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# INDIA – SRI-LANKA SUBMARINE CABLE INTERCONNECTION PROJECT

# INTERCONNECTION RELIBILITY AND STABILITY STUDY

## USAID SOUTH ASIA REGIONAL INITIATIVE FOR ENERGY (USAID SARI/ENERGY)

CONTRACT NUMBER 386-C-00-07-00033-00; TASK ORDER 1.3

October 12, 2009
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| Prepared for: | USAID/New Delhi<br>New Delhi, India |
| Prepared by: | PA Consulting Group<br>DLF Cyber City<br>Building 9B, 11th Floor<br>Gurgaon – 122 002<br>Haryana, India<br>Tel: 91 124 4737400<br>Fax: 91 124 4737444 |

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# Executive Summary

PA Consulting, the prime contractor of US AID has awarded the study of the frequency control and voltage control aspects of the Sri Lanka power system to Global energy consulting Engineers (P) Ltd., (GECE). The scope of the study comprises tuning aspects of the governors and automatic voltage regulators (AVRs), assessment of the frequency control and voltage control procedures adopted by the Ceylon Electricity Board (CEB) for the current and future power networks up to 2020. The study is to be carried out using the PSS/E (Power System Simulator for Engineering) software licensed by the CEB with the assistance of CEB engineers.

An Interim Technical Report giving the simulation results of 2008 base case power system study has been submitted along with the recommendations in June 2009. A presentation has also been made in Colombo. Subsequently, studies have been carried out on the frequency and voltage control aspects of the planned power system scenarios for 2012, 2016 and 2020. The GECE consultants have visited Colombo several times and had detailed discussions with the CEB engineers. CEB have supplied the power system data as well as the dynamic model data. The simulation studies using PSS/E have been carried out CEB engineers when the consultants were in Colombo and after wards with regular communication through e-mail.

The present report is the final report highlighting the simulation studies, analysis and the recommendations for the CEB power system up to 2020.

The software adequacies and the training requirements have also been identified.

**Frequency Control**

The tuning aspects of the governor parameters has been studied by considering a small isolated power system with a hydro power plant, a thermal power plant, a combined cycle power plant and coal based power plant separately. The transient frequency variations for the trip of a large generating unit are used as the basis. The adjustable parameters have been varied and the response curves have been studied to see the effect of parametric changes. Tuning of gains has also been studied using a Simulink model separately. Guidelines for the tuning of governor parameters have been given based on the above studies and on the experience gained in Indian power stations.

Disturbances like sudden generator trip are simulated on the peak load and off peak load base cases of 2008, 2012, 2016 and 2020 power system scenarios, considering the power system as a whole. The simulation has been repeated for various conditions like governor-free operation of all generating units, inoperative governors and with only Victoria hydro machines participating in frequency control. The frequency trends are analyzed.

For any disturbance involving generation and load mismatch, frequency changes and settles down at a different value due to the governor droops under primary regulation. To restore frequency back to the rated value, secondary regulation is required to adjust the generation set points of the governors automatically. The Load Frequency Controller (LFC) which is part of the Automatic Generation Control (AGC) system is required for the secondary control. It can be implemented as part of the Energy Management system (EMS).

The simulation study is based generally on the dynamic data provided in the PSS/E program by CEB according to the data verification carried out by the JICA study team in 2005. Wherever data is inconsistent or unavailable suitable values have been taken.

**Voltage Control**

The voltage control aspects of the CEB power system has been studied considering the entire base case power system data for 2008, 2012, 2016 and 2020 scenarios. Disturbances like three phase fault, generator trip, and sudden load change have been simulated on various 220 kV and 132 kV lines and the variations in voltages, power flows, and rotor angles at various buses have been studied by simulating using PSS/E. The effects of parametric changes in AVR have been studied. The existing practice of Voltage Control has been reviewed through discussions with the policy-making engineers of CEB and also by simulation study.

Study of reactive power management is conducted with orientation towards VAR Scheduling for the combined operation of Generator AVR and Grid Transformer Tap-Control (GTTC) and the suitability of present practice adopted has been checked using PSS/E software with the assistance of trained staff of CEB.

Further simulation studies will be carried out on voltage control strategies (VAR scheduling), with combined operation of AVRs of individual generators and GTTCs, following a typical disturbances. Based on the simulation study, it is proposed to suggest recommendations on suitable settings for the AVRs of individual generators.

The effects of automatic voltage regulator (AVR) parameters like amplifier gain, stabilization loop gain etc., have been studied on the selected generator models using Simulink program.

The use of power system stabilizers (PSS) with generating units for excitation control is well established as a means of improving the damping in the system. Power system stabilizers (PSS) are auxiliary feedback controllers which receive a signal from rotor velocity, frequency or accelerating power and provide a corrective input to the excitation system in order to damp out the oscillations in the system. An approach for the design of PSS applicable to CEB power system is presented in the Report.

Static Var Compensator (SVC) provides fast acting dynamic reactive compensation for voltage support during contingencies. SVC also aids in dampening the power swings and reduces system losses by optimized reactive power control. The power System stability can also be improved by incorporating SVCs. A methodology has been presented on the design of static var compensators for CEB power system.

**Recommendations**

With the governor parameters as provided for in the dynamic data base, the CEB power system does not exhibit any oscillatory tendencies for normal disturbances. The permanent droop value of 0.05 p.u (or 5%) generally followed is in line with the setting followed in many countries. The droop value reflects the relationship between power and frequency. For old power stations this value may not be the real value as the relationships change due to wear and tear. It is suggested that droop characteristic be plotted from measurements when a hydro power plant is commissioned after renovation and modernization. The tuning parameters as in the dynamic data give stable response. Guidelines for tuning in the parameters in case of changes at power station sites generally followed by various utilities are also given in the report.

