----------------------------------------------------------------------------------------------------------------------------
|                    rtd.V      Bus - voltage                                     Voltage - Deviation [%]                   |
|                     [kV]   [p.u.]     [kV]   [deg]          -10         -5           0          +5         +10           |

|                       rtd.V       Bus  -  voltage
|                        [kV]    [p.u.]        [kV]    [deg]
-------------------------------------------------------------
|Chambishi East
|   Chamb East66 Ma      66.00     0.956      63.13  -21.00
|   ChambEast66 Res      66.00     0.956      63.13  -21.00
|   Chambishi East      330.00     0.971     320.32  -20.36
|Kabwe
|   Kabwe 330 Reser     330.00     1.013     334.14  -13.16
|   Kabwe 66 Main        66.00     0.986      65.05   -8.80
|   Kabwe 88 Main        88.00     0.993      87.40  -13.07
|   Kabwe 88 Reserv      88.00     0.993      87.40  -13.07
|Kafue Gorge
|   Kafue Gorge 330     330.00     1.040     343.20   -6.60
|Internal Nodes
|   Kafue Gorge G1       17.50     0.992      17.36    0.00
|   Kafue Gorge G2       17.50     0.992      17.37   -0.23
|   Kafue Gorge G3       17.50     0.992      17.37   -0.22
|   Kafue Gorge G4       17.50     0.992      17.37   -0.22
|   Kafue Gorge G5       17.50     0.992      17.37   -0.22
|   Kafue Gorge G6       17.50     0.992      17.37   -0.22
|Kafue Town
|   Kafue Town 220      220.00     0.963     211.82  -15.91
|   Kafue Town 33 M      33.00     0.908      29.97  -24.20
|   Kafue Town 330      330.00     1.024     337.77   -8.21
|   Kafue Town 88 M      88.00     0.838      73.72  -20.85
|   Kafue Town 88 R      88.00     0.838      73.72  -20.85
|Kafue West
|   Kafue West Main     330.00     1.024     337.96   -8.18
|Kansanshi
|   Kansanshi 33 Ma      33.00     1.020      33.66  -28.96
|   Kansanshi 330 M     330.00     1.019     336.39  -26.13
|Kariba North
|   Kariba North C      330.00     1.050     346.50   -1.60
```



```
  Kariba North Ge     18.00    1.018     18.33 -25.09
  Kariba North Ge     18.00    1.018     18.33 -25.09
  Kariba North Ge     18.00    1.018     18.33 -25.09
  Kariba North Ge     18.00    1.018     18.33 -25.14
  Generator Neutr      0.24    0.000      0.00   0.00
  Generator Neutr      0.24    0.000      0.00   0.00
  Generator Neutr      0.24    0.000      0.00   0.00
  Generator Neutr      0.24    0.000      0.00   0.00
Kariba South
  Kariba South 33    330.00    1.050    346.49  -1.62
Kitwe
  Kitwe 220 Main     220.00    0.979    215.44 -21.51
  Kitwe 220 Reser    220.00    0.979    215.44 -21.51
  Kitwe 330 Main     330.00    0.966    318.88 -20.29
Leopards Hill
  Leopards Hill 1    132.00    1.040    137.33 -14.66
  Leopards Hill 3    330.00    1.020    336.73  -9.06
  Leopards Hill 8     88.00    1.010     88.85 -13.49
  Leopards Hill 8     88.00    1.010     88.85 -13.49
Luano
  Luano 220 Main     220.00    0.979    215.41 -21.52
  Luano 220 Reser    220.00    0.979    215.41 -21.52
  Luano 330 Main     330.00    0.972    320.84 -20.33
Internal Nodes
  Luano GTA-1 Ter     11.00    1.002     11.02   6.27
  Luano GTA-2 Ter     11.00    1.002     11.02   6.27
  Terminal(27)       220.00    0.979    215.41 -21.52
Lumwana
  Lumwana 33 Main     33.00    1.089     35.93 -28.52
  Lumwana 330 Mai    330.00    1.029    339.62 -26.93
Maposa
  Maposa 220 Main    220.00    0.975    214.53 -21.78
  Maposa 220 rese    220.00    0.975    214.53 -21.78
  Maposa 66 Main      66.00    1.045     69.00 -25.28
  Maposa 66 Reser     66.00    1.045     69.00 -25.28
```

Figure 28. Voltage profile with Kariba N-LHill line out.

After the tripping, the voltage profile stayed within the acceptable limits:

- 346 kV at Kariba North (1.05p.u.)
- 320 kV at Luano(0.97p.u.)
- 318 kV at Kitwe(0.966p.u.)
- 343 kV at Kafue Gorge (1.04p.u.)
- 339.62 kV at Lumwana (1.02)

The lowest voltage in the Copperbelt area reached 0.95p.u. at Michelo and in the south at Kafue town. See Table 7 in Appendix 10. Kariba North units generated 30.7 MVAr, which were within their reactive limits. Kafue Gorge units generated 53 MVAr, which were within their reactive limits.

5.5.2 Tripping of one of the three 330 kV Circuits between Leopards Hill and Kabwe

Following the tripping of the circuit, the behavior of the system was satisfactory, no overload occurred on the transmission system. The initial power flowing through the tripped circuit Leopards Hill – Kabwe was 34.6% for each line. After a tripping the power for one line was equally dispatched between the two remaining circuits. See Table 5 in Appendix 8.

The voltage profile of the Copper belt area kept to its initial value. Much of the reactive power was supplied by the SVC of Kitwe and Luano to the north. The Generated reactive power on all Machines at the big Generating stations in the south was within limits. The most significant voltage drop is at Kafue 88 kV substation in the south (0.84 p.u.) and Michelo 220 kV close to the lower limit (0.95 p.u.) in the north. After the tripping, the voltage profile stayed within the acceptable limits

5.5.3 Tripping of one of the two 330 kV Circuits between Kabwe and Luano

Following the tripping of the circuit, the behavior of the system was satisfactory, no overload occurred on the transmission system. The initial power flowing through the two lines to Luano from Kabwe was 30% on each line. The power flow on the tripped circuit Kabwe - Luano had been dispatched between the remaining circuit Kabwe - Luano and the two circuits Kabwe - Kitwe which were currying 36% each initially. After the tripping, the circuit Kabwe - Luano was loaded at 50% (350 MW) and the two circuits Kabwe – Kitwe were loaded at 55% each (382 MW). See Table 5 in Appendix 8.

The voltage profile of the Copper belt area was virtually kept to its initial again with the help of the SVC of Kitwe and Luano

Kariba North units generated 50% of their reactive power limits and Kafue Gorge units generated 66% of their reactive power limits. The results of the load flows calculations are displayed in Appendix 8.

5.5.4 Tripping of one of the two 330 kV circuits between Kabwe and Kitwe

Following the tripping of the circuit, the behavior of the system was satisfactory, no overload occurred on the transmission system. A similar situation to the previous scenario prevailed

5.5.5 Tripping of Kabwe-Pensulo Line

After the tripping of this line the system was stable. No overloads on the lines and no major under voltages recorded. The only problem was on the Generators on Lusiwasi s/s which could trip on under frequency because the Northern part load is transferred to these generators of limited capacity.

All critical N-1 contingency calculations are displayed in Table 6 to Table 13 in appendix 9.

5.6 Analysis at off peak for both normal and N-1 contingencies.

This operation was similar to the above analysis. This is made possible for the fact that the generation was reduced according to the adjusted load and the system compensation followed suit.

5.7 Analysis in transient state

The analysis in transient state is based on the theory presented in chapter three. Here the classification of the transient stabilities is highlighted to give a clear picture of what to consider in the presentation in this thesis. The short term stability is considered in the analysis of the rotor stability for the fact that rotor stability is the predominant among the three types of instabilities. The three types being rotor angle, voltage and frequency instability. The time frame considered in this short time stability studies is 10 seconds.

Also in chapter three is the analysis of equal area criterion for four different cases. The switching off of one line for two parallel lines, the application of the fault at the end of any line, the application of the fault in the middle of the line and clearing it and finally the effect of Auto reclosing on either transient or persistent fault. This is to get the critical clearing angle at which the system would remain stable in any situation. This of course depends on the fault clearing time.

All these scenarios are simulated and analyzed on the Zambian network. From chapter three it is shown that the initial operating point is crucial for the stability of the system. The higher the initial maximum operating power output of the generator the shorter is the critical clearing time. This is the reason for basing the analysis on the peak period in the system.

To summarize the analysis presented in chapter three, the following are the factors influencing the transient stability of the generator;

- How heavily the generator is loaded
- The generator output during the fault. This depends on the fault location and type.
- The fault clearing time.
- The post fault transmission system reactance.
- The generator reactance. A lower reactance increases peak power and reduces initial rotor angle.
- The generator inertia. The higher the inertia, the slower the rate of change in angle. This reduces the kinetic energy gained during fault, that is area A_1 is reduced.
- The generator internal voltage magnitude (E′). This depends on field excitation.
- The infinite bus voltage magnitude V_B

5.7.1 Transient State Presentation

The purpose of the study in transient state is to demonstrate that, following a severe fault normally cleared, the power system is able to recover a satisfactory behavior without loss of the synchronism of any generator and without sustained voltage or power oscillations. The voltage profile and the system frequency must remain within the acceptable limits.

The fault consists of a three-phase to ground short-circuit located close to Generating stations on one connection circuits to either 330 kV LHill Substation from Kariba and Kafue Gorge or 220 kV Kafue town substation. It is the most severe fault for the generators. The fault is assumed to be cleared by opening of the two end breakers simultaneously, isolating the faulted element.

The simulations provide the evolution versus time of the main parameters that are of great importance in power system stability: rotor angle, excitation voltage, active power and power frequency.

This part of the thesis presents hereafter the hypothesis, the main results and conclusions of the study in transient state.

5.7.2 Hypotheses

5.7.2.1 Reserve Power

This is the difference between the P_{max} of the units in operation and their generation output.

The primary reserve of Zambian system amounts to 180 MW, representing one of the biggest generating units. With the interconnections to the neighboring countries, SAAP in particular, Zambia gives a power reserve of about 70 MW [14].

The effective primary reserve of the HPP units depends on the opening time of the valves of the turbine.

5.7.3. Simulated Faults

Three phase faults were applied near generating stations to ascertain the stability of the Zambian Network. Following cases were examined:

- Three phase to ground fault eliminated by definitive tripping of the faulted line in 100 ms. That is both ends of the faulted line being isolated simultaneously.
- Three phase to ground fault eliminated by definitive tripping of the faulted line in 100 ms then the faulted line is automatically reclosed after 10s from the generating side of the line and the other end auto reclosing 5seconds thereafter. In all auto reclosing cases there was no switch on to fault. The fault was first cleared before auto reclosing.

The following faults were examined:

- Three phase fault on the transmission line close to 330 kV Kafue Gorge HPP bus bar
- Three phase fault on the transmission line close to 330 kV Kariba North HPP bus bar
- Three phase fault on the transmission line close to 220 kV Vic. Falls HHP bus bar
- Three phase fault on the transmission line close to Kafue Gorge HPP on KFG-Kafue west line
- Three phase fault on the 330 kV transmission line between LHill and Kabwe substations
- Three phase fault on the 330 kV transmission line between Kabwe and Luano substations
- Three phase fault on the 330 kV transmission line between Kabwe and Kitwe substations
- Three phase fault on the 330 kV transmission line between Kabwe and Pensulo substations
- Three phase fault on the 330 kV Kansanshi transmission line from Luano

5.7.3.1 Close up fault to Kafue Gorge on KFG-LHill Line at peak load

A three phase to ground fault was applied near Kafue gorge Power station with a capacity of 990 MW. See Figure 29 below. This fault was applied after 3 seconds from the start of simulation just to give initial conditions to compare with the post fault results. The fault was applied at a position 5% of the line from the Hydro power plant.

The fault was Isolated after 100ms. Within this time the current transformer errors, relay time and breaker contact opening period is taken care of. For the SF6 breakers that we have in circuit, it takes only one cycle, 20ms to have the contacts opened fully. Infact the recommended period for the contacts to open fully from the time of fault initiation is 70ms for ZESCO protection philosophy for the system with SF6 breakers.

The behavior of the system during and after the fault was satisfactory. The generators operated above the reactive limit during the fault but eventually stabilized. See Figure 30 below.

All groups operated in synchronism. A voltage dip close to zero for 100ms (during the fault) was recorded on Kafue Gorge 330 kV busbar. The maximum rotor angle on Kafue Gorge HPP was 80 degrees peak to peak as can be seen from Figure 30. The oscillations were damped within 10seconds see Figure 30.

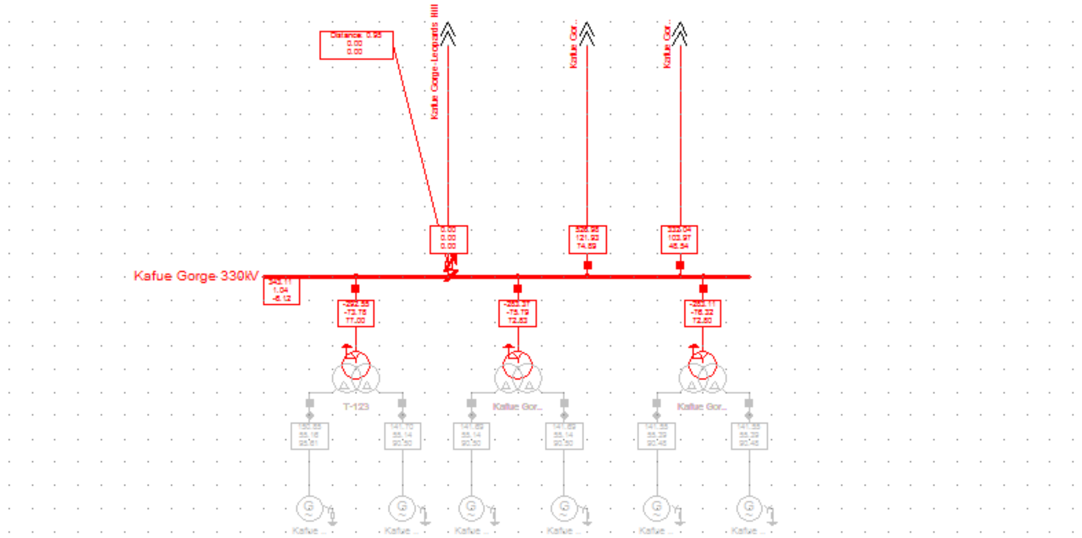


Figure 29: Three phase to ground fault on KFG-LHill line

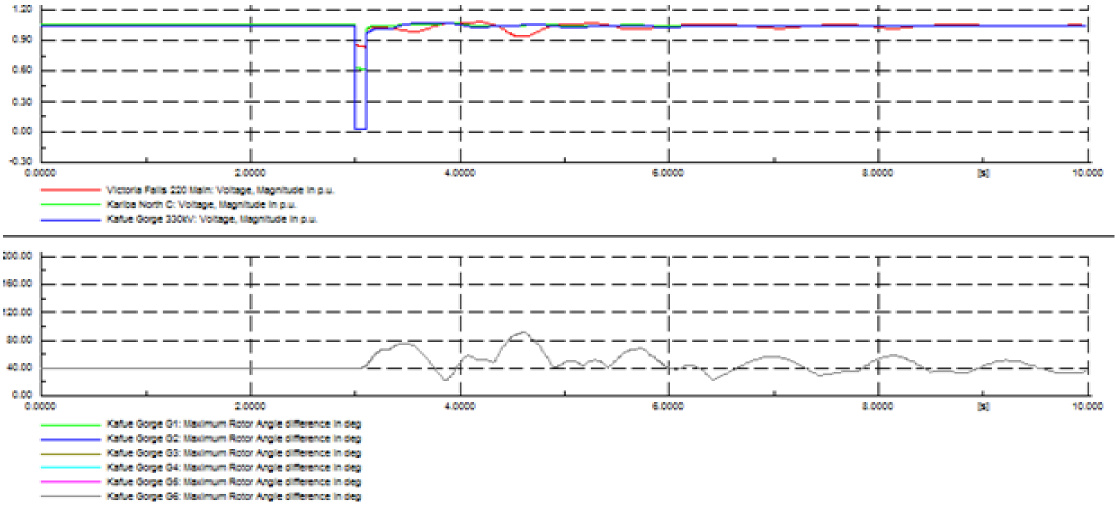


Figure 30: From top to bottom: Excitation voltage, Excitation Current, Machine reactive power, Voltage dip and Rotor angle variations before, during and after the fault close to KFG HPP

The power oscillations on the remaining KFG-LHill line reached first high value of 600 MW from initial stead state value of 210 MW before stabilizing to a value of 425 MW. The power oscillations were damped within 10seconds. No sustained oscillations were seen. See Figure 31 below;

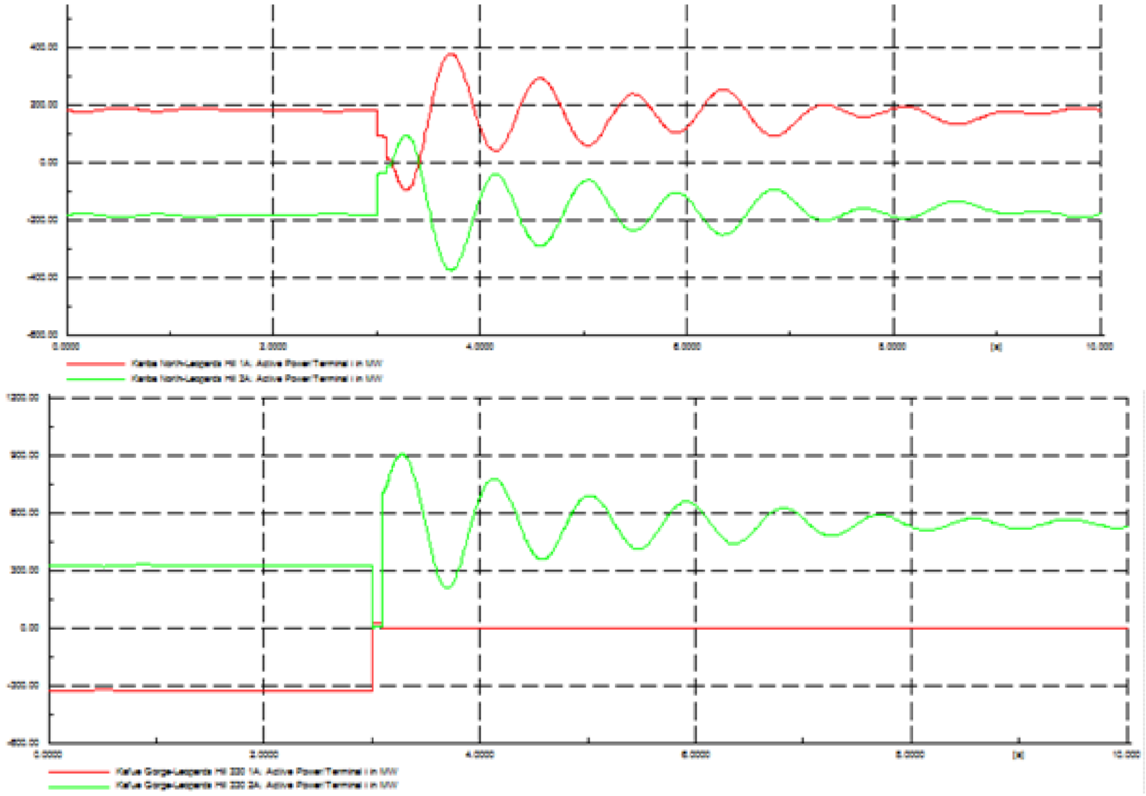


Figure 31: Power swings on the four lines from Main Generating stations to Lhill Substation

Frequency deviations were not alarming on all Generators from all major hydro power plants. They were within acceptable limits as can be seen from Figure 32.

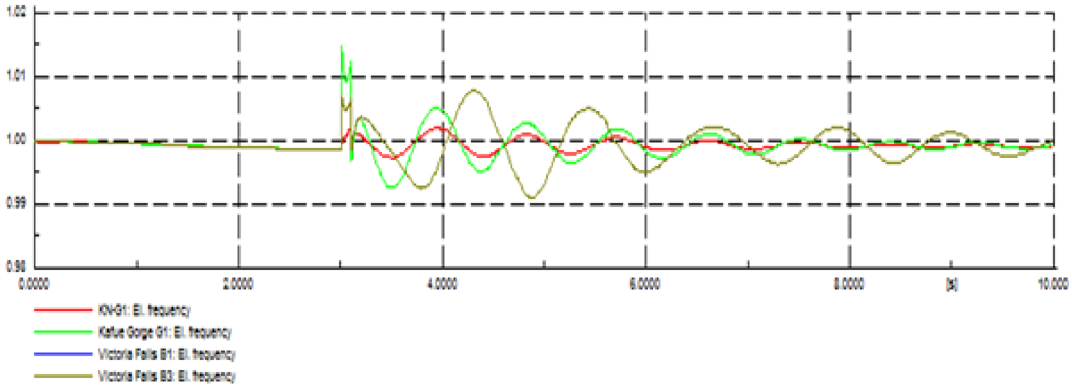


Figure 32: Frequency deviation on major Hydro Power Plants

A voltage dip of 70% was noticed on major substations on the copper belt far away from generating stations. However the voltage was recovered just after 100ms. See Figure 33 below.

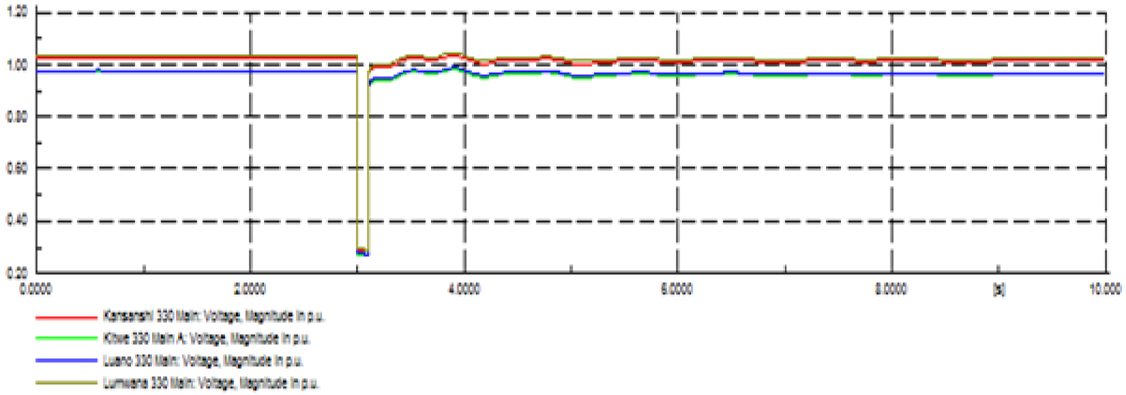


Figure 33: Voltage dip on major Load centers on the Copper belt after a fault close to KFG-HPP

Another interesting case was the increase of the clearance time to see if the line would still be stable if the fault would be cleared in 400ms according the zone two settings of the lines on the distance relay. Zone 2 is the backup protection to zone one. If the fault is not cleared in zone one then zone two should clear it.

The best clearing time that was satisfactory was 200ms further than that the system was very unstable. Oscillations were never damped. See

Figure 34 below for a 300ms fault. For more variables on this simulation see appendix 13.

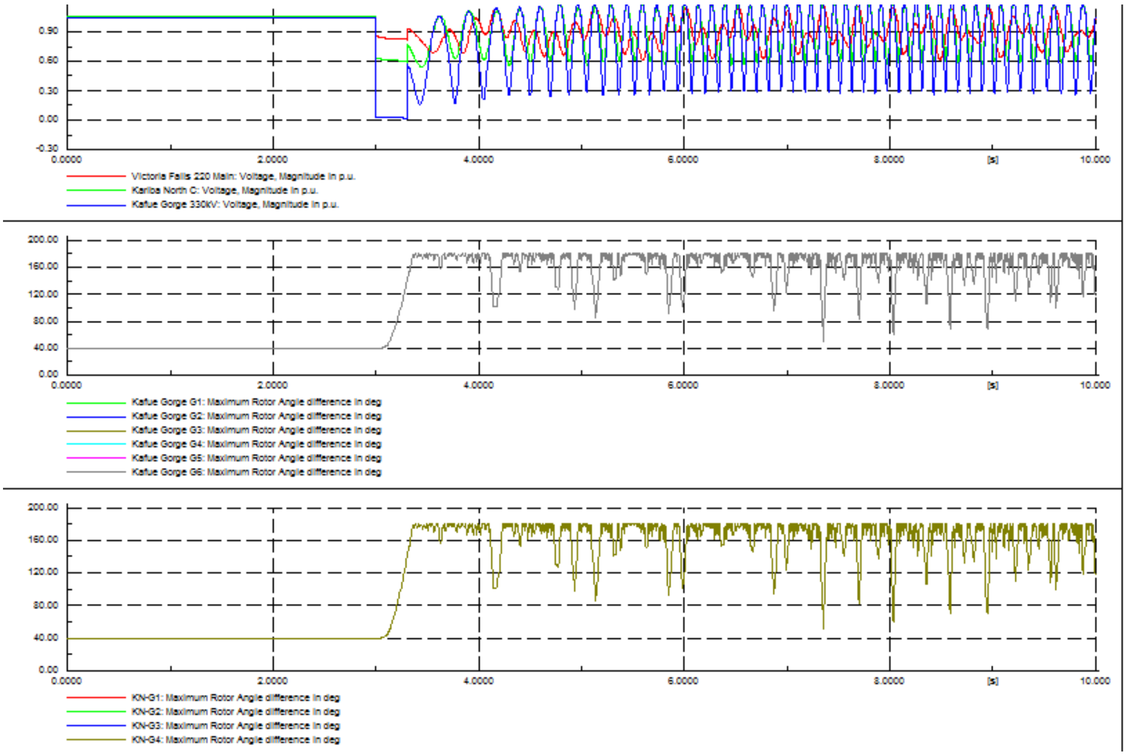


Figure 34: Voltage and rotor angle oscillations for a 300ms fault on KFG-Lhill line

5.7.3.2 Close up fault to Kafue Gorge HPP on KFG-LHill Line at peak load with auto reclosing

Another necessary simulation on the same line was auto reclosing to a transient and permanent fault. For a transient fault, a three phase fault was applied 1 second from the initiation of the simulation. After the fault was cleared, at t =1.1 seconds during simulation time, the line auto-reclosed after 10 seconds according to the relay settings. The first end of the line near, KFG HPP was reclosed at t = 11.1 then five seconds later the other end was reclosed. This line is set to be synchronized at Lhill S/S.

The system operated satisfactory after this operation. There were no sustained oscillations. See the results in Figure 35.

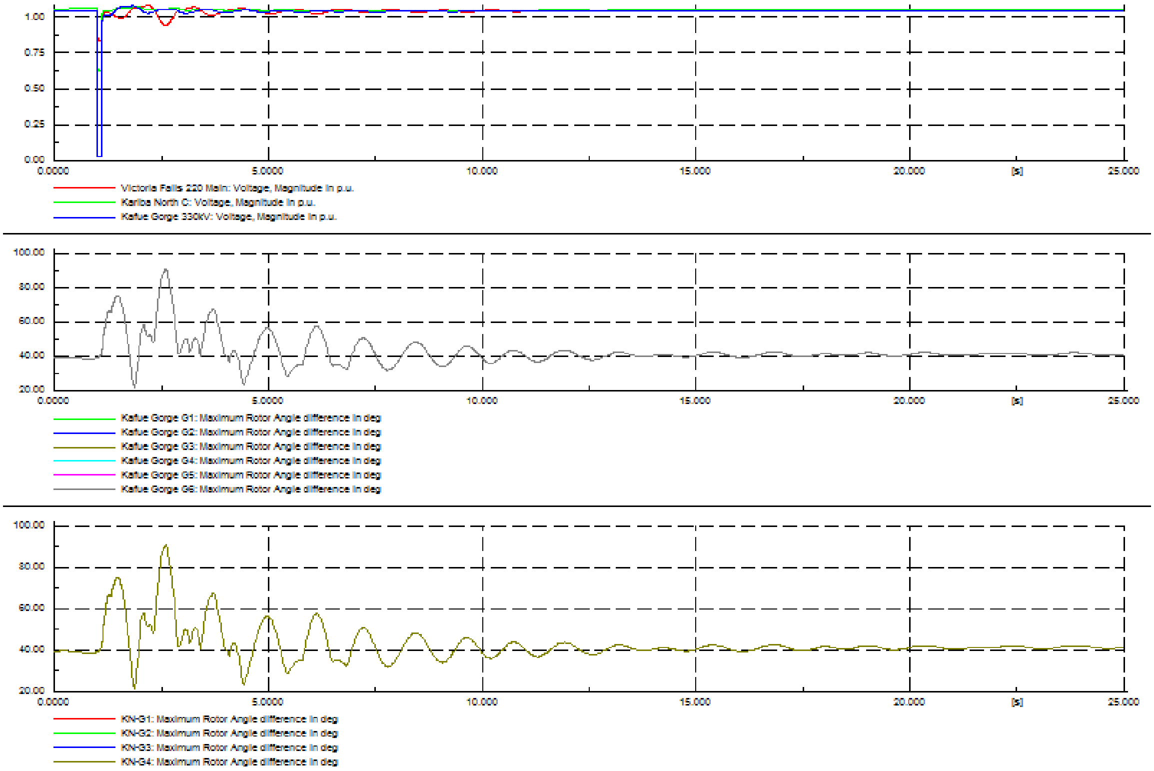


Figure 35: Auto reclosing of the KFG-Lhill line on transient fault

The voltage dip on KFG 330 kv bus bar reached almost zero. On Kariba 330 kV bus bar the voltage dip reached 65% of the nominal value and that of Vic Falls the voltage dip reached 78% see Figure 35.

The power swings on the remaining healthy lines were damped within 10 seconds. See Figure 36.

The voltage dips on major Copper belt load bus bars were recorded to have dropped to 27% because of the KFG busbar short cicuit. They were recovered just after fault clearance as can be seen from Figure 36 below.

Frequency deviations were recorded high about 1.1% on KFG machines as compared to the rest of the Machines on Kariba and Vic Falls Power Station because flow from KFG machines was interrupted hence the power input was higher than the power output..After the reclosure the frequency deviation was seen to be lower than the nominal due to increased power flow to the north. See Figure 36 below.

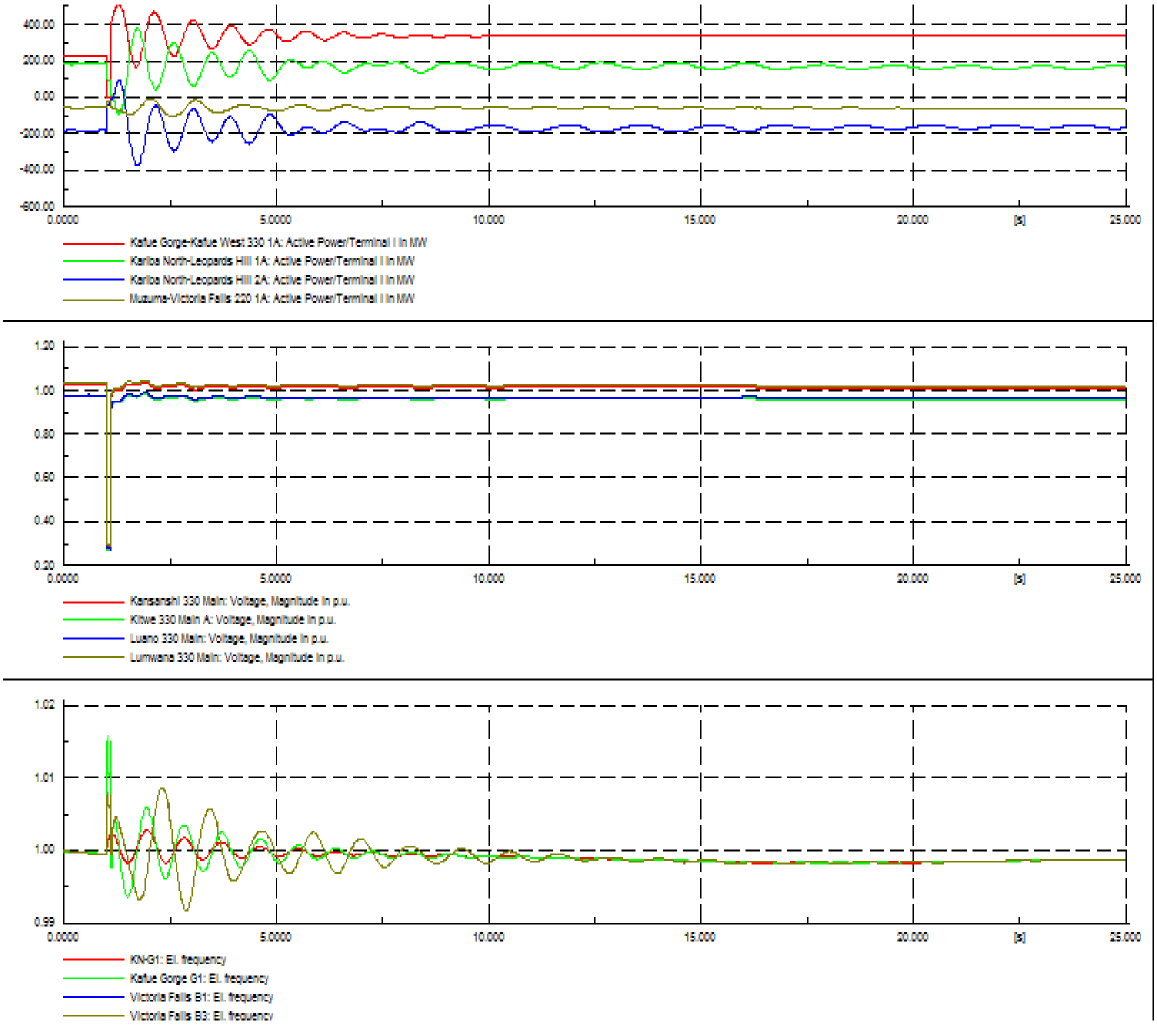


Figure 36: From top to bottom, power swings on main generating stations, Voltage dips on main Load bus bars and Frequency deviations after auto reclosing the KFG-LHill line.

5.7.3.3 Auto reclosing on to a persistent fault on KFG-Lhill.

The operation of the system after auto reclosing to a fault 10 seconds after the line was isolated was satisfactory. All oscillations were damped. The maximum rotor angle reached upon auto reclosing was almost like at the first fault. This is because the system was almost stable after 10 seconds. See Figure 37 and 38 below;

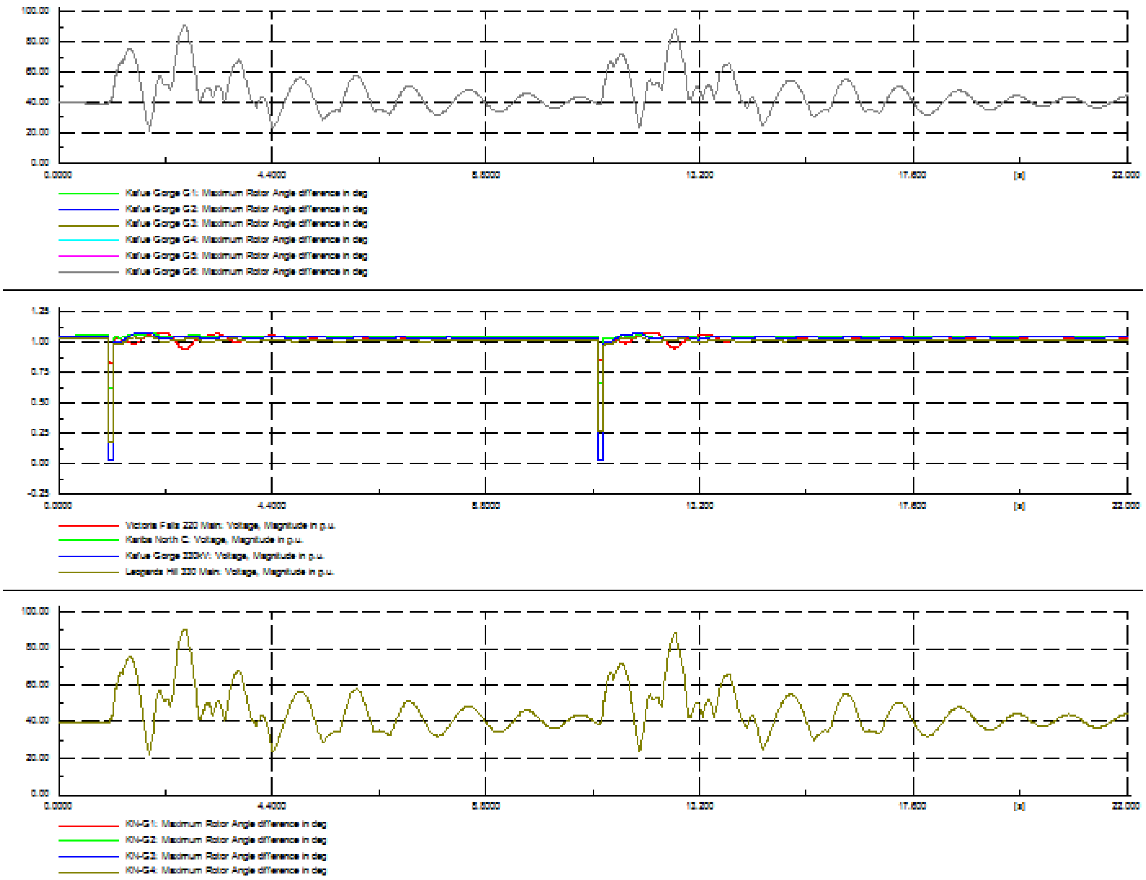


Figure 37: Auto reclosing on persistent fault and locking out

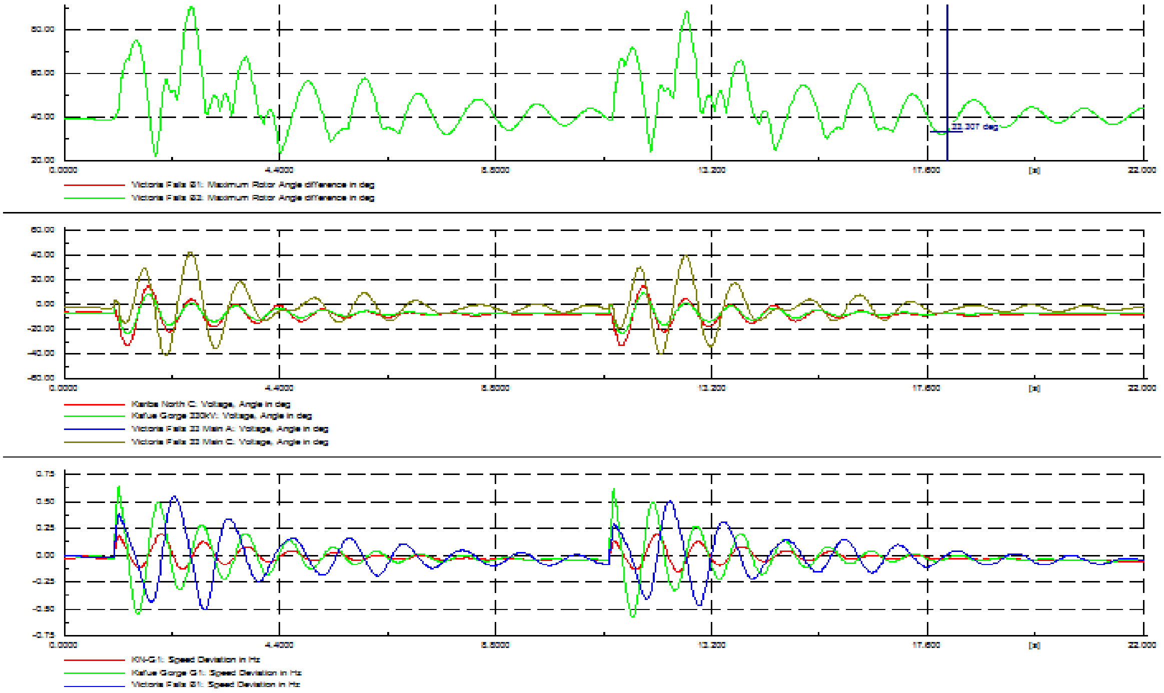


Figure 38. Auto reclosing on persistent fault

There were no major power swings on the copper belt loads. The voltage dip reached 27% of the nominal value due to system losses. The frequency on the Kafue Gorge machines went up higher than the rest of the machines on the other hydro power plants and was seen to stabilize at a lower value due to increased load flow. See Figure 39.

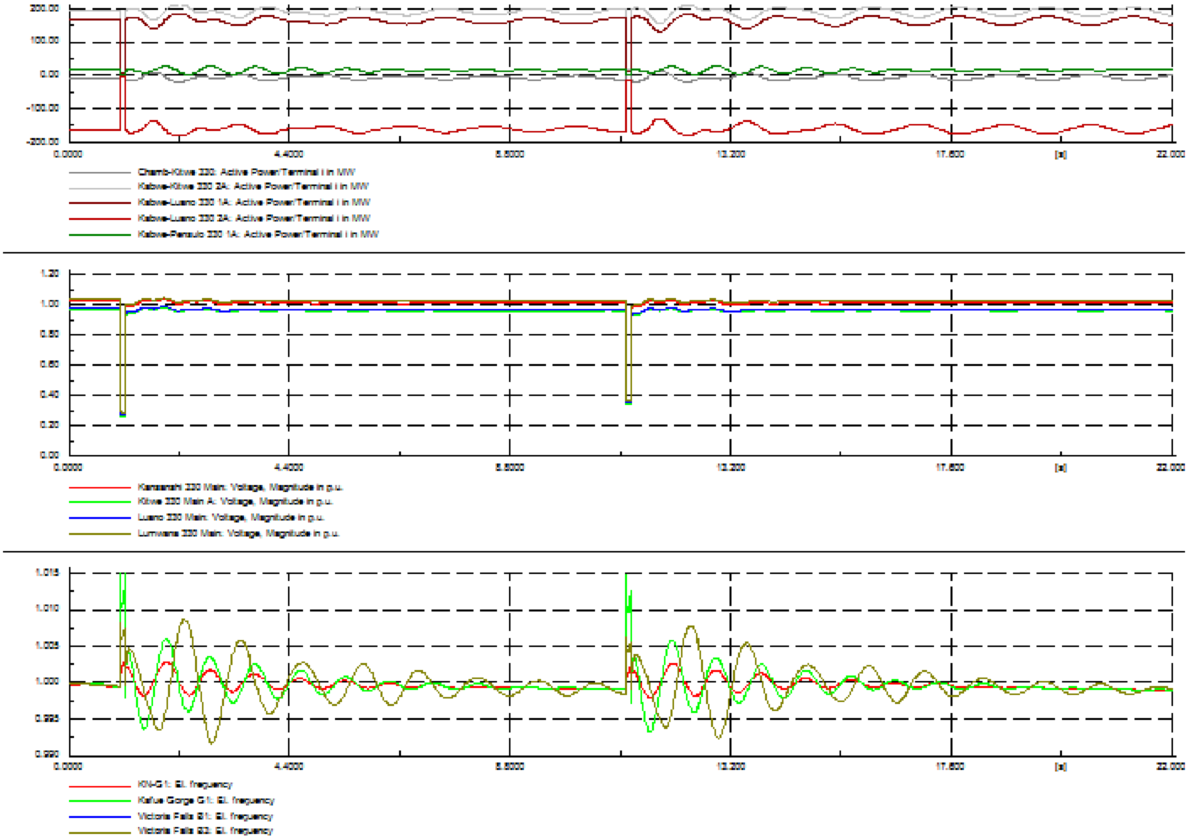


Figure 39: Auto reclosing on persistent fault- power swing on the copper belt lines, voltage profile and machine frequency on major generating stations.

The reactive power on the Kafue Gorge machines exceeded the limits but was stabilized. See Figure 40. The increase of the reactive power on the machines is as a result of the fault current flows through pure reactance to the fault hence only reactive power flows [2].

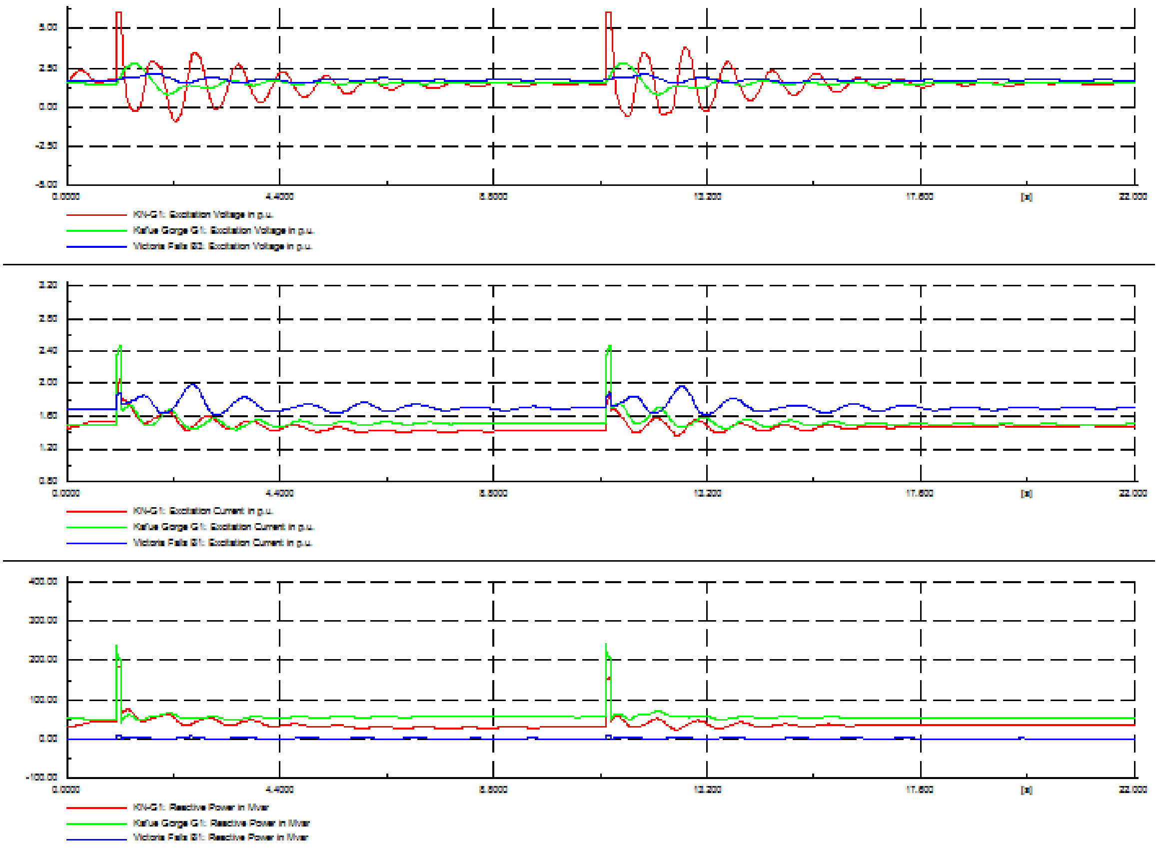


Figure 40: Excitation voltage, current and reactive power on all machines on major generating stations-auto-reclosing on a persistent fault

The power swings on the four main lines from major generating stations were damped. See Figure 41 .

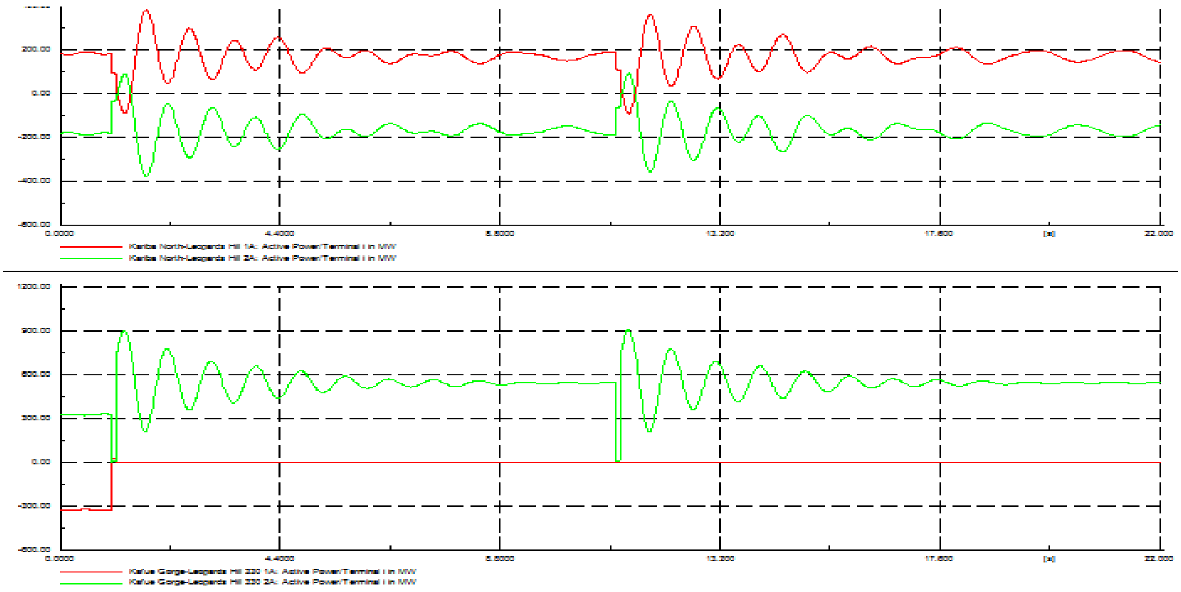


Figure 41: Power swing on the four transmission lines to LHill substation from Kariba and Kafue Gorge HPP after auto-reclosing on to a persistent fault.

5.7.3.4 High speed auto reclosing.

In this simulation the auto reclosing was deliberately initiated to close 70ms after the trip out on to a persistent fault to just find out the effect of this operation otherwise it does not apply to the Zambian system unless on single pole auto reclosing. See Figure 42 to Figure 45 for the auto-reclosing effect.