The present practice of grid frequency control is to adjust the power output of hydro machines at Victoria by reducing the droop to 1.6% (from normal 5%) when the frequency tends to fall during peak hours. But, it is necessary to provide Automatic Generation Control (AGC)/Load Frequency Control (LFC) which adjusts the set points of participating machines automatically based on the frequency error or ‘area control error’ (ACE). It is recommended to include the AGC application program in the SCADA/Energy Management System (EMS) at the System Control Center. The AGC application program includes LFC, Economic Dispatch (ED) and Interchange Scheduling (IS) functions. As CEB has plans to add several Coal based thermal power plants, ED function will also be necessary. At present, the Sri Lanka power system is considered as a single control area. But after deregulation, in future the electricity network may be divided into many areas. IS function will be necessary for multi-area systems.

The effect of wind penetration on the power system operation is studied and simulation results are presented in the Report. It is observed that penetration level up to 10% does not pose problems for frequency control and voltage control with the system settings as included in the PSS/E program.

The settings of automatic voltage regulators (AVR) provided with various generators as in the PSS/E dynamic data have been reviewed and these values do not need to be changed. But it was noticed that different types of AVRs are used in the power stations and the mathematical model does not reflect these differences in the AVR design. So it is recommended that the AVR and excitation system parameters provided at the power stations be checked by suitable tests and measurements.

Extensive simulations runs have been carried out with various fault conditions to study the voltage transients. Though some oscillations are observed, system stability is not endangered. However, proper adjustment of power system stabilizer (PSS) parameters is necessary for providing adequate stability margins. Guidelines are given in the report for adjustment of the PSS parameters.

Static Var Compensation (SVC) has been recommended to improve the stability of the power system. The reactive power (VAR) scheduling aspects for various scenarios are also discussed in the final report.

**Training Requirements**

Presently there are only two engineers trained on PSS/E on limited aspects of power system planning. It is necessary to have 10 to 12 trained engineers trained on various aspects of power system studies using PSS/E and other well known programs.

Prior to the training on PSS/E a general appreciation course covering the theoretical aspects of the power system analysis is necessary and a proposal has been given in the report.

It is also recommended to carry out tests at power stations and other sites to ascertain the control system parameters for tuning the same optimally.

**Software Inadequacies**

The PSS/E is a popular program among the utilities world- wide. For the studies involving load flows etc., it is quite convenient. The PSS/MUST and TPLAN programs offered by Siemens will be quite valuable for transmission planning and calculation of electric transmission transfer capabilities and the impact of transactions and generator dispatch. Hence, it is recommended that CEB may procure PSS/MUST and TPLAN also. To take quick operational decisions, it is recommended that CEB may acquire Power World Simulator software.

The requests for wind power plant interconnection have to be analyzed in each case. CEB may need to additional license to incorporate different wind turbine models for studies requiring fault ride through capability etc.

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# FREQUENCY AND VOLTAGE CONTROL STUDY OF CEB POWER SYSTEM

## Final Report

## Chapter 1

## INTRODUCTION

Frequency and Voltage are the two important parameters affecting the quality of power supply systems. These are to be maintained within the specified range as all the electrical equipment is designed to perform efficiently for the specified voltage and frequency. Frequency variation indicates that there is mismatch in the active power generated and consumed. Voltage variation indicates that reactive power mismatch exists. Frequency variation is a system-wide phenomenon. Voltage variation depends on local and system wide reactive power matching.

The variations in frequency and voltage depend on the power system network and the control parameters. The control parameters have to be properly tuned for optimum performance from the system. Simulation techniques help in predicting the system response for large interconnected power systems for various values of tuning constants.

Global Energy Consulting Engineers (GECE) Hyderabad, has been entrusted the task of conducting a reliability study of the power system of Sri Lanka by the PA Government Services, Inc. under the USAID funded South Asia Regional Initiative for Energy (SARI/Energy) Program with the assistance of Ceylon Electricity Board (CEB), Colombo.

The objectives of the study are:

1. To suggest the most appropriate settings and modes of individual Turbine Governors and to study and review the current practice of Frequency Control and suggest the most suitable method of frequency control for the future power system until year 2020.

2. To suggest the most appropriate settings and modes of Automatic Voltage Regulators (AVR) of the individual Generator and to study and review the current practice of Voltage Control and suggest the most suitable method of voltage control for the future power system until year 2020.

3. To study the current practice of VAr Scheduling of the power system with the combine operation of Generator AVR and Grid Transformer Tap control and shall suggest the most suitable method of Voltage Control for the current and future power system until the year 2020.

4. i) To suggest how the frequency stability could be maintained with a higher proportion of non-centrally dispatched generators such as Wind power and Mini Hydro in the future system until the year 2020.
   ii) To suggest a proportion to be imposed to non-centrally dispatched power generators such as wind and Mini Hydro.

iii) To recommend the appropriate method to maintain the frequency stability under normal conditions with a higher proportion of non-centrally dispatched generators.

GECE consultants visited CEB offices several times and had detailed discussions with the CEB engineers. Basic data required for the study has been provided by the CEB. In the first phase, study of the 2008 base case power system study has been completed using Siemens-PTI's Power system Simulator for Engineering (PSS/E) program available with CEB with the assistance of CEB engineers and the study results are presented in this Interim report. A presentation has also been made in Colombo on the recommendations given in the Interim report.

Subsequently, the base case scenarios of the power system for the years 2012, 2016 and 2020 have been considered for the simulation study. Several coal based thermal power plants are planned to be included in future. Mathematical models appropriate to the coal based power plants of 285 MW and 300 MW have been included in the simulation program. The variations in frequency and voltage for the upset conditions like trip of a large generating unit are obtained from the PSS/E simulation.

Wind power plants are also being planned in a big way. The effect of wind penetration on the frequency and voltage variations is simulated using the GE 1.5 MW wind turbine models available in the PSS/E program.

The stability of the power system can be improved by incorporating Power System Stabilizers in the excitation control systems. The parameters in the PSS have to be properly tuned. An approach for tuning of the PSS is given in the Report.

Static Var compensation helps in maintaining the voltage stability in the event of occurrence of faults in the system. An approach for the SVC incorporation is given in the Report.

Based on the simulation study and the experiences of the GECE consultants, recommendations are given for the safe reliable operation of the power system with regard to frequency control and voltage control.

# Chapter 2

## CEB POWER SYSTEM: SALIENT FEATURES

The electricity demand in Sri Lanka is growing at the rate 7-8%. Sri Lanka has ambitious plan to increase power generation capacity in the next few years. By 2012, installed capacity in the CEB power system is expected to increase to 3547 MW from 2138 MW in 2008. Installed capacity will further increase to 3857.8 MW in 2016 and will be close to 500 MW in 2020.

The share of power generation by CEB in 2008 is 58% of which 37% is from hydro power sources and 21% is by thermal. The balance 42% is by private power producers (PPP). There are many small hydro power plants in private sector contributing about 4% of total generation.

The major hydro power stations are located in Laxapana Complex (5 stations) and Mahaweli complex (6 stations). Mahaweli system is of multipurpose nature with power and irrigation components.

The thermal power generation consists of diesel power stations, gas turbine and combined cycle power plants. The major gas turbines are at Kelanitissa power station and diesel power stations are at Sapugaskanda. As Kerawallpittiya gas turbine based combined cycle power plants of 2 X 90 MW and 2 X 135 MW capacity are planned to be added by 2010.

Several coal based thermal power plants will be coming up at Puttalam (3 X 285 MW) and Trincomalee (3 X 250 MW). Nearly SIX coal power plants of 300 MW capacity are planned in East Coast and West Coast.

CEB has a wind power plant of 3 MW capacity at Hambanatota. There are 5 wind turbines of 600KW capacity. There are several proposals for wind power plants of higher capacity. The Ceylon Electricity Board has signed Letters of Intent with four commercial developers to build 34 megawatts of wind power in the Island's west coast.

The CEB transmission system is at 220 KV and 132 KV level and the distribution is at 33/11 kV level. The generating stations of CEB and IPPs are connected to the transmission system. In 1997, the Japan International Cooperation Agency (JICA) drew up a “Master Plan for the Development of a National Transmission Network" in which a development plan for 2015 was suggested.

The System Control Center (SCC) for the CEB power system is located at Dematagoda in Colombo manages the operation of both 220 kV and 132 kV transmission systems of CEB. The main duties of SCC are load dispatching and network managing. The daily schedule of generation and dispatch of power to meet the system demand is done in the most economical manner. The SCADA system with the Master station at the System Control Center is the Micro SCADA system supplied by ABB. There are plans to upgrade the System Control Center by incorporating modern SCADA and energy Management System.

The nominal frequency in Sri Lanka is 50 Hz. Under normal conditions frequency should be controlled within the limits of 49.5 Hz – 50.5 Hz (i.e. ±1%). The system frequency control is done manually. Whenever grid frequency tends to fall, generation at Victoria hydro power station is increased. If the frequency still falls, load shedding will be resorted too.

The system voltage at 132 KV is monitored during peak load times in the morning and night voltage falls. The system control center takes steps to add capacitors so that voltage builds up.

A coal fired power project of 1000 MW of power at Trincomalee by the CEB in collaboration with the National Thermal Power Corporation (NTPC) of India is also on the anvil.

Under South Asian regional Initiative (SARI) program of USAID, the concept of an Indo-Sri Lanka Power Transmission Grid Inter-connection is being explored which when completed will contribute significantly towards easing Sri Lanka's energy crisis.

# CHAPTER 3

# STUDY APPROACH

## 3.1 Introduction

The approach followed by the GECE consultants to carry out the frequency and voltage control study of the CEB power system is highlighted in this chapter.

## 3.2 Familiarization of CEB Power System

The GECE consultants have got familiarized with the CEB power system by studying various CEB reports and documents made available like JICA master plan study reports, REED reports etc., and several useful discussions were held with the Planning engineers and the System Control engineers. Several visits were made to Colombo offices and regular correspondence was there through e-mail.

Visits were made to system Control Center, substations and combined cycle power station at Kelanitissa.

## 3.3 PSS/E program and data

The GECE consultants have also been familiarized with PSS/E program licensed by CEB from Siemens which is quite popular among utilities.

Based on the simulation guidelines given by GECE consultants, CEB engineers have carried out the PSS/E simulation study and made available the results provided in this report. Based on the analysis and interpretation, results were carried out.

Load flow analysis is the PSS/E basic activity carried out by PSS/E. The power system network data as per 2008 scenario was already built-in and CEB engineers have been carrying out regular planning studies using PSS/E.

To study the frequency and voltage control aspects, dynamic simulation activity of PSS/E is required. The mathematical models of various components of power system along with data have been incorporated by CEB and were supposed to have been checked by the JICA study team in 2005.

Certain discrepancies noted have been removed. Some parameters like water inertia time whose precise values are not known were given default values.

## 3.4 Simulation Methodology

In the PSS/E program, a small isolated system with generators and loads are created around a power generating station and various disturbances like sudden load change, fault on a transmission line, one generating unit failure in a multi-unit power station etc.

The affect of varying governor gains on the frequency variation is studied and optimum values for the governor adjustable gains like temporary droop and recovery time of hydro are obtained.

The analysis is carried out for hydro stations, thermal station, combined cycle power plant and coal based thermal power plants.

As data was not available in the PSS/E program of CEB, typical data for 250 MW/ 300 MW available with GECE consultants has been incorporated. In India, several 250 MW power plants are set up.

After simulating the isolated power systems (around a plant), combined power system has been considered for simulation. The frequency behavior of the power system has been simulated by creating disturbances like generator trip and sudden load change.