From the Figure 42 below the rotor angle was raised to almost double the initial highest value. This poses a danger for instability as explained in chapter three.

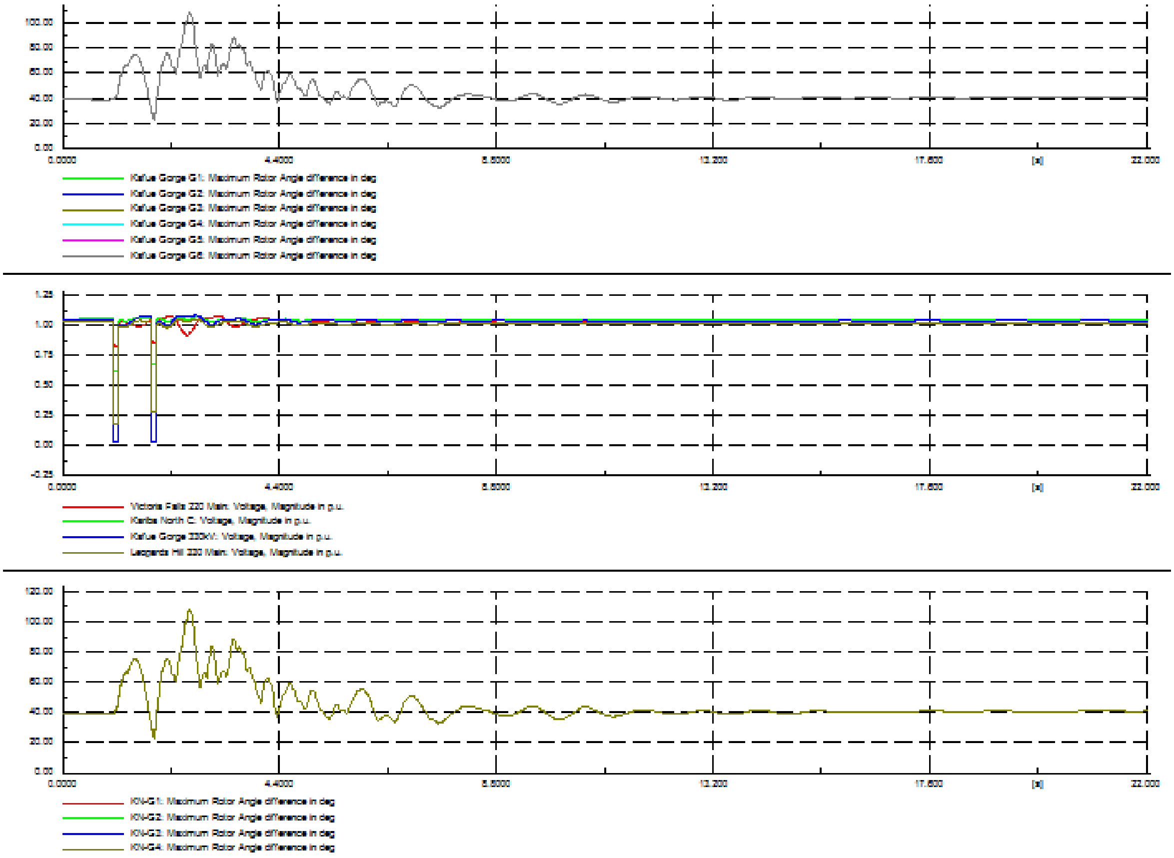


Figure 42. Effect of high speed auto reclosing (Rotor angle, Voltage profile and rotor angle difference)

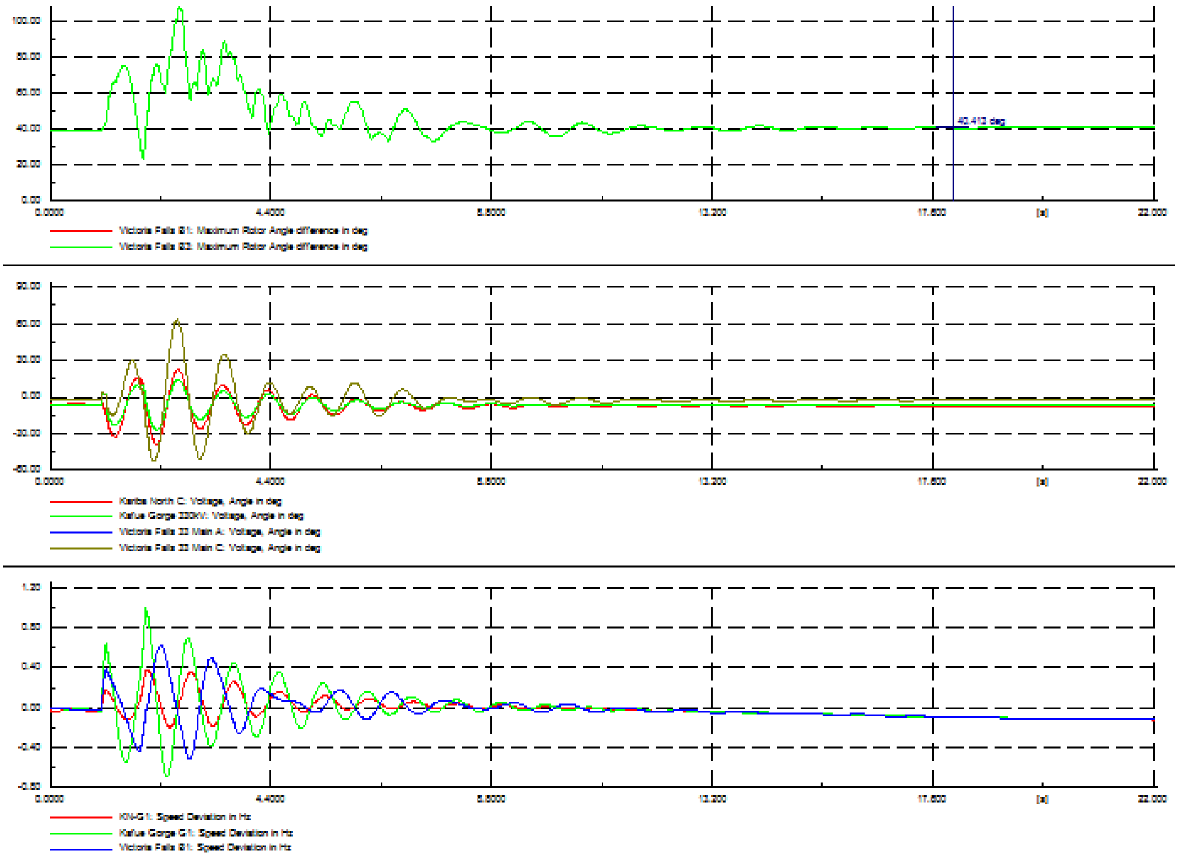


Figure 43: Effect of high speed auto reclosing (Rotor angle difference, Voltage angle & speed deviation)

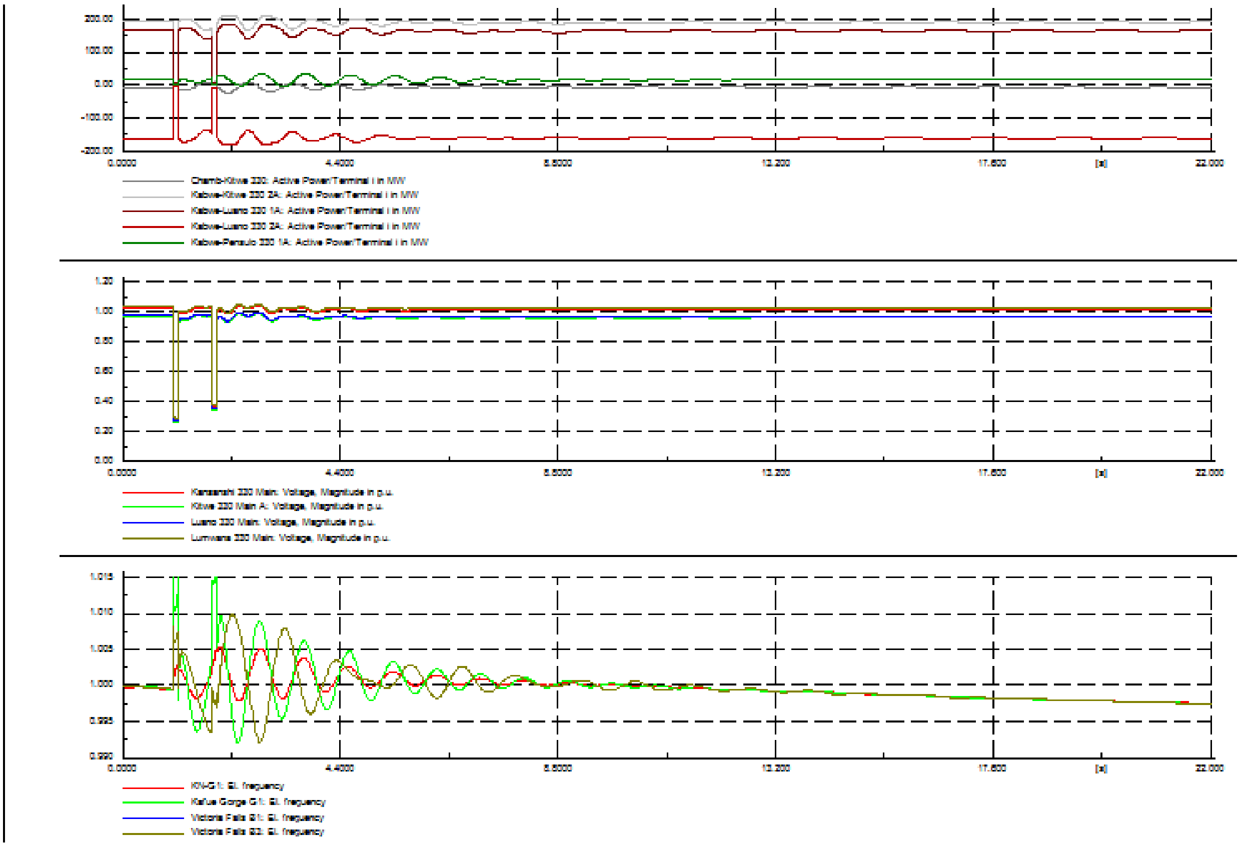


Figure 44: Effect of high speed auto reclosing (Active Power, Voltage profile & Frequency)

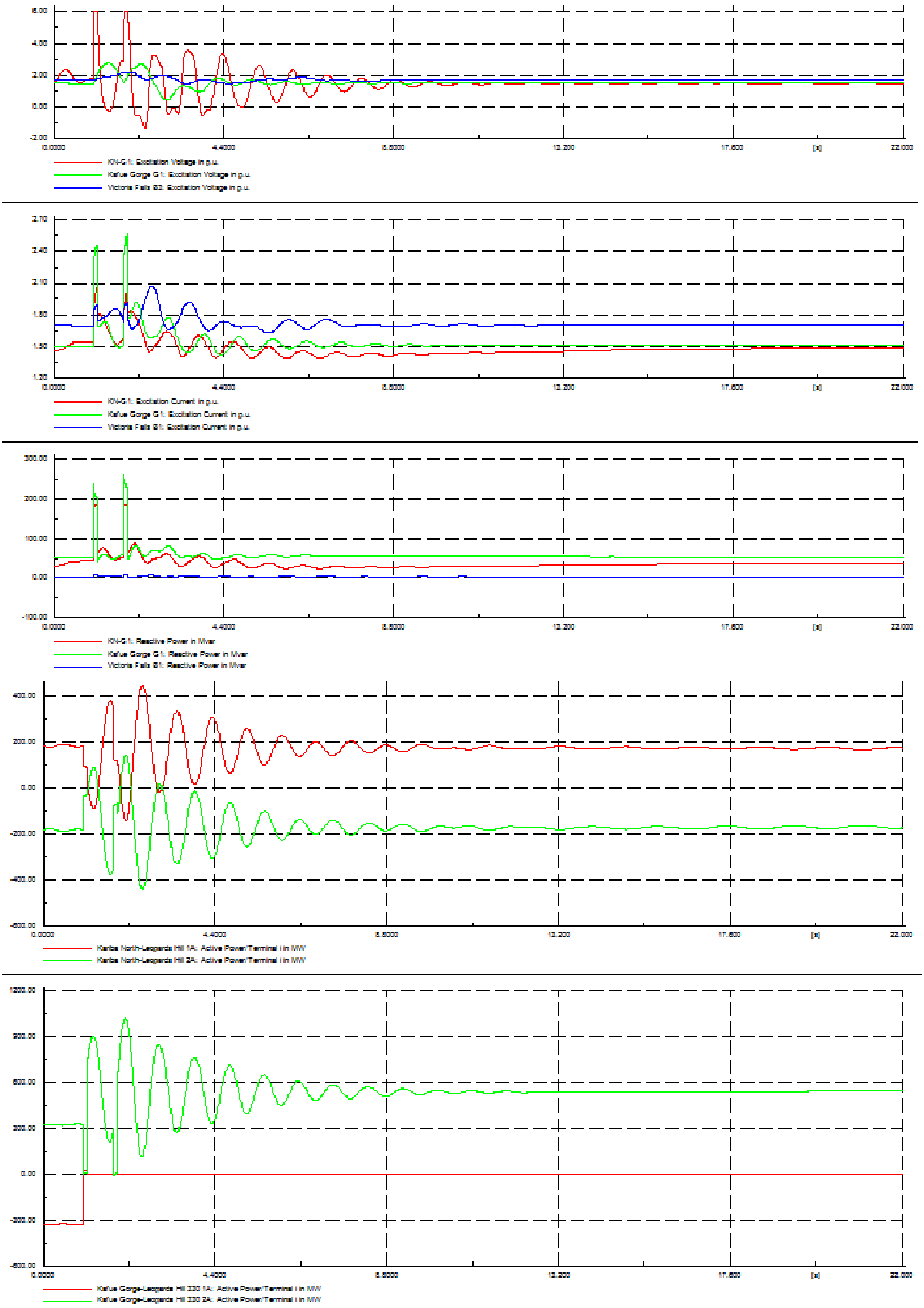


Figure 45: Effect of high speed auto reclosing (Excitation voltage, Excitation current, reactive power and Active power flow)

5.7.3.5 Faults on the remaining lines close to the main Hydro power plants.

The behavior of the whole system after a fault close to the main hydro power plants on the remaining circuits was satisfactory. The pattern of variable oscillations was similar to the one analyzed here before. The rotor angle oscillations were damped within 10seconds. No sustained oscillations of any kind were recorded for a fault cleared in 100 ms. See Figure 64 to Figure 99.

The voltage dips were recorded on the major substations on the copper belt but were not sustained. The post fault voltages were close to the initial value which means the loses were not all that high after the isolation of the faulted circuit.

5.7.3.6 Busbar faults

The only scenario on power system stability that was different from the one just analyzed here before is that of a bus bar fault. A complete bus bar fault was simulated at Leopards Hill substation. This is the focal point of all the power to the copper belt that accounts for about 45% of total power from major Generating stations. The fault was applied 1 second after the start of the simulation. The fault duration was 50 milliseconds. This fault duration accounts for CT error, relay and breaker opening times.

The power system operation after the fault was not satisfactory. This was expected since 45% of the total load was suddenly interrupted that means more power input than the power output.

The rotor angle and voltage oscillations for Kafue Gorge and Vic. Falls were not damped except for the Kariba North Hydro power plant machines. See figure 40 below. The KNBC machines were spared because of the interconnection to the Southern load that provided some inertia. Infact the machines were lightly overloaded at this stage as can be seen from the new operating angle. It dropped to 32 degrees from the initial 40 degrees.

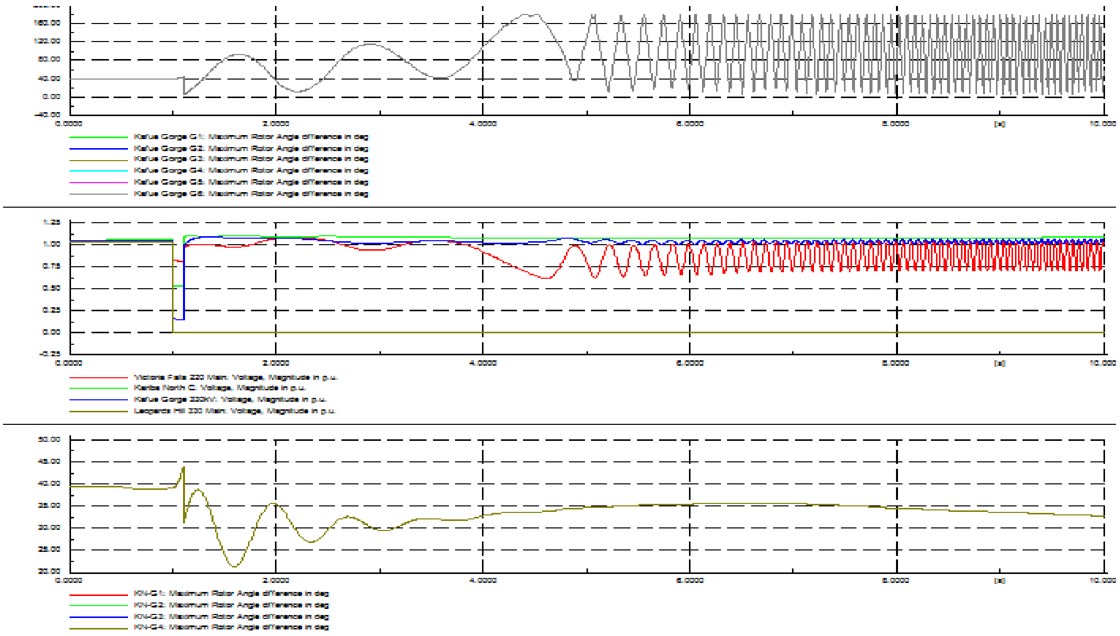


Figure 46: From top to bottom: Rotor angle for KFG HPP machines, Voltage magnitude and the rotor angle for KNBC HPP for a bus bar fault at LHill Substation.

The frequency deviation on the remaining machines was not satisfactory. The one for Vic falls looks like it was about to stabilize because of the light load to the western part of the country that are connected to the Vic falls Power Station machines. The Kariba North Bank HPP machine frequency deviation was satisfactory. There was a bit of deviation because of the light load after the fault. See Figure 48.

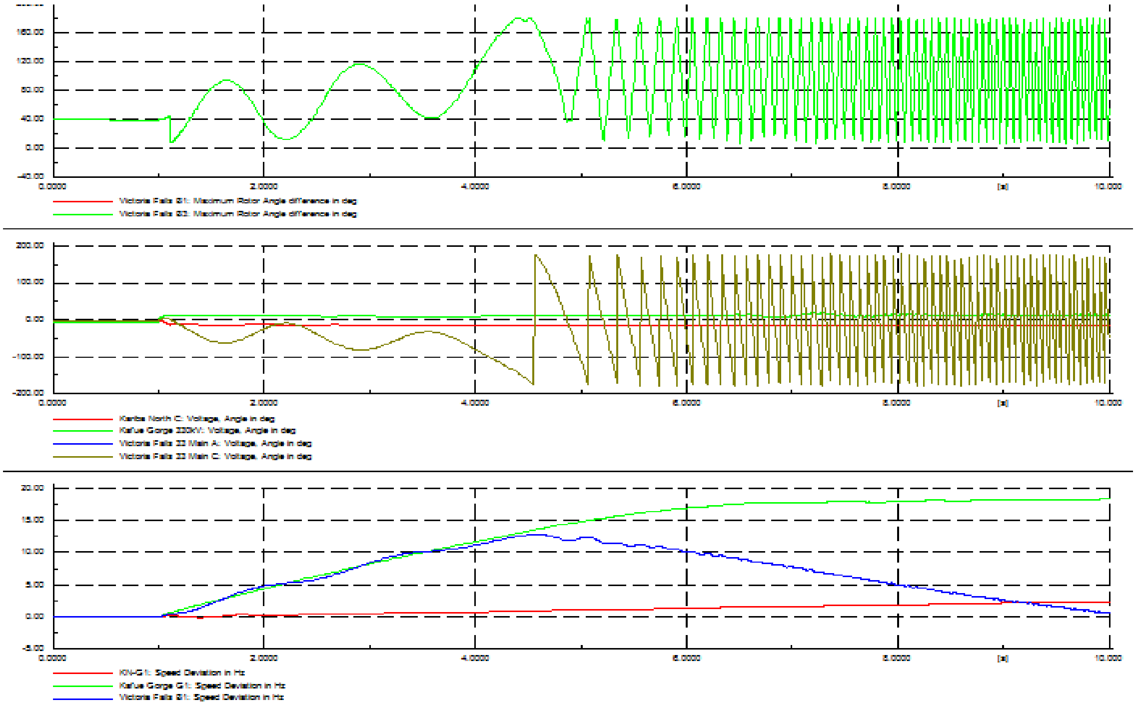


Figure 47: Rotor angle, voltage angle and speed deviation on all major HPP machines for a bus bar fault at LHill substation

As can be seen from Figure 48 below, the power flow to the north was suddenly disrupted. The voltage totally collapsed. The frequency on the KNBC HPP machines looks ok. It slightly went up for the light load as already mentioned.

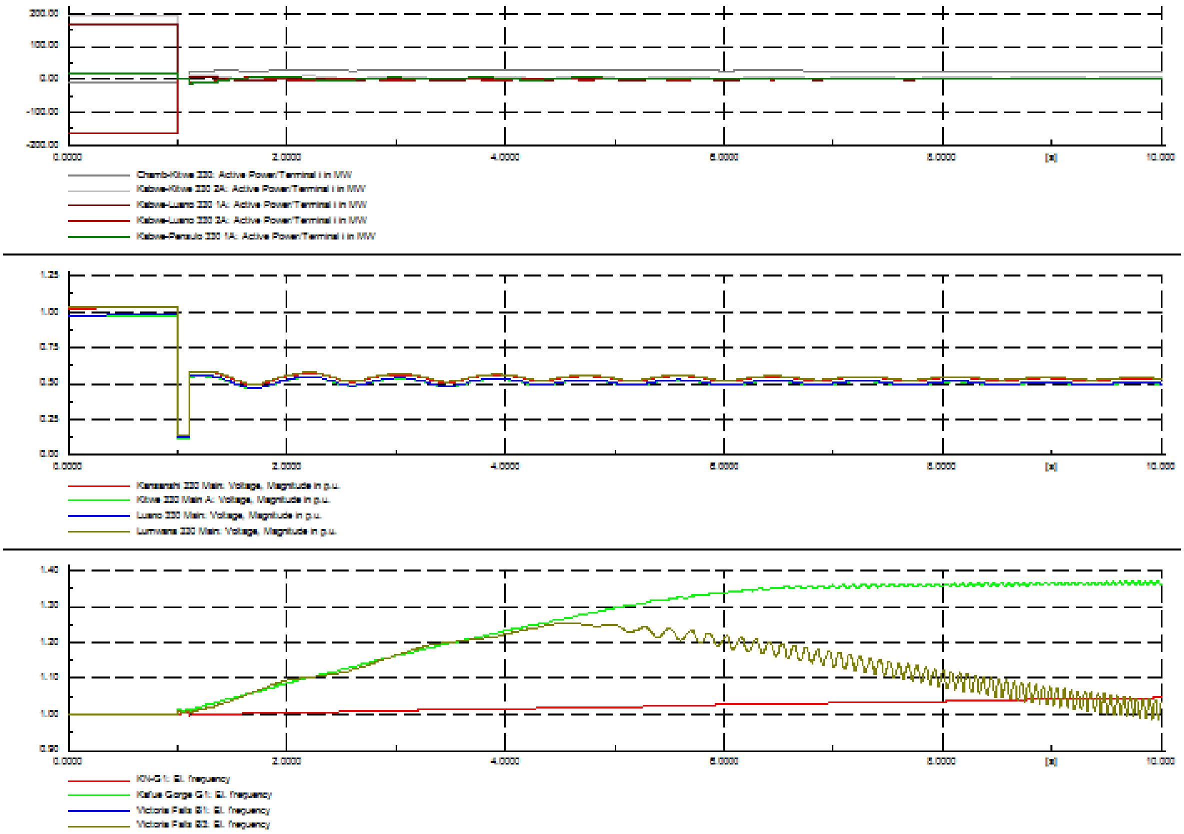


Figure 48: Active power on the transmission lines to the North, Voltage profile on the Copper belt Major substations and the frequency on all HPP generators for a bus bar fault at L.Hill substation

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The solution to the above problem is to stager the circuits on the Leopards Hill substation bus bars. At this substation there are two bus bars coupled by a bus coupler breaker. If a fault occurs on one of them the only faulted bus bar will be Isolated and the other will remain intact to save copper belt load. With this kind of simulation the results are shown in Figure 49 and Figure 50 below. All oscillations were damped and the voltage profile on the copper belt looks ok despite the added loses with the tripping of two lines connecting the next substation, Kabwe. This also reduces the power flow to copper belt as can be seen from Figure 50. With this power flow reduction the frequency value went up but it was within limits, see Figure 50.

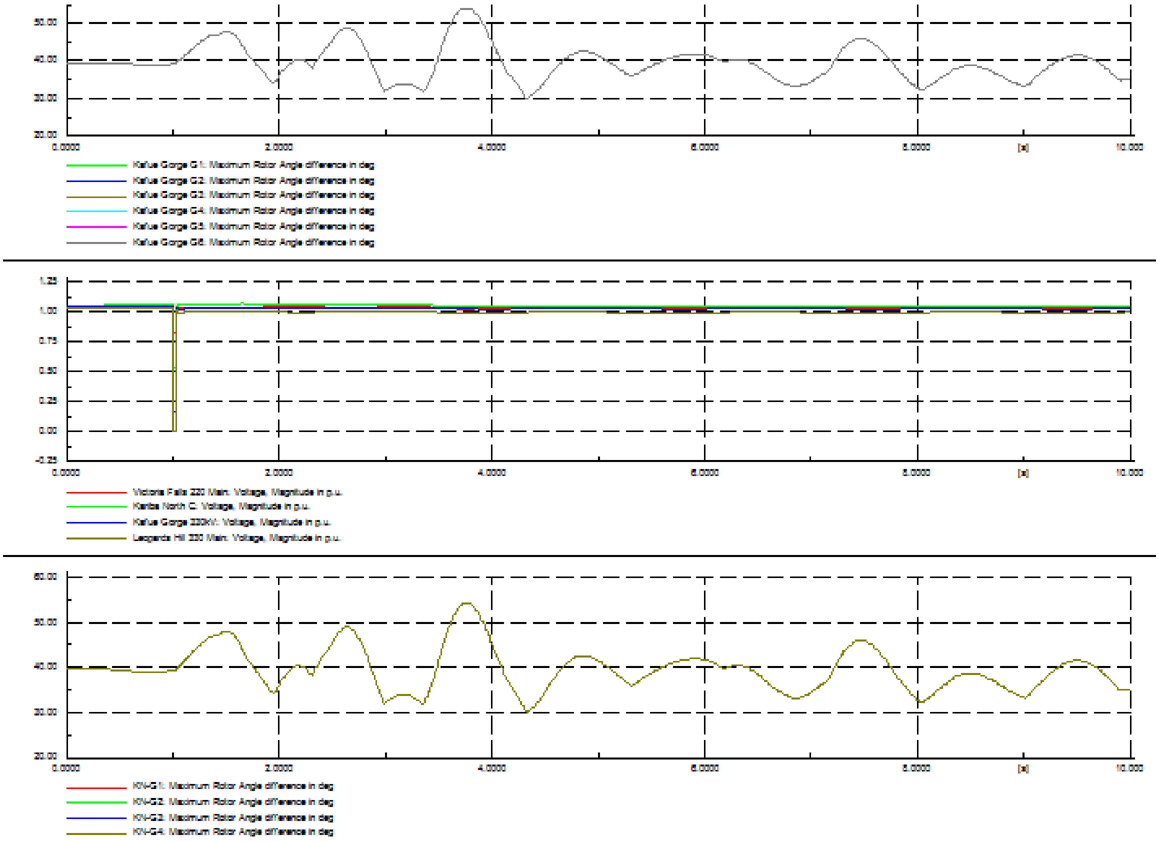

Figure 49: Rotor angle and voltage profile for the fault at Leopards hill with the staggered circuits for a bus bar fault.

Only slight voltage drop was recorded on the copper belt due to the increased loses as can be seen from Figure 50. There was some slight power swing on the northern power lines.

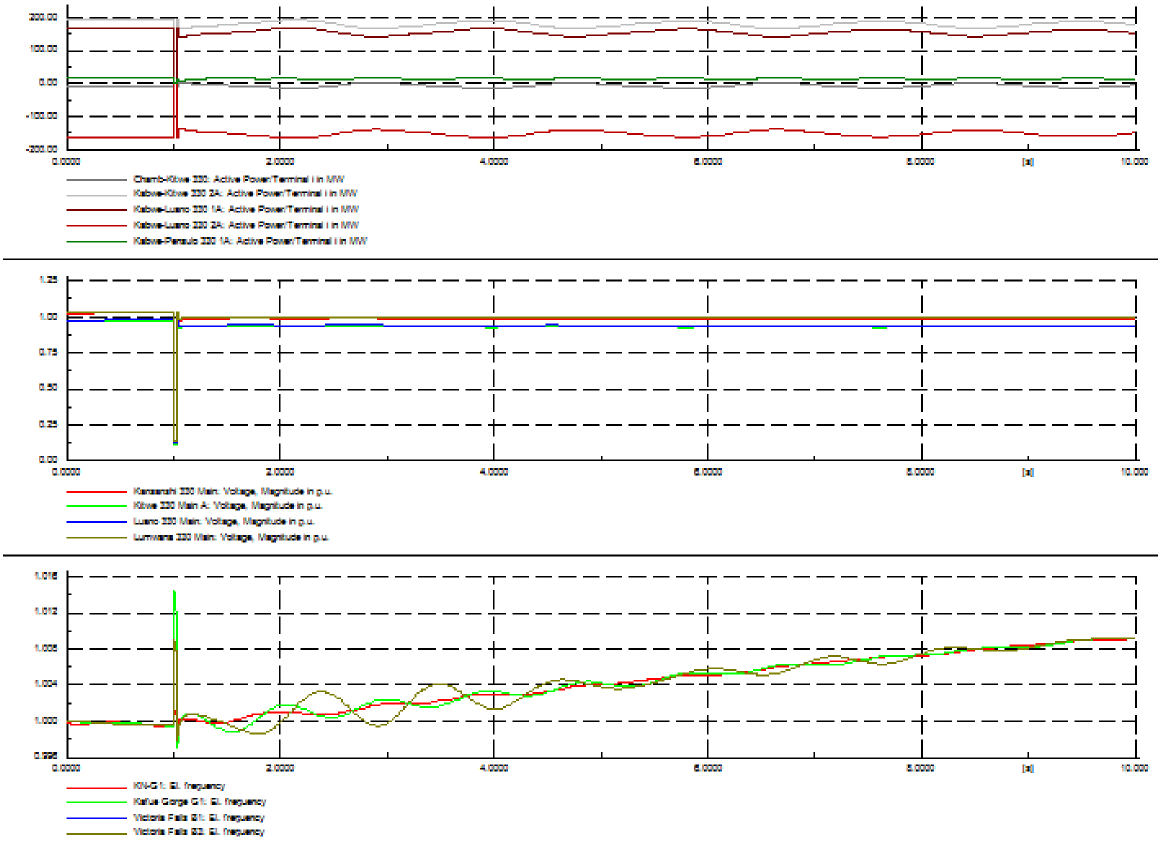

Figure 50: Active power flow to the north, voltage profile at the copper belt and the generating frequency for a bus bar fault at LHill

Chapter 6: Conclusions and Recommendations

6.1 Conclusions

Generally the Zambian system operation is very stable. On transient stability analysis for a severe fault close to major Hydro Power Plants and cleared within 100ms the operation of the system is satisfactory. But this type of fault cannot be sustained for more than 200ms. If the fault is cleared after this time the system becomes unstable. The fault clearing time reduces further if the power reserve is low. With the increase of power demand and less generated power the effect is the instability of the power system for faults close to the generating stations as the case will be in 2011 for the Zambian System if more Generating stations will not be built by then. But this situation can be avoided with the increased interconnections to the neighboring countries like Congo Dr to the North and Zimbabwe, Mozambique and South Africa to the South. This scenario will increase the reserve power for the Zambian Power System and hence the increase in the stability of the Power System.

Auto-reclosing on to a sustained fault has no major effect on the stability of the Zambian system if it is initiated 10seconds after the isolation of the fault. 10 seconds is enough period for the system to be stable following a major system disturbance. If for any reason the auto reclosing is initiated after 1ms the system is likely to become unstable and this is only applicable to three phase auto-reclosing. High speed auto-reclosing is applicable to single phase only.

For a bus bar fault the effect is pronounced if the circuits are not staggered at that particular bus bar. But this does not guaranty a good voltage profile on the Northern system because of losses resulting from increased line impedance. However this voltage profile is eased by the use of the SVCs. SVCs are better than the Capacitor banks for intermitted voltage variations.

The voltage profile on the Zambian system is generally ok both in normal and in N-1 contingencies. The installations of Capacitor banks in substations like Luano, Chambishi, Kansanshi and Lumwana has really helped in improving the voltage profile on the Copperbelt area. But these capacitor banks will not be as effective as SVC because of the low short-circuit power in the Copper belt area. A low short-circuit power means that a small reactive power variation will have a significant impact on the voltage level. The SVC is continuously bound to a voltage set point and so adjusts its reactive power to the wanted voltage value. Thus, for N-1 and peak loads the SVC, with a smooth voltage adjustment, will be a better solution on the voltage variations on the Copper belt than a bank of capacitors which will respond more bluntly and thus causing unwanted voltage variations.

The other factor affecting the voltage profile is the location of the Generating stations in relation to the load center. The generating station is in the south and the major load center in the north with the distance of about 800 km gives a great risk for a voltage collapse if a major line fault on the lines connecting the two centers occurs. There are some limitations on the operation of SVCs to arrest the voltage collapse for a situation like this one where the distance between the generating stations and the load center is long unless we had some generating stations in the north.

6.2 Recommendations

The stability of the Zambian Power System can be further enhanced if more generating plants are implemented as the load grows. As at now the spinning reserve when operating at peak loads is very small, about 70 MW. Already two by 180 MW Hydro Power Generators are being implemented at Kariba North Bank to be commissioned in 2012 but this will be taken up by the ever increasing demand with the increase in the number of mining industry.

A research to come up with the specifications to acquire and install SVCs on major substations on the copper belt is recommended for the reason already given in the conclusion remarks. There should, also, be a thought to come up with the Generating stations in the North for System stability especially voltage stability. If Generation capacity is up graded in Lusiwasi which is part of Northern part of Zambia then we cannot have further instability problems that arise from the faulted Kabwe-Pensulo line.

6.3 Future Work

Short term static and transient stability studies should be done for the inclusion on the system of the two 180 MW generators at Kariba North Bank Power Plant to ascertain their effect.

Long term Transient simulations can be done to ascertain the suitability of the said SVCs. This thesis only covers static and short term transient simulations.

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Appendix 1: System upgrades

1. ZESCO System Upgrades

1.2 Completed generation and transmission system works.

Between 1999 and 2003 ZESCO embarked upon the rehabilitation of the entire transmission system of Zambia. The specific works that were carried out are as follows**:**

New Transmission Line: Kafue west - Lusaka west

a) This involved the construction of a 43 km long 330 kV transmission line by from Kafue West Substation to the new Lusaka West Substation with most of the materials (steel towers and conductors) coming from the abandoned 330 kV Tika line project.
b) The objective of these works was to increase reliability of supply to Lusaka by providing a second Bulk Supply Point for Lusaka.
c) Victoria falls – Katima mulilo 220 kv interconnector
d) This project involved the construction of a 230 km long 220 kV transmission line from Victoria Falls Power Station in Zambia to Katima Mulilo in Namibia. The line is principally to facilitate exports of up to 200 MW to from Zambia to Namibia. On the Namibian side a high capacity HVDC line will be constructed to facilitate the interconnection of the two systems. The line was completed and commissioned by August 2006.
e) Refurbishment and uprating of Generators
f) All three major power stations at Kafue Gorge, Kariba North Bank and Victoria Falls are being refurbished to give them another 30 years of reliable service life. In addition at Kafue Gorge the six generators will be uprated from 150 MW to 165 MW each giving a total capacity of 990 MW from the current 900 MW. The four machines at Kariba North will be uprated from 150 MW to 180 MW to increase the installed capacity from the current 600 MW to 720 MW. The uprating also applies to the generator transformers. Protection and control systems are also being modernized.

Appendix2: Identification of relevant sub-systems of the network

The Zambian power network has all the major hydro power stations located in the southern part of the country**.** The major power stations are linked to Leopards Hill substation in Lusaka, which in turn is connected to the Copper belt via Kabwe step down substation.

The Zambian power system is linked to the Zimbabwean System through two 330 kV transmission lines from Kariba North Bank power station to Kariba South power station in Zimbabwe. It is also linked to the SNEL power system in Congo through the 220kV Luano-Karavia transmission line.

The relevant interconnected power sub-systems are depicted in Figure 51.

The fact that all the major power stations are located in the south and the major load centers in the north linked by long transmission lines creates a reliability challenge. Further, although the transmission lines are a strong link for bulk transfer of electrical power, they are all located within a common way-leave making them vulnerable to common cause damage.

Nevertheless, system reliability could be enhanced by distributed generation, strengthening of inter-connectors with neighboring countries, and reinforcing the nation grid with alternative transmission lines through different geographical routes.

Currently, the link to the south is very strong with a capacity of 1400 MW which is capable of carrying most of the current Zambian peak demand of 1670 MW. On the other hand, the connection to DRC is weak with a capacity of 250 MW. To strengthen the interconnection to DRC, CEC and ZESCO are considering building new lines.

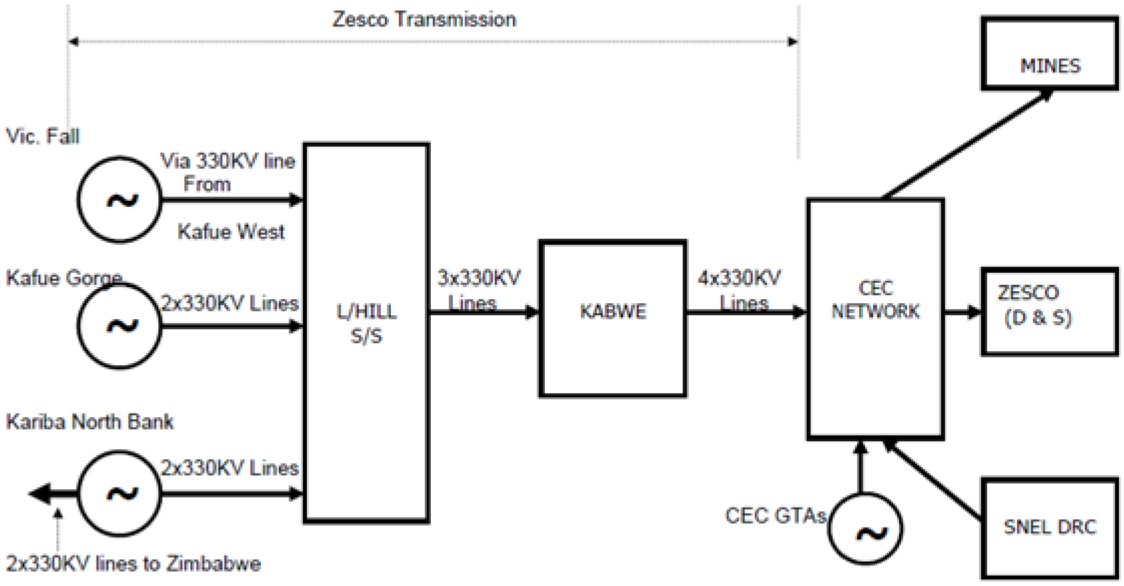


Figure 51: Relevant interconnected power sub-systems

Appendix 3: ZESCO protection philosophy

3. 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 difficult 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, the Corporation 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 330 kV 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 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.

3.1 Old Protection Philosophy

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

Backup Protection: Electro-mechanical Over current and Earth Fault relay with IDMT Characteristics.

3.2 New Protection System Philosophy

As part of the preparation for the transmission rehabilitation project, Nor consult 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. Nor consult and ZESCO formulated the new protection philosophy jointly. The main principles of the philosophy are; Main 1 protection that is Numerical Differential, Main 2 protection which is Numerical Distance and Breaker failure protection. Backup protection: Directional earth fault (DEF) with a permissive overreach feature. Over-current and earth fault with IDMT characteristics. Bus bar protection with two zones: main and check whose Primary function is to protect bus-bars,Breaker Failure protection which is fast local backup and Two tripping Supply system.

The set time for differential protection is instantaneous tripping and for distance protection the time is graded in three zones. Zone 1 is instantaneous tripping, zone 2 we have 400 seconds and zone 3 is 1.5 s.

Appendix4: Previous major faults

In order to do a better stability study on the Zambian power network, there is need to review the past major system disturbances.

Previous experiences affecting the Zambian system in the past 20 years include the 1989 Kafue Gorge Power Plant fire that led to the disconnection of all the six generators and gave severe impact on the ZESA system in neighboring Zimbabwe. The 1994 Kariba South Power Station bus-bar fault that tripped out Kariba North Bank Power Plant. The Kabwe step down bus-bar fault, when Kafue Gorge power station was lost and the system survived. The table below depicts incidents of loss of supply in the past 20 years.

Table 1: Loss of supply in the past 20 years.

ITEM NO.	INCIDENT DATE	LOCATION	DESCRIPTION OF INCIDENT	INCIDENT DURATION & LOAD LOST	COMMENT
1.	26/03/1989	Kafue Gorge Power Station	The power station experienced extensive damage due to fire	Re-commission G1-2/12/1989 G2-2/12/1989 G3-24/2/1990 G4- 6/2/1990 G5-8/8/1991 G6-10/12/1991	1.ZESA power system was affected 2. Import support from neighbors Zimbabwe and Congo DR
2.	1994	Kariba South Power station	Bus bar fault in the switch yard	N/A	Tripping of Kariba North power station
3.	14/11/1997	Kafue West – Leopards Hill 330Kv line	Collapsed towers on the Kafue West-L/Hill 330kV line. Kafue Gorge power station and all lines from power station tripped following attempted high	15:01 to 15:14hrs	SAPP frequency dropped to 45.7Hz. Tie lines to ZESA tripped on under frequency.

			speed auto reclose onto faulty line		
4.	17/12/2005	Kabwe Step Down Substation	Bus bar fault	17:25 to 18:13hrs; 530 MW	Loss of whole Copper belt and tie line to DRC.
5.	24/12/2005	Loss of Kafue Gorge	Mudslide at 20:52hrs	First two generators restored at 07:22hrs on 25/12/2005. Third generator on 29/12/2005. Fourth generator on 23/01/2006	No load loss. Import support from SAPP

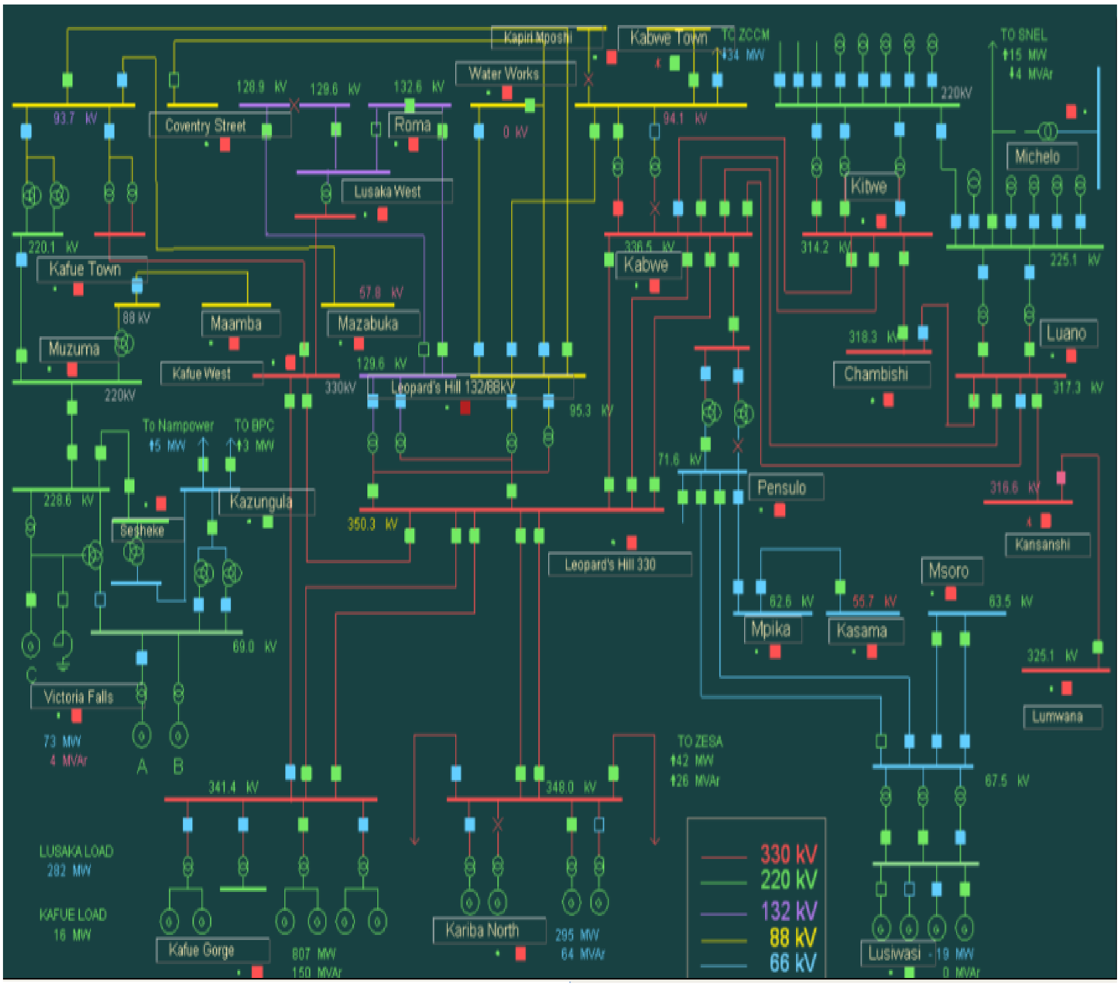
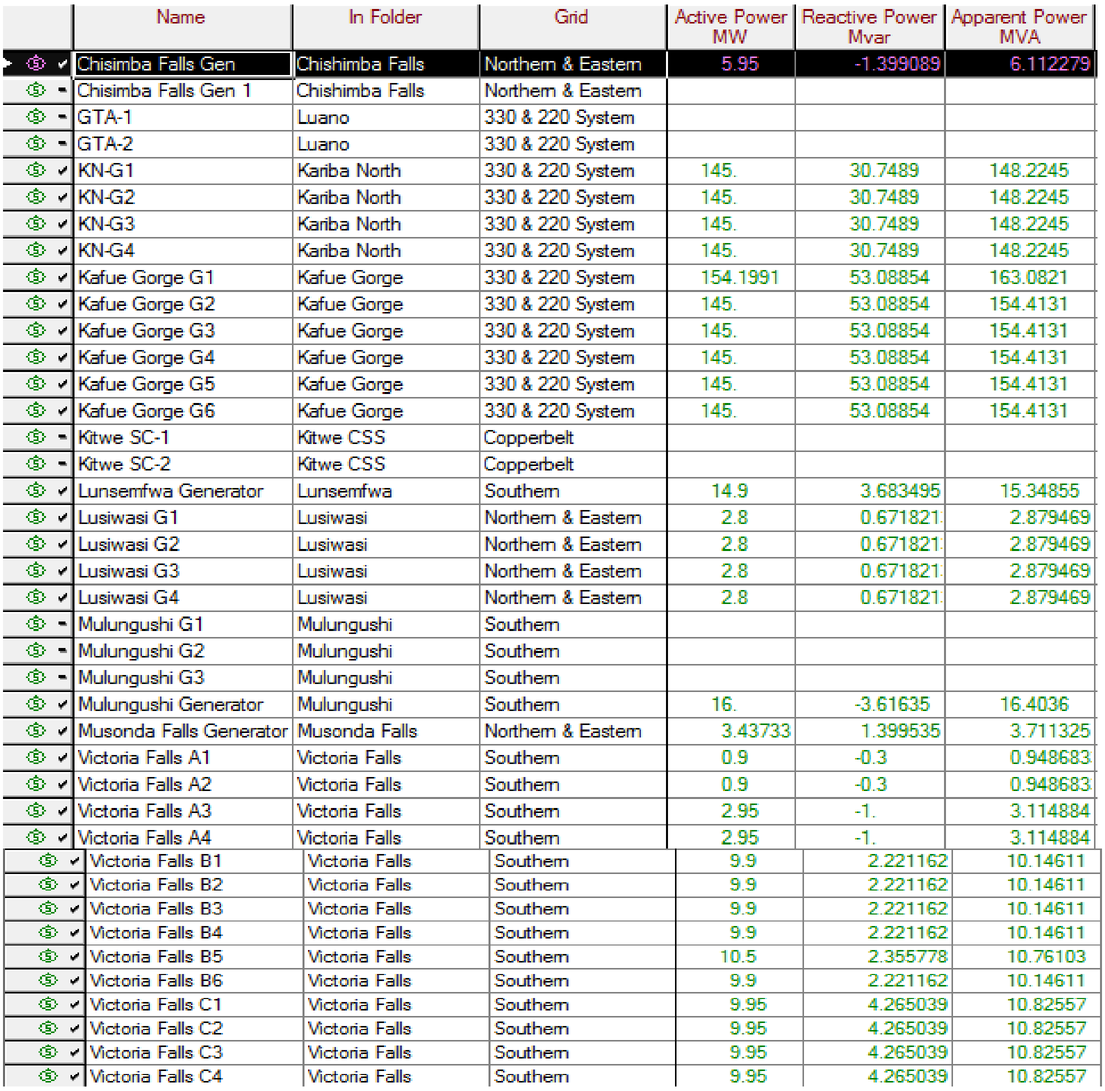


Figure 52: Single line diagram of the Zambia Power System

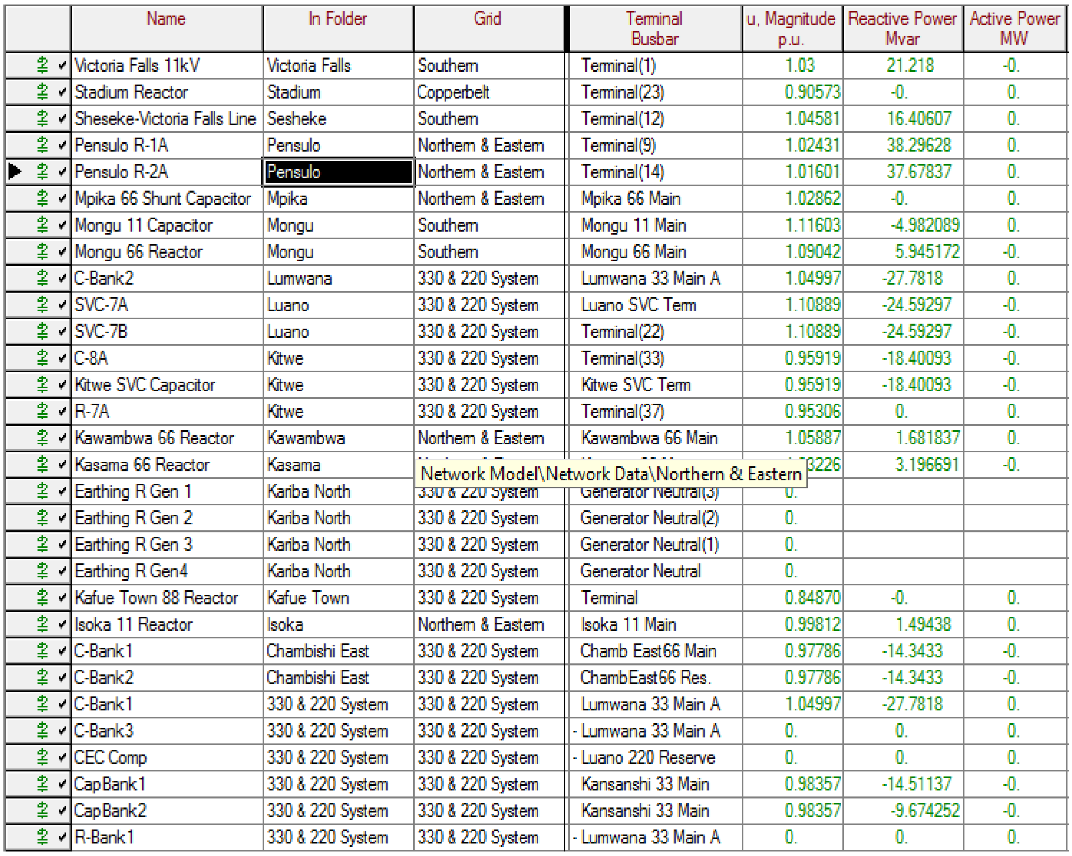
Appendix6: Unit Commitment



	Name	In Folder	Grid	Active Power MW	Reactive Power Mvar	Apparent Power MVA
✓	Chisimba Falls Gen	Chishimba Falls	Northern & Eastern	5.95	-1.399089	6.112279
-	Chisimba Falls Gen 1	Chishimba Falls	Northern & Eastern			
-	GTA-1	Luano	330 & 220 System			
-	GTA-2	Luano	330 & 220 System			
✓	KN-G1	Kariba North	330 & 220 System	145.	30.7489	148.2245
✓	KN-G2	Kariba North	330 & 220 System	145.	30.7489	148.2245
✓	KN-G3	Kariba North	330 & 220 System	145.	30.7489	148.2245
✓	KN-G4	Kariba North	330 & 220 System	145.	30.7489	148.2245
✓	Kafue Gorge G1	Kafue Gorge	330 & 220 System	154.1991	53.08854	163.0821
✓	Kafue Gorge G2	Kafue Gorge	330 & 220 System	145.	53.08854	154.4131
✓	Kafue Gorge G3	Kafue Gorge	330 & 220 System	145.	53.08854	154.4131
✓	Kafue Gorge G4	Kafue Gorge	330 & 220 System	145.	53.08854	154.4131
✓	Kafue Gorge G5	Kafue Gorge	330 & 220 System	145.	53.08854	154.4131
✓	Kafue Gorge G6	Kafue Gorge	330 & 220 System	145.	53.08854	154.4131
-	Kitwe SC-1	Kitwe CSS	Copperbelt			
-	Kitwe SC-2	Kitwe CSS	Copperbelt			
✓	Lunsemfwa Generator	Lunsemfwa	Southern	14.9	3.683495	15.34855
✓	Lusiwasi G1	Lusiwasi	Northern & Eastern	2.8	0.671821	2.879469
✓	Lusiwasi G2	Lusiwasi	Northern & Eastern	2.8	0.671821	2.879469
✓	Lusiwasi G3	Lusiwasi	Northern & Eastern	2.8	0.671821	2.879469
✓	Lusiwasi G4	Lusiwasi	Northern & Eastern	2.8	0.671821	2.879469
-	Mulungushi G1	Mulungushi	Southern			
-	Mulungushi G2	Mulungushi	Southern			
-	Mulungushi G3	Mulungushi	Southern			
✓	Mulungushi Generator	Mulungushi	Southern	16.	-3.61635	16.4036
✓	Musonda Falls Generator	Musonda Falls	Northern & Eastern	3.43733	1.399535	3.711325
✓	Victoria Falls A1	Victoria Falls	Southern	0.9	-0.3	0.948683
✓	Victoria Falls A2	Victoria Falls	Southern	0.9	-0.3	0.948683
✓	Victoria Falls A3	Victoria Falls	Southern	2.95	-1.	3.114884
✓	Victoria Falls A4	Victoria Falls	Southern	2.95	-1.	3.114884
✓	Victoria Falls B1	Victoria Falls	Southern	9.9	2.221162	10.14611
✓	Victoria Falls B2	Victoria Falls	Southern	9.9	2.221162	10.14611
✓	Victoria Falls B3	Victoria Falls	Southern	9.9	2.221162	10.14611
✓	Victoria Falls B4	Victoria Falls	Southern	9.9	2.221162	10.14611
✓	Victoria Falls B5	Victoria Falls	Southern	10.5	2.355778	10.76103
✓	Victoria Falls B6	Victoria Falls	Southern	9.9	2.221162	10.14611
✓	Victoria Falls C1	Victoria Falls	Southern	9.95	4.265039	10.82557
✓	Victoria Falls C2	Victoria Falls	Southern	9.95	4.265039	10.82557
✓	Victoria Falls C3	Victoria Falls	Southern	9.95	4.265039	10.82557
✓	Victoria Falls C4	Victoria Falls	Southern	9.95	4.265039	10.82557

Table 2: Unit commitment

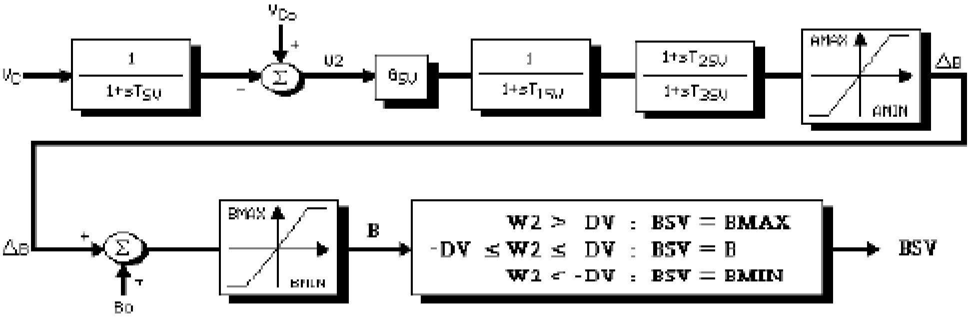
Appendix 7: Reactive power compensation and SVC Models



	Name	In Folder	Grid	Terminal Busbar	u, Magnitude p.u.	Reactive Power Mvar	Active Power MW
✓	Victoria Falls 11kV	Victoria Falls	Southern	Terminal(1)	1.03	21.218	-0.
✓	Stadium Reactor	Stadium	Copperbelt	Terminal(23)	0.90573	-0.	0.
✓	Sheseke-Victoria Falls Line	Sesheke	Southern	Terminal(12)	1.04581	16.40607	0.
✓	Pensulo R-1A	Pensulo	Northern & Eastern	Terminal(9)	1.02431	38.29628	0.
▶ ✓	Pensulo R-2A	Pensulo	Northern & Eastern	Terminal(14)	1.01601	37.67837	0.
✓	Mpika 66 Shunt Capacitor	Mpika	Northern & Eastern	Mpika 66 Main	1.02862	-0.	0.
✓	Mongu 11 Capacitor	Mongu	Southern	Mongu 11 Main	1.11603	-4.982089	0.
✓	Mongu 66 Reactor	Mongu	Southern	Mongu 66 Main	1.09042	5.945172	-0.
✓	C-Bank2	Lumwana	330 & 220 System	Lumwana 33 Main A	1.04997	-27.7818	0.
✓	SVC-7A	Luano	330 & 220 System	Luano SVC Term	1.10889	-24.59297	-0.
✓	SVC-7B	Luano	330 & 220 System	Terminal(22)	1.10889	-24.59297	-0.
✓	C-8A	Kitwe	330 & 220 System	Terminal(33)	0.95919	-18.40093	-0.
✓	Kitwe SVC Capacitor	Kitwe	330 & 220 System	Kitwe SVC Term	0.95919	-18.40093	-0.
✓	R-7A	Kitwe	330 & 220 System	Terminal(37)	0.95306	0.	0.
✓	Kawambwa 66 Reactor	Kawambwa	Northern & Eastern	Kawambwa 66 Main	1.05887	1.681837	0.
✓	Kasama 66 Reactor	Kasama	[illegible]	[illegible]	[illegible]	3.196691	-0.
✓	Earthing R Gen 1	Kariba North	330 & 220 System	Generator Neutral(3)	0.		
✓	Earthing R Gen 2	Kariba North	330 & 220 System	Generator Neutral(2)	0.		
✓	Earthing R Gen 3	Kariba North	330 & 220 System	Generator Neutral(1)	0.		
✓	Earthing R Gen4	Kariba North	330 & 220 System	Generator Neutral	0.		
✓	Kafue Town 88 Reactor	Kafue Town	330 & 220 System	Terminal	0.84870	-0.	0.
✓	Isoka 11 Reactor	Isoka	Northern & Eastern	Isoka 11 Main	0.99812	1.49438	0.
✓	C-Bank1	Chambishi East	330 & 220 System	Chamb East66 Main	0.97786	-14.3433	-0.
✓	C-Bank2	Chambishi East	330 & 220 System	ChambEast66 Res.	0.97786	-14.3433	-0.
✓	C-Bank1	330 & 220 System	330 & 220 System	Lumwana 33 Main A	1.04997	-27.7818	0.
✓	C-Bank3	330 & 220 System	330 & 220 System	- Lumwana 33 Main A	0.	0.	0.
✓	CEC Comp	330 & 220 System	330 & 220 System	- Luano 220 Reserve	0.	0.	0.
✓	CapBank1	330 & 220 System	330 & 220 System	Kansanshi 33 Main	0.98357	-14.51137	-0.
✓	CapBank2	330 & 220 System	330 & 220 System	Kansanshi 33 Main	0.98357	-9.674252	-0.
✓	R-Bank1	330 & 220 System	330 & 220 System	- Lumwana 33 Main A	0.	0.	0.

Network Model\Network Data\Northern & Eastern

Table 3: Reactive power compensation and SVC Models



Parameters	(unity)	Value
TSV	s	0,02
T1SV	s	0,05
GSV	pu	100
T2SV	s	0
T3SV	s	0
AMAX	pu	10
AMIN	pu	-10
BMAX	pu	5
BMIN	pu	-5
DV	pu	0,2

Figure 53: Model3 of SVC and its parameters

Appendix8: Loading on the lines at peak load

Name	Loading	Active Power	Total Active Power	Power Factor	Active Power	Reactive Power
	%	Terminal i in MW	Terminal i in MW	Terminal i	Terminal j in MW	Terminal i in Mvar
Chamb-Kitwe 330	8.80184	-7.541726	-7.541726	-0.1470049	7.570425	50.74518
Chamb-Luano 330	5.06364	-12.61616	-12.61616	-0.3656218	12.6222	-32.11697
Cosak-Kitwe 220 A1	3.84417	12.26885	12.26885	0.993063	-12.25749	-1.452693
Cosak-Luano 220 1A	11.3479	37.97378	37.97378	0.9972368	-37.9425	2.828823
Coventry Street-Leopards Hill 132 1A	112.722	-100.8296	-100.8296	-0.8565973	105.1196	-60.7364
Coventry Street-Lusaka West 132 1A	36.5936	-32.69939	-32.69939	-0.8557193	32.81259	-19.77282
Kabwe-Kitwe 330 1A	30.2226	-191.5655	-191.5655	-0.9343334	194.5554	-73.07239
Kabwe-Kitwe 330 2A	30.2226	194.5554	194.5554	0.993513	-191.5655	22.26907
Kabwe-Leopards Hill 330 1A	34.6296	-246.0871	-246.0871	-0.9991524	248.0859	-10.13877
Kabwe-Leopards Hill 330	34.6296	248.0859	248.0859	0.9992647	-246.0871	-9.519106

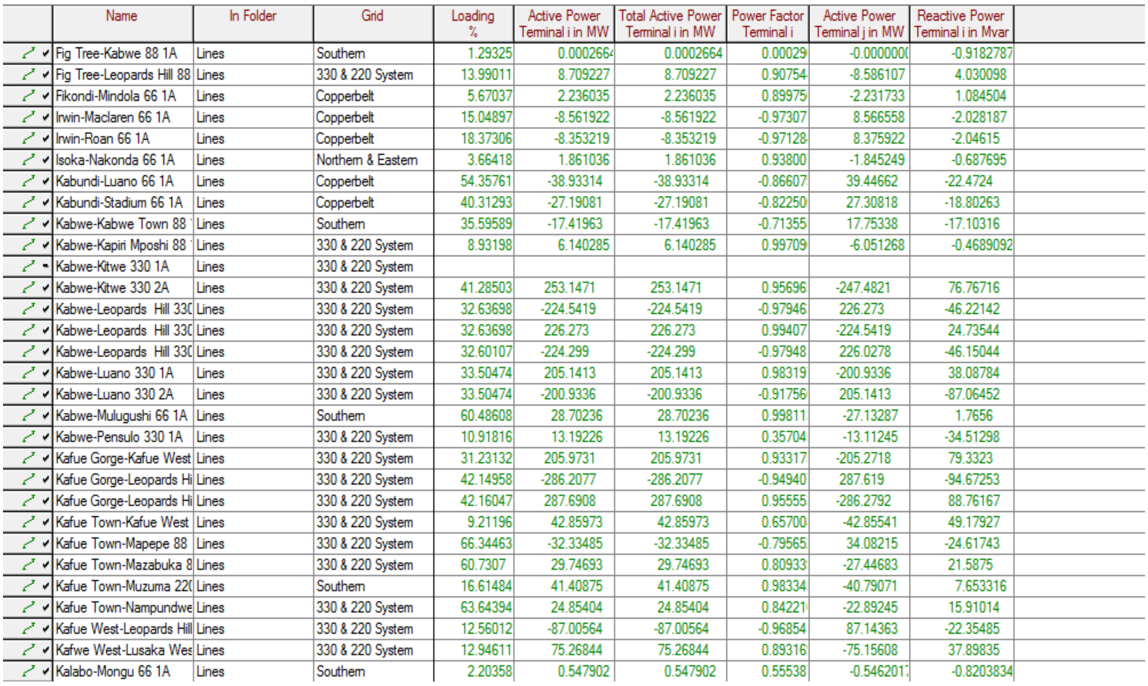
2A						
Kabwe-Leopards Hill 330 3A	34.6296	-246.0871	-246.0871	-0.9991524	248.0859	-10.13877
Kabwe-Luano 330 1A	26.1079	167.5389	167.5389	0.9999606	-165.0016	-1.486959
Kabwe-Luano 330 2A	26.1079	-165.0016	-165.0016	-0.9259354	167.5389	-67.3029
Kabwe-Mulugushi 66 1A	60.0244	28.54312	28.54312	0.9999437	-26.99797	0.3029644
Kabwe-Pensulo 330 1A	11.2683	15.45993	15.45993	0.4068937	-15.303	-34.7075
Kafue Gorge-Kafue West 330 1A	33.9255	229.2601	229.2601	0.9504632	-228.4275	74.97669
Kafue Gorge-Leopards Hill 330 1A	46.1438	-323.2666	-323.2666	-0.9769574	324.9695	-70.62361
Kafue Gorge-Leopards Hill 330 2A	46.1438	324.9695	324.9695	0.9792662	-323.2666	67.22543
Kafue Town-Kafue West 330 1A	10.3166	48.16573	48.16573	0.6581263	-48.1603	55.10241
Kafue Town-Mapepe 88 1A	73.8787	-36.65598	-36.65598	-0.8258529	38.82577	-25.0284
Kafue Town-Mazabuka 88 1A	63.1638	30.18383	30.18383	0.8045265	-27.69411	22.28227

Kafue Town-Muzuma 220 1A	16.0758	37.27079	37.27079	0.9673094	-36.71681	9.771266
Kafue Town-Nampundwe 88 1A	66.451	25.34926	25.34926	0.8382546	-23.20938	16.48952
Kafue West-Leopards Hill 330 1A	14.1493	-100.5722	-100.5722	-0.9982039	100.7523	-6.035961
Kafwe West-Lusaka West 330 1A	13.7946	79.50955	79.50955	0.8820955	-79.38147	42.46095
Kansanshi-Luano 330 1A	28.3571	153.3937	153.3937	0.7925187	-151.1513	-118.0373
Kansanshi-Lumwana 330_1	12.3634	-59.99999	-59.99999	-0.8445348	60.15133	38.04466
Kansuswa-Kitwe 220 1A	21.0658	62.05134	62.05134	0.9030602	-61.8534	29.51289
Kansuswa-Luano 220 1A	18.3552	-53.52842	-53.52842	-0.8737011	53.69635	-29.80378
Kansuswa-Mufulira 66 1A	39.6584	31.45798	31.45798	0.8908249	-31.27241	16.04449
Kaoma-Mongu 66 1A	5.6858	-0.9382667	-0.9382667	-0.94	0.9622468	-0.3405454
Kapiri Mposhi-Mpongwe 88 1A	4.26147	2.815774	2.815774	0.9955617	-2.803672	-0.2661782
Kariba North-Kariba South 330	14.2943	105.0035	105.0035	0.9999936	-105	-0.3767628

1A						
Kariba North-Kariba South 330 2A	14.2943	105.0035	105.0035	0.9999936	-105	-0.3767628
Kariba North-Leopards Hill 1A	27.0442	184.3965	184.3965	0.9885398	-182.9511	28.15931
Kariba North-Leopards Hill 2A	27.0442	-182.9511	-182.9511	-0.9433842	184.3965	-64.32717
Kasama-Lubushi T 66 1A	8.45604	-2.64167	-2.64167	-0.6608541	2.693184	3.000075
Kasama-Mbala 66 1A	4.03681	1.595049	1.595049	0.713272	-1.575619	-1.567354
Kasama-Mpika 66 1A	6.1263	-2.190335	-2.190335	-0.9972292	2.246813	-0.1633924
Katima Mulilo-Sesheke 66 1A	13.5182	-5.337541	-5.337541	-0.9285997	5.373889	-2.132965
Kawambwa-Mporokoso 66 1A	3.99435	-0.4529975	-0.4529975	-0.9583056	0.4634235	-0.1350736
Kazunglu-Victoria Falls 66 1A	11.3935	6.040201	6.040201	0.9458043	-5.920346	-2.073874
Kazungula-Sesheke 66 1A	5.53092	-1.891165	-1.891165	-0.9305622	1.922004	0.7440875
Kitwe-Luangwa 66 1A	10.617	5.411549	5.411549	0.9546633	-5.399999	1.687456
Kitwe-Maposa 220 1A	21.7689	61.97115	61.97115	0.8567064	-61.88778	37.3115

Kitwe-Maposa 220 2A	21.7689	-61.88778	-61.88778	-0.8472292	61.97115	-38.80473
Kitwe-Mill 66 1A	42.6683	27.69582	27.69582	0.7110207	-27.49054	27.39006
Leopards Hill-Mapape 88 1A	88.7652	51.79385	51.79385	0.808556	-49.03719	37.69249
Leopards Hill-Roma 132 1A	101.215	-92.13582	-92.13582	-0.8644669	95.59285	-53.57723
Leopards Hill-Waterworks 88 1A	90.6773	55.07073	55.07073	0.8400122	-52.92	35.57042
Leopards Hill-Waterworks 88 2A	96.9644	50.54311	50.54311	0.7215814	-48.09081	48.49418
Luano-Michelo-T 220 1A	43.8695	109.7458	109.7458	0.7562832	-108.1156	-94.93878
Maamba-Muzuma 88 1A	19.4381	11.01746	11.01746	0.8553236	-10.77662	6.673594
Muzuma-Victoria Falls 220 1A	20.576	-58.22862	-58.22862	-0.9252146	59.12194	-23.88042
Pensulo-Serenje 66 1A	2.15778	1.126691	1.126691	0.9869169	-1.124458	-0.1840642
Senanga-Sesheke 66 1A	15.6326	-3.672729	-3.672729	-0.7720273	4.065207	3.023659
Sheseke-Victoria Falls 220_1	6.68725	-11.98455	-11.98455	-0.6310039	12.05305	-14.73425

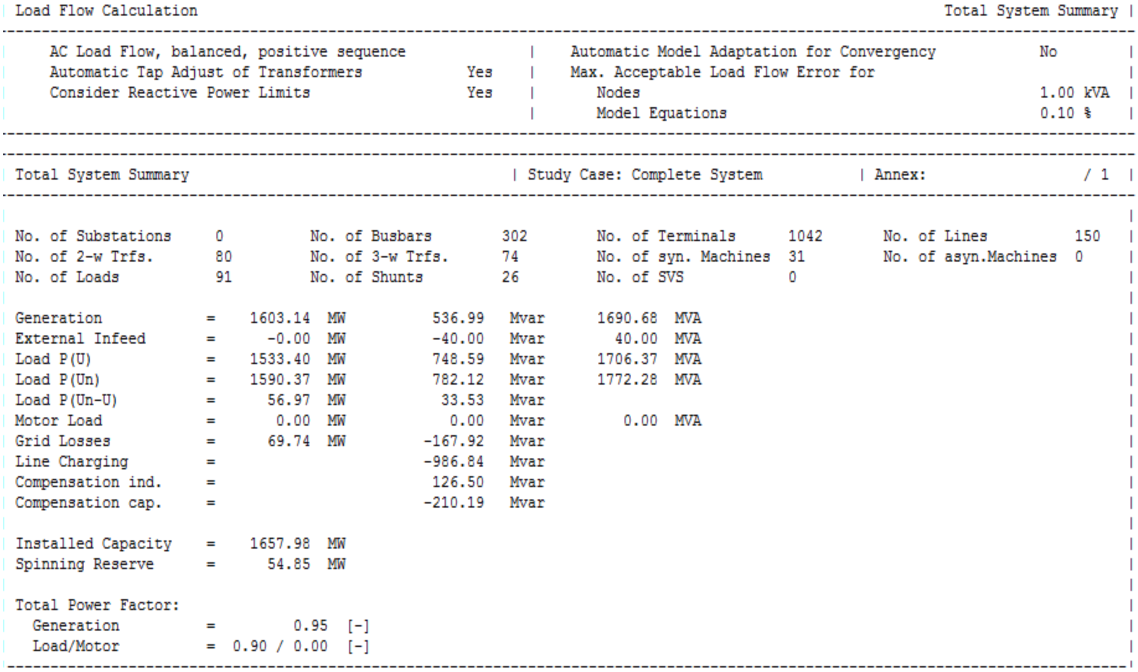
Table 4: Loading on the lines at peak load



	Name	In Folder	Grid	Loading %	Active Power Terminal i in MW	Total Active Power Terminal i in MW	Power Factor Terminal i	Active Power Terminal j in MW	Reactive Power Terminal i in Mvar
✓	Fig Tree-Kabwe 88 1A	Lines	Southern	1.29325	0.000266	0.0002664	0.00029	-0.000000	-0.9182787
✓	Fig Tree-Leopards Hill 88	Lines	330 & 220 System	13.99011	8.709227	8.709227	0.90754	-8.586107	4.030098
✓	Fikondi-Mindola 66 1A	Lines	Copperbelt	5.67037	2.236035	2.236035	0.89975	-2.231733	1.084504
✓	Irwin-Maclaren 66 1A	Lines	Copperbelt	15.04897	-8.561922	-8.561922	-0.97307	8.566558	-2.028187
✓	Irwin-Roan 66 1A	Lines	Copperbelt	18.37306	-8.353219	-8.353219	-0.97128	8.375922	-2.04615
✓	Isoka-Nakonda 66 1A	Lines	Northern & Eastern	3.66418	1.861036	1.861036	0.93800	-1.845249	-0.687695
✓	Kabundi-Luano 66 1A	Lines	Copperbelt	54.35761	-38.93314	-38.93314	-0.86607	39.44662	-22.4724
✓	Kabundi-Stadium 66 1A	Lines	Copperbelt	40.31293	-27.19081	-27.19081	-0.82250	27.30818	-18.80263
✓	Kabwe-Kabwe Town 88	Lines	Southern	35.59589	-17.41963	-17.41963	-0.71355	17.75338	-17.10316
✓	Kabwe-Kapiri Mposhi 88	Lines	330 & 220 System	8.93198	6.140285	6.140285	0.99709	-6.051268	-0.4689092
-	Kabwe-Kitwe 330 1A	Lines	330 & 220 System						
✓	Kabwe-Kitwe 330 2A	Lines	330 & 220 System	41.28503	253.1471	253.1471	0.95696	-247.4821	76.76716
✓	Kabwe-Leopards Hill 330	Lines	330 & 220 System	32.63698	-224.5419	-224.5419	-0.97946	226.273	-46.22142
✓	Kabwe-Leopards Hill 330	Lines	330 & 220 System	32.63698	226.273	226.273	0.99407	-224.5419	24.73544
✓	Kabwe-Leopards Hill 330	Lines	330 & 220 System	32.60107	-224.299	-224.299	-0.97948	226.0278	-46.15044
✓	Kabwe-Luano 330 1A	Lines	330 & 220 System	33.50474	205.1413	205.1413	0.98319	-200.9336	38.08784
✓	Kabwe-Luano 330 2A	Lines	330 & 220 System	33.50474	-200.9336	-200.9336	-0.91756	205.1413	-87.06452
✓	Kabwe-Mulugushi 66 1A	Lines	Southern	60.48608	28.70236	28.70236	0.99811	-27.13287	1.7656
✓	Kabwe-Pensulo 330 1A	Lines	330 & 220 System	10.91816	13.19226	13.19226	0.35704	-13.11245	-34.51298
✓	Kafue Gorge-Kafue West	Lines	330 & 220 System	31.23132	205.9731	205.9731	0.93317	-205.2718	79.3323
✓	Kafue Gorge-Leopards Hi	Lines	330 & 220 System	42.14958	-286.2077	-286.2077	-0.94940	287.619	-94.67253
✓	Kafue Gorge-Leopards Hi	Lines	330 & 220 System	42.16047	287.6908	287.6908	0.95555	-286.2792	88.76167
✓	Kafue Town-Kafue West	Lines	330 & 220 System	9.21196	42.85973	42.85973	0.65700	-42.85541	49.17927
✓	Kafue Town-Mapepe 88	Lines	330 & 220 System	66.34463	-32.33485	-32.33485	-0.79565	34.08215	-24.61743
✓	Kafue Town-Mazabuka 8	Lines	330 & 220 System	60.7307	29.74693	29.74693	0.80933	-27.44683	21.5875
✓	Kafue Town-Muzuma 220	Lines	Southern	16.61484	41.40875	41.40875	0.98334	-40.79071	7.653316
✓	Kafue Town-Nampundwe	Lines	330 & 220 System	63.64394	24.85404	24.85404	0.84221	-22.89245	15.91014
✓	Kafue West-Leopards Hill	Lines	330 & 220 System	12.56012	-87.00564	-87.00564	-0.96854	87.14363	-22.35485
✓	Kafwe West-Lusaka Wes	Lines	330 & 220 System	12.94611	75.26844	75.26844	0.89316	-75.15608	37.89835
✓	Kalabo-Mongu 66 1A	Lines	Southern	2.20358	0.547902	0.547902	0.55538	-0.546201	-0.8203834

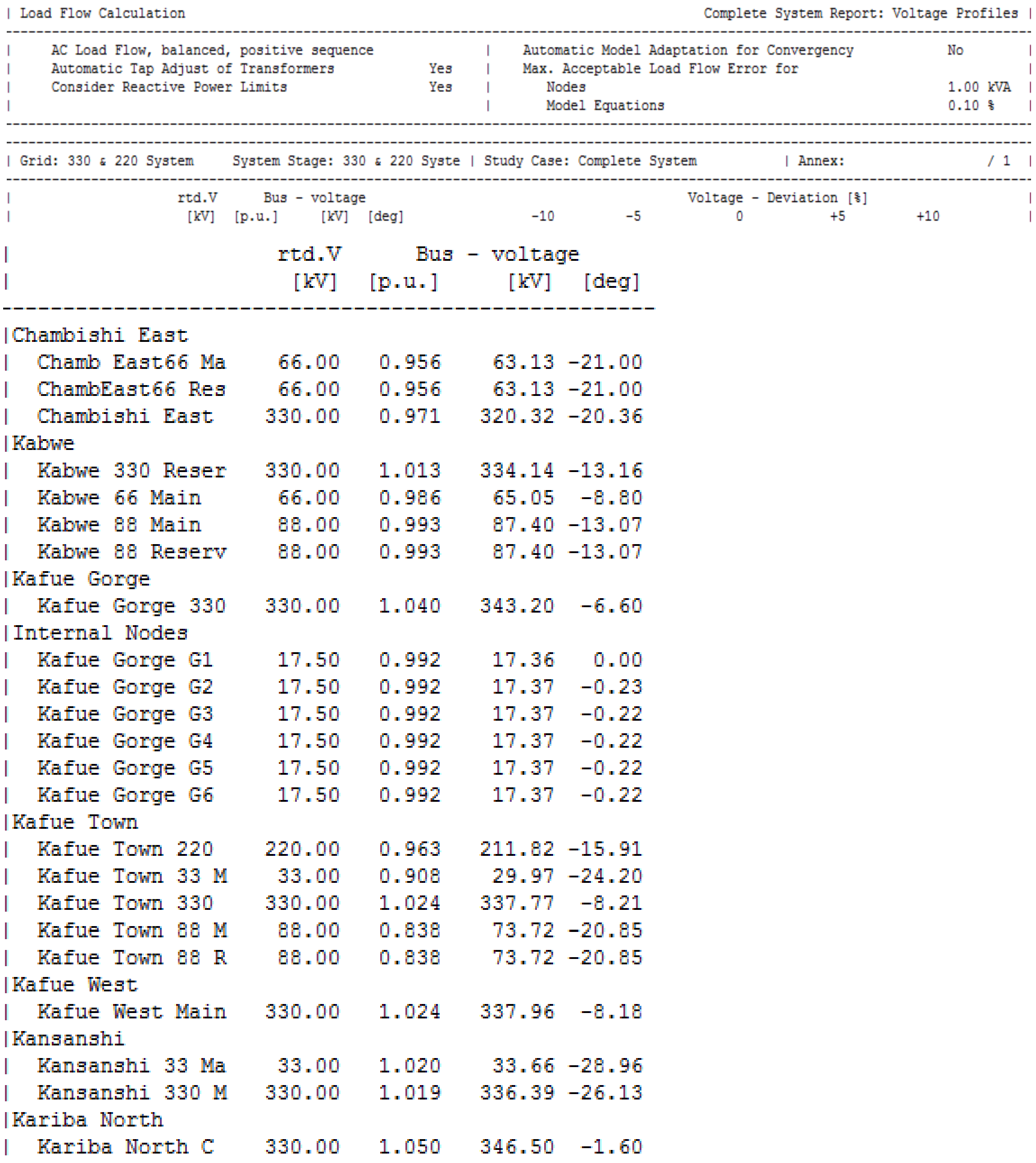
Table 5: Load flow with Kabwe-Kitwe line out at peak load

Appendix 9: Load flow calculations on N-1

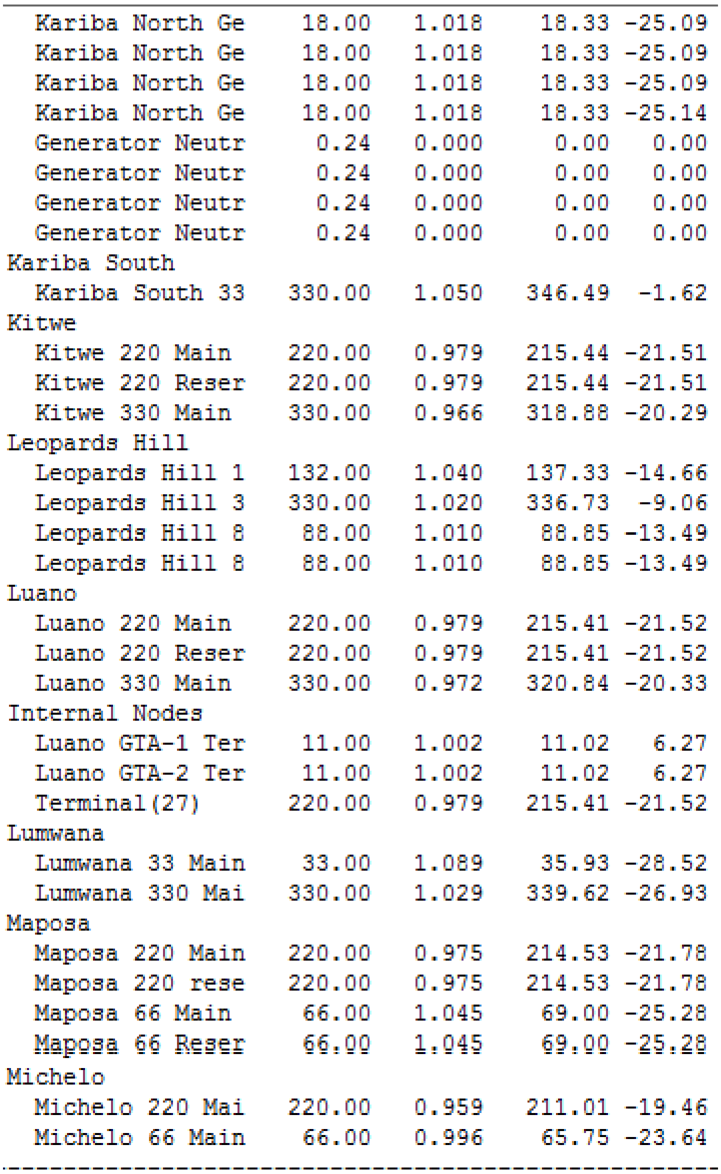


```
| Load Flow Calculation                                                                                     Total System Summary |
-----------------------------------------------------------------------------------------------------------------------------------
|    AC Load Flow, balanced, positive sequence              |    Automatic Model Adaptation for Convergency            No        |
|    Automatic Tap Adjust of Transformers           Yes     |    Max. Acceptable Load Flow Error for                           |
|    Consider Reactive Power Limits                 Yes     |       Nodes                                          1.00 kVA    |
|                                                           |       Model Equations                                0.10 %      |
-----------------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------------
| Total System Summary                                     | Study Case: Complete System          | Annex:                 / 1  |
-----------------------------------------------------------------------------------------------------------------------------------
|                                                                                                                                 |
| No. of Substations     0          No. of Busbars       302       No. of Terminals      1042      No. of Lines          150     |
| No. of 2-w Trfs.       80         No. of 3-w Trfs.     74        No. of syn. Machines  31        No. of asyn.Machines  0       |
| No. of Loads           91         No. of Shunts        26        No. of SVS            0                                        |
|                                                                                                                                 |
| Generation           =    1603.14  MW        536.99   Mvar     1690.68  MVA                                                     |
| External Infeed      =      -0.00  MW        -40.00   Mvar       40.00  MVA                                                     |
| Load P(U)            =    1533.40  MW        748.59   Mvar     1706.37  MVA                                                     |
| Load P(Un)           =    1590.37  MW        782.12   Mvar     1772.28  MVA                                                     |
| Load P(Un-U)         =      56.97  MW         33.53   Mvar                                                                      |
| Motor Load           =       0.00  MW          0.00   Mvar        0.00  MVA                                                     |
| Grid Losses          =      69.74  MW       -167.92   Mvar                                                                      |
| Line Charging        =                       -986.84   Mvar                                                                      |
| Compensation ind.    =                        126.50   Mvar                                                                      |
| Compensation cap.    =                       -210.19   Mvar                                                                      |
|                                                                                                                                 |
| Installed Capacity   =    1657.98  MW                                                                                           |
| Spinning Reserve     =      54.85  MW                                                                                           |
|                                                                                                                                 |
| Total Power Factor:                                                                                                             |
|   Generation         =         0.95  [-]                                                                                        |
|   Load/Motor         =  0.90 / 0.00  [-]                                                                                        |
-----------------------------------------------------------------------------------------------------------------------------------
```

Table 6: Load flow with Kariba north and LHill line out (Load reduced to account for increased loses).

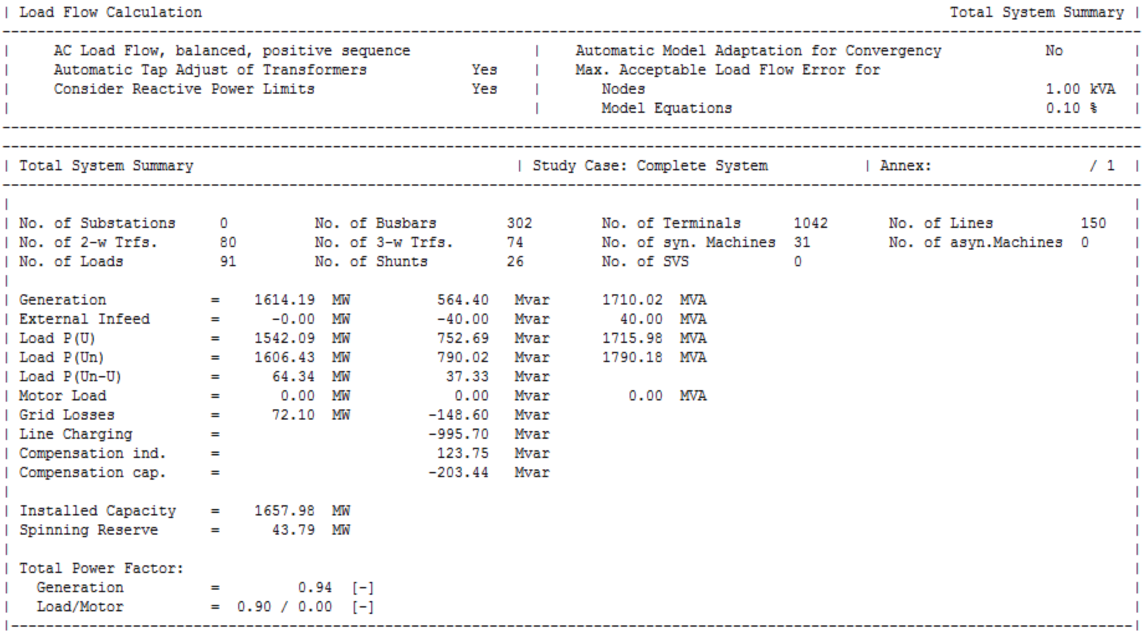


```
| Load Flow Calculation                                                        Complete System Report: Voltage Profiles |
-------------------------------------------------------------------------------------------------------------------------
|     AC Load Flow, balanced, positive sequence                    |   Automatic Model Adaptation for Convergency       No      |
|     Automatic Tap Adjust of Transformers               Yes       |   Max. Acceptable Load Flow Error for                      |
|     Consider Reactive Power Limits                     Yes       |      Nodes                                       1.00 kVA  |
|                                                                  |      Model Equations                             0.10 %    |
-------------------------------------------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------------------------------------------
| Grid: 330 & 220 System     System Stage: 330 & 220 Syste | Study Case: Complete System          | Annex:              / 1  |
-------------------------------------------------------------------------------------------------------------------------
|                    rtd.V      Bus - voltage                                 Voltage - Deviation [%]                     |
|                     [kV]  [p.u.]      [kV]  [deg]            -10          -5           0          +5          +10       |
|                    rtd.V      Bus - voltage
|                     [kV]  [p.u.]      [kV]  [deg]
--------------------------------------------------
|Chambishi East
|  Chamb East66 Ma    66.00   0.956    63.13 -21.00
|  ChambEast66 Res    66.00   0.956    63.13 -21.00
|  Chambishi East    330.00   0.971   320.32 -20.36
|Kabwe
|  Kabwe 330 Reser   330.00   1.013   334.14 -13.16
|  Kabwe 66 Main      66.00   0.986    65.05  -8.80
|  Kabwe 88 Main      88.00   0.993    87.40 -13.07
|  Kabwe 88 Reserv    88.00   0.993    87.40 -13.07
|Kafue Gorge
|  Kafue Gorge 330   330.00   1.040   343.20  -6.60
|Internal Nodes
|  Kafue Gorge G1     17.50   0.992    17.36   0.00
|  Kafue Gorge G2     17.50   0.992    17.37  -0.23
|  Kafue Gorge G3     17.50   0.992    17.37  -0.22
|  Kafue Gorge G4     17.50   0.992    17.37  -0.22
|  Kafue Gorge G5     17.50   0.992    17.37  -0.22
|  Kafue Gorge G6     17.50   0.992    17.37  -0.22
|Kafue Town
|  Kafue Town 220    220.00   0.963   211.82 -15.91
|  Kafue Town 33 M    33.00   0.908    29.97 -24.20
|  Kafue Town 330    330.00   1.024   337.77  -8.21
|  Kafue Town 88 M    88.00   0.838    73.72 -20.85
|  Kafue Town 88 R    88.00   0.838    73.72 -20.85
|Kafue West
|  Kafue West Main   330.00   1.024   337.96  -8.18
|Kansanshi
|  Kansanshi 33 Ma    33.00   1.020    33.66 -28.96
|  Kansanshi 330 M   330.00   1.019   336.39 -26.13
|Kariba North
|  Kariba North C    330.00   1.050   346.50  -1.60
```



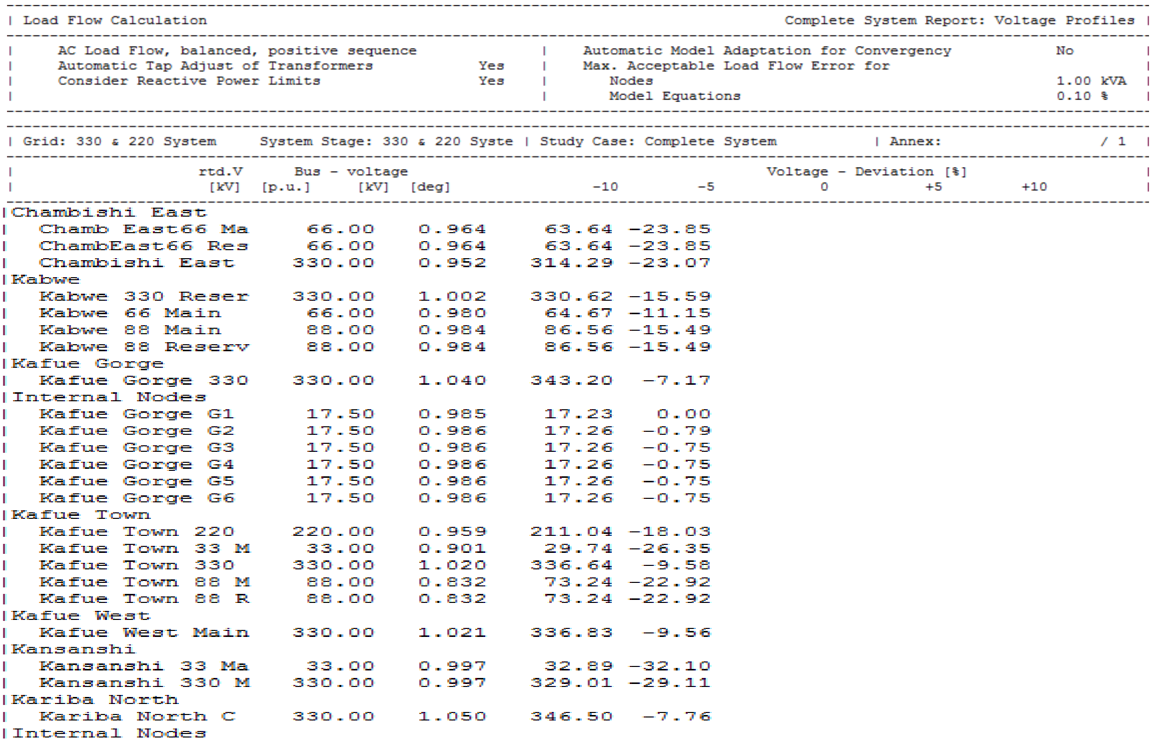
```
   Kariba North Ge     18.00    1.018     18.33 -25.09
   Kariba North Ge     18.00    1.018     18.33 -25.09
   Kariba North Ge     18.00    1.018     18.33 -25.09
   Kariba North Ge     18.00    1.018     18.33 -25.14
   Generator Neutr      0.24    0.000      0.00   0.00
   Generator Neutr      0.24    0.000      0.00   0.00
   Generator Neutr      0.24    0.000      0.00   0.00
   Generator Neutr      0.24    0.000      0.00   0.00
Kariba South
   Kariba South 33    330.00    1.050    346.49  -1.62
Kitwe
   Kitwe 220 Main     220.00    0.979    215.44 -21.51
   Kitwe 220 Reser    220.00    0.979    215.44 -21.51
   Kitwe 330 Main     330.00    0.966    318.88 -20.29
Leopards Hill
   Leopards Hill 1    132.00    1.040    137.33 -14.66
   Leopards Hill 3    330.00    1.020    336.73  -9.06
   Leopards Hill 8     88.00    1.010     88.85 -13.49
   Leopards Hill 8     88.00    1.010     88.85 -13.49
Luano
   Luano 220 Main     220.00    0.979    215.41 -21.52
   Luano 220 Reser    220.00    0.979    215.41 -21.52
   Luano 330 Main     330.00    0.972    320.84 -20.33
Internal Nodes
   Luano GTA-1 Ter     11.00    1.002     11.02   6.27
   Luano GTA-2 Ter     11.00    1.002     11.02   6.27
   Terminal(27)       220.00    0.979    215.41 -21.52
Lumwana
   Lumwana 33 Main     33.00    1.089     35.93 -28.52
   Lumwana 330 Mai    330.00    1.029    339.62 -26.93
Maposa
   Maposa 220 Main    220.00    0.975    214.53 -21.78
   Maposa 220 rese    220.00    0.975    214.53 -21.78
   Maposa 66 Main      66.00    1.045     69.00 -25.28
   Maposa 66 Reser     66.00    1.045     69.00 -25.28
Michelo
   Michelo 220 Mai    220.00    0.959    211.01 -19.46
   Michelo 66 Main     66.00    0.996     65.75 -23.64
-----------------------------------------------------
```

Table 7: Voltage profile with Kariba North- LHill line out.



```
| Load Flow Calculation                                                                        Total System Summary |
---------------------------------------------------------------------------------------------------------------------
|     AC Load Flow, balanced, positive sequence                 |   Automatic Model Adaptation for Convergency        No     |
|     Automatic Tap Adjust of Transformers            Yes       |   Max. Acceptable Load Flow Error for                      |
|     Consider Reactive Power Limits                  Yes       |      Nodes                                        1.00 kVA |
|                                                               |      Model Equations                              0.10 %   |
---------------------------------------------------------------------------------------------------------------------
---------------------------------------------------------------------------------------------------------------------
| Total System Summary                                  | Study Case: Complete System          | Annex:              / 1  |
---------------------------------------------------------------------------------------------------------------------
|                                                                                                                   |
| No. of Substations     0         No. of Busbars       302        No. of Terminals      1042      No. of Lines          150  |
| No. of 2-w Trfs.       80        No. of 3-w Trfs.     74         No. of syn. Machines  31        No. of asyn.Machines  0    |
| No. of Loads           91        No. of Shunts        26         No. of SVS            0                                   |
|                                                                                                                   |
| Generation           =    1614.19  MW         564.40  Mvar      1710.02  MVA                                      |
| External Infeed      =      -0.00  MW         -40.00  Mvar        40.00  MVA                                      |
| Load P(U)            =    1542.09  MW         752.69  Mvar      1715.98  MVA                                      |
| Load P(Un)           =    1606.43  MW         790.02  Mvar      1790.18  MVA                                      |
| Load P(Un-U)         =      64.34  MW          37.33  Mvar                                                        |
| Motor Load           =       0.00  MW           0.00  Mvar         0.00  MVA                                      |
| Grid Losses          =      72.10  MW        -148.60  Mvar                                                        |
| Line Charging        =                       -995.70  Mvar                                                        |
| Compensation ind.    =                        123.75  Mvar                                                        |
| Compensation cap.    =                       -203.44  Mvar                                                        |
|                                                                                                                   |
| Installed Capacity   =    1657.98  MW                                                                            |
| Spinning Reserve     =      43.79  MW                                                                            |
|                                                                                                                   |
| Total Power Factor:                                                                                               |
|   Generation         =         0.94  [-]                                                                          |
|   Load/Motor         =  0.90 / 0.00  [-]                                                                          |
|-------------------------------------------------------------------------------------------------------------------|
```

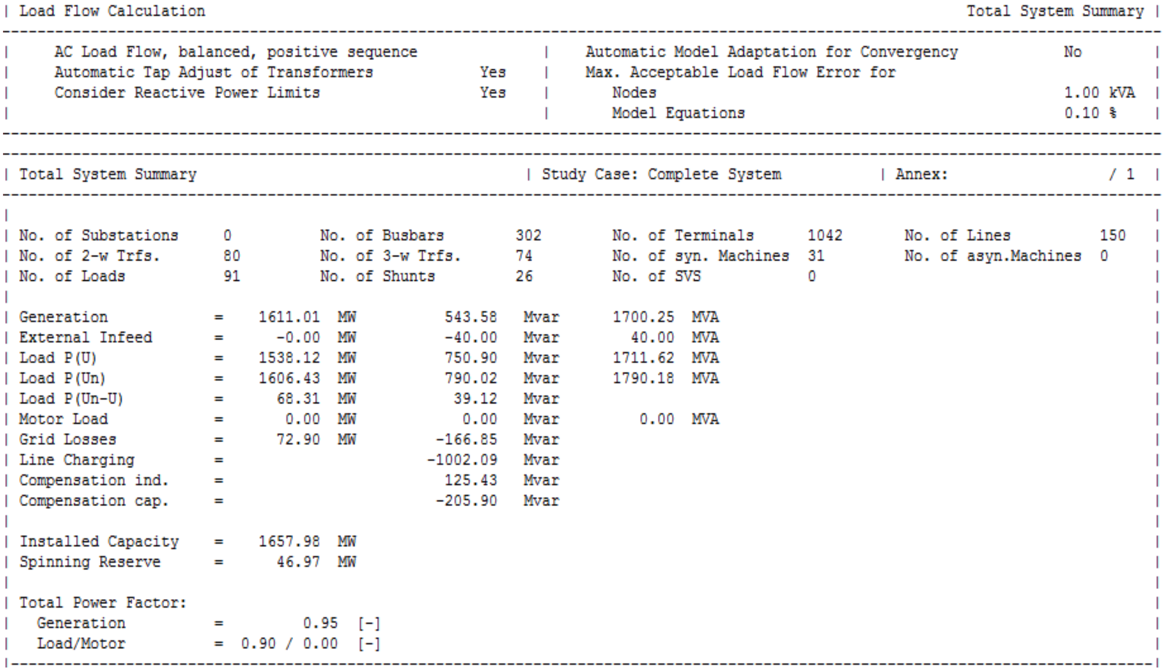
Table 8: Load flow with KFG-LHil line out.