The frequency variation for disturbance like load change, short circuit or generator trip depends on the total interconnected system inertia (including that of loads). Typical disturbances are created in the Dynamic Simulation program of PSS/E and the power system frequency transients are studied. The effect of frequency control by the spinning reserve unit at Victoria power station is simulated. The effect of varying governor parameters at select locations is observed and optimum adjustment criteria were obtained. The participation in the restoration process by CEB's hydro and thermal generating units and the IPP's power generating units is also studied.

To estimate the grid composite inertia, disturbances are created without individual governor actions and the frequency variation for step load disturbance was used to estimate the system inertia value and the self-regulation characteristic.

### 3.5 Simulation Using MATLAB/SIMULINK

To study the tuning aspects of governors and AVRs, mathematical models have been created using MATLAB/ SIMULINK for hydro power plant, combined cycle power plant and single machine infinite bus power system. Simulation of load change is carried out and frequency variation and voltage variation have been obtained for various values of governor gains and AVR gains.

The generating units and their governors are represented in a composite fashion. The hydro power plants are simulated with one equivalent hydro turbine governor. The thermal power plants are simulated by an equivalent model. The load frequency control is simulated on the Automatic Generation Control (AGC) model. A single load model is considered on the composite system.

### 3.6 Analytical Approach

Approach for Power System Stabilizer design and Static Var Compensation design has been prepared based on the research carried out by the GECE consultants and the published articles.

Similarly wind penetration study has been carried out based on the extensive study of published papers.

# Chapter 4

# FREQUENCY CONTROL: SIMULATION STUDY

## 4.1 Introduction

Frequency varies when the active power (MW) balance is disturbed due to change in the connected load or the generation. Under normal conditions, load varies throughout the day and night. There will be small variations in the frequency and automatic correction takes place due to the action of governors. When large disturbances occur like trip of a turbine-generator or the trip of a transmission line connecting various loads frequency falls or rises suddenly.

The ‘frequency stability’ depends upon the rotating inertias of the generators and rotating loads (or the aggregate inertia) and the settings of the governors of individual turbine governors.

The transient variation in frequency for various power system scenarios can be obtained based on simulation of the detailed power system mathematical model.

CEB power system model has been simulated using the PSS/E program by CEB engineers. The simulation results are analyzed in this chapter. The base cases of 2008, 2012, 2016 and 2020 are considered for various peak loads and off peak loads.

## 4.2 Frequency behavior of CEB power system: 2008 base case

**<u>Thermal Maximum Night peak</u>**

The load on the power system for thermal night peak (THNP) for 2008 base case is 1910 MW. The installed capacity is 2138.3 MW. The largest generating unit for 2008 case is gas turbine GT-7 of 115 MW capacity.

The worst disturbance can be the trip of GT-7. The trip of GT-7 has been simulated for the load condition of thermal maximum night peak and the frequency variation is shown in Fig 4.1 as obtained from the PSS/E simulation study.

When there is a disturbance like GT-7 trip, frequency started falling and with governors in action the power outputs have increased and frequency fall is arrested. When the generation matches with the new load frequency settles down at the corresponding value of frequency which is lower than the operating frequency.

The frequency characteristic of the CEB power system is given by the variation in frequency when all the governors are out of action. The Victoria hydro power plant generating 72 MW is suddenly tripped when the load on the 2008 base case power system is 1910 MW. As shown in Fig 4.2, the system frequency falls to 2% (i.e., 1 Hz) below the rated frequency for a generation change of 3.8%. The system frequency characteristic is 3.8% (MW/Hz).

Additional simulation results of 2008 base case are given in the Interim report.