```
---------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                      Complete System Report: Voltage Profiles |
---------------------------------------------------------------------------------------------------------------------
|     AC Load Flow, balanced, positive sequence                 |   Automatic Model Adaptation for Convergency        No     |
|     Automatic Tap Adjust of Transformers            Yes       |   Max. Acceptable Load Flow Error for                      |
|     Consider Reactive Power Limits                  Yes       |      Nodes                                        1.00 kVA |
|                                                               |      Model Equations                              0.10 %   |
---------------------------------------------------------------------------------------------------------------------
---------------------------------------------------------------------------------------------------------------------
| Grid: 330 & 220 System     System Stage: 330 & 220 Syste | Study Case: Complete System          | Annex:          / 1 |
---------------------------------------------------------------------------------------------------------------------
|                    rtd.V     Bus - voltage                                   Voltage - Deviation [%]                |
|                     [kV]   [p.u.]      [kV]   [deg]          -10        -5          0          +5         +10     |
---------------------------------------------------------------------------------------------------------------------
|Chambishi East
|   Chamb East66 Ma     66.00    0.964     63.64 -23.85
|   ChambEast66 Res     66.00    0.964     63.64 -23.85
|   Chambishi East     330.00    0.952    314.29 -23.07
|Kabwe
|   Kabwe 330 Reser    330.00    1.002    330.62 -15.59
|   Kabwe 66 Main       66.00    0.980     64.67 -11.15
|   Kabwe 88 Main       88.00    0.984     86.56 -15.49
|   Kabwe 88 Reserv     88.00    0.984     86.56 -15.49
|Kafue Gorge
|   Kafue Gorge 330    330.00    1.040    343.20  -7.17
|Internal Nodes
|   Kafue Gorge G1      17.50    0.985     17.23   0.00
|   Kafue Gorge G2      17.50    0.986     17.26  -0.79
|   Kafue Gorge G3      17.50    0.986     17.26  -0.75
|   Kafue Gorge G4      17.50    0.986     17.26  -0.75
|   Kafue Gorge G5      17.50    0.986     17.26  -0.75
|   Kafue Gorge G6      17.50    0.986     17.26  -0.75
|Kafue Town
|   Kafue Town 220     220.00    0.959    211.04 -18.03
|   Kafue Town 33 M     33.00    0.901     29.74 -26.35
|   Kafue Town 330     330.00    1.020    336.64  -9.58
|   Kafue Town 88 M     88.00    0.832     73.24 -22.92
|   Kafue Town 88 R     88.00    0.832     73.24 -22.92
|Kafue West
|   Kafue West Main    330.00    1.021    336.83  -9.56
|Kansanshi
|   Kansanshi 33 Ma     33.00    0.997     32.89 -32.10
|   Kansanshi 330 M    330.00    0.997    329.01 -29.11
|Kariba North
|   Kariba North C     330.00    1.050    346.50  -7.76
|Internal Nodes
```

```
  Kariba North Ge    18.00   1.033    18.60 -31.34
  Kariba North Ge    18.00   1.033    18.60 -31.34
  Kariba North Ge    18.00   1.033    18.60 -31.34
  Kariba North Ge    18.00   1.033    18.60 -31.39
  Generator Neutr     0.24   0.000     0.00   0.00
  Generator Neutr     0.24   0.000     0.00   0.00
  Generator Neutr     0.24   0.000     0.00   0.00
  Generator Neutr     0.24   0.000     0.00   0.00
Kariba South
  Kariba South 33   330.00   1.050   346.49  -7.77
Kitwe
  Kitwe 220 Main    220.00   0.960   211.15 -24.29
  Kitwe 220 Reser   220.00   0.960   211.15 -24.29
  Kitwe 330 Main    330.00   0.948   312.90 -23.00
Leopards Hill
  Leopards Hill 1   132.00   1.034   136.47 -16.87
  Leopards Hill 3   330.00   1.014   334.78 -11.39
  Leopards Hill 8    88.00   1.003    88.29 -15.81
  Leopards Hill 8    88.00   1.003    88.29 -15.81
Luano
  Luano 220 Main    220.00   0.959   210.95 -24.30
  Luano 220 Reser   220.00   0.959   210.95 -24.30
  Luano 330 Main    330.00   0.954   314.78 -23.04
Internal Nodes
  Luano GTA-1 Ter    11.00   0.979    10.77   3.35
  Luano GTA-2 Ter    11.00   0.979    10.77   3.35
  Terminal(27)      220.00   0.959   210.95 -24.30
Lumwana
  Lumwana 33 Main    33.00   1.064    35.11 -31.63
  Lumwana 330 Mai   330.00   1.006   332.05 -29.95
Maposa
  Maposa 220 Main   220.00   0.955   210.20 -24.57
  Maposa 220 rese   220.00   0.955   210.20 -24.57
  Maposa 66 Main     66.00   1.022    67.44 -28.26
  Maposa 66 Reser    66.00   1.022    67.44 -28.26
Michelo
  Michelo 220 Mai   220.00   0.938   206.36 -22.16
  Michelo 66 Main    66.00   0.972    64.16 -26.57
--------------------------------------------------
```

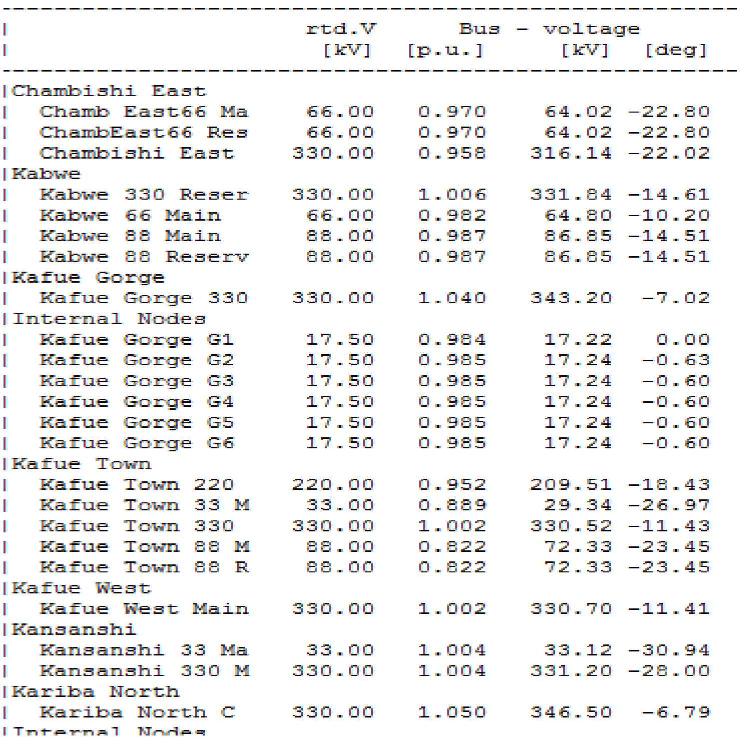
Table 9: Voltage profile with KFG-LHil line out



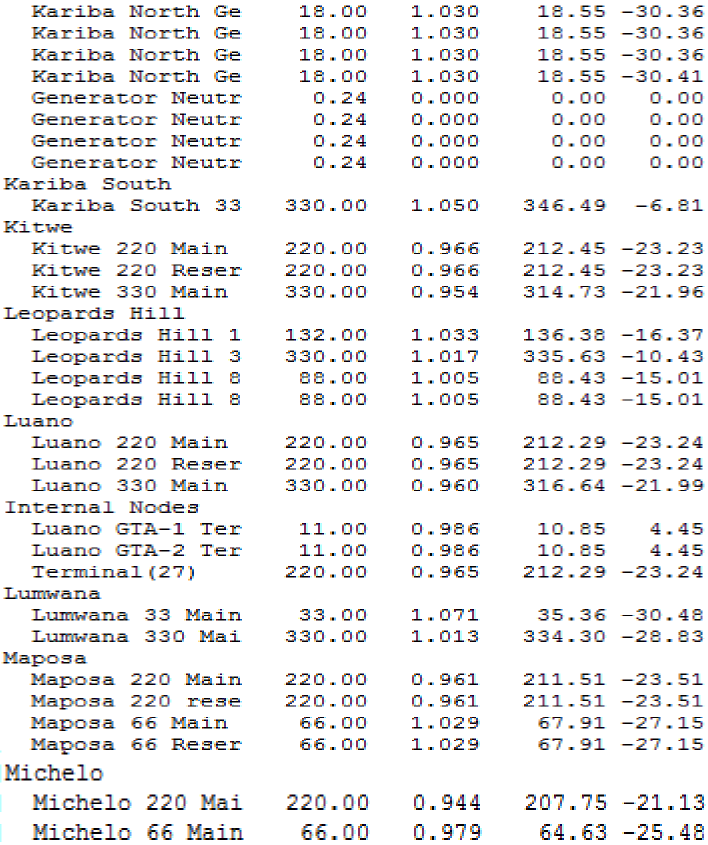
```
| Load Flow Calculation                                                                              Total System Summary |
----------------------------------------------------------------------------------------------------------------------------
|    AC Load Flow, balanced, positive sequence                |    Automatic Model Adaptation for Convergency         No      |
|    Automatic Tap Adjust of Transformers              Yes    |    Max. Acceptable Load Flow Error for                        |
|    Consider Reactive Power Limits                    Yes    |      Nodes                                         1.00 kVA  |
|                                                             |      Model Equations                               0.10 %    |
----------------------------------------------------------------------------------------------------------------------------
----------------------------------------------------------------------------------------------------------------------------
| Total System Summary                                 | Study Case: Complete System         | Annex:                   / 1  |
----------------------------------------------------------------------------------------------------------------------------
|                                                                                                                           |
| No. of Substations     0         No. of Busbars       302       No. of Terminals     1042      No. of Lines           150  |
| No. of 2-w Trfs.       80        No. of 3-w Trfs.     74        No. of syn. Machines 31        No. of asyn.Machines   0    |
| No. of Loads           91        No. of Shunts        26        No. of SVS           0                                    |
|                                                                                                                           |
| Generation           =    1611.01  MW          543.58  Mvar     1700.25  MVA                                             |
| External Infeed      =      -0.00  MW          -40.00  Mvar       40.00  MVA                                             |
| Load P(U)            =    1538.12  MW          750.90  Mvar     1711.62  MVA                                             |
| Load P(Un)           =    1606.43  MW          790.02  Mvar     1790.18  MVA                                             |
| Load P(Un-U)         =      68.31  MW           39.12  Mvar                                                              |
| Motor Load           =       0.00  MW            0.00  Mvar        0.00  MVA                                             |
| Grid Losses          =      72.90  MW         -166.85  Mvar                                                              |
| Line Charging        =                        -1002.09  Mvar                                                              |
| Compensation ind.    =                          125.43  Mvar                                                              |
| Compensation cap.    =                         -205.90  Mvar                                                              |
|                                                                                                                           |
| Installed Capacity   =    1657.98  MW                                                                                    |
| Spinning Reserve     =      46.97  MW                                                                                    |
|                                                                                                                           |
| Total Power Factor:                                                                                                       |
|   Generation         =         0.95  [-]                                                                                  |
|   Load/Motor         =  0.90 / 0.00  [-]                                                                                  |
|---------------------------------------------------------------------------------------------------------------------------|
```

Table 10: Load flow with KFG-Kafue west line out.

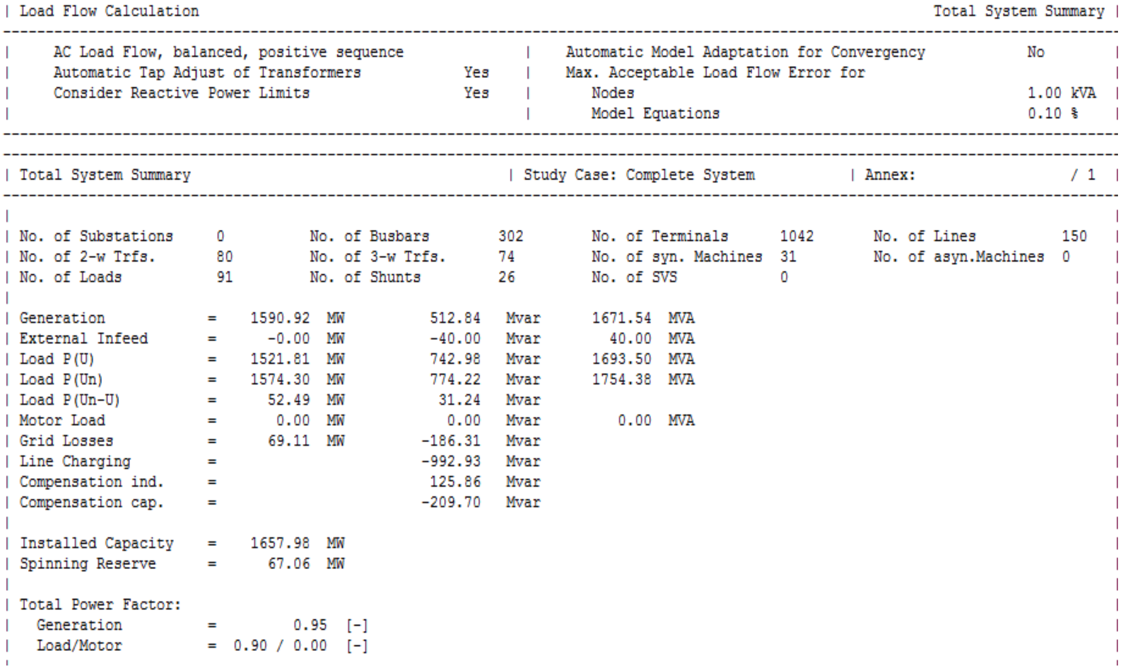
See voltage profile below with the Kafue Gorge- Kafue West Line out



```
--------------------------------------------------
|                        rtd.V       Bus - voltage
|                         [kV]   [p.u.]     [kV]   [deg]
--------------------------------------------------
|Chambishi East
|  Chamb East66 Ma      66.00   0.970    64.02 -22.80
|  ChambEast66 Res      66.00   0.970    64.02 -22.80
|  Chambishi East      330.00   0.958   316.14 -22.02
|Kabwe
|  Kabwe 330 Reser     330.00   1.006   331.84 -14.61
|  Kabwe 66 Main        66.00   0.982    64.80 -10.20
|  Kabwe 88 Main        88.00   0.987    86.85 -14.51
|  Kabwe 88 Reserv      88.00   0.987    86.85 -14.51
|Kafue Gorge
|  Kafue Gorge 330     330.00   1.040   343.20  -7.02
|Internal Nodes
|  Kafue Gorge G1       17.50   0.984    17.22   0.00
|  Kafue Gorge G2       17.50   0.985    17.24  -0.63
|  Kafue Gorge G3       17.50   0.985    17.24  -0.60
|  Kafue Gorge G4       17.50   0.985    17.24  -0.60
|  Kafue Gorge G5       17.50   0.985    17.24  -0.60
|  Kafue Gorge G6       17.50   0.985    17.24  -0.60
|Kafue Town
|  Kafue Town 220      220.00   0.952   209.51 -18.43
|  Kafue Town 33 M      33.00   0.889    29.34 -26.97
|  Kafue Town 330      330.00   1.002   330.52 -11.43
|  Kafue Town 88 M      88.00   0.822    72.33 -23.45
|  Kafue Town 88 R      88.00   0.822    72.33 -23.45
|Kafue West
|  Kafue West Main     330.00   1.002   330.70 -11.41
|Kansanshi
|  Kansanshi 33 Ma      33.00   1.004    33.12 -30.94
|  Kansanshi 330 M     330.00   1.004   331.20 -28.00
|Kariba North
|  Kariba North C      330.00   1.050   346.50  -6.79
|Internal Nodes
```



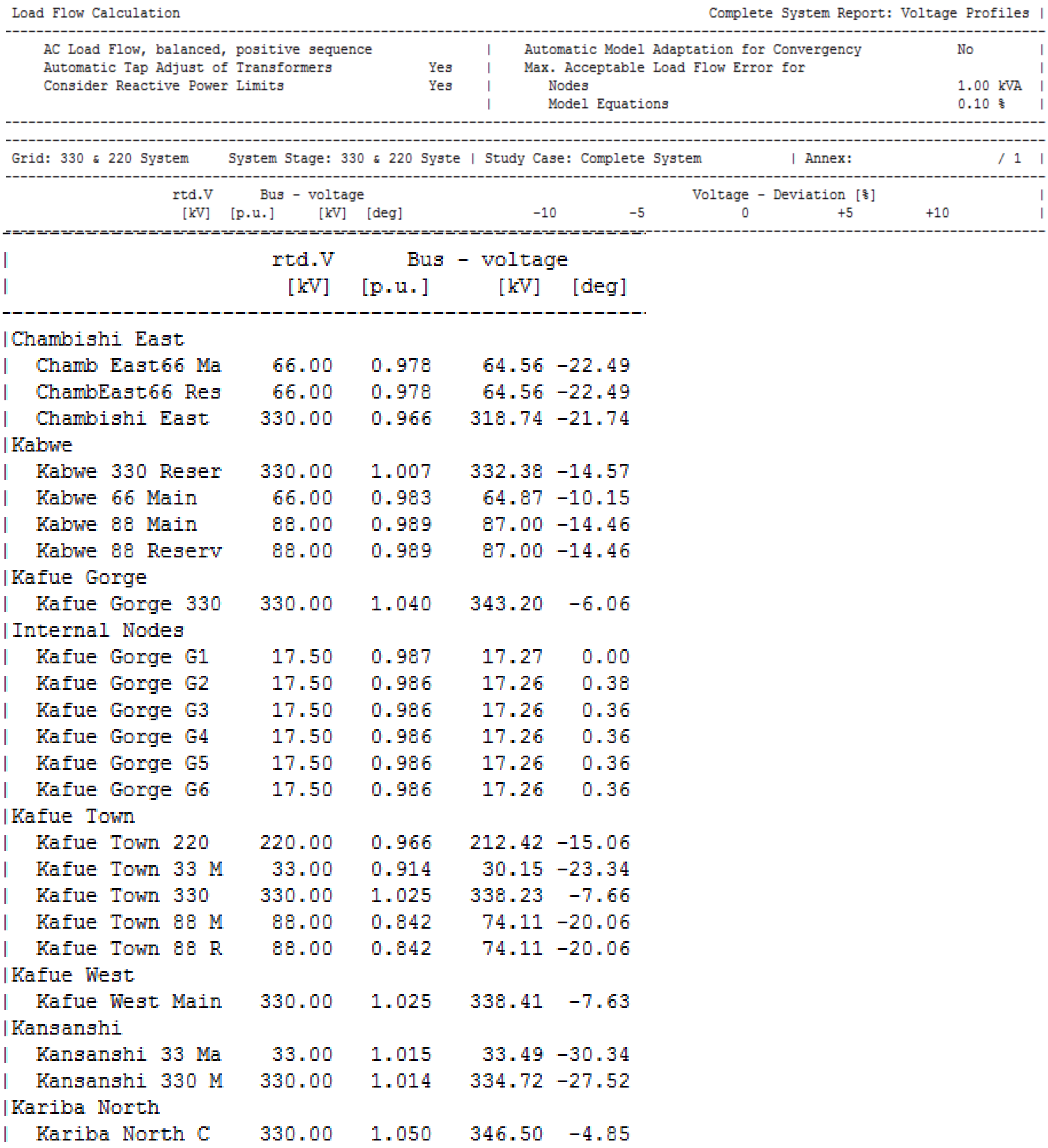
```
  Kariba North Ge    18.00   1.030    18.55 -30.36
  Kariba North Ge    18.00   1.030    18.55 -30.36
  Kariba North Ge    18.00   1.030    18.55 -30.36
  Kariba North Ge    18.00   1.030    18.55 -30.41
  Generator Neutr     0.24   0.000     0.00   0.00
  Generator Neutr     0.24   0.000     0.00   0.00
  Generator Neutr     0.24   0.000     0.00   0.00
  Generator Neutr     0.24   0.000     0.00   0.00
Kariba South
  Kariba South 33   330.00   1.050   346.49  -6.81
Kitwe
  Kitwe 220 Main    220.00   0.966   212.45 -23.23
  Kitwe 220 Reser   220.00   0.966   212.45 -23.23
  Kitwe 330 Main    330.00   0.954   314.73 -21.96
Leopards Hill
  Leopards Hill 1   132.00   1.033   136.38 -16.37
  Leopards Hill 3   330.00   1.017   335.63 -10.43
  Leopards Hill 8    88.00   1.005    88.43 -15.01
  Leopards Hill 8    88.00   1.005    88.43 -15.01
Luano
  Luano 220 Main    220.00   0.965   212.29 -23.24
  Luano 220 Reser   220.00   0.965   212.29 -23.24
  Luano 330 Main    330.00   0.960   316.64 -21.99
Internal Nodes
  Luano GTA-1 Ter    11.00   0.986    10.85   4.45
  Luano GTA-2 Ter    11.00   0.986    10.85   4.45
  Terminal(27)      220.00   0.965   212.29 -23.24
Lumwana
  Lumwana 33 Main    33.00   1.071    35.36 -30.48
  Lumwana 330 Mai   330.00   1.013   334.30 -28.83
Maposa
  Maposa 220 Main   220.00   0.961   211.51 -23.51
  Maposa 220 rese   220.00   0.961   211.51 -23.51
  Maposa 66 Main     66.00   1.029    67.91 -27.15
  Maposa 66 Reser    66.00   1.029    67.91 -27.15
Michelo
  Michelo 220 Mai   220.00   0.944   207.75 -21.13
  Michelo 66 Main    66.00   0.979    64.63 -25.48
```



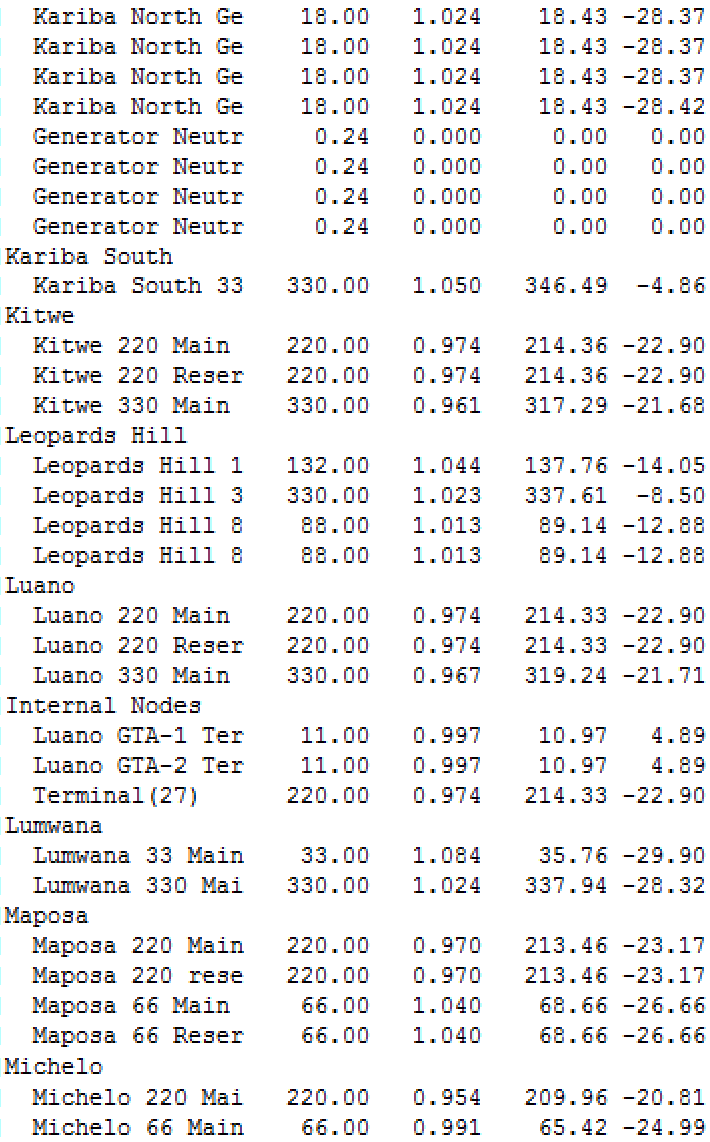
```
| Load Flow Calculation                                                                     Total System Summary |
------------------------------------------------------------------------------------------------------------------
|    AC Load Flow, balanced, positive sequence          |    Automatic Model Adaptation for Convergency       No     |
|    Automatic Tap Adjust of Transformers          Yes  |    Max. Acceptable Load Flow Error for                     |
|    Consider Reactive Power Limits                Yes  |       Nodes                                      1.00 kVA |
|                                                       |       Model Equations                            0.10 %   |
------------------------------------------------------------------------------------------------------------------
------------------------------------------------------------------------------------------------------------------
| Total System Summary                                  | Study Case: Complete System        | Annex:          / 1 |
------------------------------------------------------------------------------------------------------------------
|                                                                                                                |
| No. of Substations     0        No. of Busbars      302       No. of Terminals     1042      No. of Lines        150  |
| No. of 2-w Trfs.       80       No. of 3-w Trfs.    74        No. of syn. Machines 31        No. of asyn.Machines 0   |
| No. of Loads           91       No. of Shunts       26        No. of SVS           0                                 |
|                                                                                                                |
| Generation         =   1590.92  MW        512.84  Mvar    1671.54  MVA                                          |
| External Infeed    =     -0.00  MW        -40.00  Mvar      40.00  MVA                                          |
| Load P(U)          =   1521.81  MW        742.98  Mvar    1693.50  MVA                                          |
| Load P(Un)         =   1574.30  MW        774.22  Mvar    1754.38  MVA                                          |
| Load P(Un-U)       =     52.49  MW         31.24  Mvar                                                         |
| Motor Load         =      0.00  MW          0.00  Mvar       0.00  MVA                                          |
| Grid Losses        =     69.11  MW       -186.31  Mvar                                                         |
| Line Charging      =                     -992.93  Mvar                                                         |
| Compensation ind.  =                      125.86  Mvar                                                         |
| Compensation cap.  =                     -209.70  Mvar                                                         |
|                                                                                                                |
| Installed Capacity =   1657.98  MW                                                                             |
| Spinning Reserve   =     67.06  MW                                                                             |
|                                                                                                                |
| Total Power Factor:                                                                                            |
|   Generation       =         0.95  [-]                                                                         |
|   Load/Motor       =  0.90 / 0.00  [-]                                                                         |
```

Table 11: Load flow with Lhill-Kabwe line out (load reduced to 98% to account for increased transmission loses).

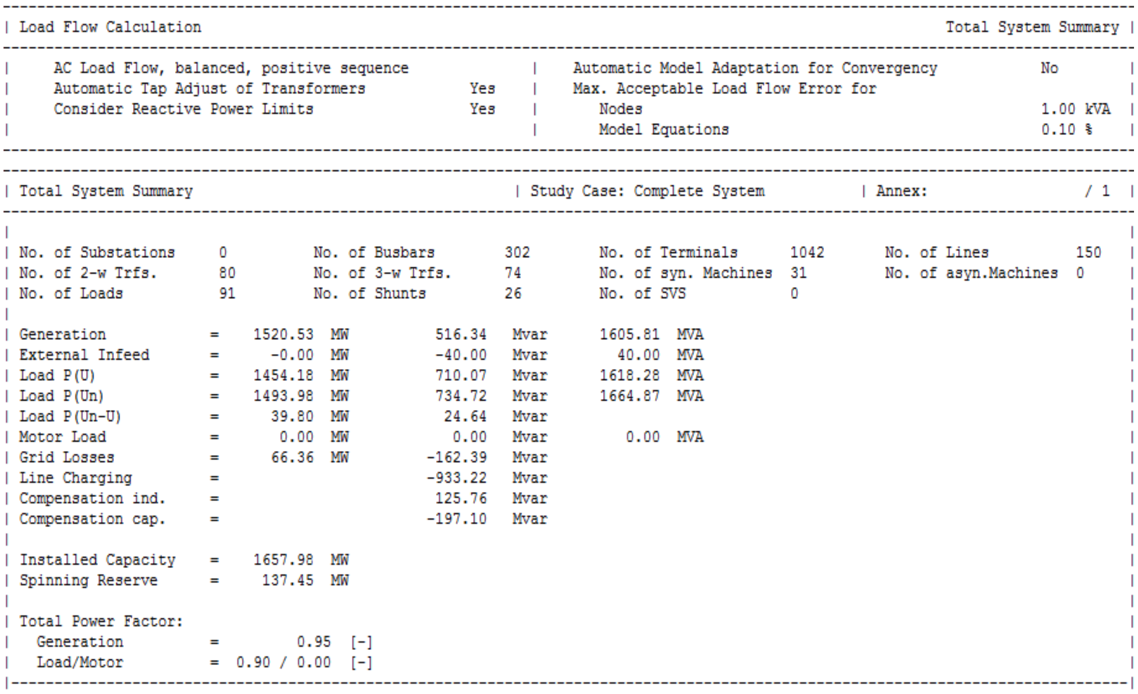
See voltage profile below



```
 Load Flow Calculation                                                            Complete System Report: Voltage Profiles |
---------------------------------------------------------------------------------------------------------------------------
    AC Load Flow, balanced, positive sequence                   |   Automatic Model Adaptation for Convergency          No      |
    Automatic Tap Adjust of Transformers             Yes        |   Max. Acceptable Load Flow Error for                         |
    Consider Reactive Power Limits                   Yes        |      Nodes                                            1.00 kVA  |
                                                                |      Model Equations                                  0.10 %    |
---------------------------------------------------------------------------------------------------------------------------
---------------------------------------------------------------------------------------------------------------------------
 Grid: 330 & 220 System     System Stage: 330 & 220 Syste | Study Case: Complete System           | Annex:                / 1  |
---------------------------------------------------------------------------------------------------------------------------
                    rtd.V      Bus - voltage                                          Voltage - Deviation [%]                   |
                     [kV]  [p.u.]      [kV]  [deg]               -10         -5           0          +5         +10              |
---------------------------------------------------------------------------------------------------------------------------
|                    rtd.V      Bus - voltage
|                     [kV]  [p.u.]      [kV]  [deg]
----------------------------------------------------
|Chambishi East
|  Chamb East66 Ma    66.00   0.978    64.56 -22.49
|  ChambEast66 Res    66.00   0.978    64.56 -22.49
|  Chambishi East    330.00   0.966   318.74 -21.74
|Kabwe
|  Kabwe 330 Reser   330.00   1.007   332.38 -14.57
|  Kabwe 66 Main      66.00   0.983    64.87 -10.15
|  Kabwe 88 Main      88.00   0.989    87.00 -14.46
|  Kabwe 88 Reserv    88.00   0.989    87.00 -14.46
|Kafue Gorge
|  Kafue Gorge 330   330.00   1.040   343.20  -6.06
|Internal Nodes
|  Kafue Gorge G1     17.50   0.987    17.27   0.00
|  Kafue Gorge G2     17.50   0.986    17.26   0.38
|  Kafue Gorge G3     17.50   0.986    17.26   0.36
|  Kafue Gorge G4     17.50   0.986    17.26   0.36
|  Kafue Gorge G5     17.50   0.986    17.26   0.36
|  Kafue Gorge G6     17.50   0.986    17.26   0.36
|Kafue Town
|  Kafue Town 220    220.00   0.966   212.42 -15.06
|  Kafue Town 33 M    33.00   0.914    30.15 -23.34
|  Kafue Town 330    330.00   1.025   338.23  -7.66
|  Kafue Town 88 M    88.00   0.842    74.11 -20.06
|  Kafue Town 88 R    88.00   0.842    74.11 -20.06
|Kafue West
|  Kafue West Main   330.00   1.025   338.41  -7.63
|Kansanshi
|  Kansanshi 33 Ma    33.00   1.015    33.49 -30.34
|  Kansanshi 330 M   330.00   1.014   334.72 -27.52
|Kariba North
|  Kariba North C    330.00   1.050   346.50  -4.85
```



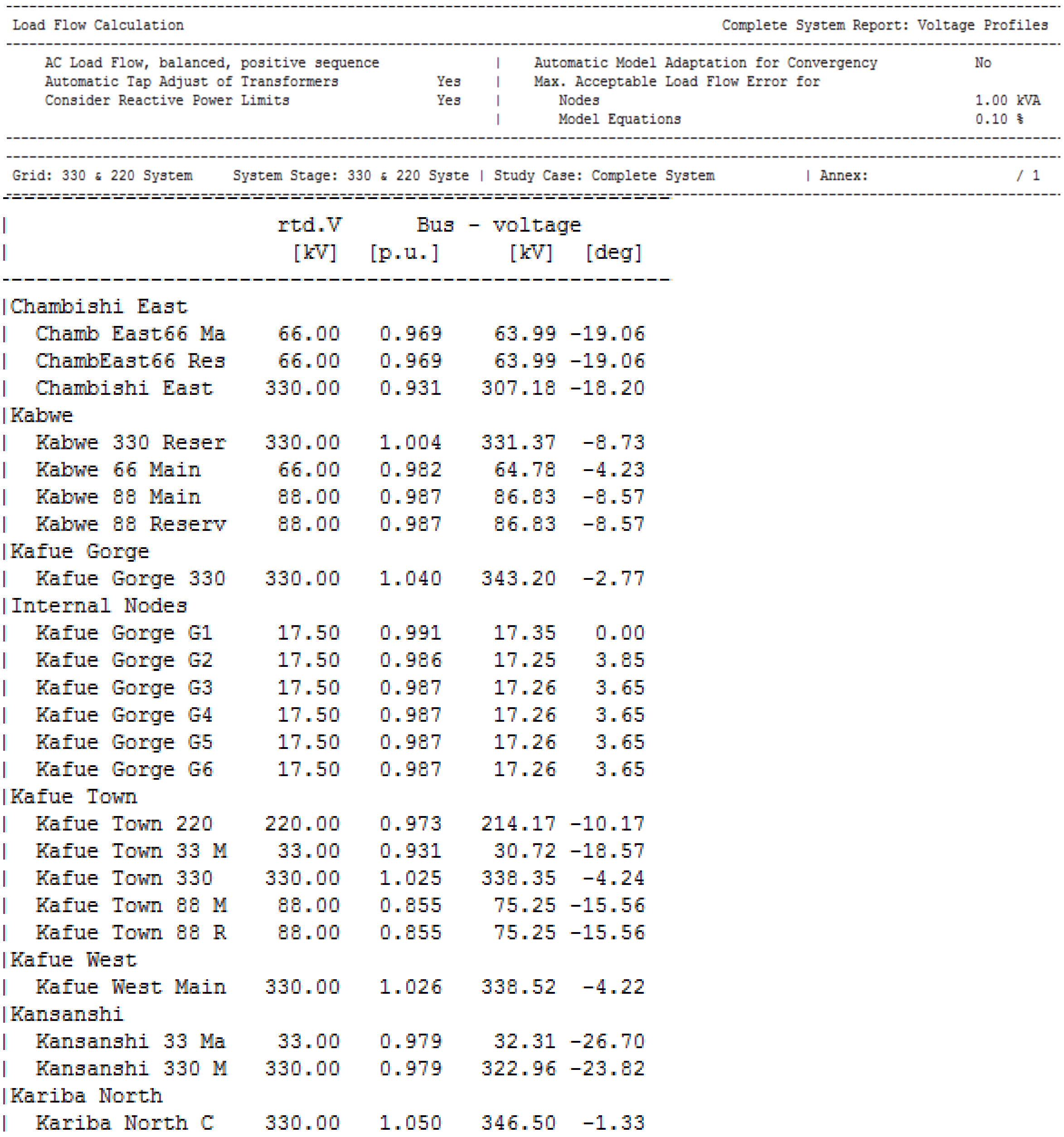
```
|  Kariba North Ge    18.00   1.024    18.43 -28.37
|  Kariba North Ge    18.00   1.024    18.43 -28.37
|  Kariba North Ge    18.00   1.024    18.43 -28.37
|  Kariba North Ge    18.00   1.024    18.43 -28.42
|  Generator Neutr     0.24   0.000     0.00   0.00
|  Generator Neutr     0.24   0.000     0.00   0.00
|  Generator Neutr     0.24   0.000     0.00   0.00
|  Generator Neutr     0.24   0.000     0.00   0.00
|Kariba South
|  Kariba South 33   330.00   1.050   346.49  -4.86
|Kitwe
|  Kitwe 220 Main    220.00   0.974   214.36 -22.90
|  Kitwe 220 Reser   220.00   0.974   214.36 -22.90
|  Kitwe 330 Main    330.00   0.961   317.29 -21.68
|Leopards Hill
|  Leopards Hill 1   132.00   1.044   137.76 -14.05
|  Leopards Hill 3   330.00   1.023   337.61  -8.50
|  Leopards Hill 8    88.00   1.013    89.14 -12.88
|  Leopards Hill 8    88.00   1.013    89.14 -12.88
|Luano
|  Luano 220 Main    220.00   0.974   214.33 -22.90
|  Luano 220 Reser   220.00   0.974   214.33 -22.90
|  Luano 330 Main    330.00   0.967   319.24 -21.71
|Internal Nodes
|  Luano GTA-1 Ter    11.00   0.997    10.97   4.89
|  Luano GTA-2 Ter    11.00   0.997    10.97   4.89
|  Terminal(27)      220.00   0.974   214.33 -22.90
|Lumwana
|  Lumwana 33 Main    33.00   1.084    35.76 -29.90
|  Lumwana 330 Mai   330.00   1.024   337.94 -28.32
|Maposa
|  Maposa 220 Main   220.00   0.970   213.46 -23.17
|  Maposa 220 rese   220.00   0.970   213.46 -23.17
|  Maposa 66 Main     66.00   1.040    68.66 -26.66
|  Maposa 66 Reser    66.00   1.040    68.66 -26.66
|Michelo
|  Michelo 220 Mai   220.00   0.954   209.96 -20.81
|  Michelo 66 Main    66.00   0.991    65.42 -24.99
```



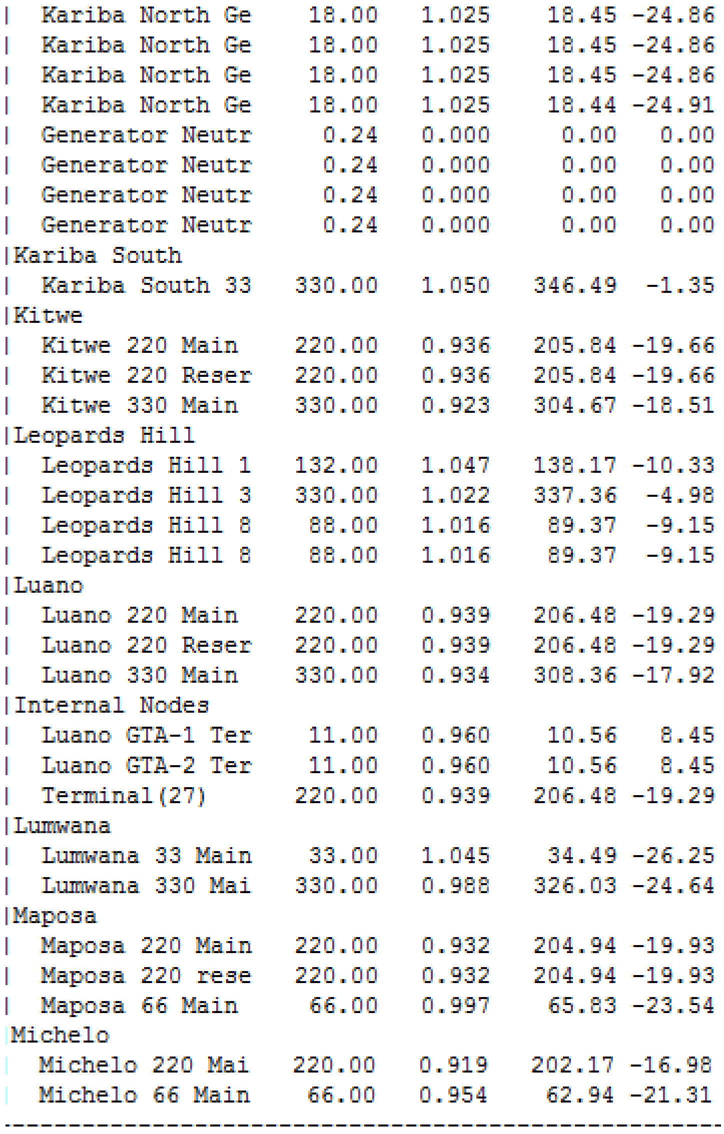
```
-------------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                                             Total System Summary |
-------------------------------------------------------------------------------------------------------------------------
|     AC Load Flow, balanced, positive sequence              |   Automatic Model Adaptation for Convergency          No      |
|     Automatic Tap Adjust of Transformers               Yes |   Max. Acceptable Load Flow Error for                         |
|     Consider Reactive Power Limits                     Yes |      Nodes                                          1.00 kVA |
|                                                            |      Model Equations                                0.10 %   |
-------------------------------------------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------------------------------------------
| Total System Summary                                  | Study Case: Complete System          | Annex:               / 1 |
-------------------------------------------------------------------------------------------------------------------------
|                                                                                                                        |
| No. of Substations     0         No. of Busbars        302       No. of Terminals     1042       No. of Lines         150 |
| No. of 2-w Trfs.       80        No. of 3-w Trfs.      74        No. of syn. Machines 31         No. of asyn.Machines 0   |
| No. of Loads           91        No. of Shunts         26        No. of SVS           0                                 |
|                                                                                                                        |
| Generation          =    1520.53  MW          516.34   Mvar     1605.81  MVA                                            |
| External Infeed     =      -0.00  MW          -40.00   Mvar       40.00  MVA                                            |
| Load P(U)           =    1454.18  MW          710.07   Mvar     1618.28  MVA                                            |
| Load P(Un)          =    1493.98  MW          734.72   Mvar     1664.87  MVA                                            |
| Load P(Un-U)        =      39.80  MW           24.64   Mvar                                                            |
| Motor Load          =       0.00  MW            0.00   Mvar        0.00  MVA                                            |
| Grid Losses         =      66.36  MW         -162.39   Mvar                                                            |
| Line Charging       =                        -933.22   Mvar                                                            |
| Compensation ind.   =                         125.76   Mvar                                                            |
| Compensation cap.   =                        -197.10   Mvar                                                            |
|                                                                                                                        |
| Installed Capacity  =    1657.98  MW                                                                                   |
| Spinning Reserve    =     137.45  MW                                                                                   |
|                                                                                                                        |
| Total Power Factor:                                                                                                    |
|   Generation        =         0.95  [-]                                                                                |
|   Load/Motor        =  0.90 / 0.00  [-]                                                                                |
|------------------------------------------------------------------------------------------------------------------------|
```

Table 12: Load flow calculations with Kabwe- Kitwe line out (load reduced to 93% to account for increased losses).

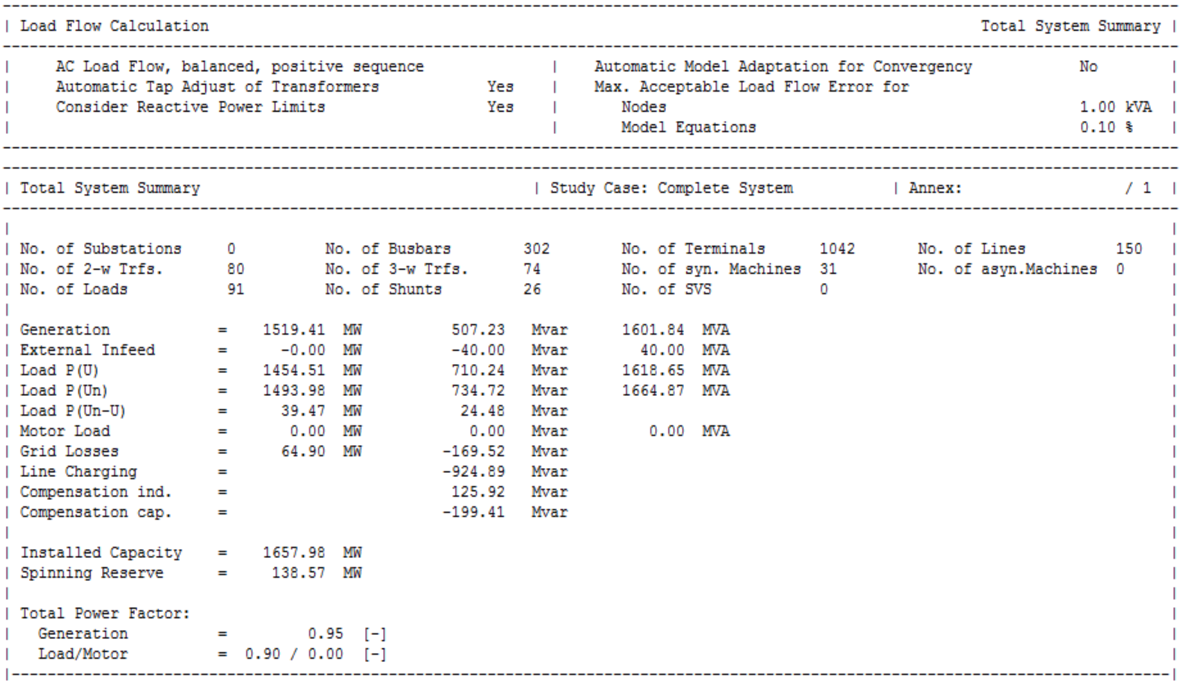
See corresponding voltage profile below.



```
-----------------------------------------------------------------------------------------------------------------------------
 Load Flow Calculation                                                                    Complete System Report: Voltage Profiles
-----------------------------------------------------------------------------------------------------------------------------
     AC Load Flow, balanced, positive sequence               |    Automatic Model Adaptation for Convergency            No
     Automatic Tap Adjust of Transformers              Yes   |    Max. Acceptable Load Flow Error for
     Consider Reactive Power Limits                    Yes   |       Nodes                                            1.00 kVA
                                                              |       Model Equations                                  0.10 %
-----------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------
 Grid: 330 & 220 System     System Stage: 330 & 220 Syste | Study Case: Complete System          | Annex:              / 1
-----------------------------------------------------------------------------------------------------------------------------
|                     rtd.V       Bus - voltage
|                     [kV]   [p.u.]     [kV]   [deg]
----------------------------------------------------
|Chambishi East
|  Chamb East66 Ma    66.00   0.969    63.99 -19.06
|  ChambEast66 Res    66.00   0.969    63.99 -19.06
|  Chambishi East    330.00   0.931   307.18 -18.20
|Kabwe
|  Kabwe 330 Reser   330.00   1.004   331.37  -8.73
|  Kabwe 66 Main      66.00   0.982    64.78  -4.23
|  Kabwe 88 Main      88.00   0.987    86.83  -8.57
|  Kabwe 88 Reserv    88.00   0.987    86.83  -8.57
|Kafue Gorge
|  Kafue Gorge 330   330.00   1.040   343.20  -2.77
|Internal Nodes
|  Kafue Gorge G1     17.50   0.991    17.35   0.00
|  Kafue Gorge G2     17.50   0.986    17.25   3.85
|  Kafue Gorge G3     17.50   0.987    17.26   3.65
|  Kafue Gorge G4     17.50   0.987    17.26   3.65
|  Kafue Gorge G5     17.50   0.987    17.26   3.65
|  Kafue Gorge G6     17.50   0.987    17.26   3.65
|Kafue Town
|  Kafue Town 220    220.00   0.973   214.17 -10.17
|  Kafue Town 33 M    33.00   0.931    30.72 -18.57
|  Kafue Town 330    330.00   1.025   338.35  -4.24
|  Kafue Town 88 M    88.00   0.855    75.25 -15.56
|  Kafue Town 88 R    88.00   0.855    75.25 -15.56
|Kafue West
|  Kafue West Main   330.00   1.026   338.52  -4.22
|Kansanshi
|  Kansanshi 33 Ma    33.00   0.979    32.31 -26.70
|  Kansanshi 330 M   330.00   0.979   322.96 -23.82
|Kariba North
|  Kariba North C    330.00   1.050   346.50  -1.33
```



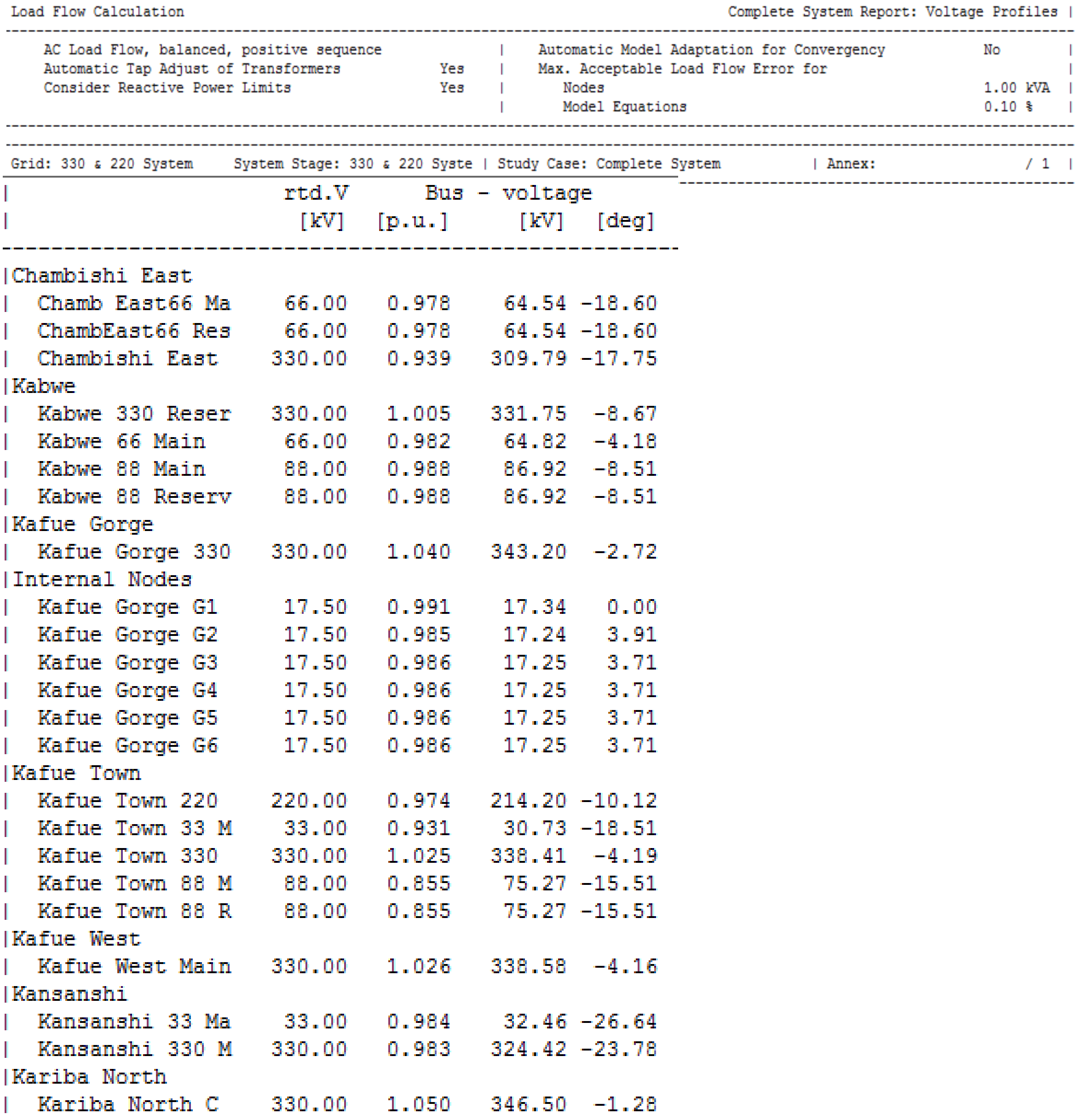
```
|  Kariba North Ge    18.00   1.025    18.45 -24.86
|  Kariba North Ge    18.00   1.025    18.45 -24.86
|  Kariba North Ge    18.00   1.025    18.45 -24.86
|  Kariba North Ge    18.00   1.025    18.44 -24.91
|  Generator Neutr     0.24   0.000     0.00   0.00
|  Generator Neutr     0.24   0.000     0.00   0.00
|  Generator Neutr     0.24   0.000     0.00   0.00
|  Generator Neutr     0.24   0.000     0.00   0.00
|Kariba South
|  Kariba South 33   330.00   1.050   346.49  -1.35
|Kitwe
|  Kitwe 220 Main    220.00   0.936   205.84 -19.66
|  Kitwe 220 Reser   220.00   0.936   205.84 -19.66
|  Kitwe 330 Main    330.00   0.923   304.67 -18.51
|Leopards Hill
|  Leopards Hill 1   132.00   1.047   138.17 -10.33
|  Leopards Hill 3   330.00   1.022   337.36  -4.98
|  Leopards Hill 8    88.00   1.016    89.37  -9.15
|  Leopards Hill 8    88.00   1.016    89.37  -9.15
|Luano
|  Luano 220 Main    220.00   0.939   206.48 -19.29
|  Luano 220 Reser   220.00   0.939   206.48 -19.29
|  Luano 330 Main    330.00   0.934   308.36 -17.92
|Internal Nodes
|  Luano GTA-1 Ter    11.00   0.960    10.56   8.45
|  Luano GTA-2 Ter    11.00   0.960    10.56   8.45
|  Terminal(27)      220.00   0.939   206.48 -19.29
|Lumwana
|  Lumwana 33 Main    33.00   1.045    34.49 -26.25
|  Lumwana 330 Mai   330.00   0.988   326.03 -24.64
|Maposa
|  Maposa 220 Main   220.00   0.932   204.94 -19.93
|  Maposa 220 rese   220.00   0.932   204.94 -19.93
|  Maposa 66 Main     66.00   0.997    65.83 -23.54
|Michelo
|  Michelo 220 Mai   220.00   0.919   202.17 -16.98
|  Michelo 66 Main    66.00   0.954    62.94 -21.31
---------------------------------------------------
```



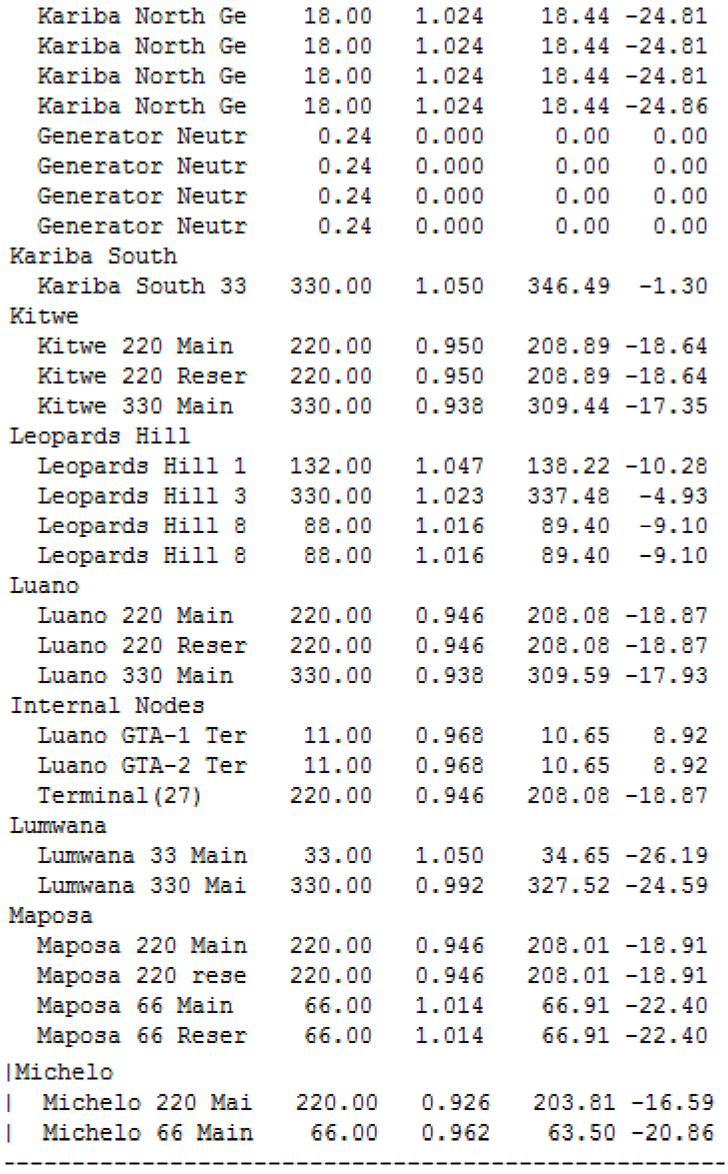
```
---------------------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                                                    Total System Summary |
---------------------------------------------------------------------------------------------------------------------------------
|     AC Load Flow, balanced, positive sequence             |    Automatic Model Adaptation for Convergency           No         |
|     Automatic Tap Adjust of Transformers          Yes     |    Max. Acceptable Load Flow Error for                             |
|     Consider Reactive Power Limits                Yes     |       Nodes                                             1.00 kVA   |
|                                                           |       Model Equations                                   0.10 %     |
---------------------------------------------------------------------------------------------------------------------------------
---------------------------------------------------------------------------------------------------------------------------------
| Total System Summary                                     | Study Case: Complete System          | Annex:                / 1  |
---------------------------------------------------------------------------------------------------------------------------------
|                                                                                                                               |
| No. of Substations     0          No. of Busbars        302         No. of Terminals      1042       No. of Lines          150 |
| No. of 2-w Trfs.       80         No. of 3-w Trfs.      74          No. of syn. Machines  31         No. of asyn.Machines  0   |
| No. of Loads           91         No. of Shunts         26          No. of SVS            0                                    |
|                                                                                                                               |
| Generation            =    1519.41  MW          507.23   Mvar      1601.84  MVA                                               |
| External Infeed       =      -0.00  MW          -40.00   Mvar        40.00  MVA                                               |
| Load P(U)             =    1454.51  MW          710.24   Mvar      1618.65  MVA                                               |
| Load P(Un)            =    1493.98  MW          734.72   Mvar      1664.87  MVA                                               |
| Load P(Un-U)          =      39.47  MW           24.48   Mvar                                                                  |
| Motor Load            =       0.00  MW            0.00   Mvar         0.00  MVA                                               |
| Grid Losses           =      64.90  MW         -169.52   Mvar                                                                  |
| Line Charging         =                        -924.89   Mvar                                                                  |
| Compensation ind.     =                         125.92   Mvar                                                                  |
| Compensation cap.     =                        -199.41   Mvar                                                                  |
|                                                                                                                               |
| Installed Capacity    =    1657.98  MW                                                                                        |
| Spinning Reserve      =     138.57  MW                                                                                        |
|                                                                                                                               |
| Total Power Factor:                                                                                                           |
|   Generation          =         0.95  [-]                                                                                     |
|   Load/Motor          =  0.90 / 0.00  [-]                                                                                     |
|-------------------------------------------------------------------------------------------------------------------------------|
```

Table 13: Load flow calculation with Kabwe-Luano line out.

See corresponding voltage profile below

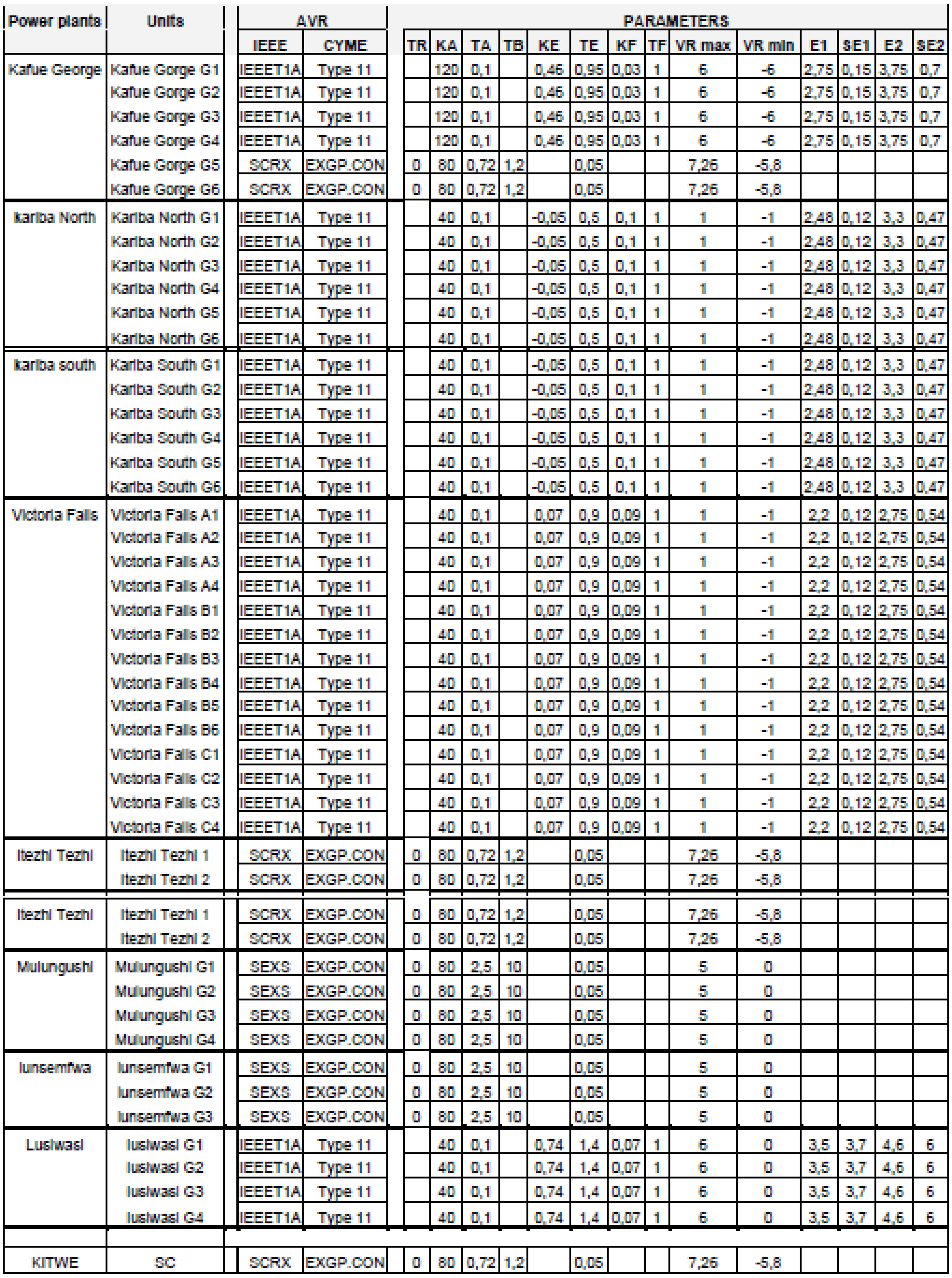


```
 Load Flow Calculation                                                                 Complete System Report: Voltage Profiles |
---------------------------------------------------------------------------------------------------------------------------------
     AC Load Flow, balanced, positive sequence                    |    Automatic Model Adaptation for Convergency            No      |
     Automatic Tap Adjust of Transformers               Yes       |    Max. Acceptable Load Flow Error for                           |
     Consider Reactive Power Limits                     Yes       |       Nodes                                             1.00 kVA  |
                                                                  |       Model Equations                                   0.10 %    |
---------------------------------------------------------------------------------------------------------------------------------
---------------------------------------------------------------------------------------------------------------------------------
 Grid: 330 & 220 System     System Stage: 330 & 220 Syste | Study Case: Complete System           | Annex:                / 1  |
|                      rtd.V       Bus - voltage           ------------------------------------------------
|                       [kV]   [p.u.]       [kV]   [deg]
-----------------------------------------------------
|Chambishi East
|  Chamb East66 Ma     66.00   0.978     64.54 -18.60
|  ChambEast66 Res     66.00   0.978     64.54 -18.60
|  Chambishi East     330.00   0.939    309.79 -17.75
|Kabwe
|  Kabwe 330 Reser    330.00   1.005    331.75  -8.67
|  Kabwe 66 Main       66.00   0.982     64.82  -4.18
|  Kabwe 88 Main       88.00   0.988     86.92  -8.51
|  Kabwe 88 Reserv     88.00   0.988     86.92  -8.51
|Kafue Gorge
|  Kafue Gorge 330    330.00   1.040    343.20  -2.72
|Internal Nodes
|  Kafue Gorge G1      17.50   0.991     17.34   0.00
|  Kafue Gorge G2      17.50   0.985     17.24   3.91
|  Kafue Gorge G3      17.50   0.986     17.25   3.71
|  Kafue Gorge G4      17.50   0.986     17.25   3.71
|  Kafue Gorge G5      17.50   0.986     17.25   3.71
|  Kafue Gorge G6      17.50   0.986     17.25   3.71
|Kafue Town
|  Kafue Town 220     220.00   0.974    214.20 -10.12
|  Kafue Town 33 M     33.00   0.931     30.73 -18.51
|  Kafue Town 330     330.00   1.025    338.41  -4.19
|  Kafue Town 88 M     88.00   0.855     75.27 -15.51
|  Kafue Town 88 R     88.00   0.855     75.27 -15.51
|Kafue West
|  Kafue West Main    330.00   1.026    338.58  -4.16
|Kansanshi
|  Kansanshi 33 Ma     33.00   0.984     32.46 -26.64
|  Kansanshi 330 M    330.00   0.983    324.42 -23.78
|Kariba North
|  Kariba North C     330.00   1.050    346.50  -1.28
```



```
   Kariba North Ge    18.00   1.024    18.44 -24.81
   Kariba North Ge    18.00   1.024    18.44 -24.81