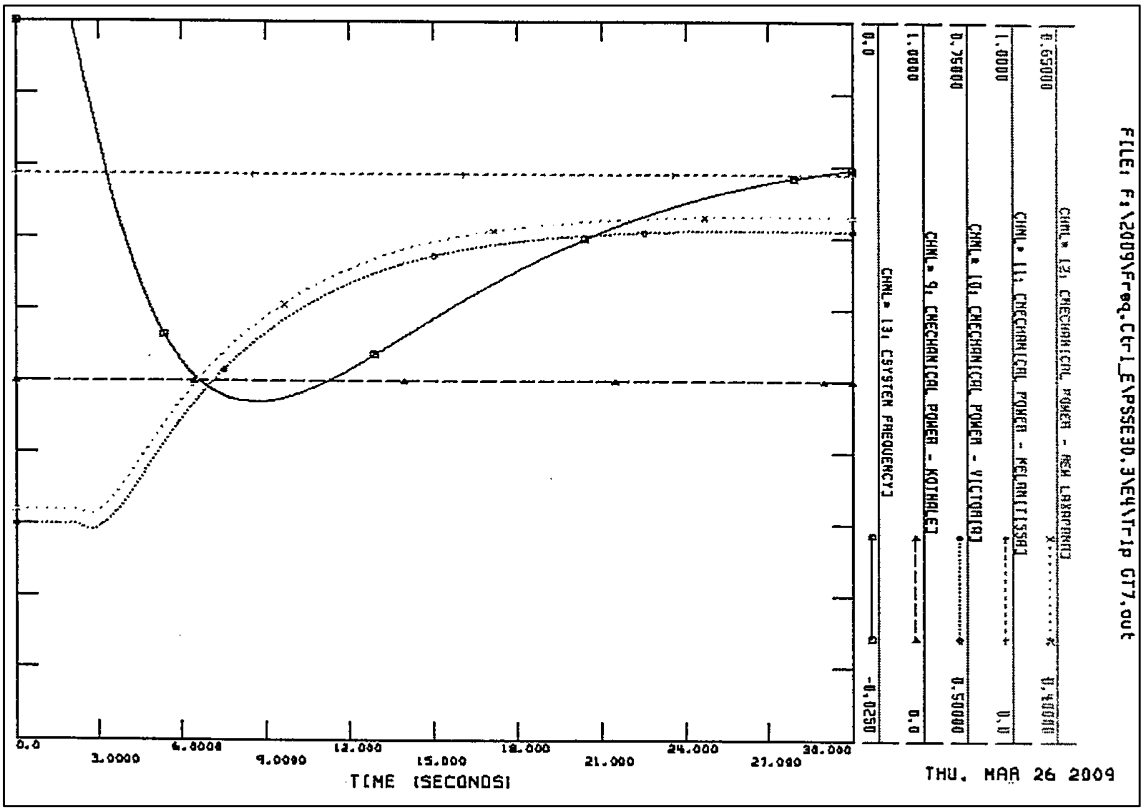

Fig 4.1 Simulation of GT-7 trip (115 MW): Transient variation in frequency and power outputs

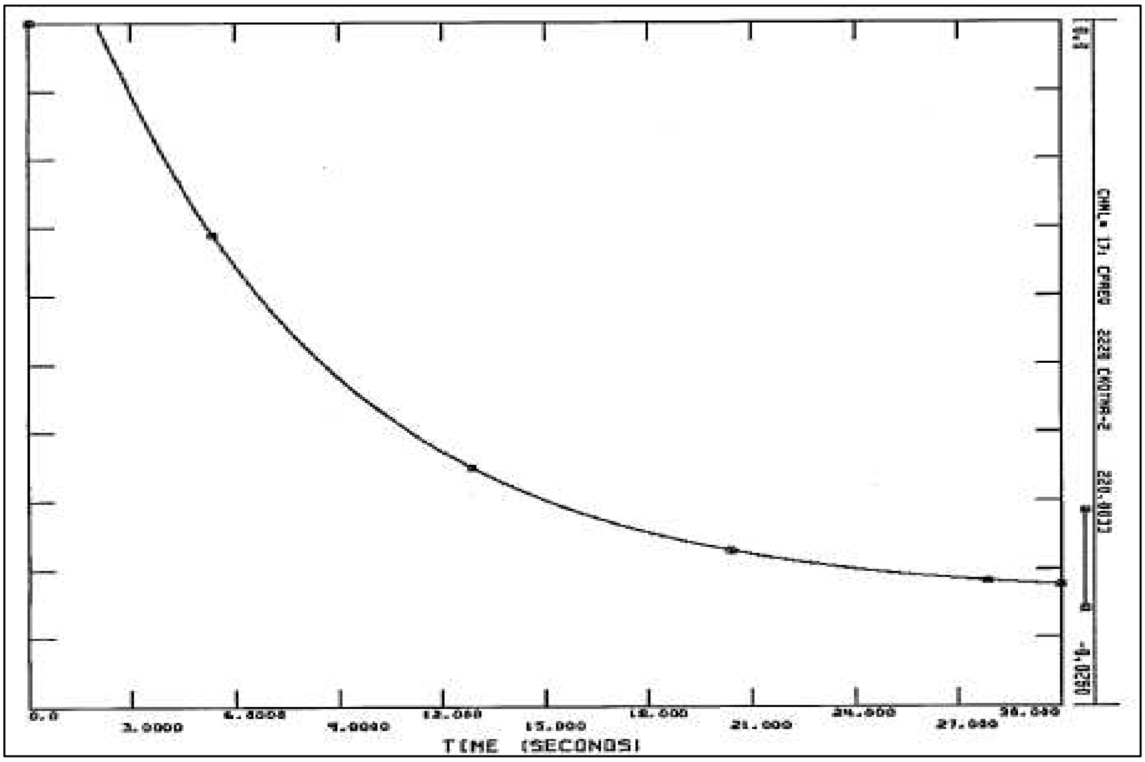

Fig 4.2 Simulation of Victoria unit (72 MW) trip: Transient variation in frequency WITHOUT governors in action

## 2008: Off peak Load

The trip of GT-7 has been simulated for the off-peak load condition. The frequency variation with all governors connected is shown in Fig 4.3. The frequency falls to 1.8% below rated frequency and recovers due to governor actions and settles down at 0.4% below rated value. No oscillations are observed.

Same GT-7 trip is simulated WITHOUT any governors and the transient frequency variation is shown in Fig 4.4.

It would be interesting to see the response only when Victoria machines are in control with all other governors blocked. The simulation result is shown in Fig 4.5. Frequency drop during transient is more than that with all governors in action.