   Kariba North Ge    18.00   1.024    18.44 -24.81
   Kariba North Ge    18.00   1.024    18.44 -24.86
   Generator Neutr     0.24   0.000     0.00   0.00
   Generator Neutr     0.24   0.000     0.00   0.00
   Generator Neutr     0.24   0.000     0.00   0.00
   Generator Neutr     0.24   0.000     0.00   0.00
 Kariba South
   Kariba South 33   330.00   1.050   346.49  -1.30
 Kitwe
   Kitwe 220 Main    220.00   0.950   208.89 -18.64
   Kitwe 220 Reser   220.00   0.950   208.89 -18.64
   Kitwe 330 Main    330.00   0.938   309.44 -17.35
 Leopards Hill
   Leopards Hill 1   132.00   1.047   138.22 -10.28
   Leopards Hill 3   330.00   1.023   337.48  -4.93
   Leopards Hill 8    88.00   1.016    89.40  -9.10
   Leopards Hill 8    88.00   1.016    89.40  -9.10
 Luano
   Luano 220 Main    220.00   0.946   208.08 -18.87
   Luano 220 Reser   220.00   0.946   208.08 -18.87
   Luano 330 Main    330.00   0.938   309.59 -17.93
 Internal Nodes
   Luano GTA-1 Ter    11.00   0.968    10.65   8.92
   Luano GTA-2 Ter    11.00   0.968    10.65   8.92
   Terminal(27)      220.00   0.946   208.08 -18.87
 Lumwana
   Lumwana 33 Main    33.00   1.050    34.65 -26.19
   Lumwana 330 Mai   330.00   0.992   327.52 -24.59
 Maposa
   Maposa 220 Main   220.00   0.946   208.01 -18.91
   Maposa 220 rese   220.00   0.946   208.01 -18.91
   Maposa 66 Main     66.00   1.014    66.91 -22.40
   Maposa 66 Reser    66.00   1.014    66.91 -22.40
|Michelo
|  Michelo 220 Mai   220.00   0.926   203.81 -16.59
|  Michelo 66 Main    66.00   0.962    63.50 -20.86
----------------------------------------------------
```

Appendix 10. Detailed parameters of the AVRs



Power plants	Units	AVR		PARAMETERS													
		IEEE	CYME	TR	KA	TA	TB	KE	TE	KF	TF	VR max	VR min	E1	SE1	E2	SE2
Kafue George	Kafue Gorge G1	IEEET1A	Type 11		120	0,1		0,46	0,95	0,03	1	6	-6	2,75	0,15	3,75	0,7
	Kafue Gorge G2	IEEET1A	Type 11		120	0,1		0,46	0,95	0,03	1	6	-6	2,75	0,15	3,75	0,7
	Kafue Gorge G3	IEEET1A	Type 11		120	0,1		0,46	0,95	0,03	1	6	-6	2,75	0,15	3,75	0,7
	Kafue Gorge G4	IEEET1A	Type 11		120	0,1		0,46	0,95	0,03	1	6	-6	2,75	0,15	3,75	0,7
	Kafue Gorge G5	SCRX	EXGP.CON	0	80	0,72	1,2		0,05			7,26	-5,8				
	Kafue Gorge G6	SCRX	EXGP.CON	0	80	0,72	1,2		0,05			7,26	-5,8				
kariba North	Kariba North G1	IEEET1A	Type 11		40	0,1		-0,05	0,5	0,1	1	1	-1	2,48	0,12	3,3	0,47
	Kariba North G2	IEEET1A	Type 11		40	0,1		-0,05	0,5	0,1	1	1	-1	2,48	0,12	3,3	0,47
	Kariba North G3	IEEET1A	Type 11		40	0,1		-0,05	0,5	0,1	1	1	-1	2,48	0,12	3,3	0,47
	Kariba North G4	IEEET1A	Type 11		40	0,1		-0,05	0,5	0,1	1	1	-1	2,48	0,12	3,3	0,47
	Kariba North G5	IEEET1A	Type 11		40	0,1		-0,05	0,5	0,1	1	1	-1	2,48	0,12	3,3	0,47
	Kariba North G6	IEEET1A	Type 11		40	0,1		-0,05	0,5	0,1	1	1	-1	2,48	0,12	3,3	0,47
kariba south	Kariba South G1	IEEET1A	Type 11		40	0,1		-0,05	0,5	0,1	1	1	-1	2,48	0,12	3,3	0,47
	Kariba South G2	IEEET1A	Type 11		40	0,1		-0,05	0,5	0,1	1	1	-1	2,48	0,12	3,3	0,47
	Kariba South G3	IEEET1A	Type 11		40	0,1		-0,05	0,5	0,1	1	1	-1	2,48	0,12	3,3	0,47
	Kariba South G4	IEEET1A	Type 11		40	0,1		-0,05	0,5	0,1	1	1	-1	2,48	0,12	3,3	0,47
	Kariba South G5	IEEET1A	Type 11		40	0,1		-0,05	0,5	0,1	1	1	-1	2,48	0,12	3,3	0,47
	Kariba South G6	IEEET1A	Type 11		40	0,1		-0,05	0,5	0,1	1	1	-1	2,48	0,12	3,3	0,47
Victoria Falls	Victoria Falls A1	IEEET1A	Type 11		40	0,1		0,07	0,9	0,09	1	1	-1	2,2	0,12	2,75	0,54
	Victoria Falls A2	IEEET1A	Type 11		40	0,1		0,07	0,9	0,09	1	1	-1	2,2	0,12	2,75	0,54
	Victoria Falls A3	IEEET1A	Type 11		40	0,1		0,07	0,9	0,09	1	1	-1	2,2	0,12	2,75	0,54
	Victoria Falls A4	IEEET1A	Type 11		40	0,1		0,07	0,9	0,09	1	1	-1	2,2	0,12	2,75	0,54
	Victoria Falls B1	IEEET1A	Type 11		40	0,1		0,07	0,9	0,09	1	1	-1	2,2	0,12	2,75	0,54
	Victoria Falls B2	IEEET1A	Type 11		40	0,1		0,07	0,9	0,09	1	1	-1	2,2	0,12	2,75	0,54
	Victoria Falls B3	IEEET1A	Type 11		40	0,1		0,07	0,9	0,09	1	1	-1	2,2	0,12	2,75	0,54
	Victoria Falls B4	IEEET1A	Type 11		40	0,1		0,07	0,9	0,09	1	1	-1	2,2	0,12	2,75	0,54
	Victoria Falls B5	IEEET1A	Type 11		40	0,1		0,07	0,9	0,09	1	1	-1	2,2	0,12	2,75	0,54
	Victoria Falls B6	IEEET1A	Type 11		40	0,1		0,07	0,9	0,09	1	1	-1	2,2	0,12	2,75	0,54
	Victoria Falls C1	IEEET1A	Type 11		40	0,1		0,07	0,9	0,09	1	1	-1	2,2	0,12	2,75	0,54
	Victoria Falls C2	IEEET1A	Type 11		40	0,1		0,07	0,9	0,09	1	1	-1	2,2	0,12	2,75	0,54
	Victoria Falls C3	IEEET1A	Type 11		40	0,1		0,07	0,9	0,09	1	1	-1	2,2	0,12	2,75	0,54
	Victoria Falls C4	IEEET1A	Type 11		40	0,1		0,07	0,9	0,09	1	1	-1	2,2	0,12	2,75	0,54
Itezhi Tezhi	Itezhi Tezhi 1	SCRX	EXGP.CON	0	80	0,72	1,2		0,05			7,26	-5,8				
	Itezhi Tezhi 2	SCRX	EXGP.CON	0	80	0,72	1,2		0,05			7,26	-5,8				
Itezhi Tezhi	Itezhi Tezhi 1	SCRX	EXGP.CON	0	80	0,72	1,2		0,05			7,26	-5,8				
	Itezhi Tezhi 2	SCRX	EXGP.CON	0	80	0,72	1,2		0,05			7,26	-5,8				
Mulungushi	Mulungushi G1	SEXS	EXGP.CON	0	80	2,5	10		0,05			5	0				
	Mulungushi G2	SEXS	EXGP.CON	0	80	2,5	10		0,05			5	0				
	Mulungushi G3	SEXS	EXGP.CON	0	80	2,5	10		0,05			5	0				
	Mulungushi G4	SEXS	EXGP.CON	0	80	2,5	10		0,05			5	0				
lunsemfwa	lunsemfwa G1	SEXS	EXGP.CON	0	80	2,5	10		0,05			5	0				
	lunsemfwa G2	SEXS	EXGP.CON	0	80	2,5	10		0,05			5	0				
	lunsemfwa G3	SEXS	EXGP.CON	0	80	2,5	10		0,05			5	0				
Lusiwasi	lusiwasi G1	IEEET1A	Type 11		40	0,1		0,74	1,4	0,07	1	6	0	3,5	3,7	4,6	6
	lusiwasi G2	IEEET1A	Type 11		40	0,1		0,74	1,4	0,07	1	6	0	3,5	3,7	4,6	6
	lusiwasi G3	IEEET1A	Type 11		40	0,1		0,74	1,4	0,07	1	6	0	3,5	3,7	4,6	6
	lusiwasi G4	IEEET1A	Type 11		40	0,1		0,74	1,4	0,07	1	6	0	3,5	3,7	4,6	6
KITWE	SC	SCRX	EXGP.CON	0	80	0,72	1,2		0,05			7,26	-5,8				

Table 14: Detailed parameters of the AVRs

Appendix 11. Detailed parameters of speed Governors.

Power plants	Units	type of SG	Sn	H	TW	Tr	Rt=delta	TG	TP	UO	UC	Pmax	Pmin	sigma	A11	A13	A21	A23
			(MVA)		s													
Kafue George	Kafue Gorge G1	IEEEG3.CON	167,00	2,7	0,57	2,97	0,25	0,1	0,05	0,067	0,14	0,76	0	0,04	0,5	1,5	1	1
	Kafue Gorge G2	IEEEG3.CON	167,00	2,7	0,57	2,97	0,25	0,1	0,05	0,067	0,14	0,76	0	0,04	0,5	1,5	1	1
	Kafue Gorge G3	IEEEG3.CON	167,00	2,7	0,57	2,97	0,25	0,1	0,05	0,067	0,14	0,76	0	0,04	0,5	1,5	1	1
	Kafue Gorge G4	IEEEG3.CON	167,00	2,7	0,57	2,97	0,25	0,1	0,05	0,067	0,14	0,76	0	0,04	0,5	1,5	1	1
	Kafue Gorge G5	IEEEG3.CON	167,00	2,7	0,57	2,97	0,25	0,1	0,05	0,067	0,14	0,76	0	0,04	0,5	1,5	1	1
	Kafue Gorge G6	IEEEG3.CON	167,00	2,7	0,57	2,97	0,25	0,1	0,05	0,067	0,14	0,76	0	0,04	0,5	1,5	1	1
kariba North	Kariba North G1	IEEEG3.CON	200,00	3,44	1,55	7,34	0,50	0,1	0,05	0,063	0,14	0,876	0	0,04	0,5	1,5	1	1
	Kariba North G2	IEEEG3.CON	200,00	3,44	1,67	7,77	0,53	0,1	0,05	0,063	0,14	0,876	0	0,04	0,5	1,5	1	1
	Kariba North G3	IEEEG3.CON	200,00	3,44	1,53	7,26	0,49	0,1	0,05	0,063	0,14	0,876	0	0,04	0,5	1,5	1	1
	Kariba North G4	IEEEG3.CON	200,00	3,44	1,51	7,16	0,49	0,1	0,05	0,063	0,14	0,876	0	0,04	0,5	1,5	1	1
	Kariba North G5	IEEEG3.CON	200,00	3,44	2,62	10,97	0,78	0,1	0,05	0,063	0,14	0,876	0	0,04	0,5	1,5	1	1
	Kariba North G6	IEEEG3.CON	200,00	3,44	2,62	10,97	0,78	0,1	0,05	0,063	0,14	0,876	0	0,04	0,5	1,5	1	1
Victoria Falls	Victoria Falls A1	IEEEG3.CON	1,25	2,5	3,72	13,53	1,41	0,1	0,05	0,125	-0,25	0,8	0	0,04	0,5	1,5	1	1
	Victoria Falls A2	IEEEG3.CON	1,25	2,5	3,72	13,53	1,41	0,1	0,05	0,125	-0,25	0,8	0	0,04	0,5	1,5	1	1
	Victoria Falls A3	IEEEG3.CON	3,75	2,5	3,72	13,53	1,41	0,1	0,05	0,125	-0,25	0,85	0	0,04	0,5	1,5	1	1
	Victoria Falls A4	IEEEG3.CON	3,75	2,5	3,72	13,53	1,41	0,1	0,05	0,125	-0,25	0,85	0	0,04	0,5	1,5	1	1
	Victoria Falls B1	IEEEG3.CON	11,77	1,8	1,50	7,13	0,93	0,1	0,05	0,1	-0,2	0,85	0	0,04	0,5	1,5	1	1
	Victoria Falls B2	IEEEG3.CON	11,77	1,8	1,50	7,13	0,93	0,1	0,05	0,1	-0,2	0,85	0	0,04	0,5	1,5	1	1
	Victoria Falls B3	IEEEG3.CON	11,77	1,8	1,50	7,13	0,93	0,1	0,05	0,1	-0,2	0,85	0	0,04	0,5	1,5	1	1
	Victoria Falls B4	IEEEG3.CON	11,77	1,8	1,50	7,13	0,93	0,1	0,05	0,1	-0,2	0,85	0	0,04	0,5	1,5	1	1
	Victoria Falls B5	IEEEG3.CON	11,77	1,8	1,50	7,13	0,93	0,1	0,05	0,1	-0,2	0,85	0	0,04	0,5	1,5	1	1
	Victoria Falls B6	IEEEG3.CON	11,77	1,8	1,50	7,13	0,93	0,1	0,05	0,1	-0,2	0,85	0	0,04	0,5	1,5	1	1
	Victoria Falls C1	IEEEG3.CON	11,77	1,8	2,45	10,48	1,42	0,1	0,05	0,1	-0,2	0,85	0	0,04	0,5	1,5	1	1
	Victoria Falls C2	IEEEG3.CON	11,77	1,8	2,45	10,48	1,42	0,1	0,05	0,1	-0,2	0,85	0	0,04	0,5	1,5	1	1
	Victoria Falls C3	IEEEG3.CON	11,77	1,8	2,45	10,48	1,42	0,1	0,05	0,1	-0,2	0,85	0	0,04	0,5	1,5	1	1
	Victoria Falls C4	IEEEG3.CON	11,77	1,8	2,45	10,48	1,42	0,1	0,05	0,1	-0,2	0,85	0	0,04	0,5	1,5	1	1
Itezhi Tezhi	Itezhi Tezhi 1	IEEEG3.CON	66,7	3,28	0,91	4,61	0,32	0,30	0,05	0,083	0,167	0,9	0	0,04	0,5	1,5	1	1
	Itezhi Tezhi 2	IEEEG3.CON	66,7	3,28	0,91	4,61	0,32	0,30	0,05	0,083	0,167	0,9	0	0,04	0,5	1,5	1	1
Mulungushi	Mulungushi G1	IEEEG3.CON	6,3	2,5	0,87	4,38	0,40	0,1	0,05	0,125	0,25	0,85	0	0,04	0,5	1,5	1	1
	Mulungushi G2	IEEEG3.CON	6,3	2,5	0,87	4,38	0,40	0,1	0,05	0,125	0,25	0,85	0	0,04	0,5	1,5	1	1
	Mulungushi G3	IEEEG3.CON	8,0	2,5	0,87	4,38	0,40	0,1	0,05	0,125	0,25	0,85	0	0,04	0,5	1,5	1	1
	Mulungushi G4	IEEEG3.CON	2,5	2,5	0,87	4,38	0,40	0,1	0,05	0,125	0,25	0,85	0	0,04	0,5	1,5	1	1
Lunsemfwa	Lunsemfwa G1	IEEEG3.CON	6,0	2,4	0,87	4,38	0,42	0,1	0,05	0,125	0,25	0,85	0	0,04	0,5	1,5	1	1
	Lunsemfwa G2	IEEEG3.CON	6,0	2,4	0,87	4,38	0,42	0,1	0,05	0,125	0,25	0,85	0	0,04	0,5	1,5	1	1
	Lunsemfwa G3	IEEEG3.CON	6,0	2,4	0,87	4,38	0,42	0,1	0,05	0,125	0,25	0,85	0	0,04	0,5	1,5	1	1
Lusiwasi	Lusiwasi G1	IEEEG3.CON	3,5	2,5	0,51	2,69	0,24	0,1	0,05	0,125	0,25	0,91	0	0,04	0,5	1,5	1	1
	Lusiwasi G2	IEEEG3.CON	3,5	2,5	0,51	2,69	0,24	0,1	0,05	0,125	0,25	0,91	0	0,04	0,5	1,5	1	1
	Lusiwasi G3	IEEEG3.CON	3,5	2,5	0,51	2,69	0,24	0,1	0,05	0,125	0,25	0,91	0	0,04	0,5	1,5	1	1
	Lusiwasi G4	IEEEG3.CON	3,5	2,5	0,51	2,69	0,24	0,1	0,05	0,125	0,25	0,91	0	0,04	0,5	1,5	1	1

Table 15: Detailed parameters of speed Governors.

Appendix 12. Transient Simulations and results

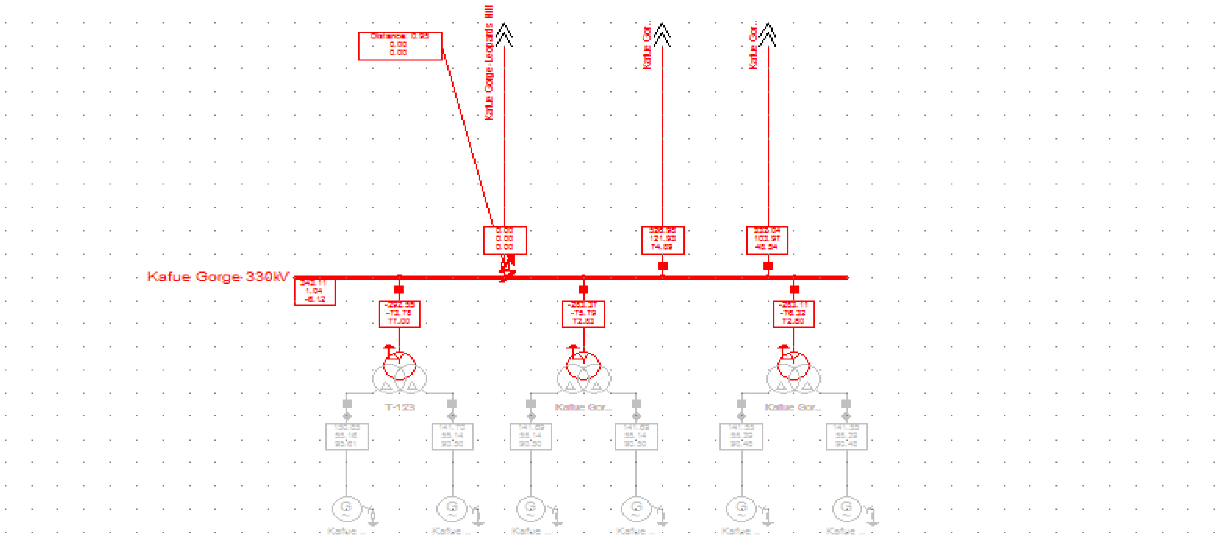


Figure 54: Simulated fault on KFG-Lhill Line close to KFG HPP

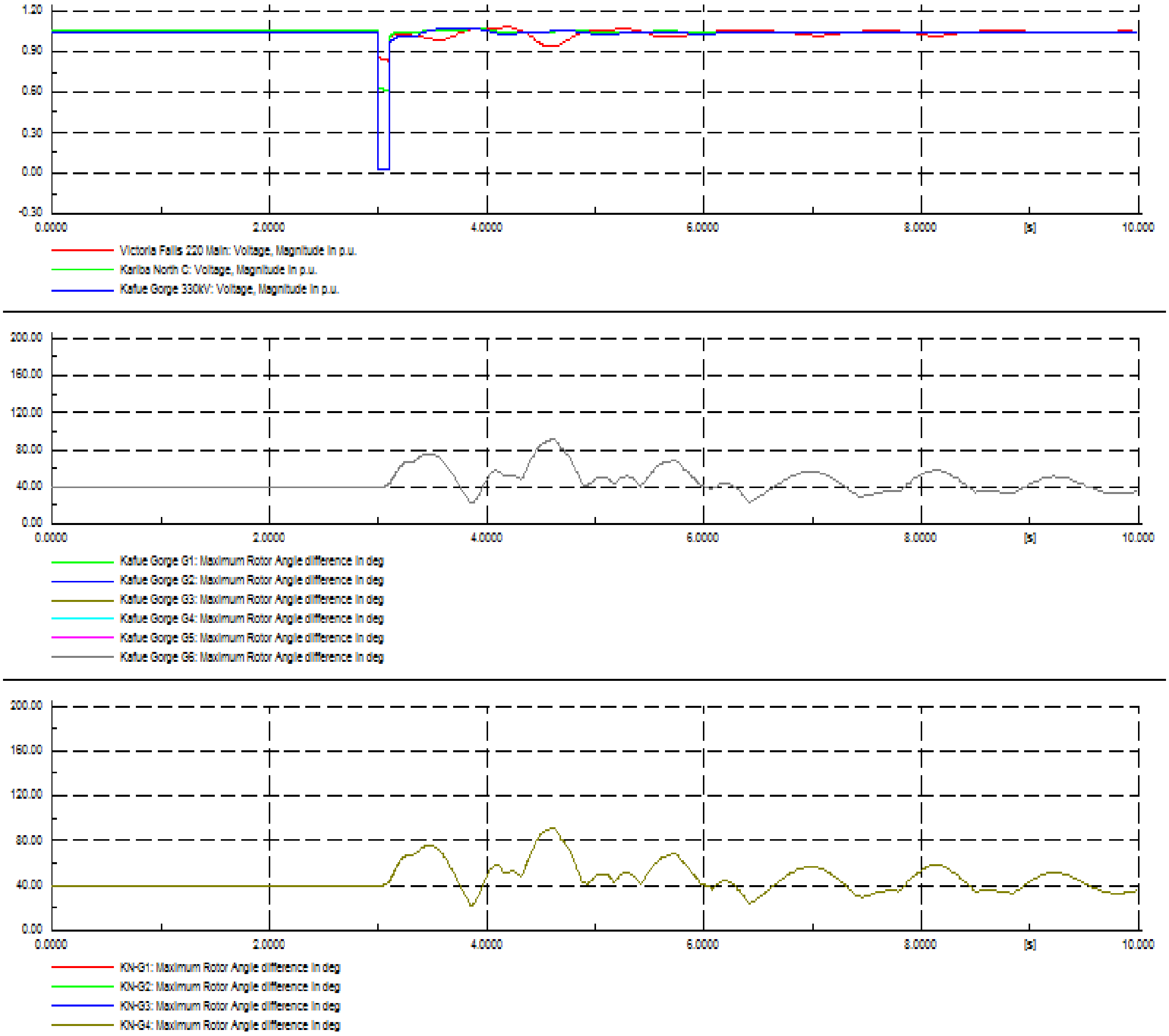


Figure 55: Voltage magnitude and rotor angle for a fault close to KFG HPP

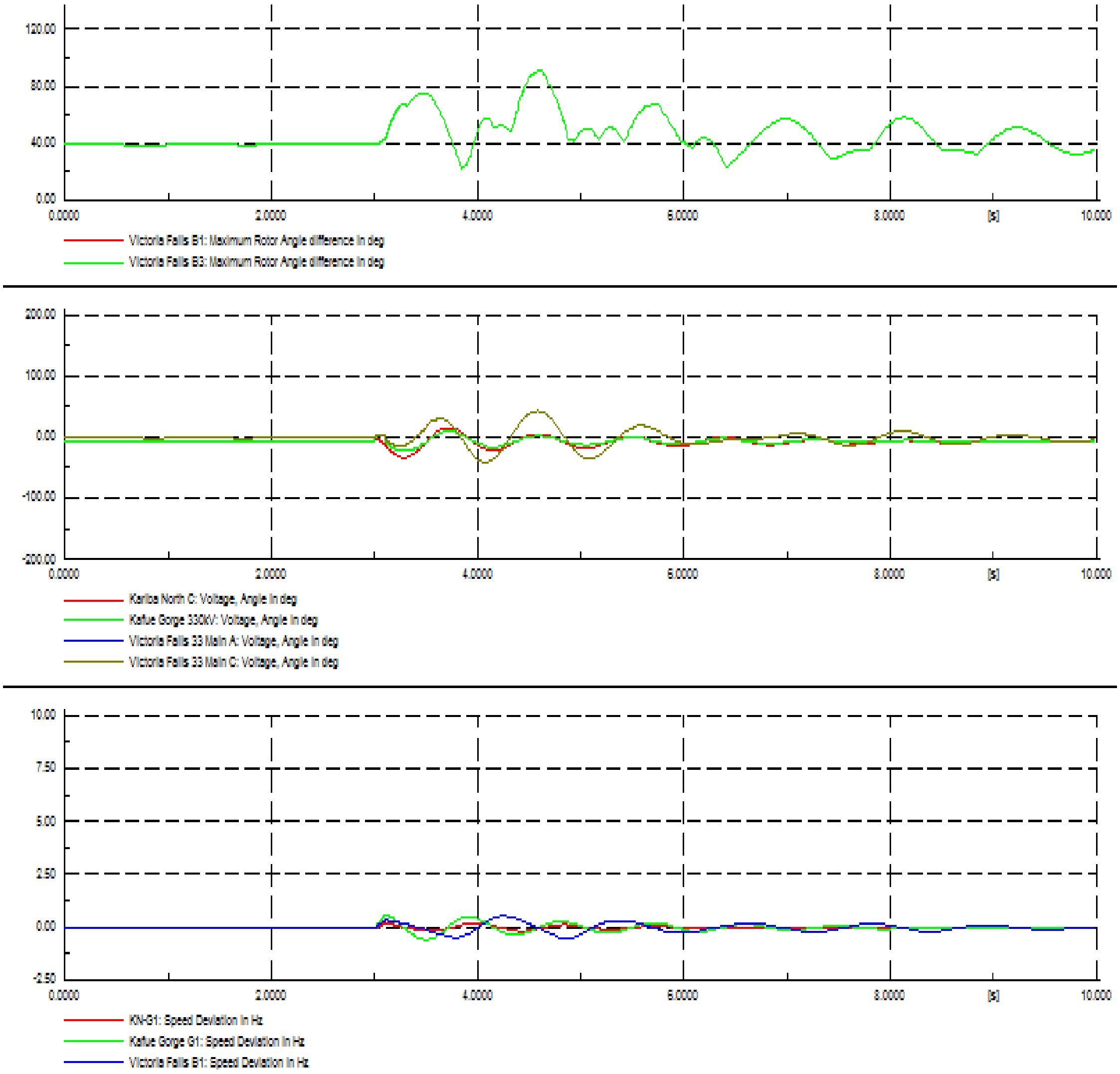


Figure 56: Close-up fault to Kafue gorge bus bar on KFG-LHill line

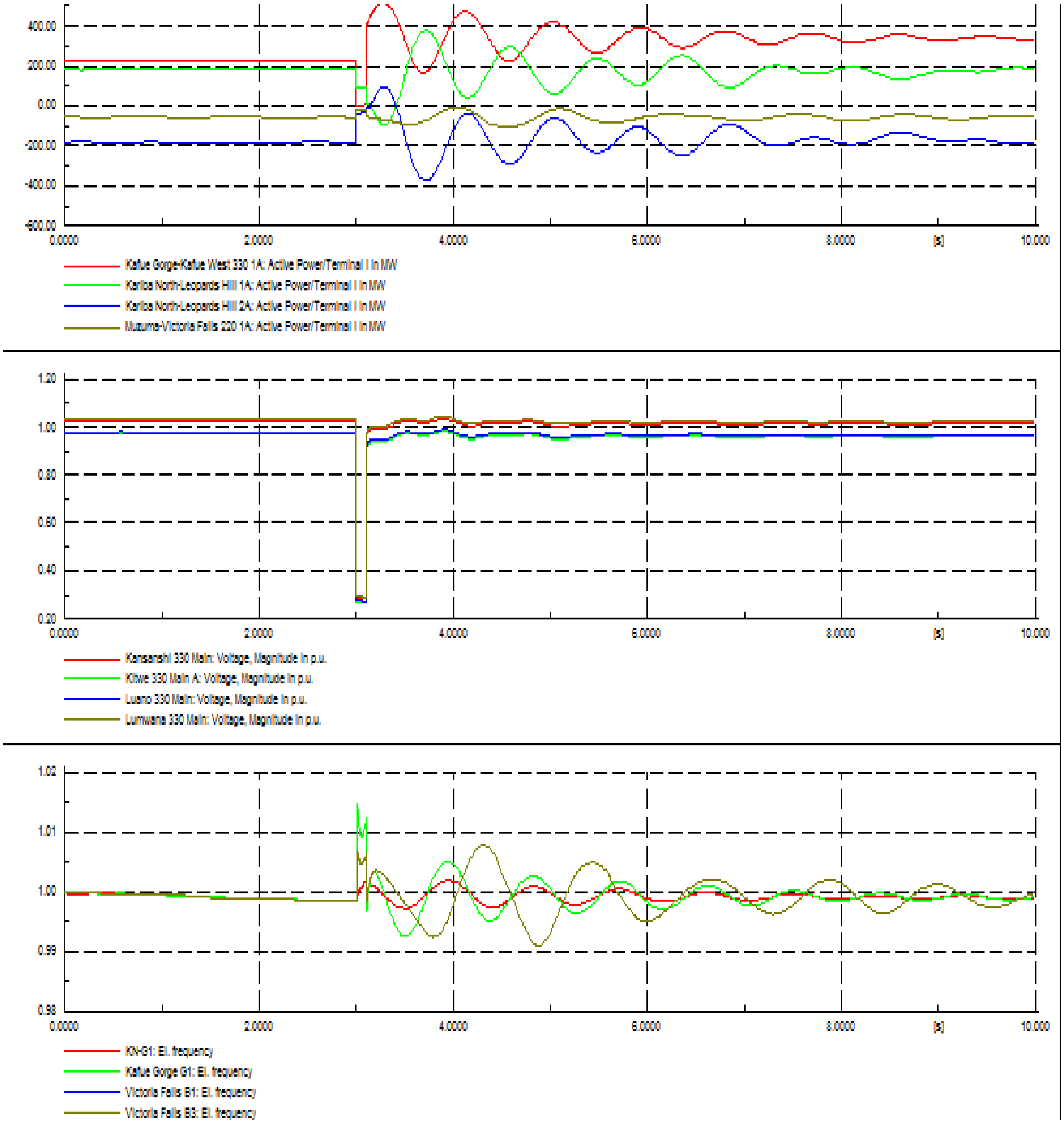


Figure 57: Close-up fault to Kafue Gorge bus bar on KFG-LHill line

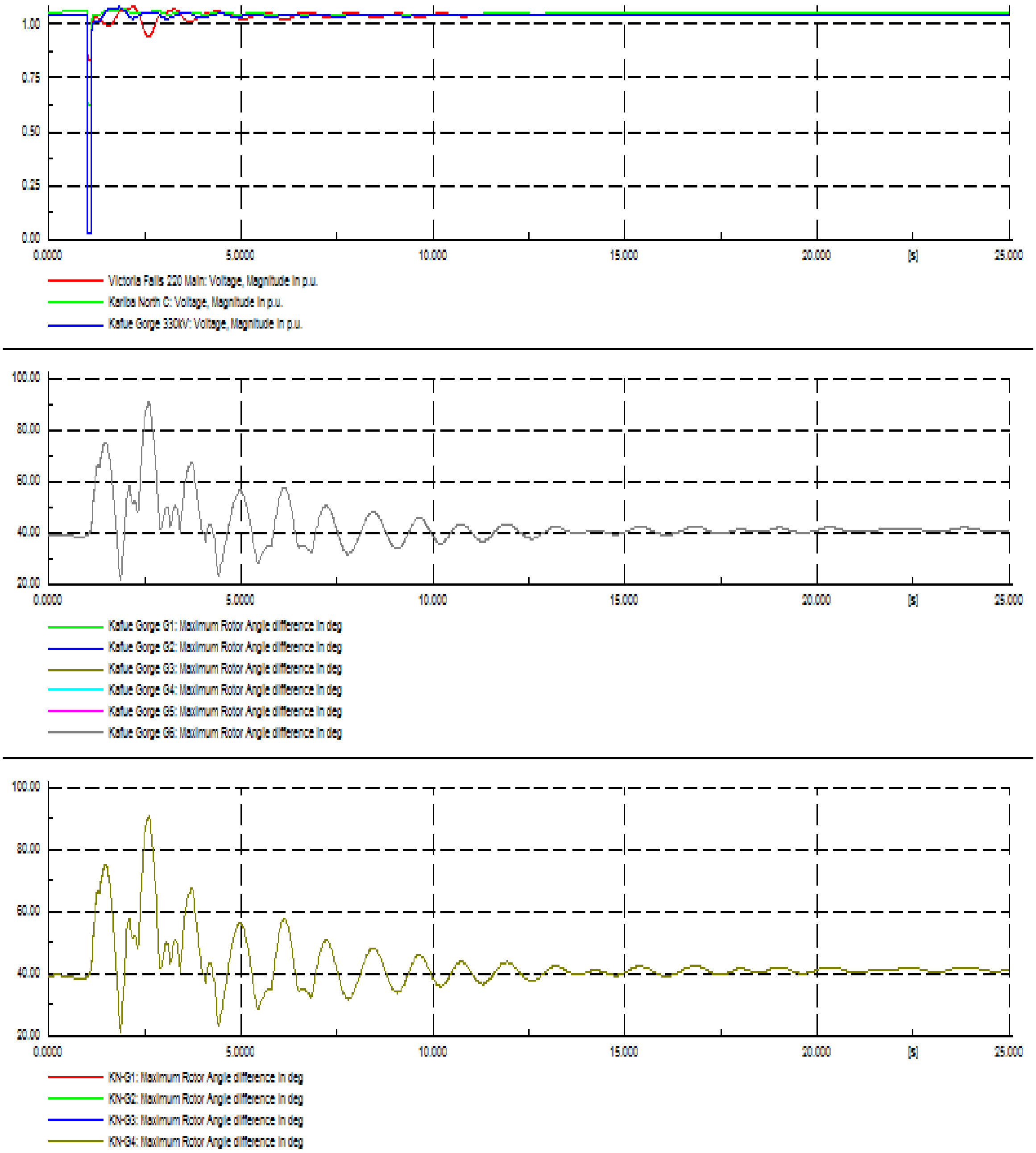


Figure 58: Auto reclosing on KFG-LHill line

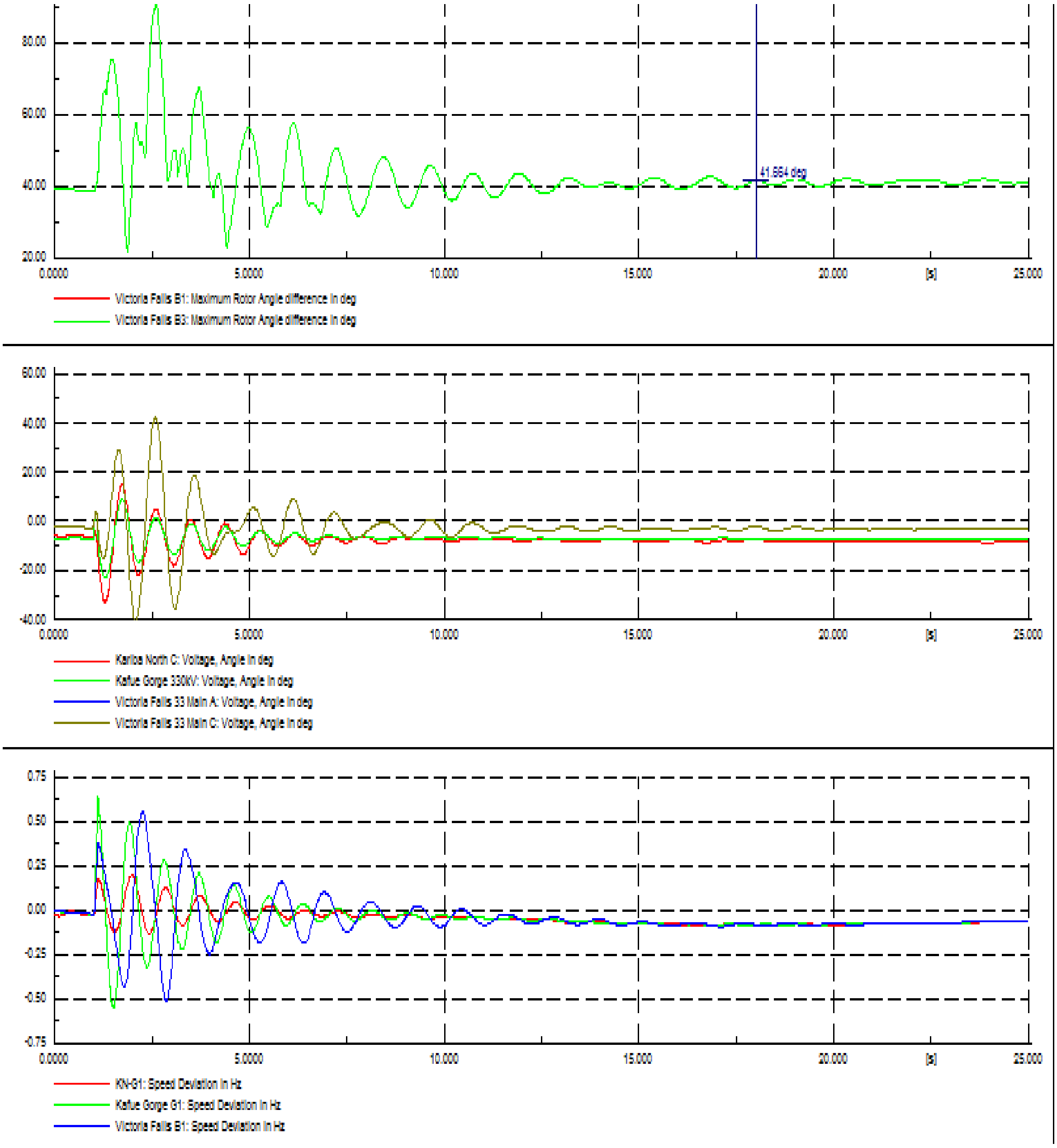


Figure 59: Auto reclosing on KFG-Lhill line

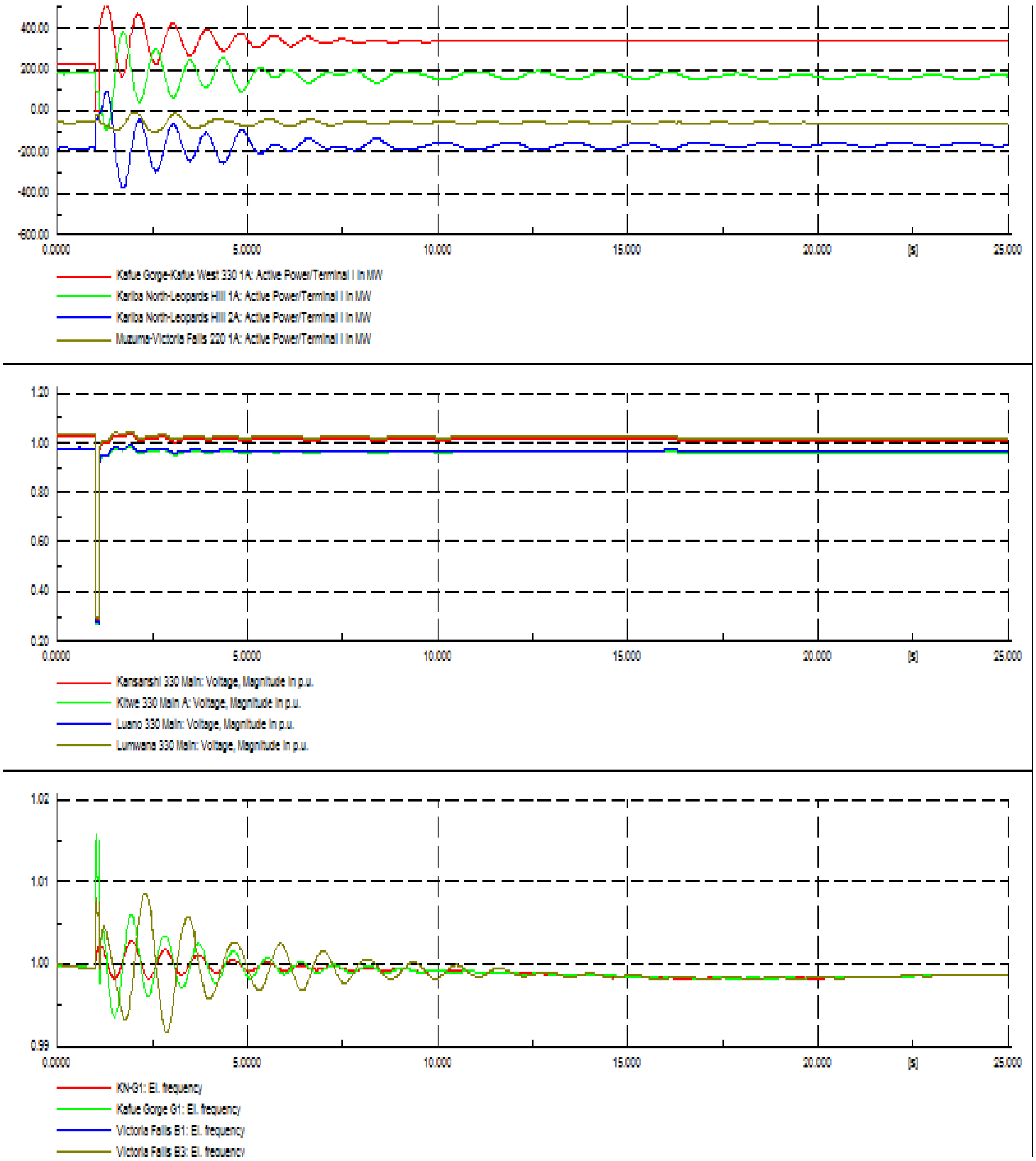


Figure 60: Auto reclosing on KFG-LHill line

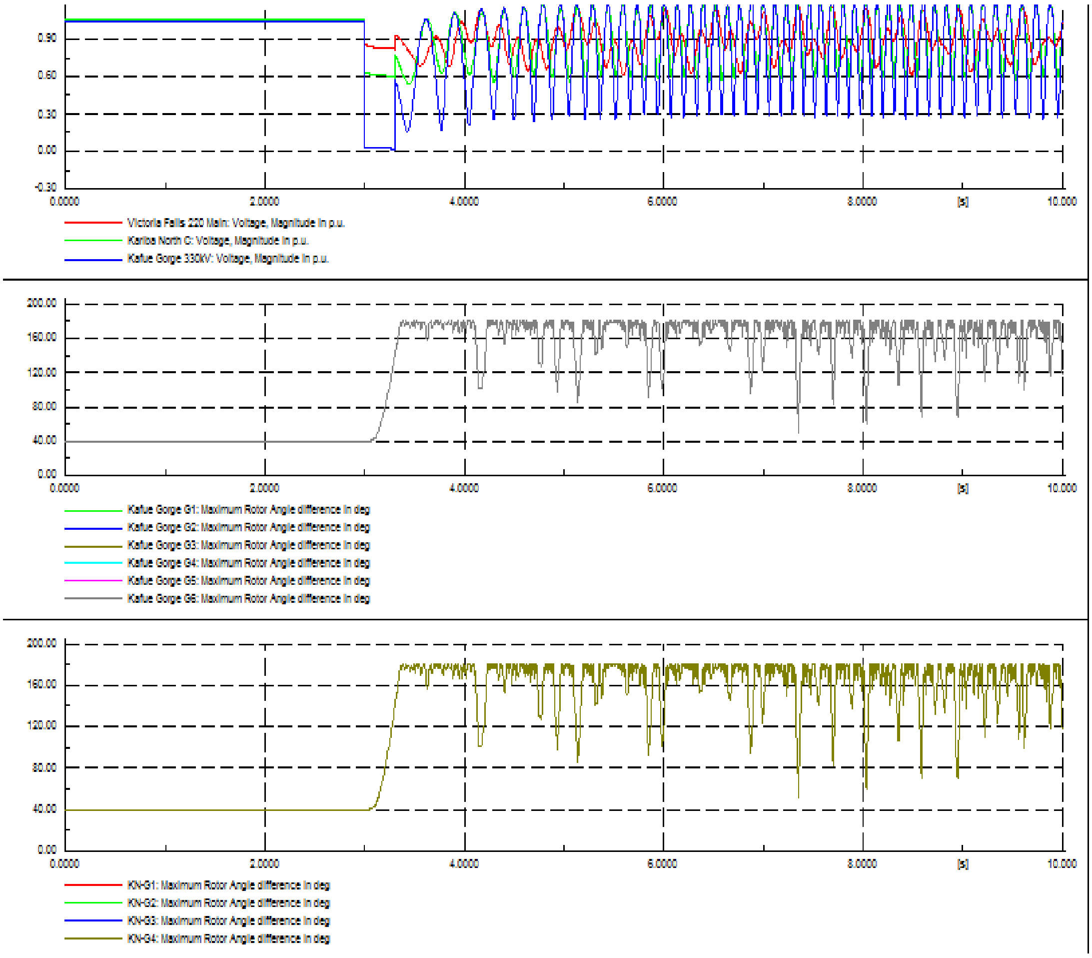


Figure 61: Clearing time at 300ms for a close up fault to KFG HPP on KFG-LHILL Line (Voltage magnitude and angle difference)

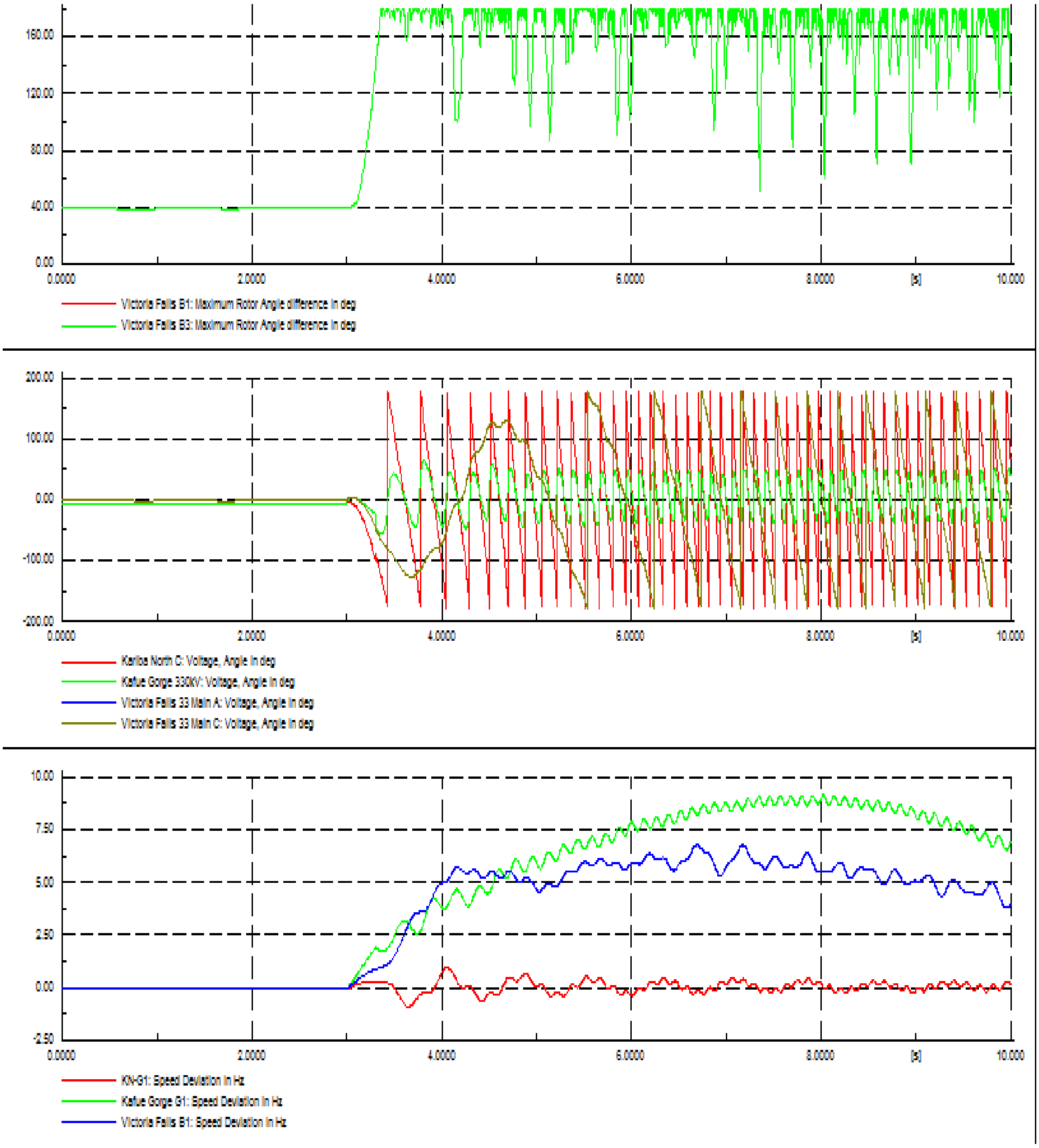


Figure 62: Clearing time at 300ms (Rotor angle, Voltage angle) for a KFG HPP close up fault.

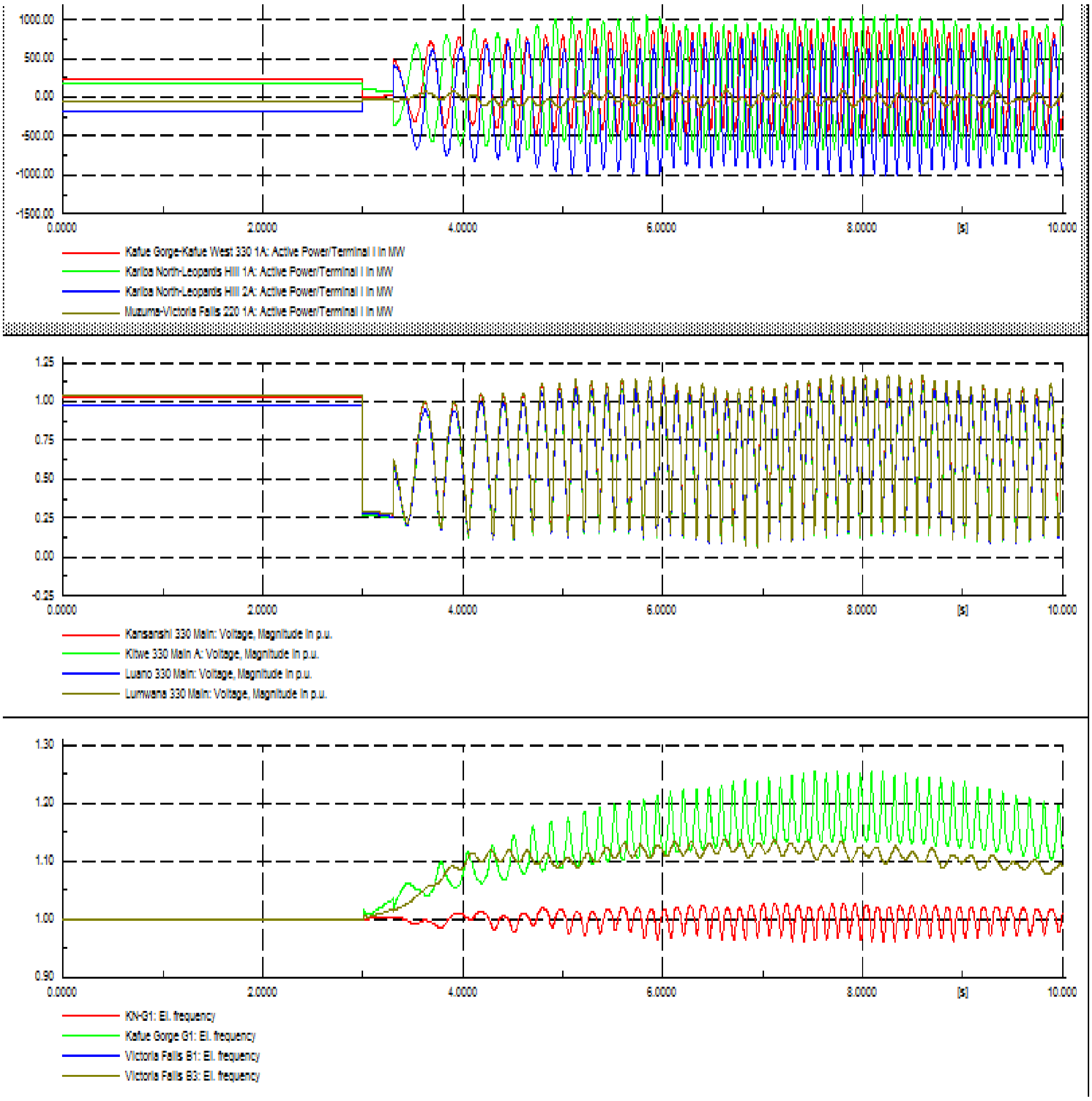


Figure 63: Clearing time at 300ms for a close up fault at KFG HPP (Active power,Voltage magnitude and frequency)

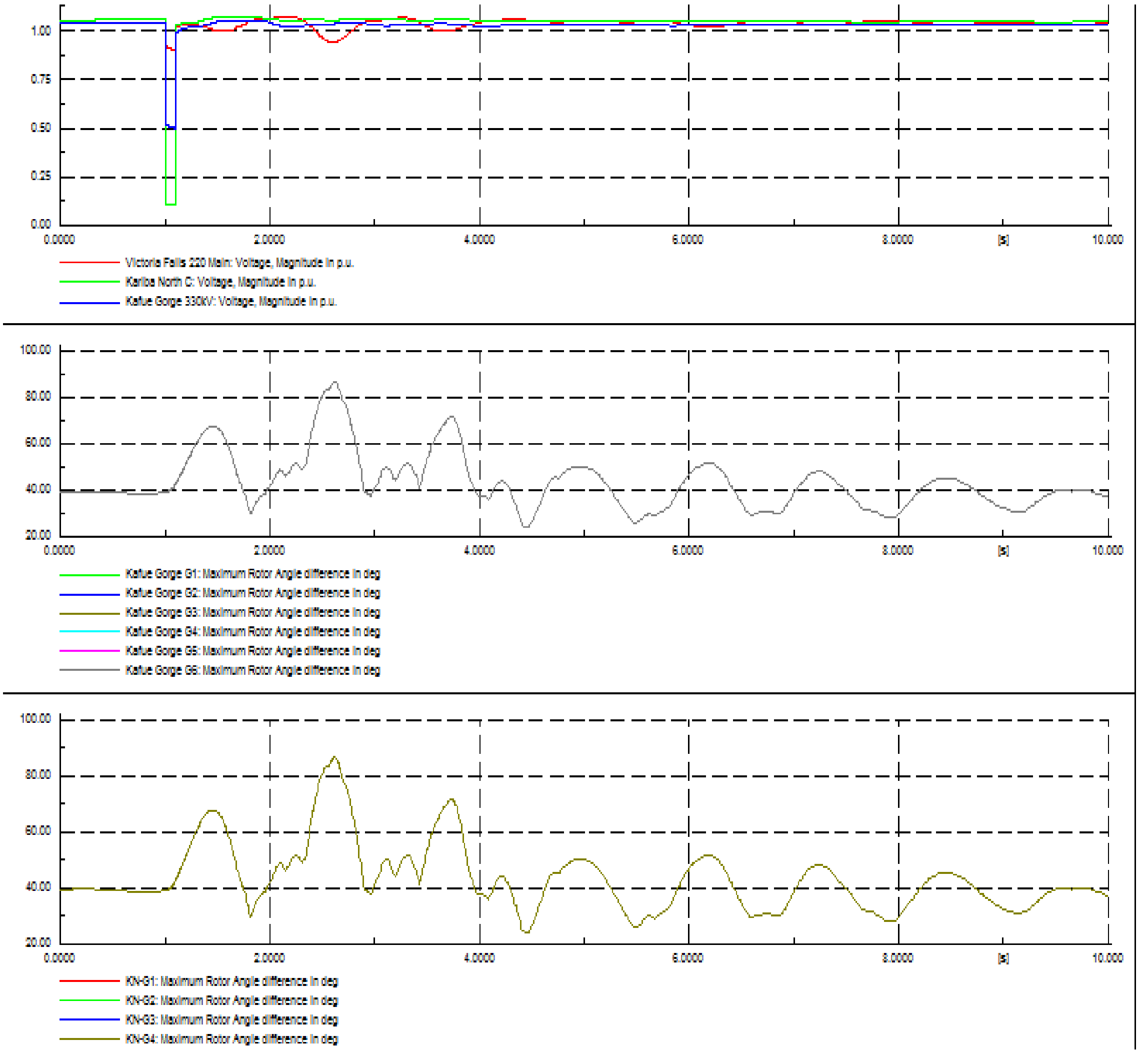


Figure 64: Close-up fault to Kariba bus bar on KNB-LHIll line

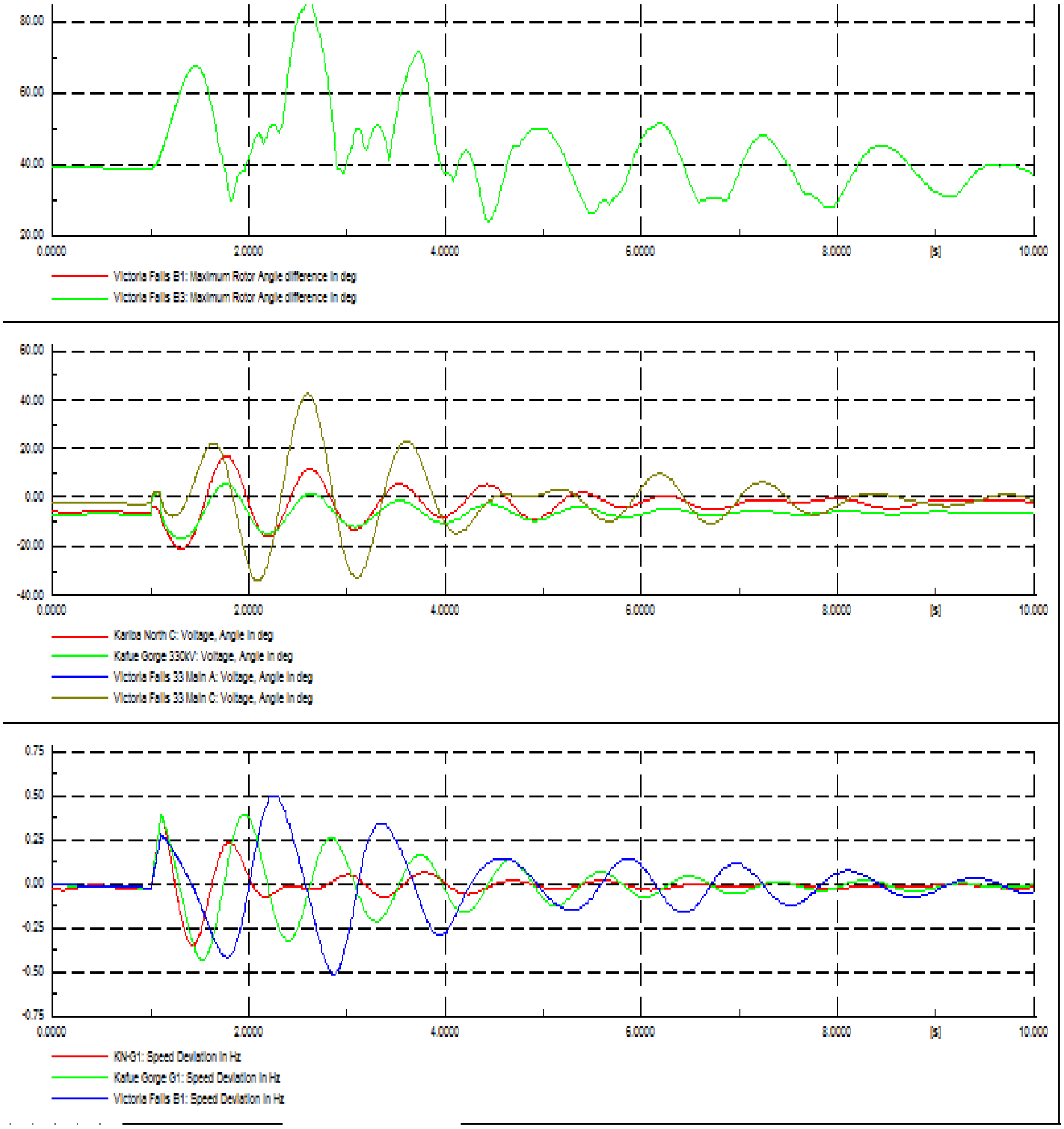


Figure 65: Close-up fault to Kariba bus bar on KNB-LHIll line

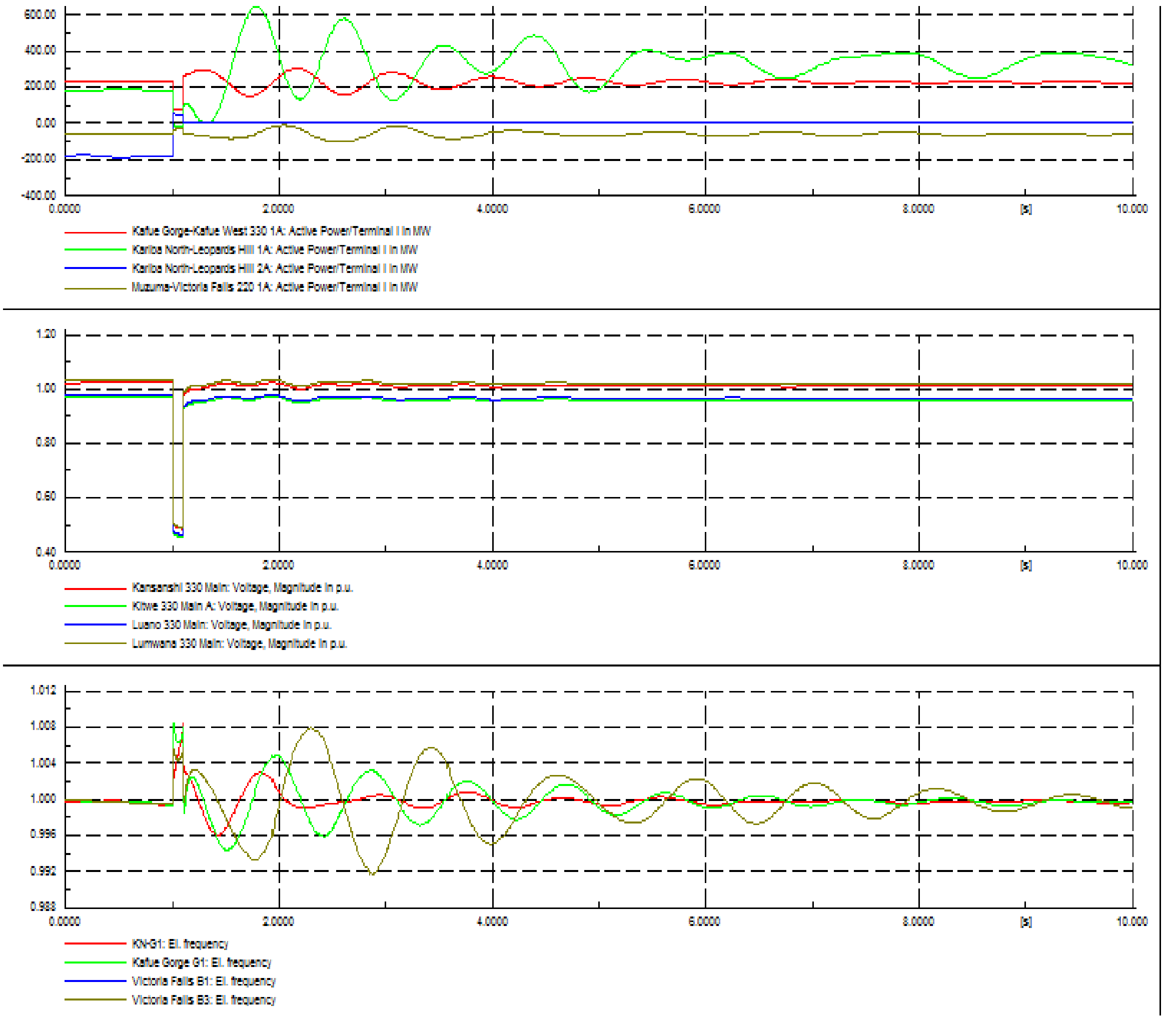


Figure 66: Close-up fault to Kariba bus bar on KNB-LHIll line

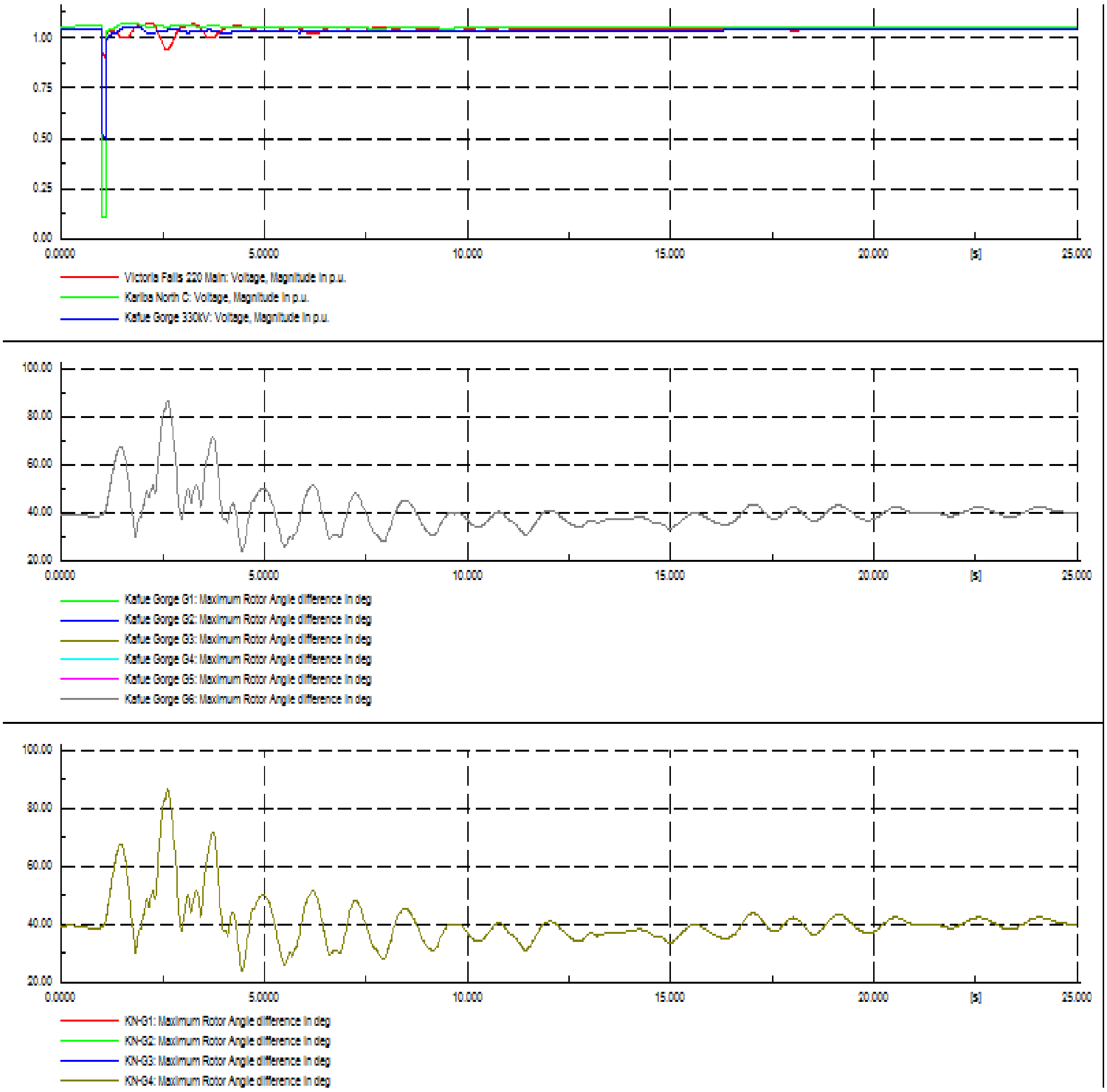


Figure 67: Auto reclosing at Kariba end then at LHill end

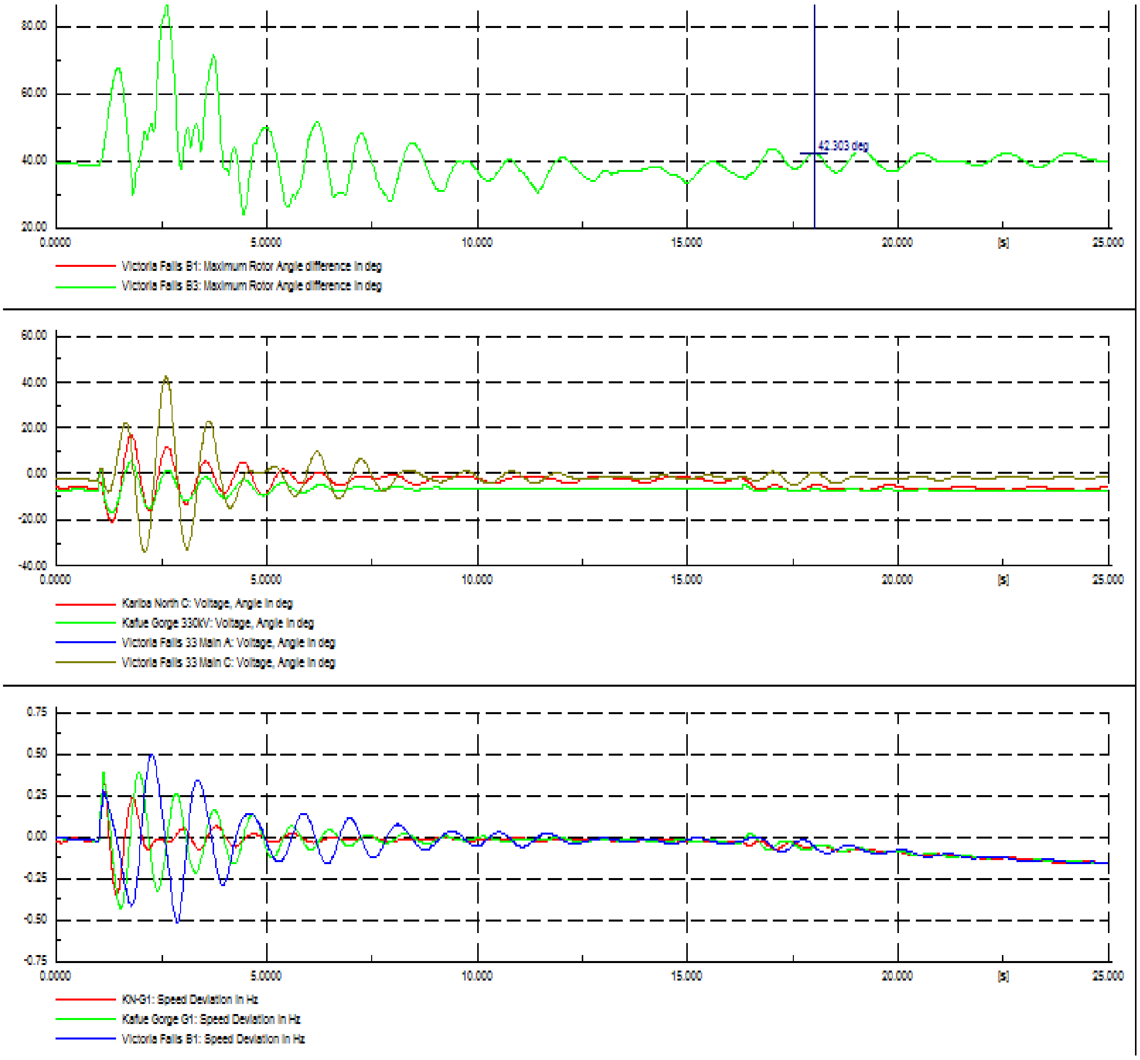


Figure 68: Auto reclosing at Kariba end then at LHill end

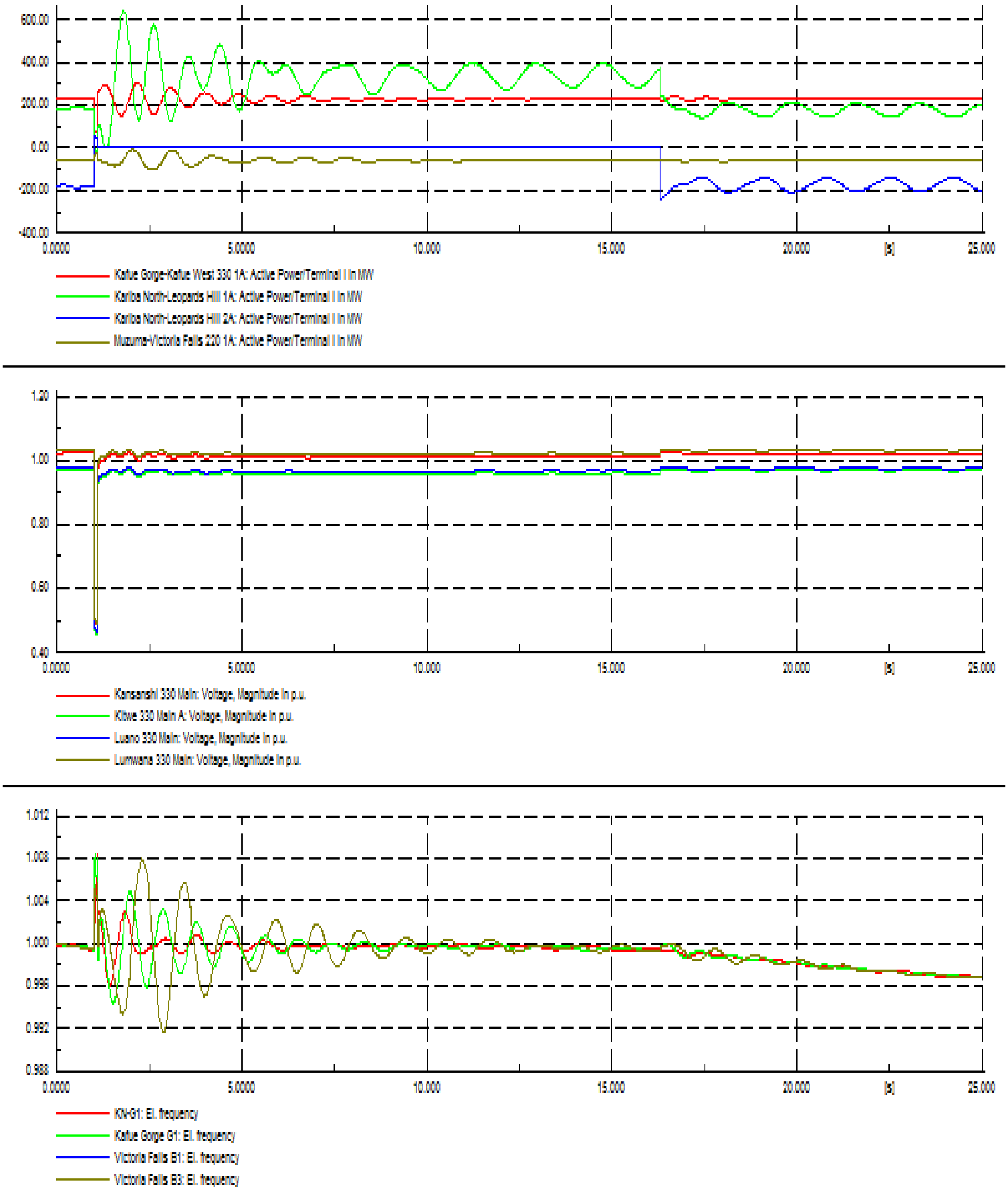


Figure 69: Auto reclosing Kariba LHill line

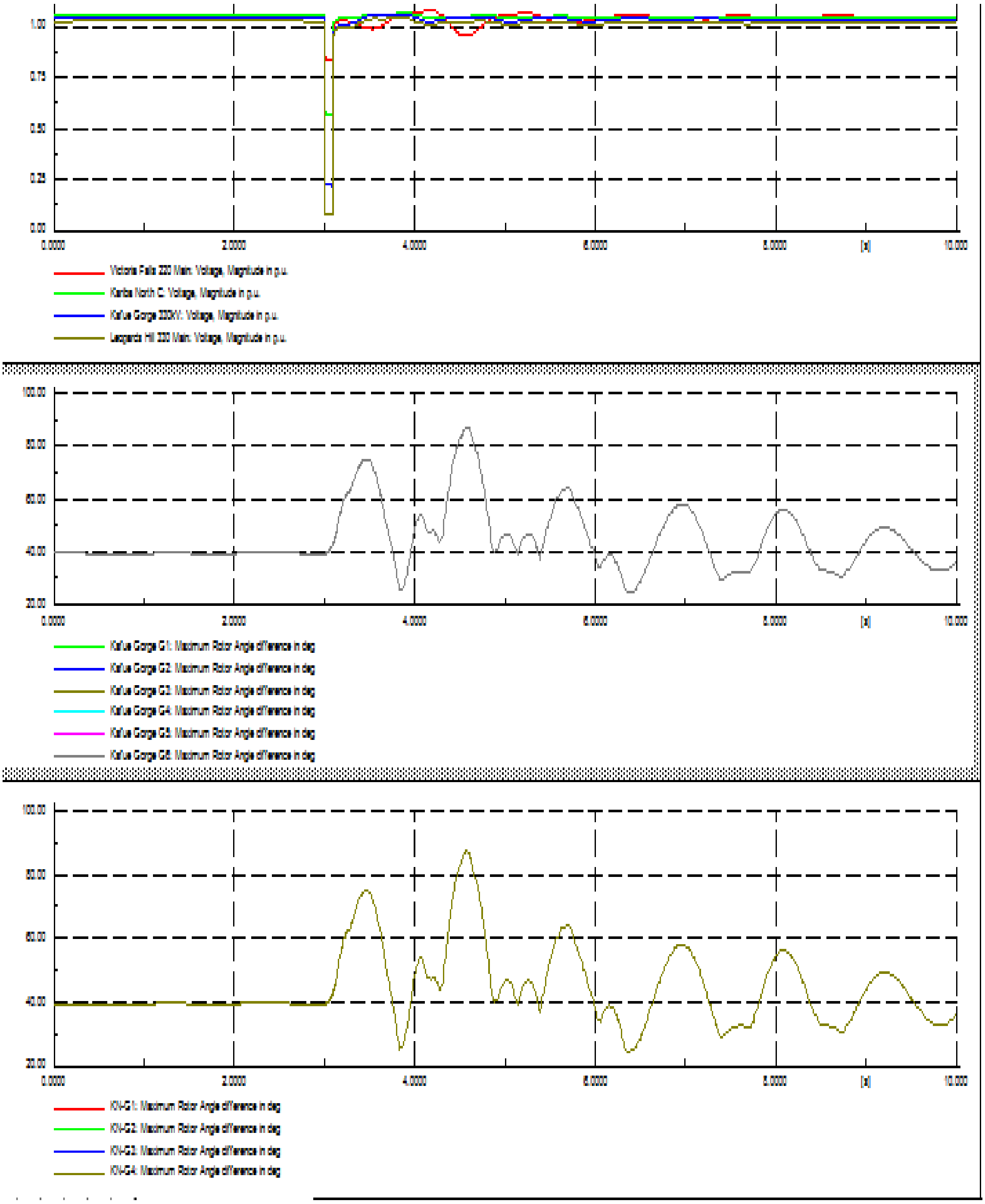


Figure 70: Fault on LHill-Kabwe line

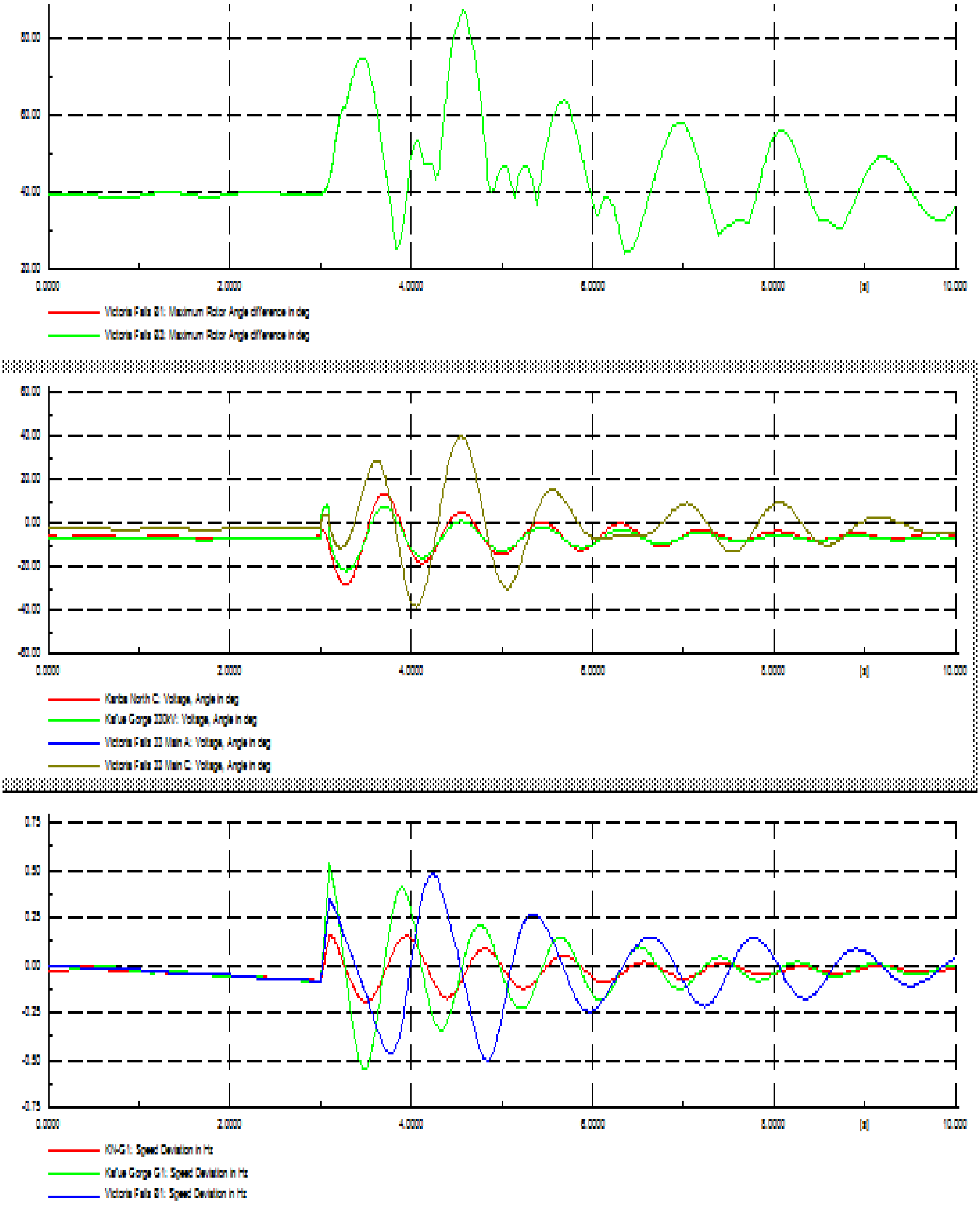


Figure 71: Fault on LHill –Kabwe line

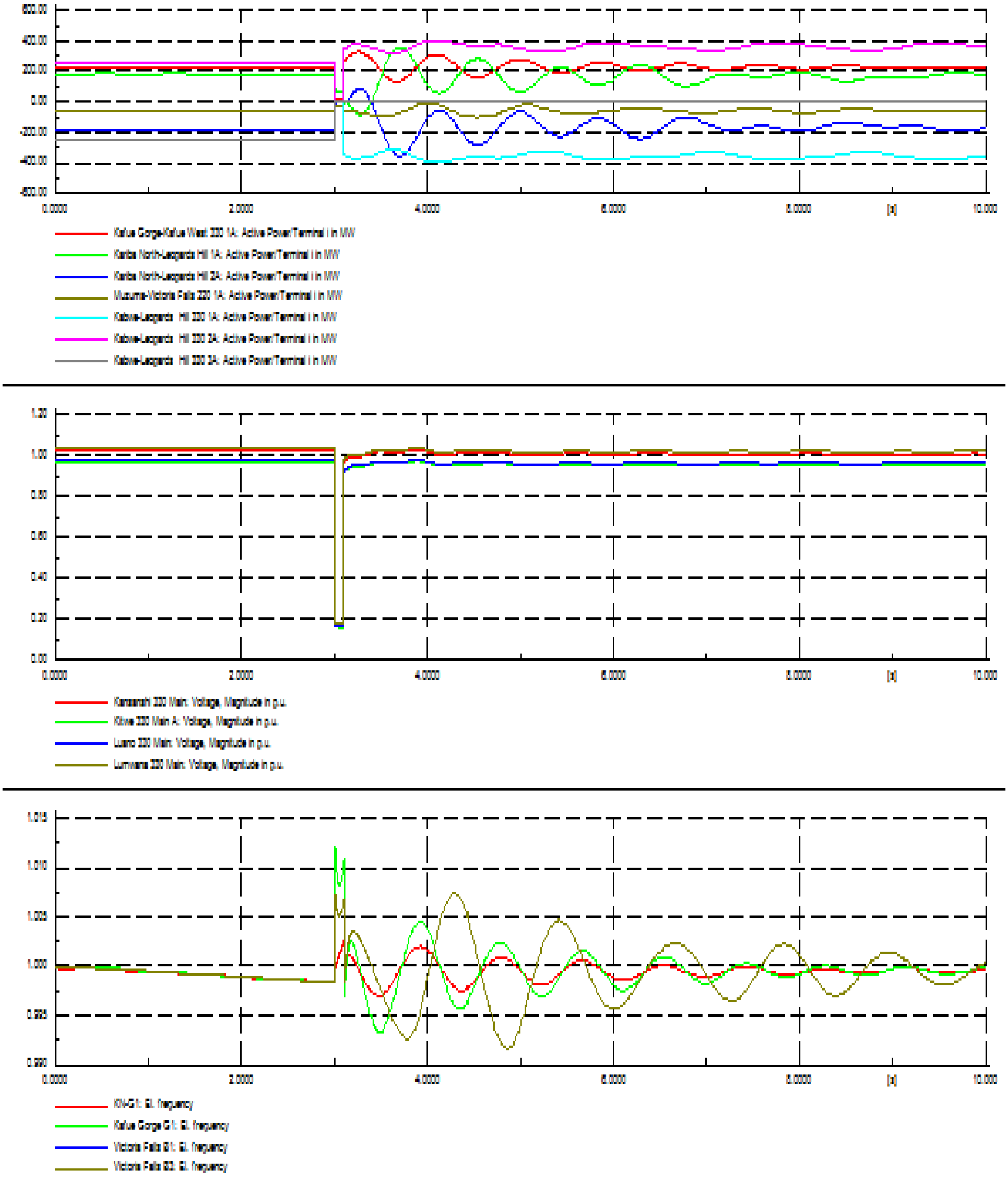


Figure 72: Fault on LHill-Kabwe line

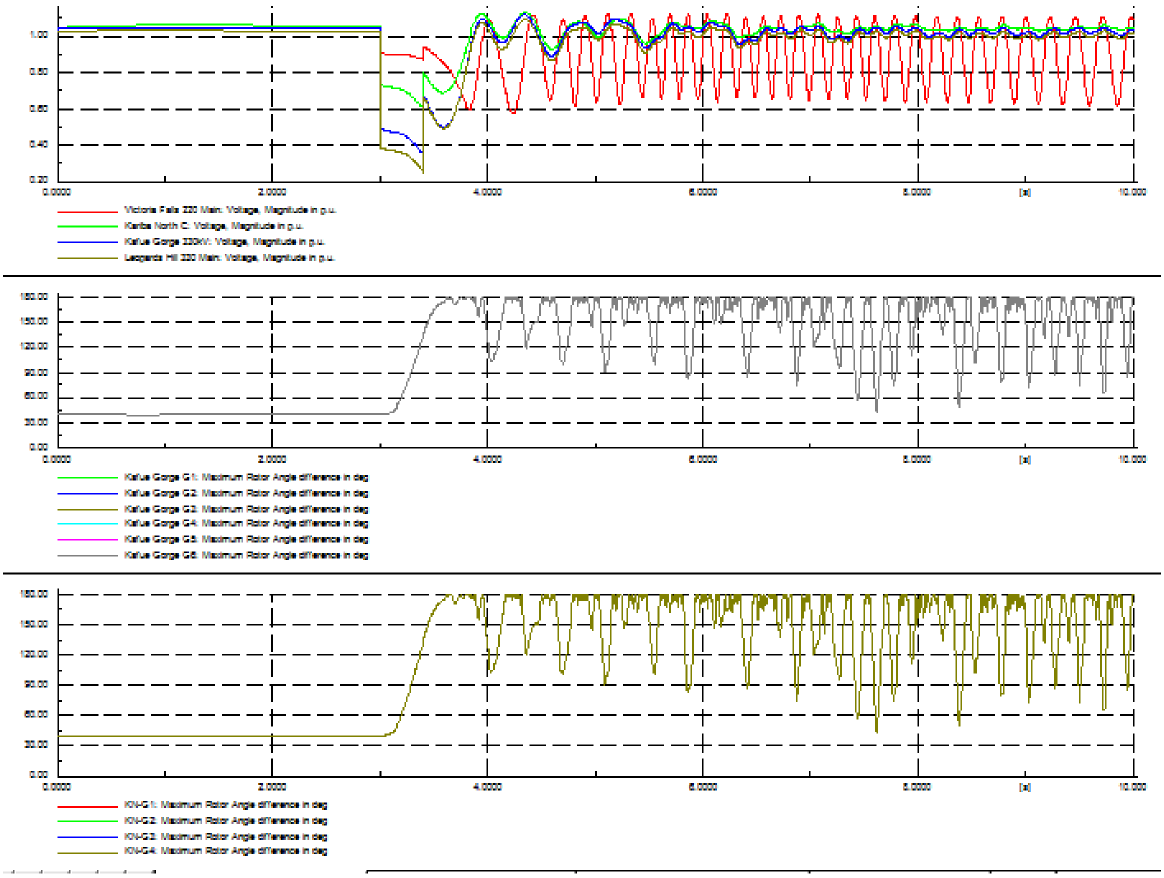


Figure 73: LHill-Kabwe fault 400ms clearing time.

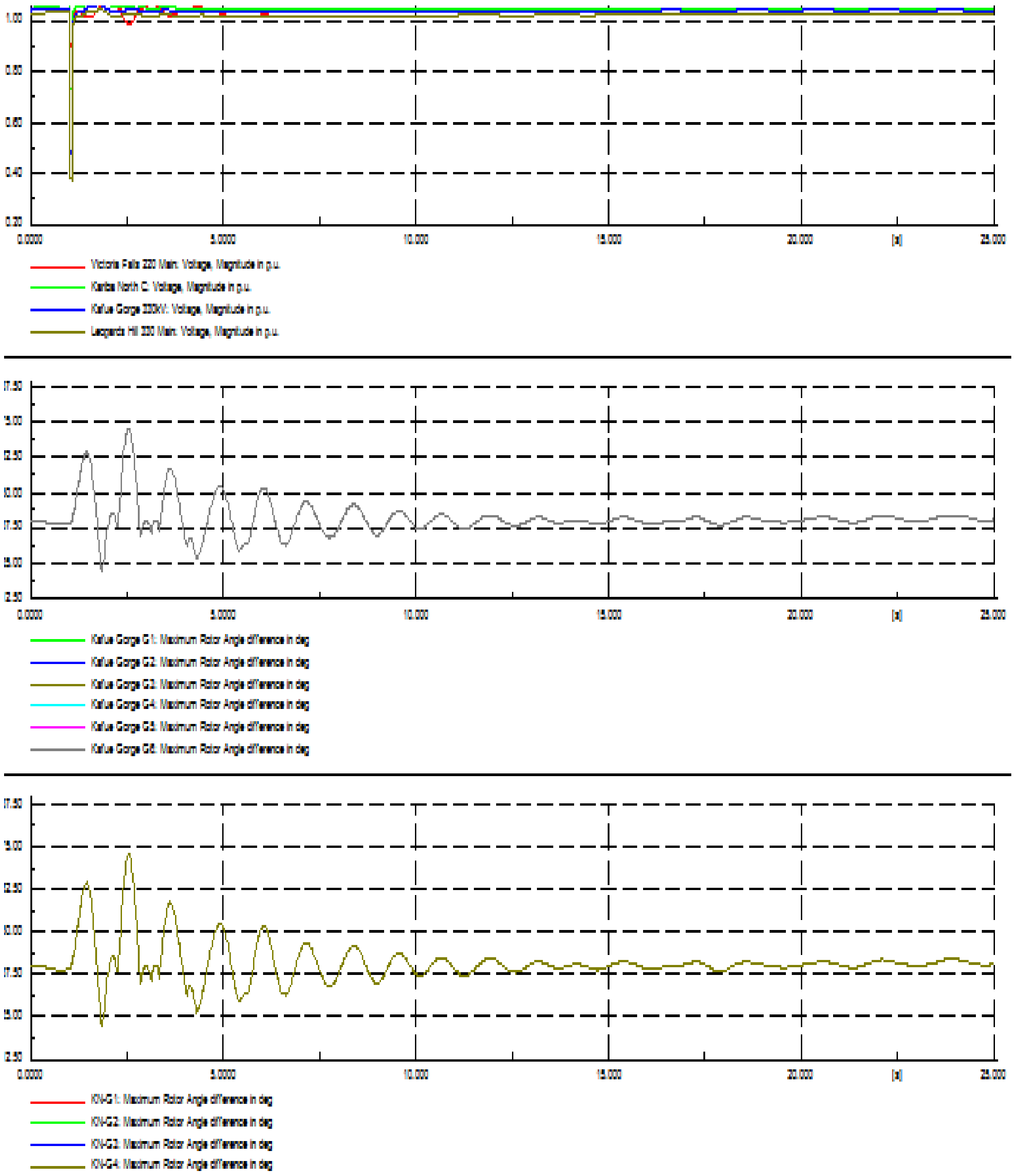


Figure 74: LHill-Kabwe fault and auto reclosing

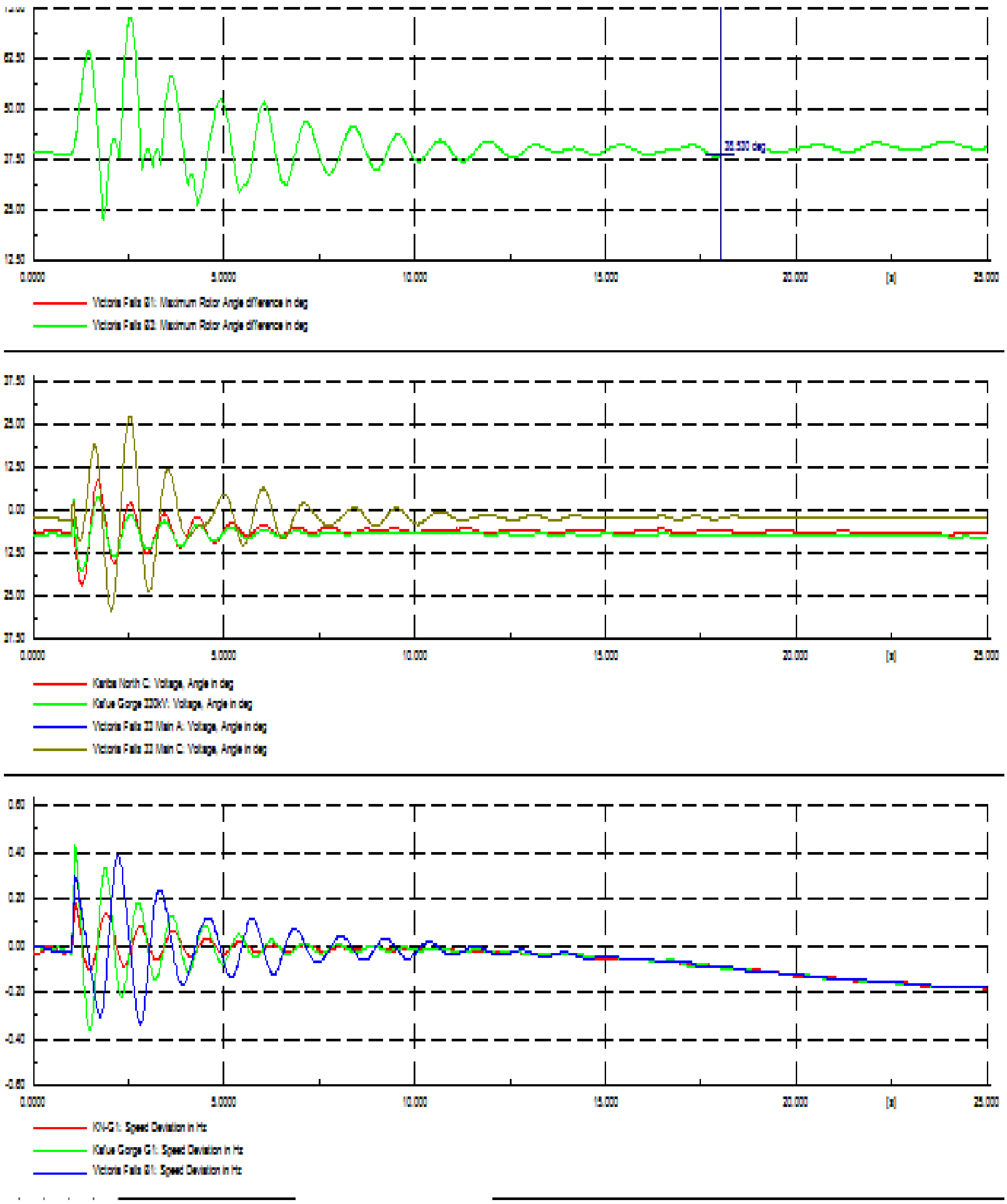


Figure 75: LHill Kabwe fault and auto reclosing

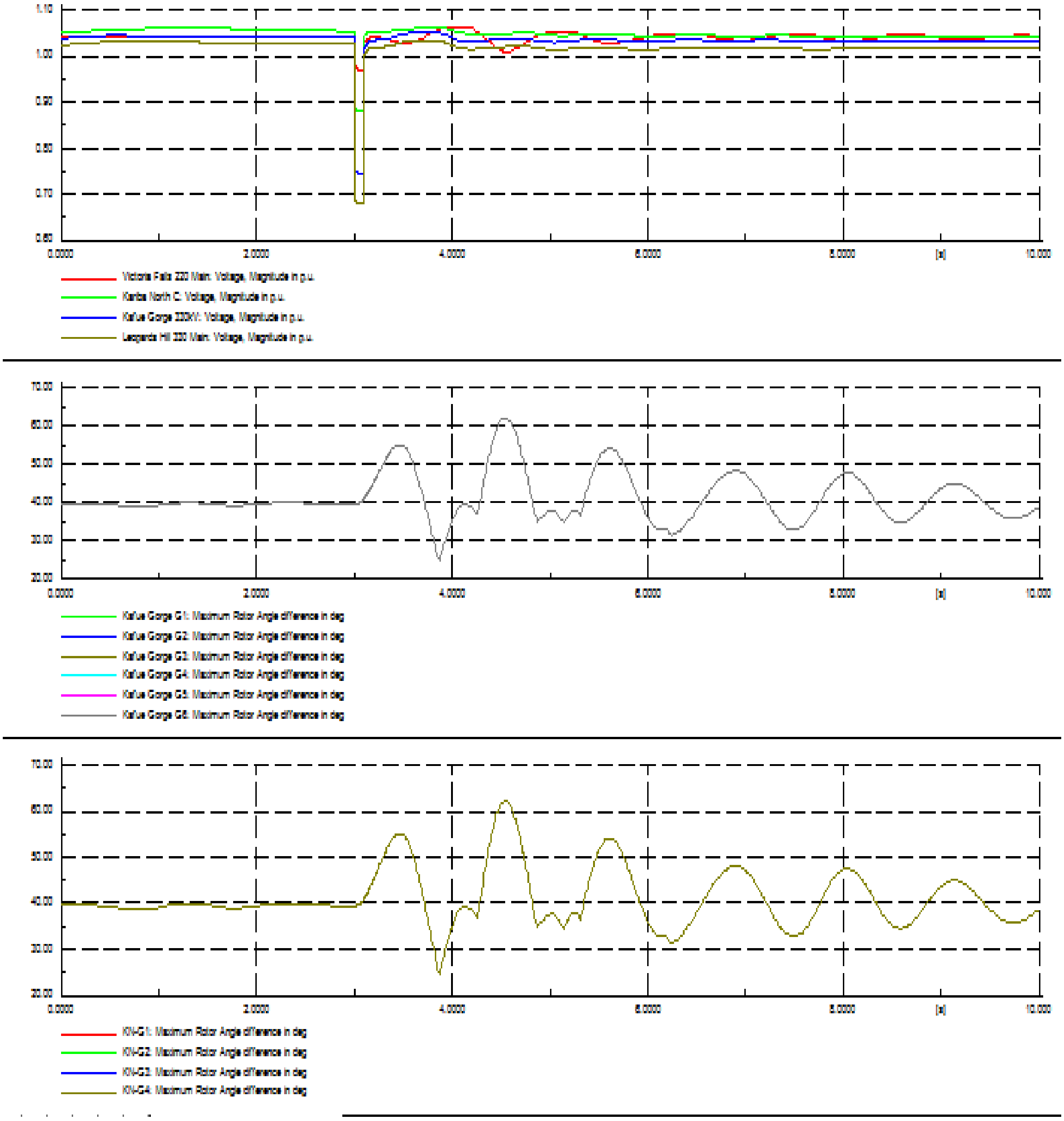


Figure 76: Kabwe –Kitwe line fault

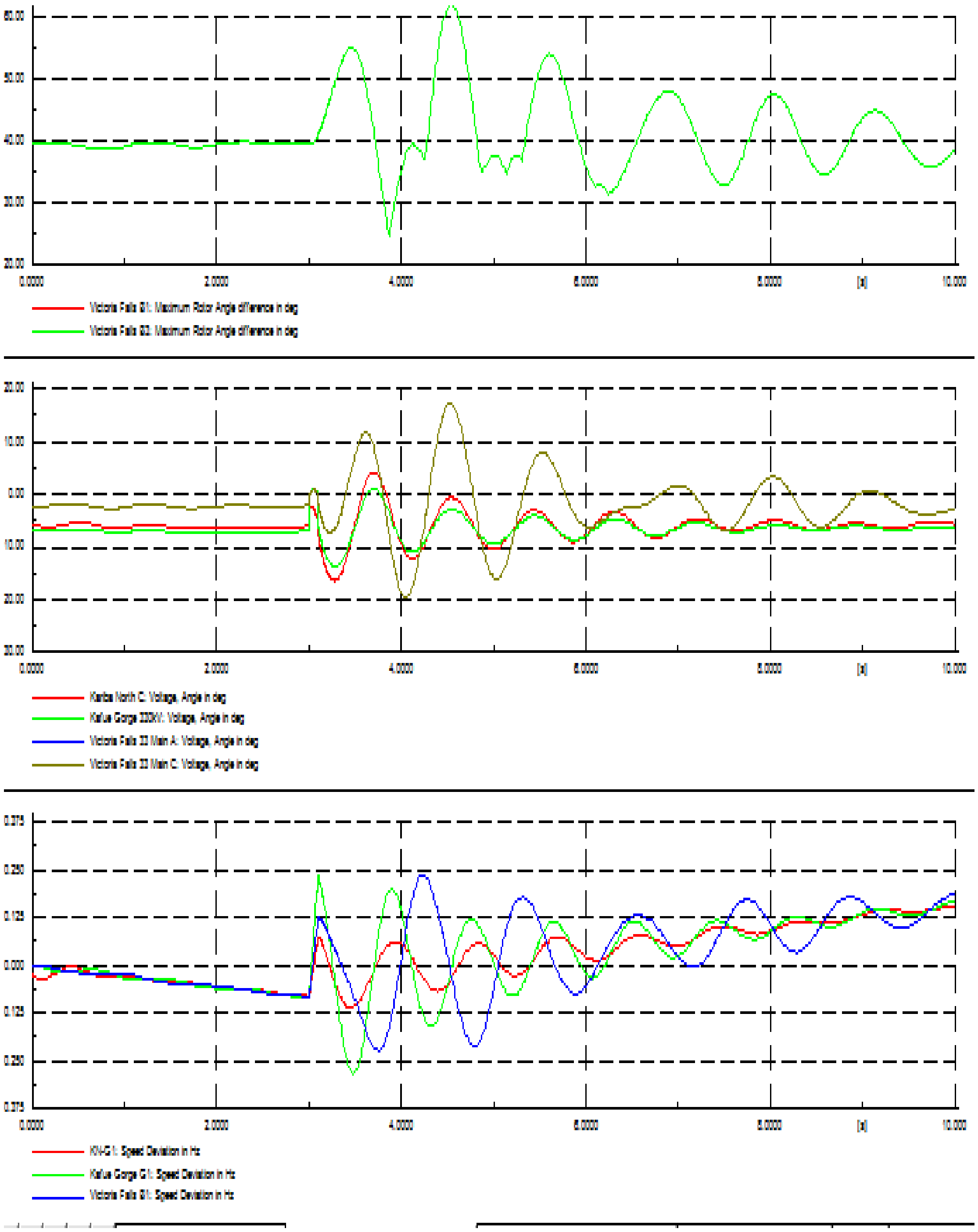


Figure 77: Kabwe-Kitwe line fault

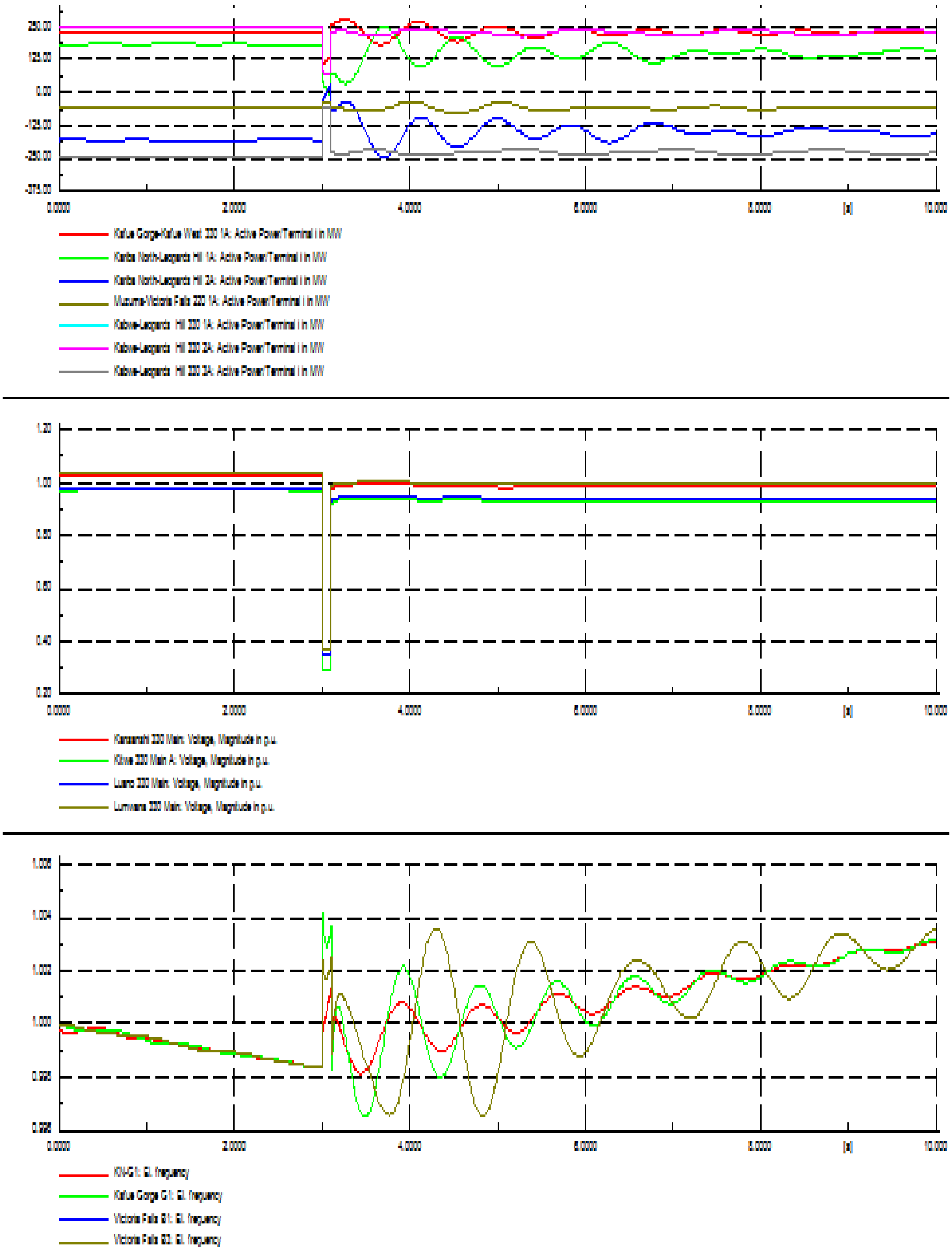


Figure 78: Kabwe-Kitwe line fault

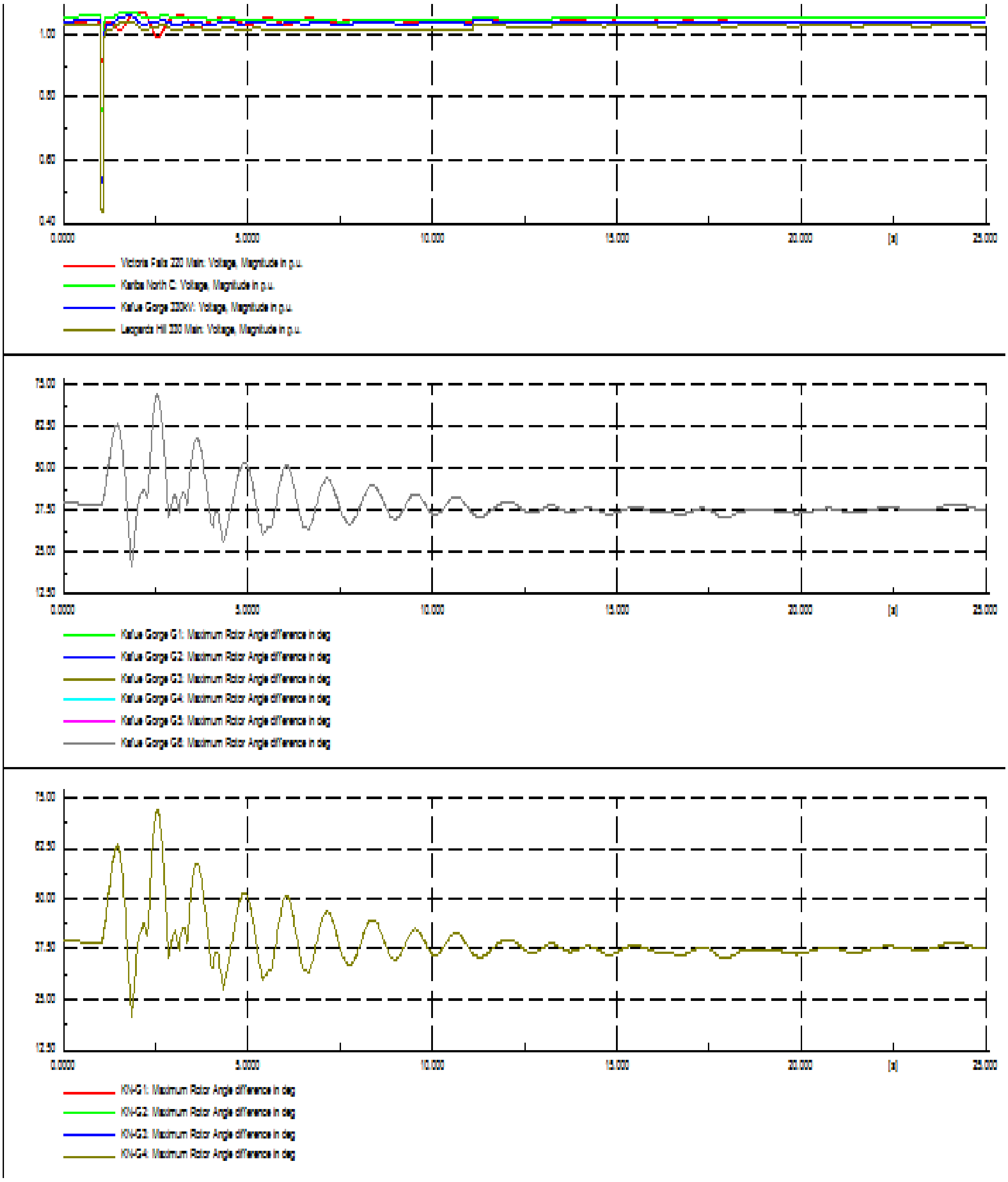


Figure 79: Kabwe-Kitwe auto reclosing

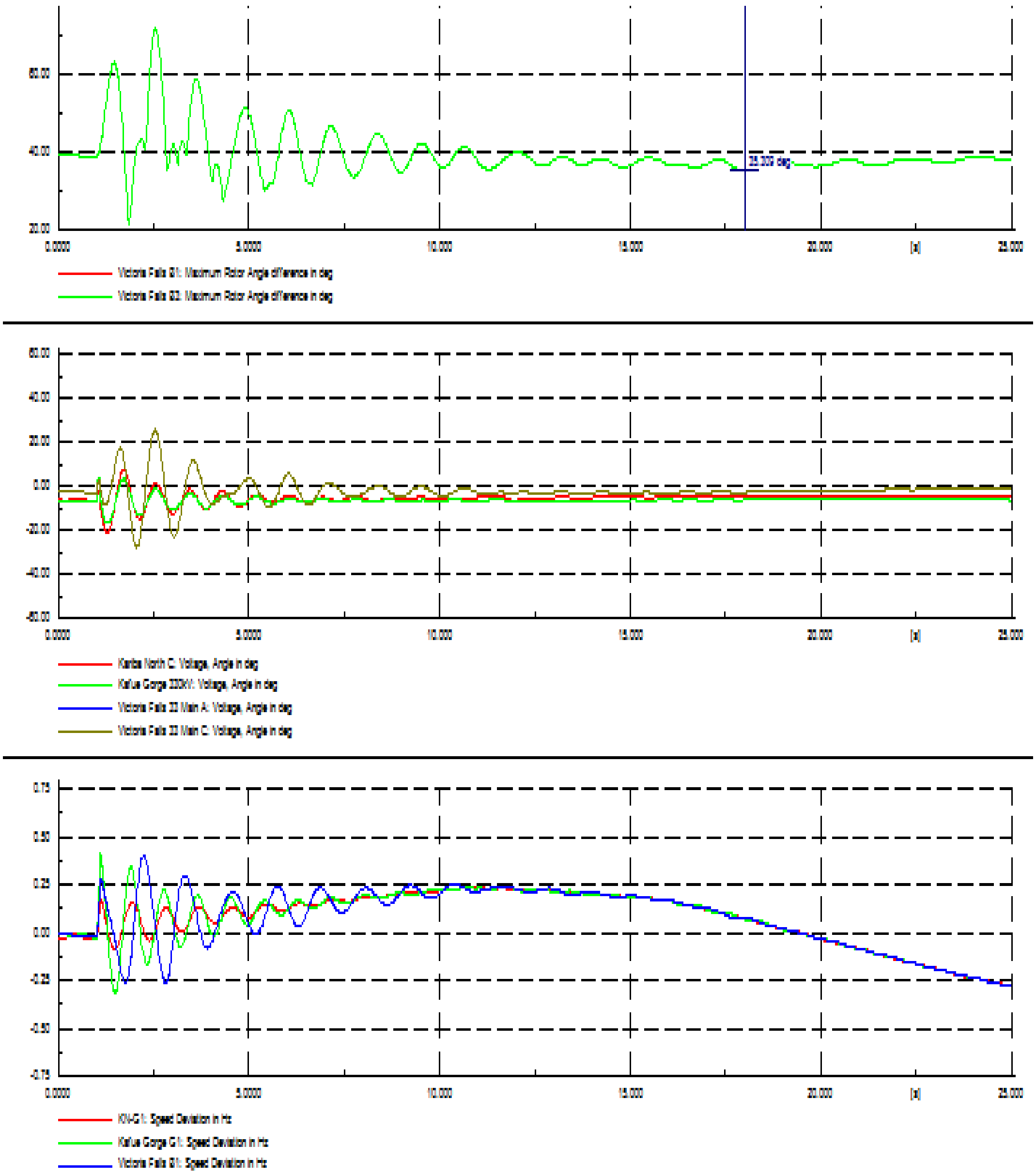


Figure 80: Kabwe-kitwe auto reclosing

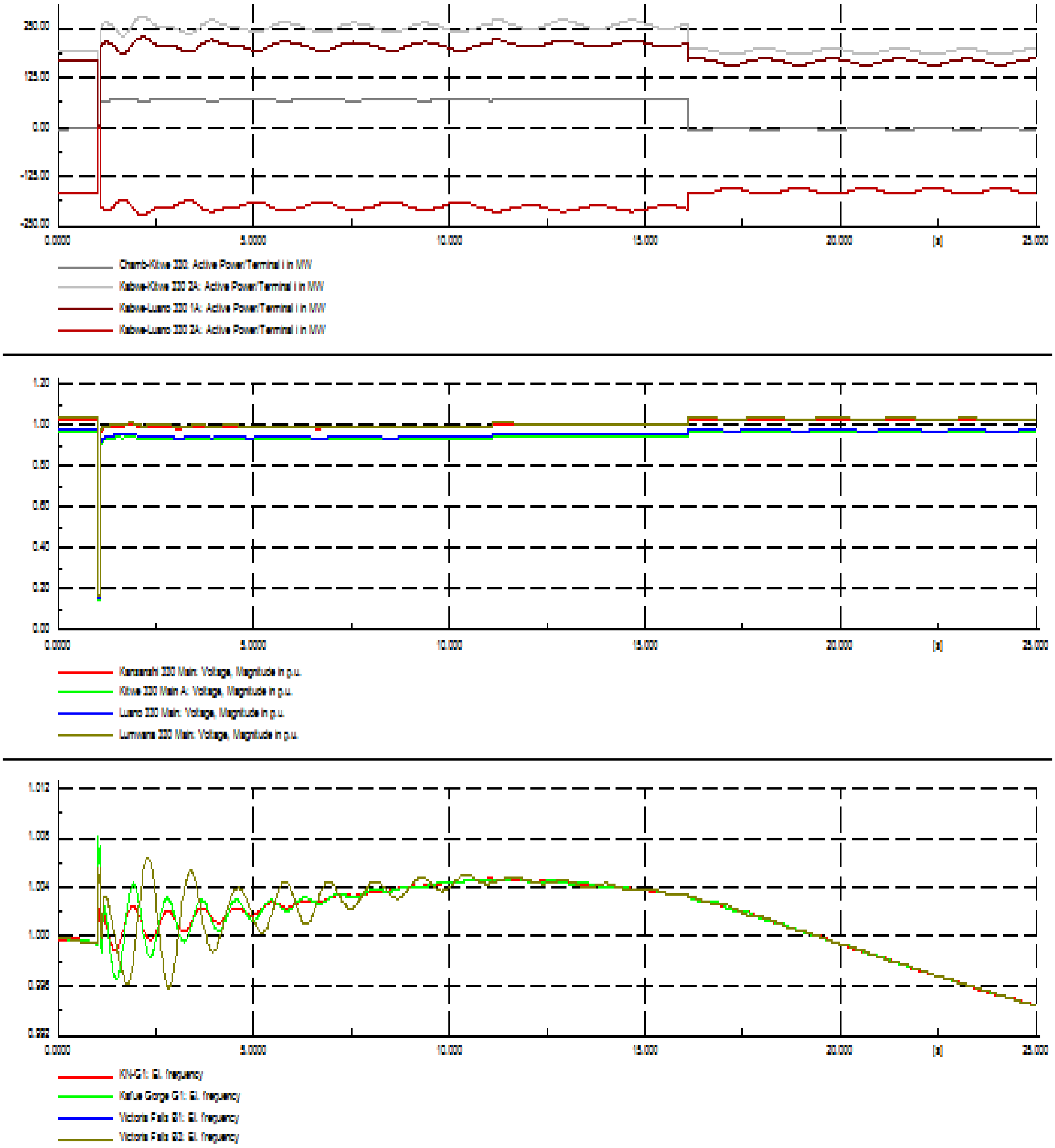


Figure 81: Kabwe –Kitwe line auto reclosing

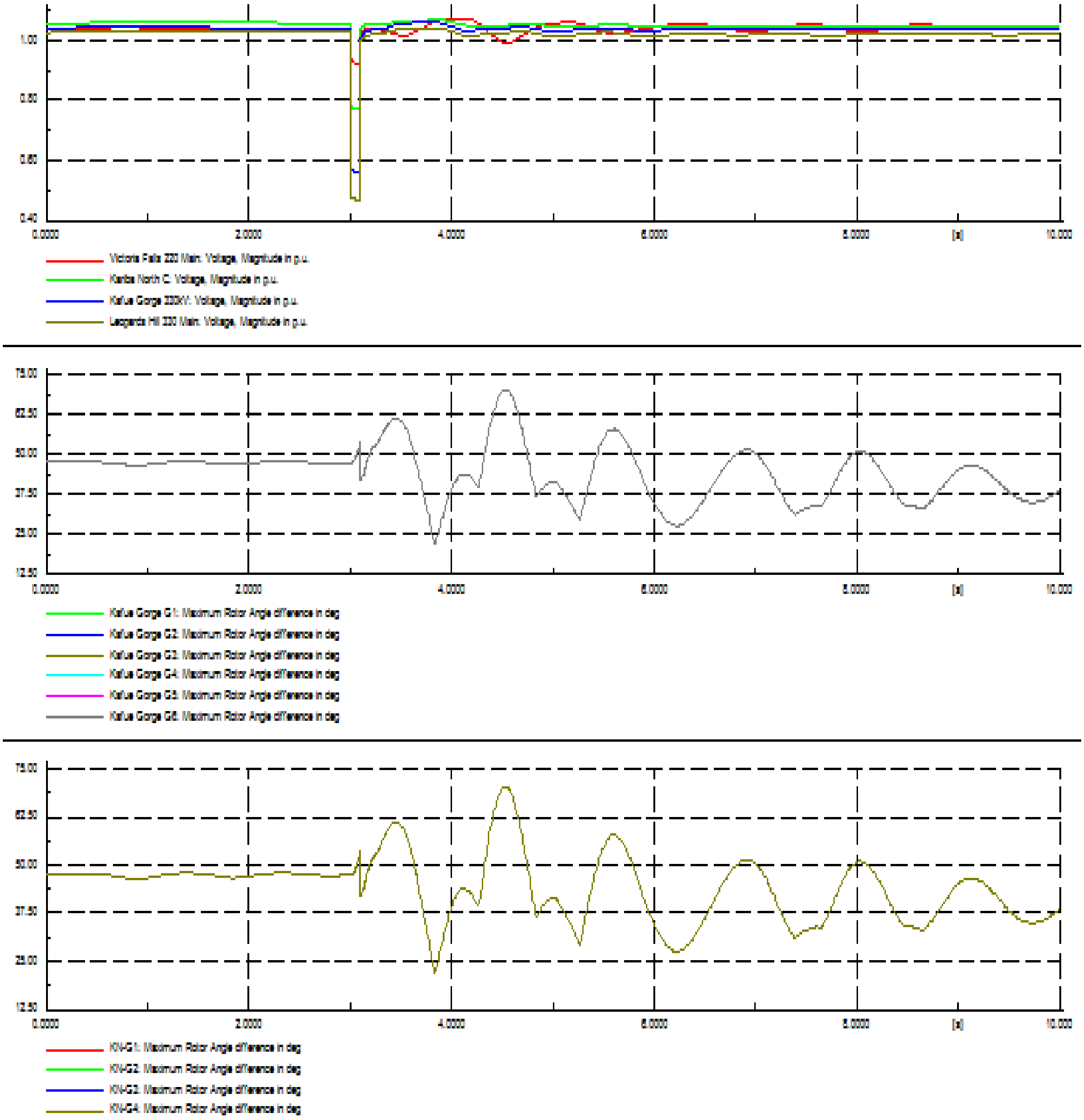


Figure 82: Fault on Kabwe pensulo line

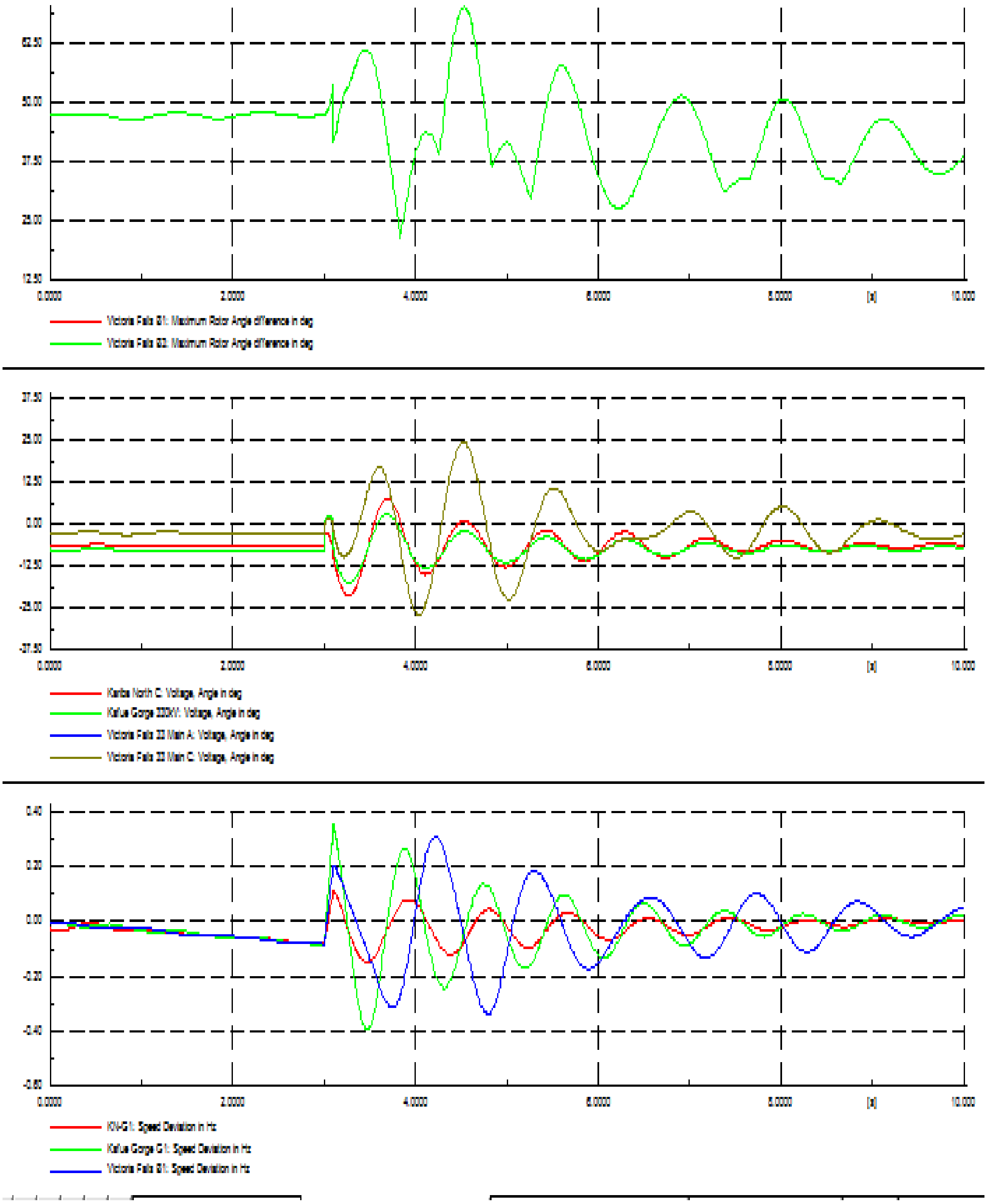


Figure 83: Kabwe-pensulo line fault

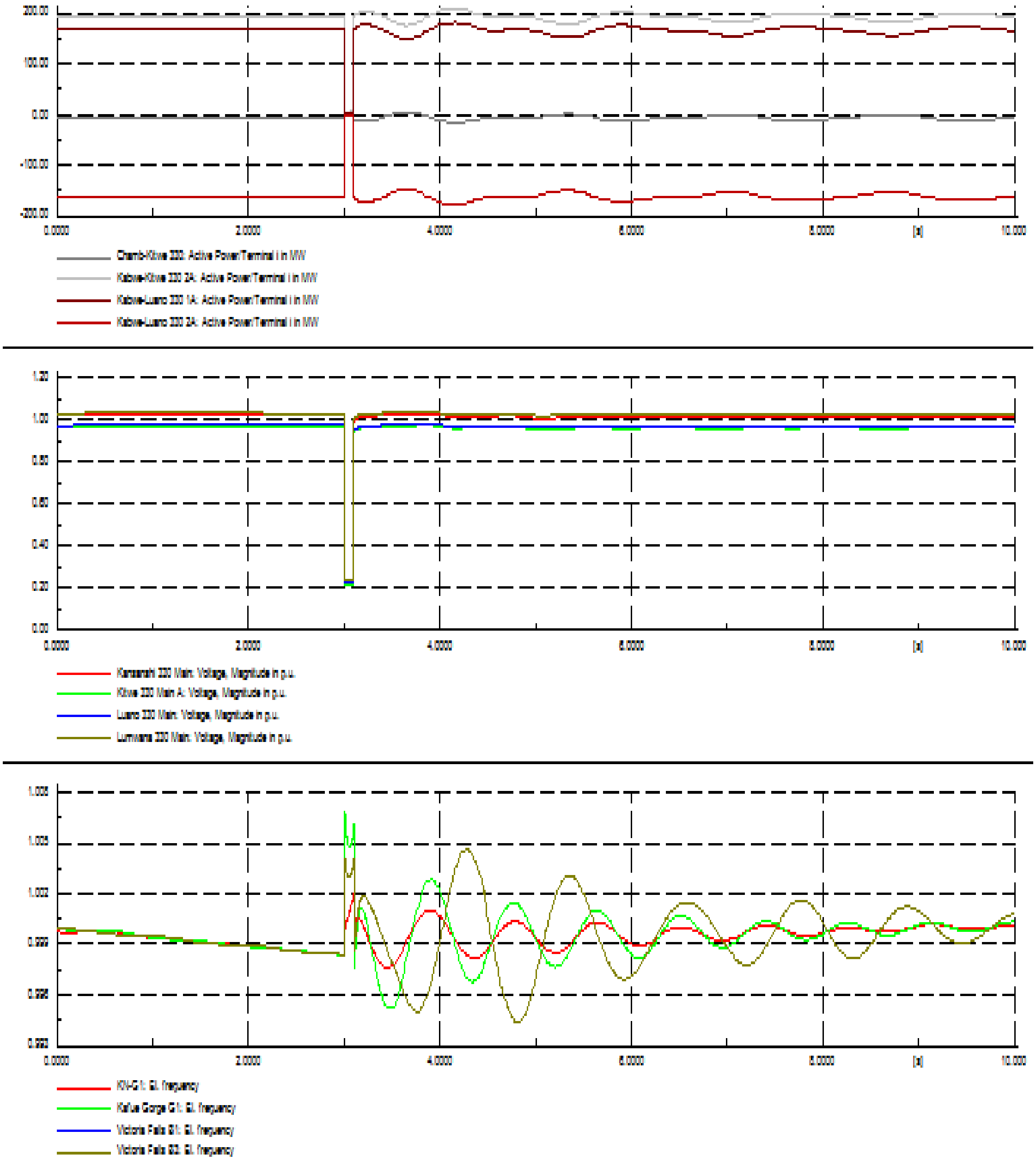


Figure 84: Kabwe-pensulo line fault

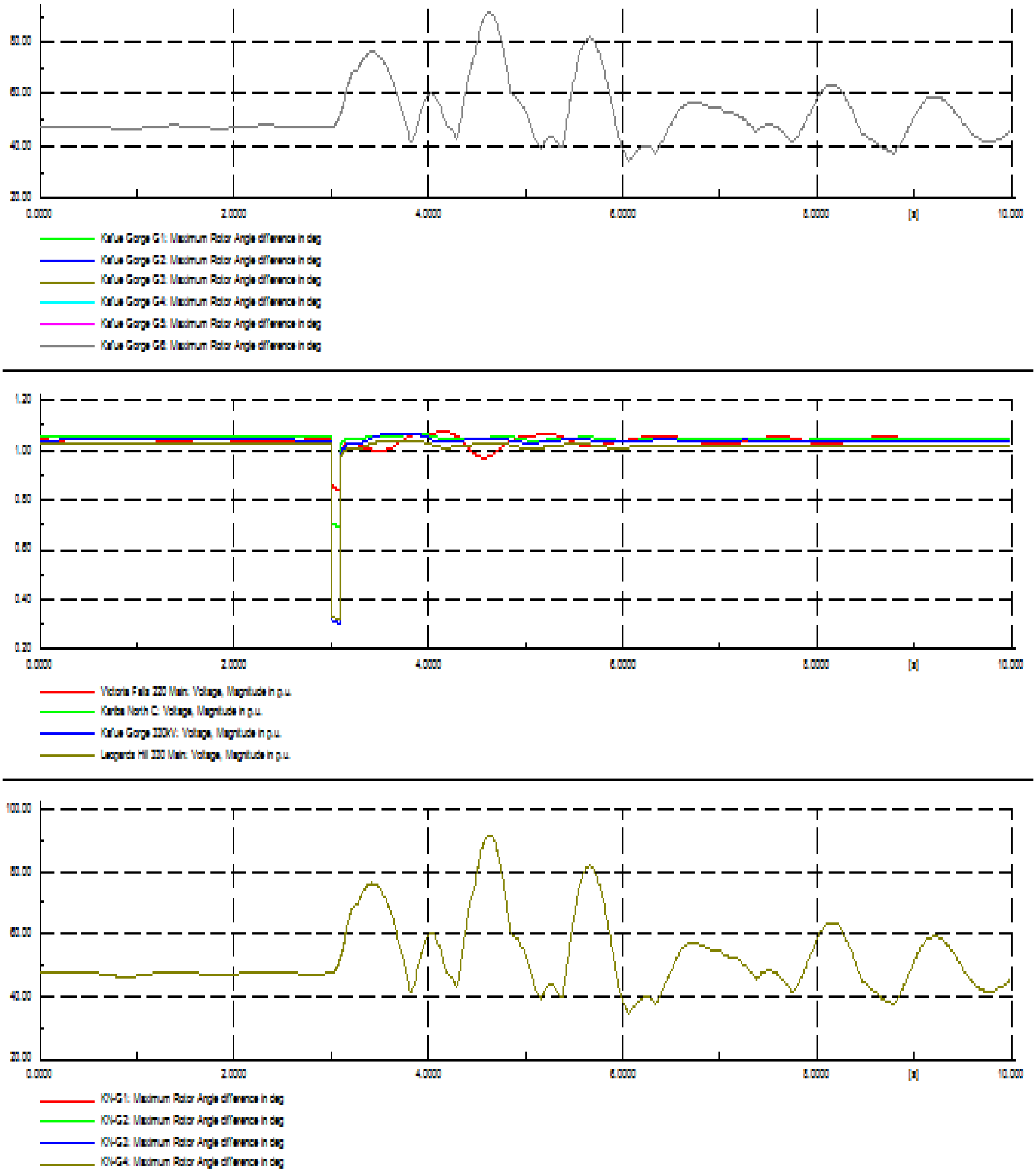


Figure 85: KFG-Kfue west fault (close to Kafue west)

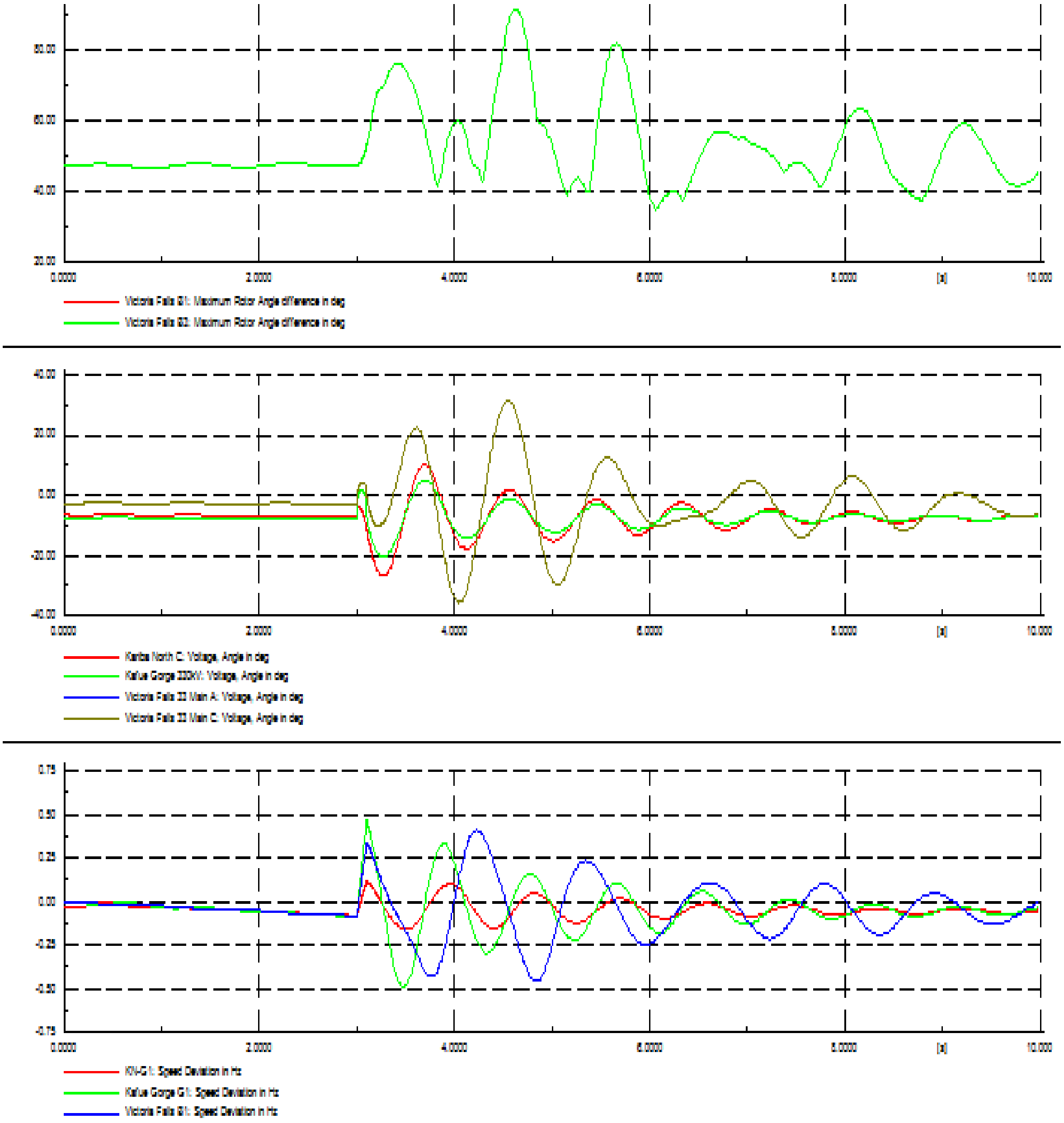


Figure 86: KFG-Kfwest line fault

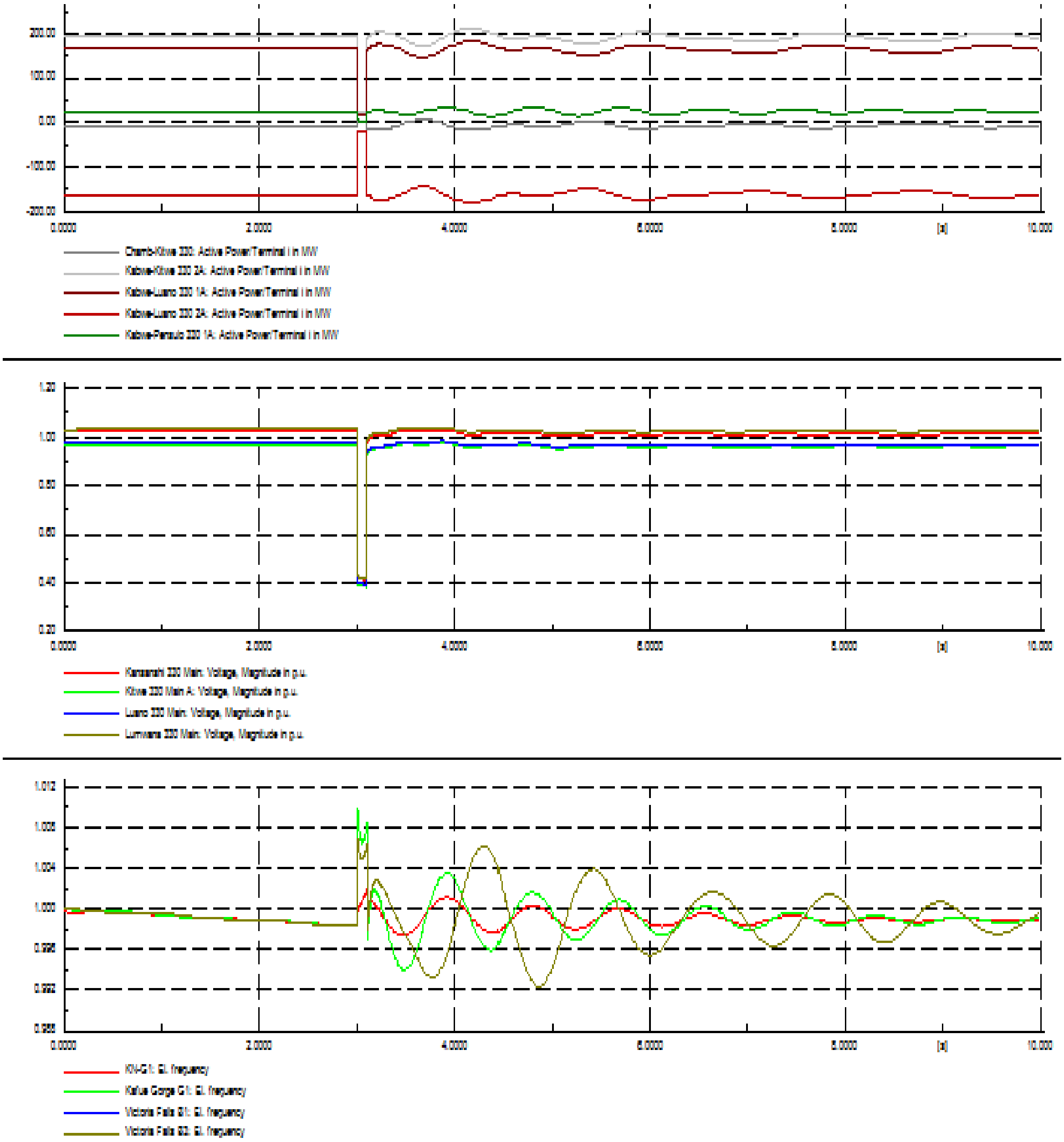


Figure 87: KFG-KFWest line fault

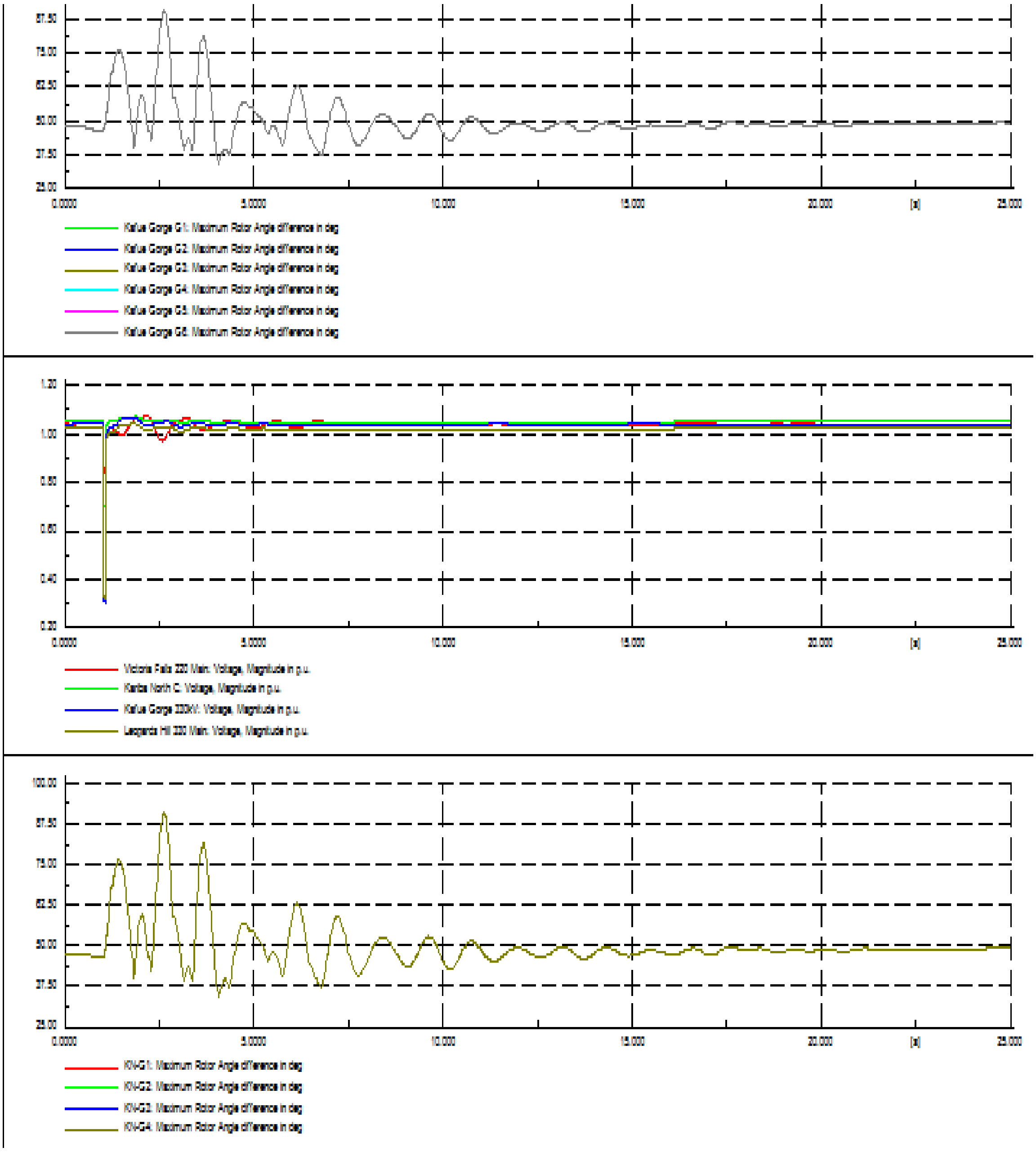


Figure 88: KFG-KFWest auto reclosing