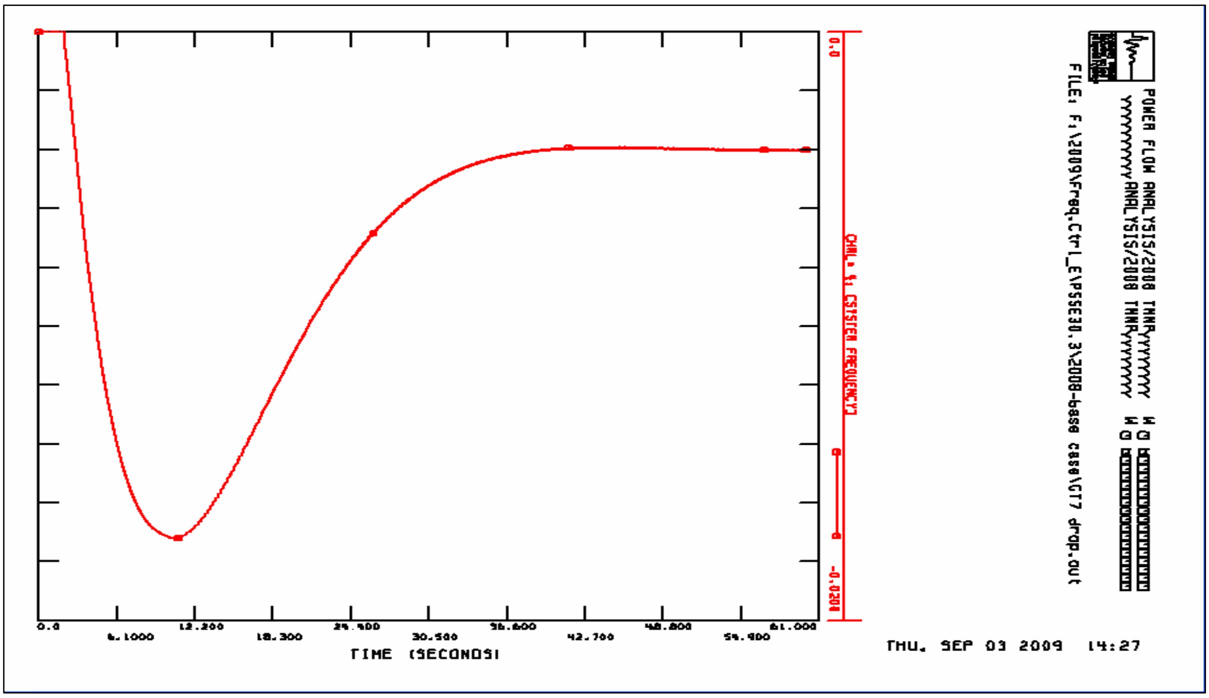


**Fig 4.3 Simulation of GT-7 (115 MW) trip: Transient variation in frequency WITH governors in control**

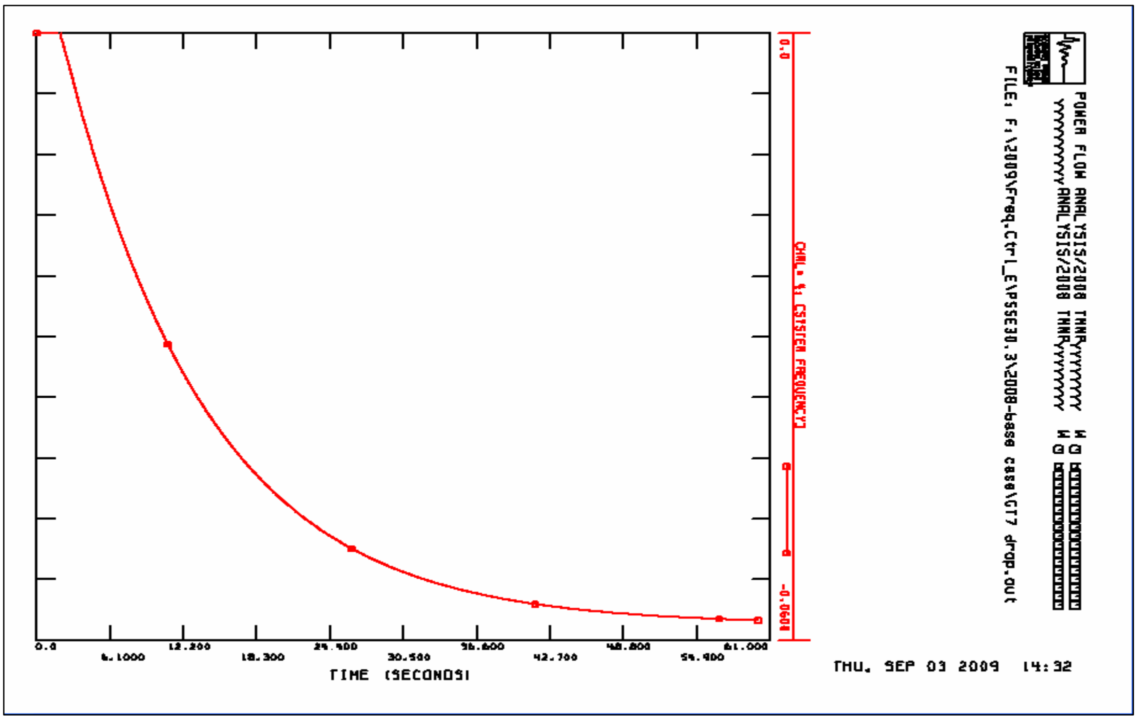


**Fig 4.4 Simulation of GT-7 (115 MW) trip: Transient variation in frequency WITHOUT governor action**

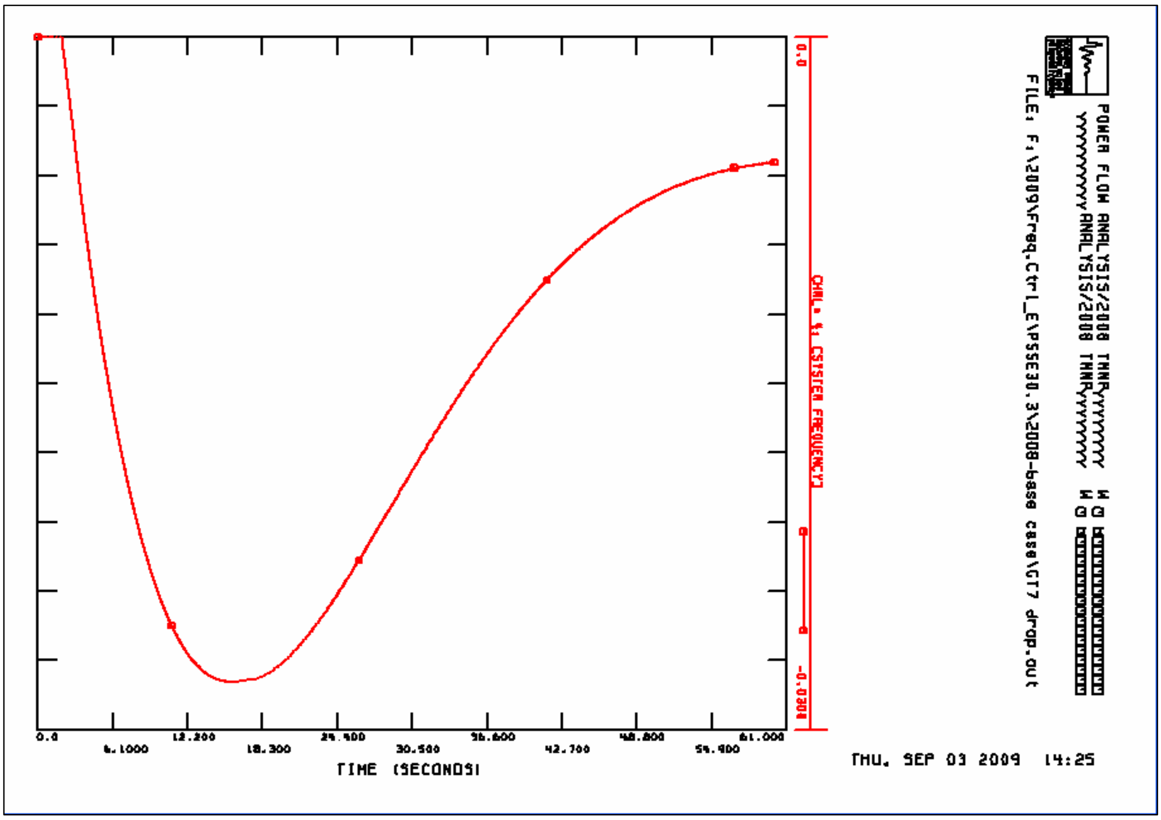


**Fig 4.5 Simulation of GT-7 (115 MW) trip: Transient variation in frequency WITH only Victoria governors in control**

## 4.3 Frequency behavior of CEB power system: 2012 base case

The 2012 base case power system is characterized by the addition of large coal based thermal power plant at Puttalam. To study the frequency characteristic of the 2012 planned power system, the Puttalam coal unit generating 285 MW has been tripped. The simulation is carried out with all governors in service, without any governor in service and with only Victoria governor in action. The respective simulation results are given in Fig.5 to Fig.7. Frequency variation as well as voltage variations at various buses is shown.

Governor droop setting for all the machines except Victoria machines is 5% and for Victoria machines 1.6% droop value is set so that these machines can participate in secondary regulation.

When the coal unit at Puttalam generating 285 MW is tripped, frequency falls to 6% in about 25 seconds **without** governors in action, as shown in Fig 4.6. Voltage at 132 KV bus falls by about 0.5% after few oscillations.

With only Victoria governor in action with 1.6% droop, the frequency fall is less (4%) as shown in Fig 4.7. The increase in power output by Victoria can also be seen in the figure. When all the governors are in action, the frequency restoration is better as shown in Fig 4.8.

Simulation results of GT-7 trip are given in Fig 4.9 to Fig 4.10 without governors and with governors. The deviations in frequency are less than those due to Coal unit trip.

The voltage variations at the connected buses are also shown. It is observed that change in voltage is not significant.