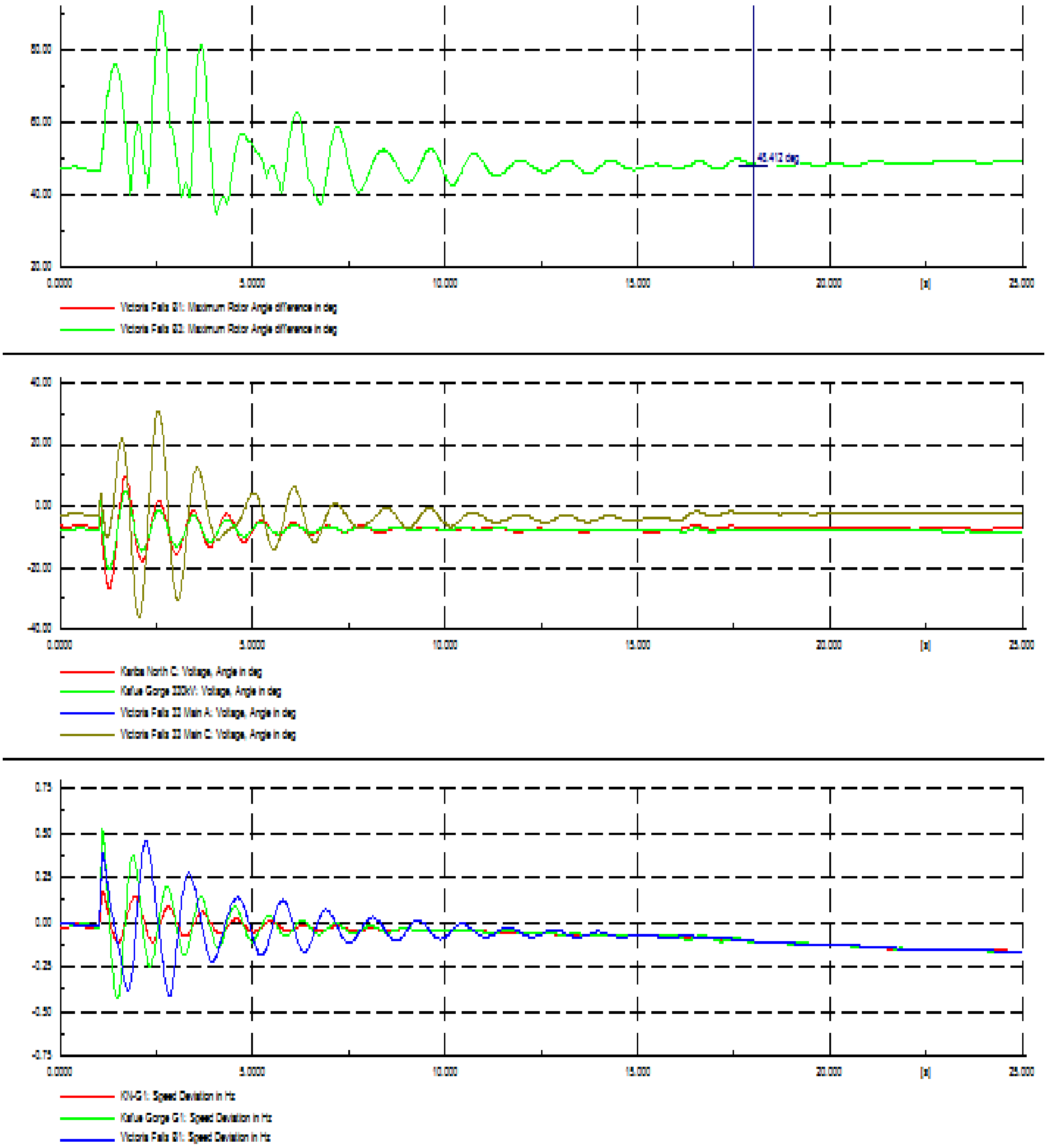


Figure 89: KFG-KFWEST line auto reclosing

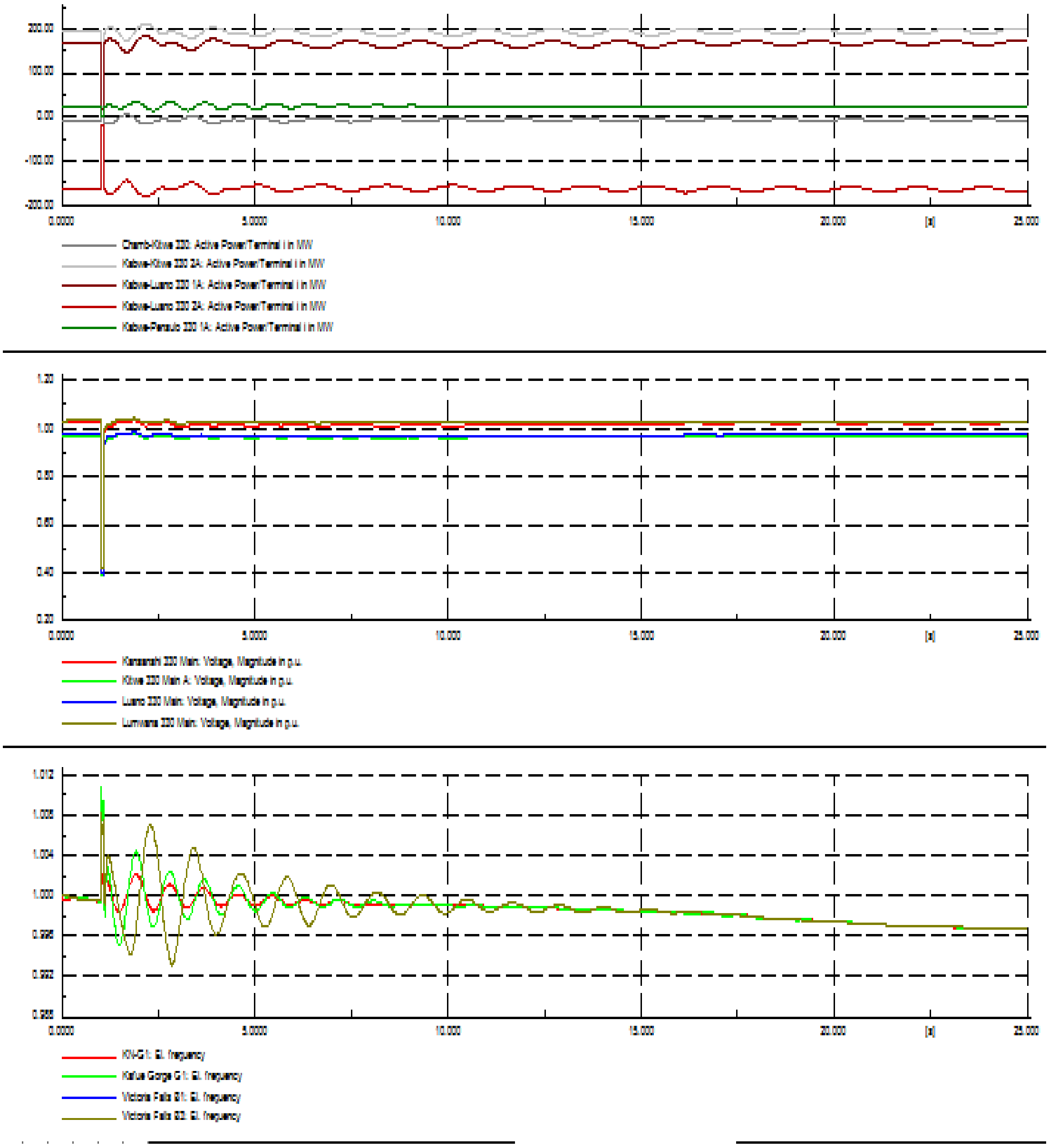


Figure 90: KFG-KFWest line auto reclosing

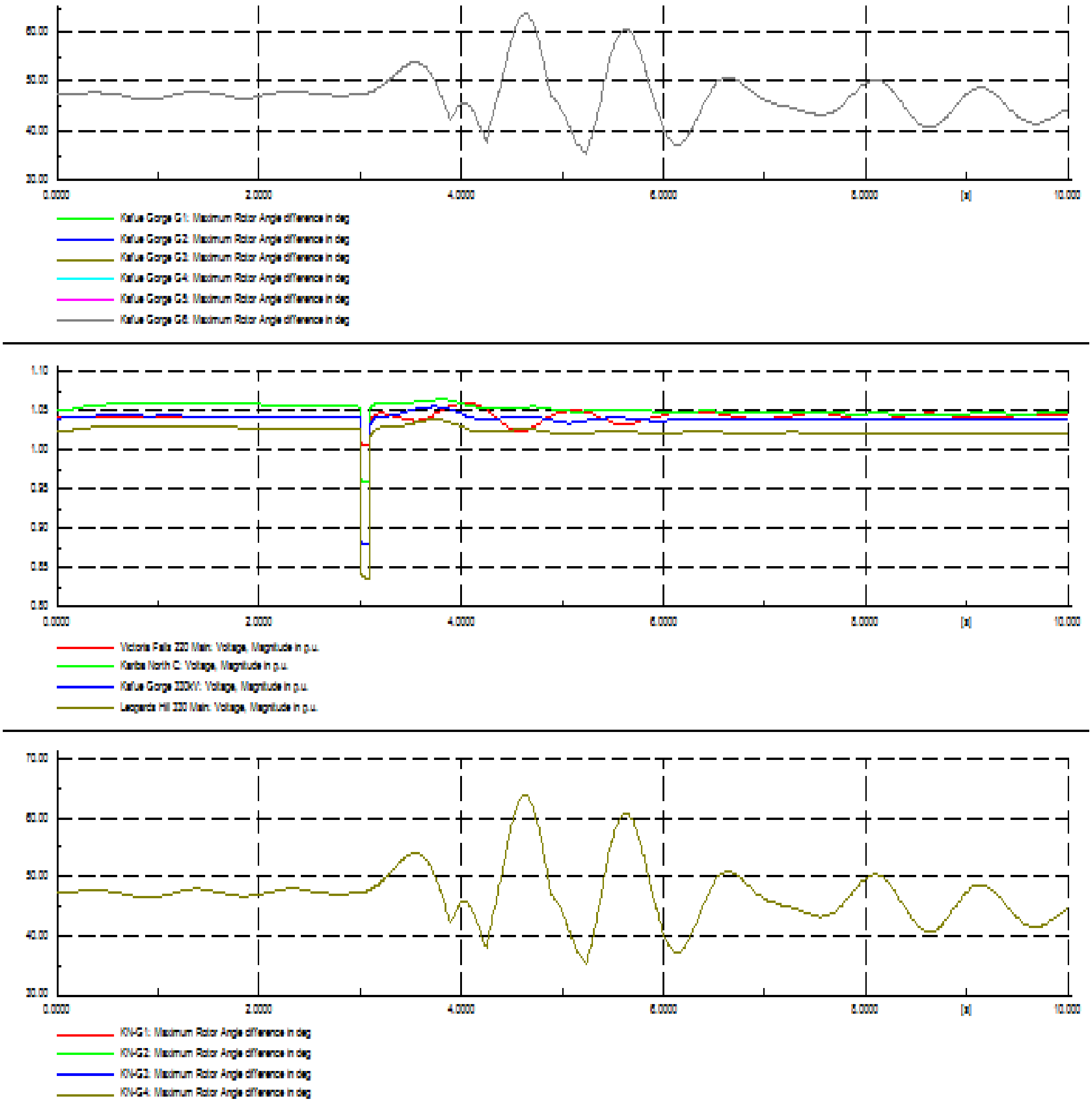


Figure 91: Fault on Luano-Kansanshi line

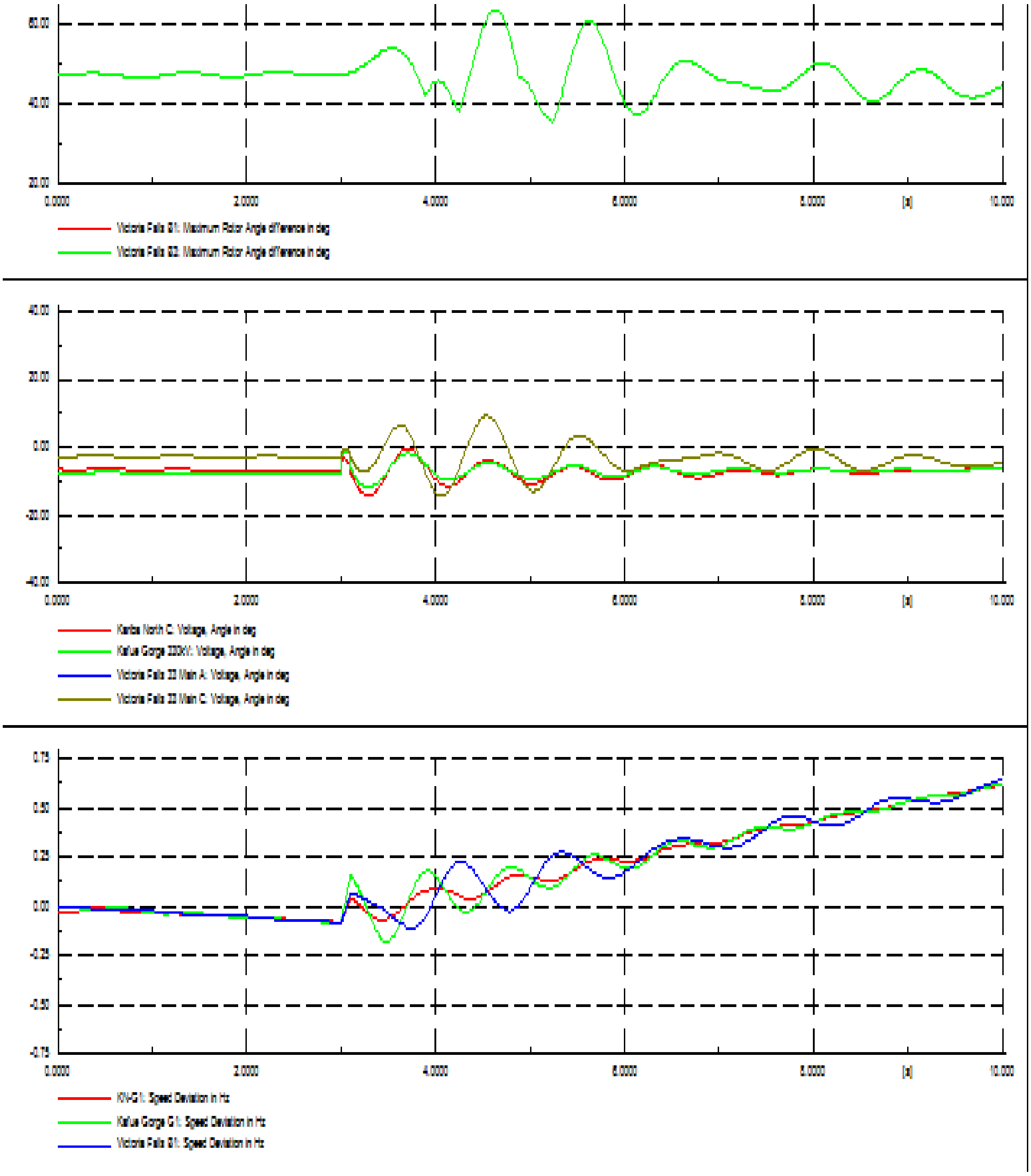


Figure 92: Fault on Luano-Kansahi line

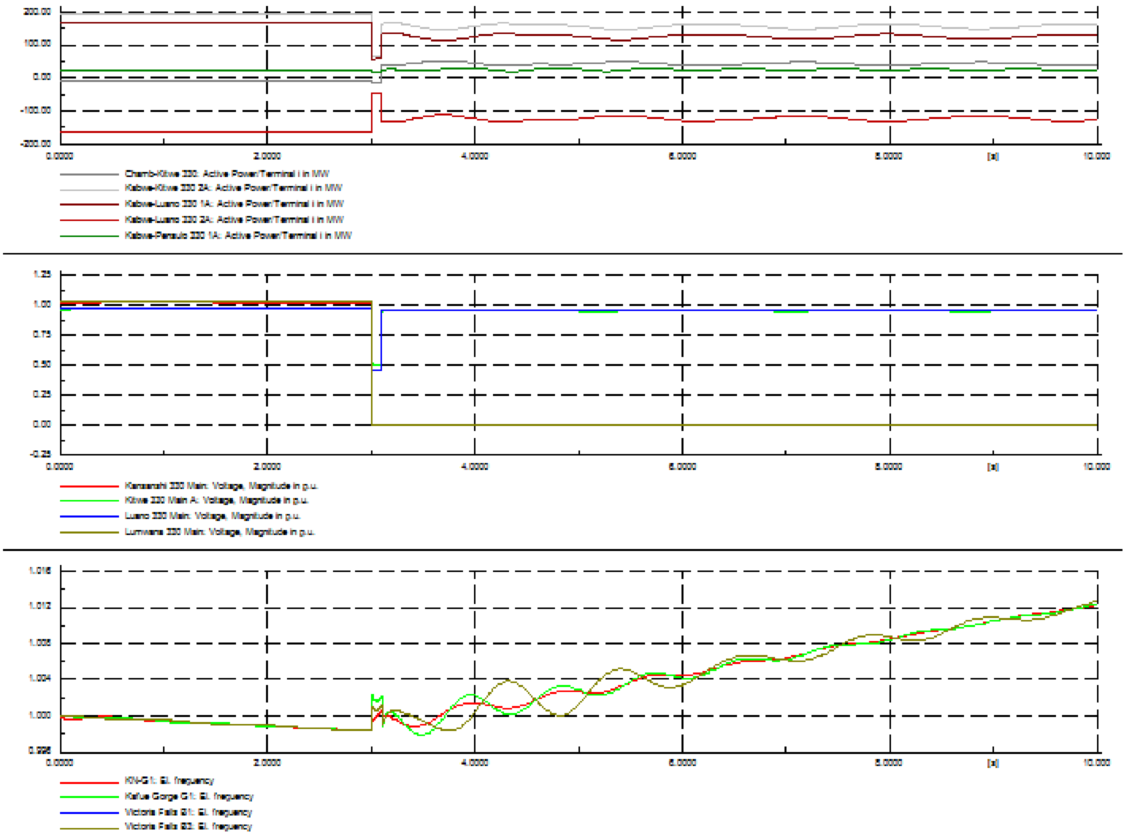


Figure 93: Fault on Luano Kansanshi line

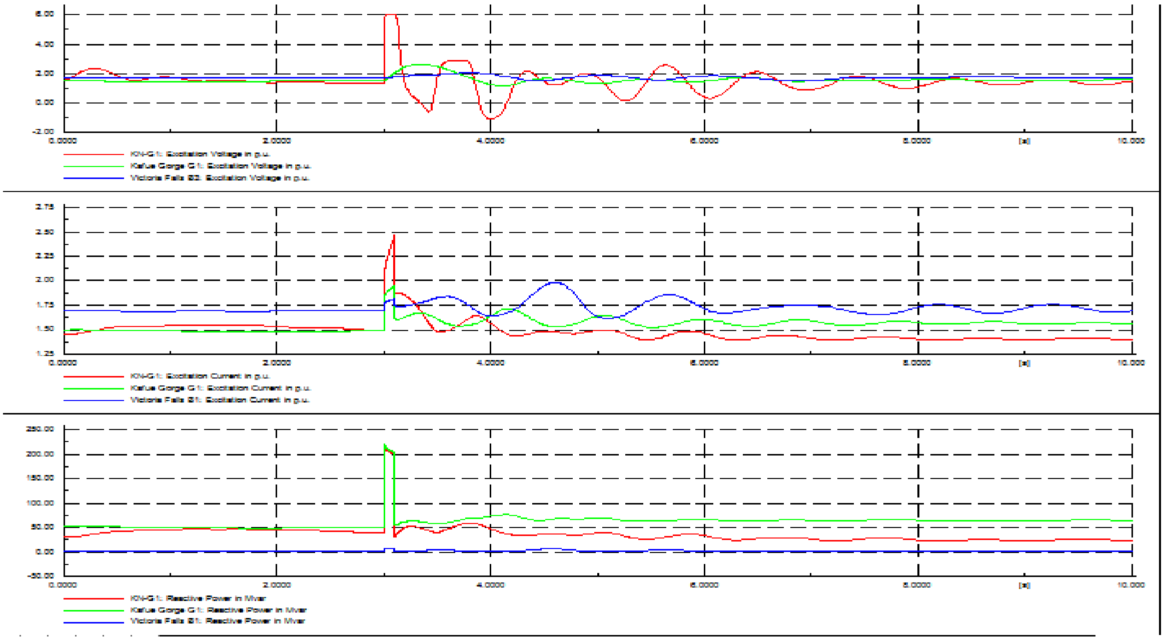


Figure 94: Reactive Power, Excitation Voltage and current of the Generating Machines for the fault close to KNBC HPP

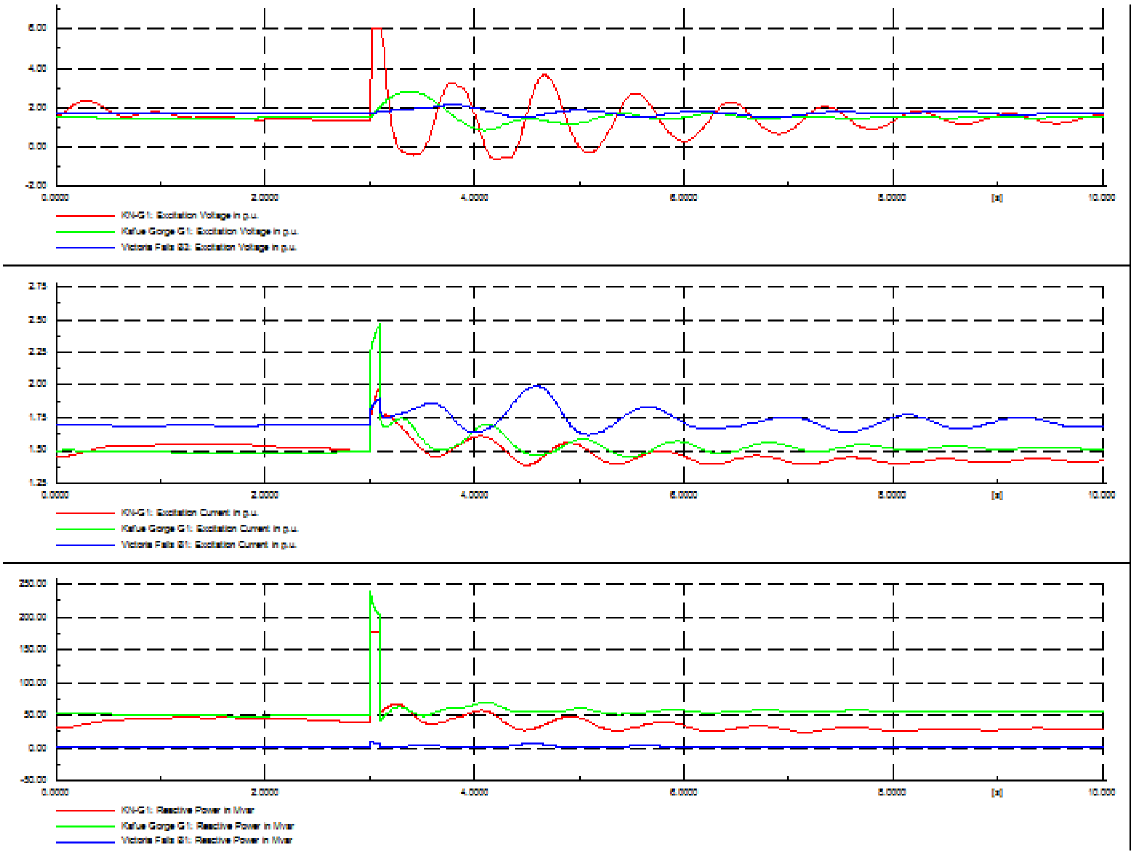


Figure 95: Reactive power, excitation voltage and current of the machines for a fault close to KFG HHP

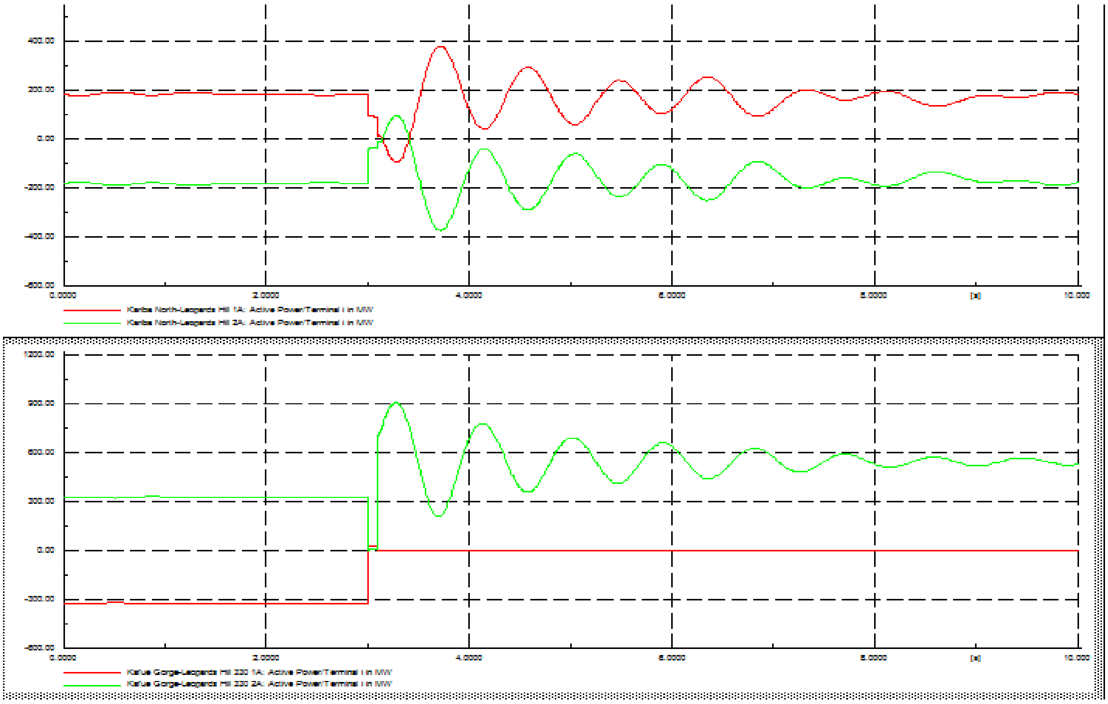


Figure 96: Power swing for a fault close to KFG HHP

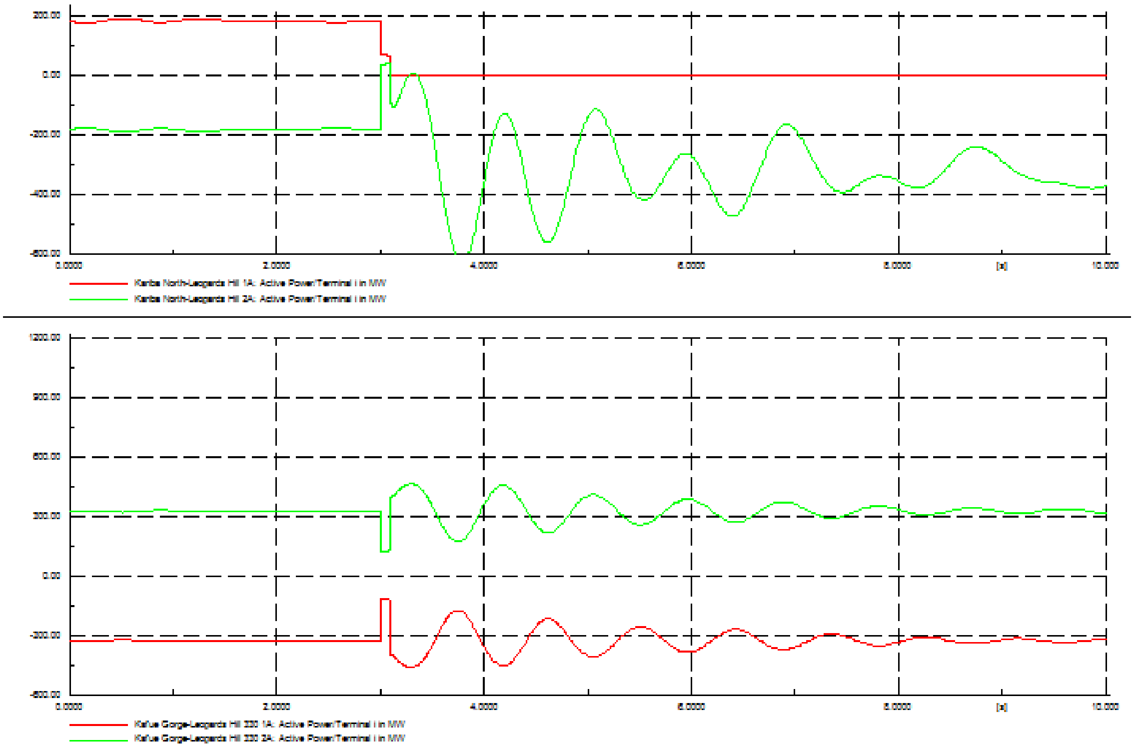


Figure 97: Power Swing for a fault close to KNBC HPP

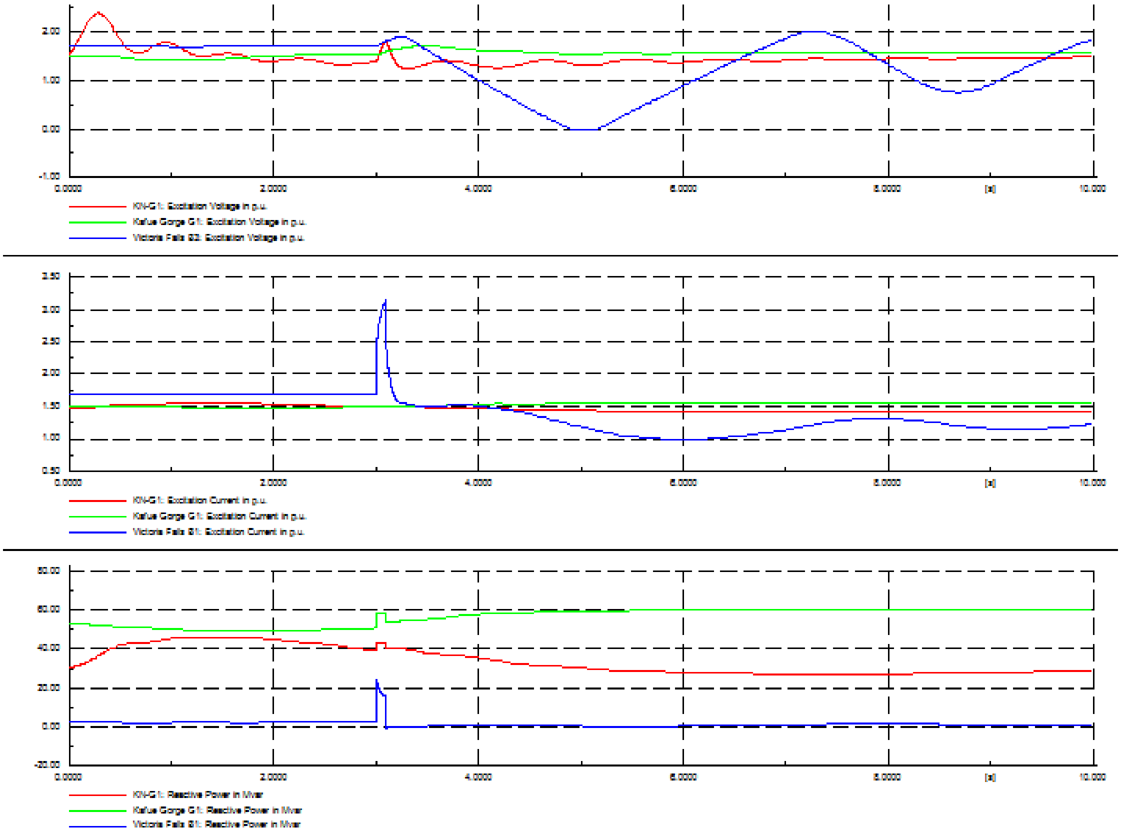


Figure 98: Excitation voltage after a fault close to Vic Falls

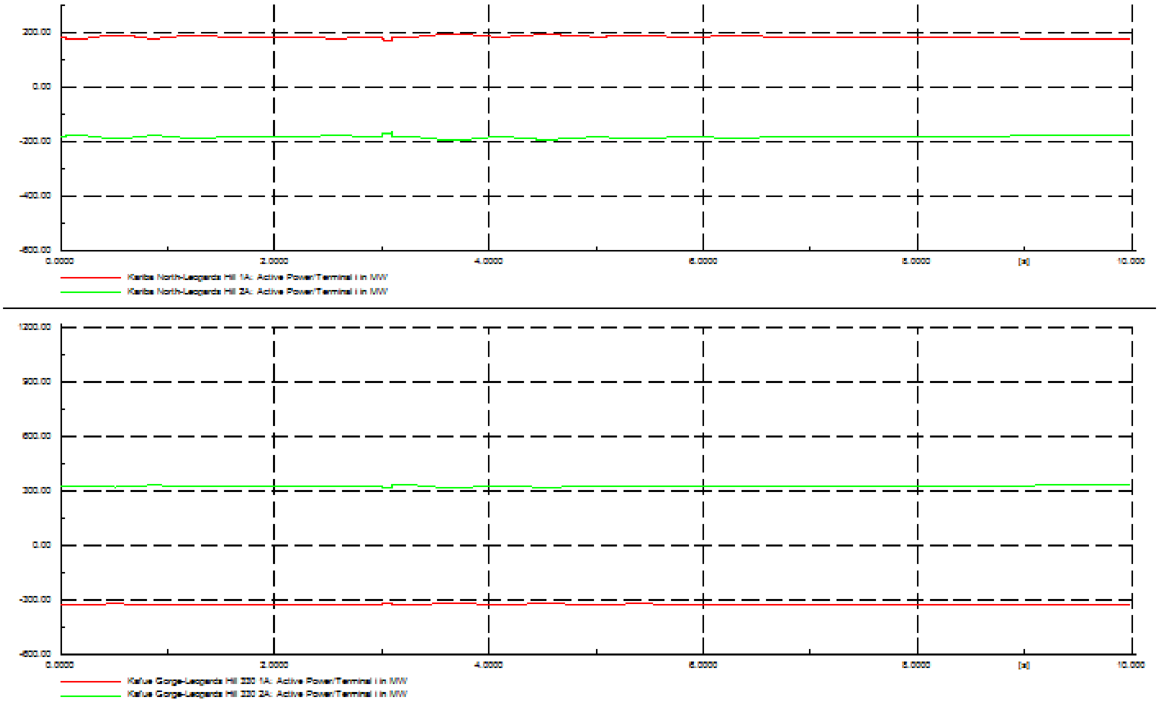


Figure 99: Power swing for a fault close to Vic. falls on Kariba HPP – Lhill Line and KFG HPP - LHill Line

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