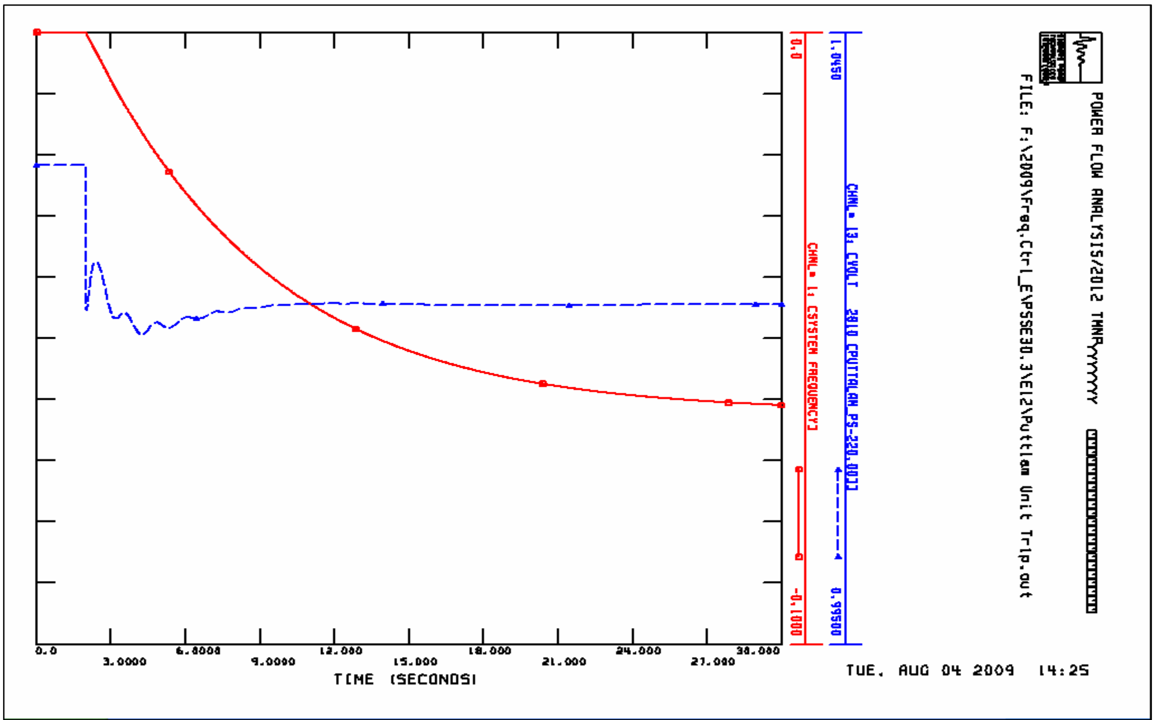


**Fig 4.6 Simulation of coal unit (285 MW) trip: Transient variation in frequency WITHOUT governors in action**

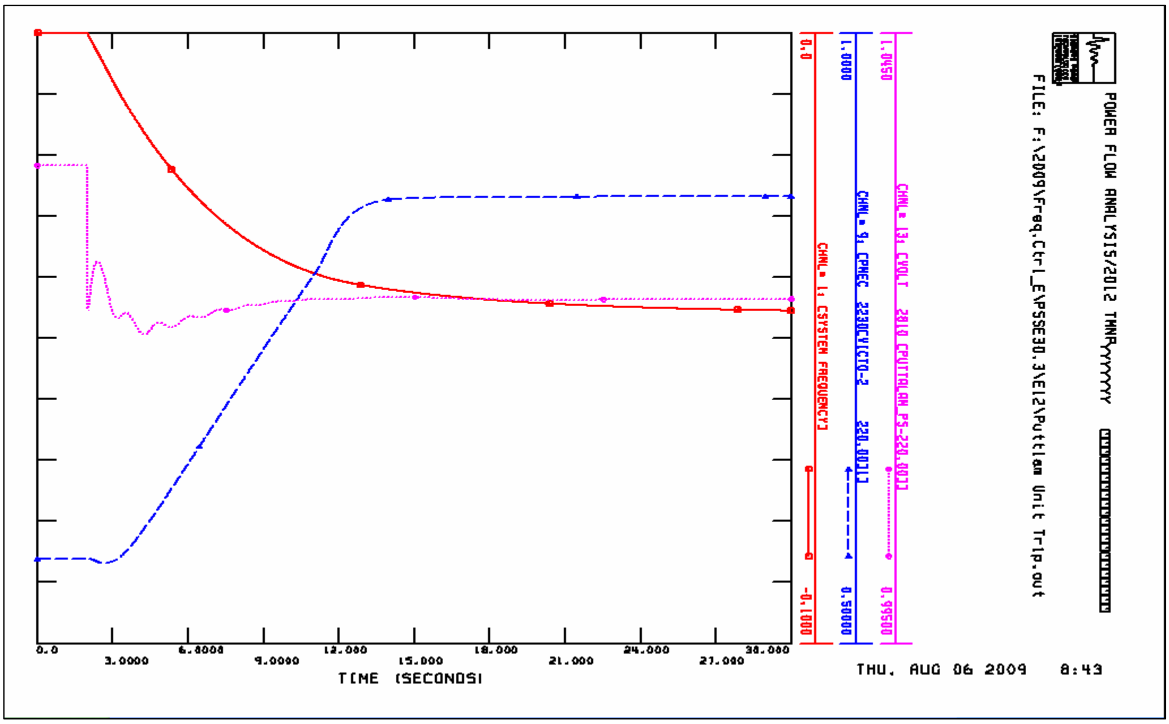


**Fig 4.7 Simulation of coal unit (285 MW) trip: Transient variation in frequency WITH Victoria governors in action**

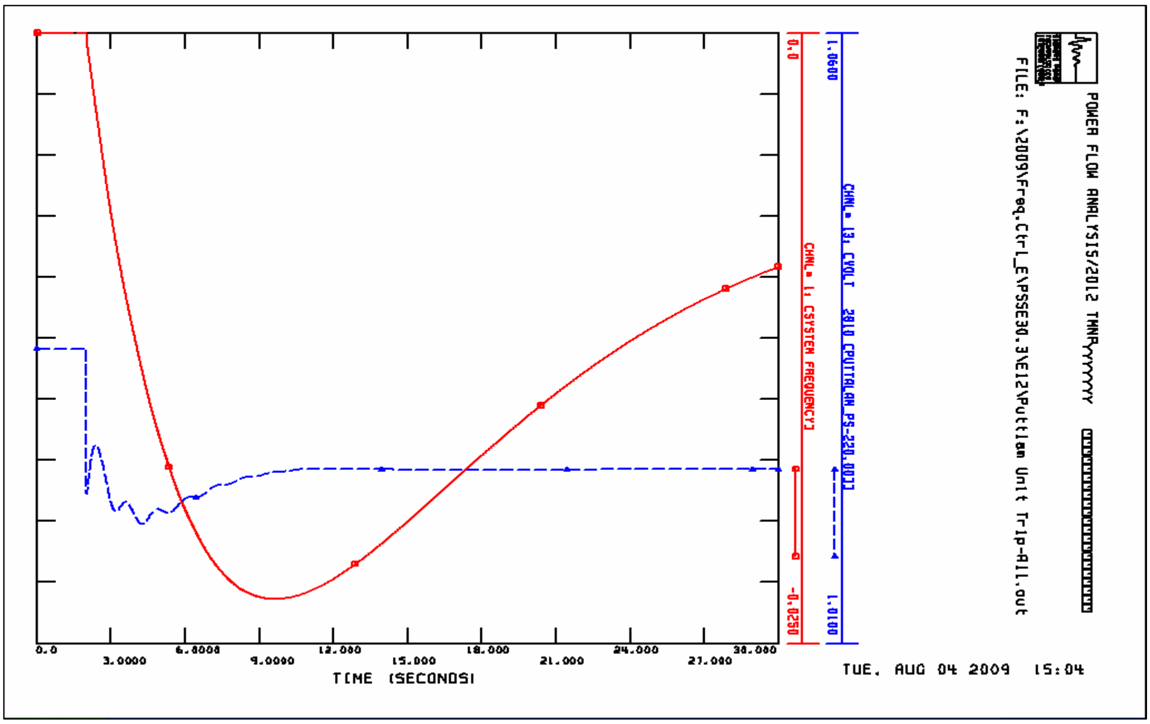


**Fig 4.8 Simulation of coal unit (285 MW) trip: Transient variation in frequency WITH all governors in action**

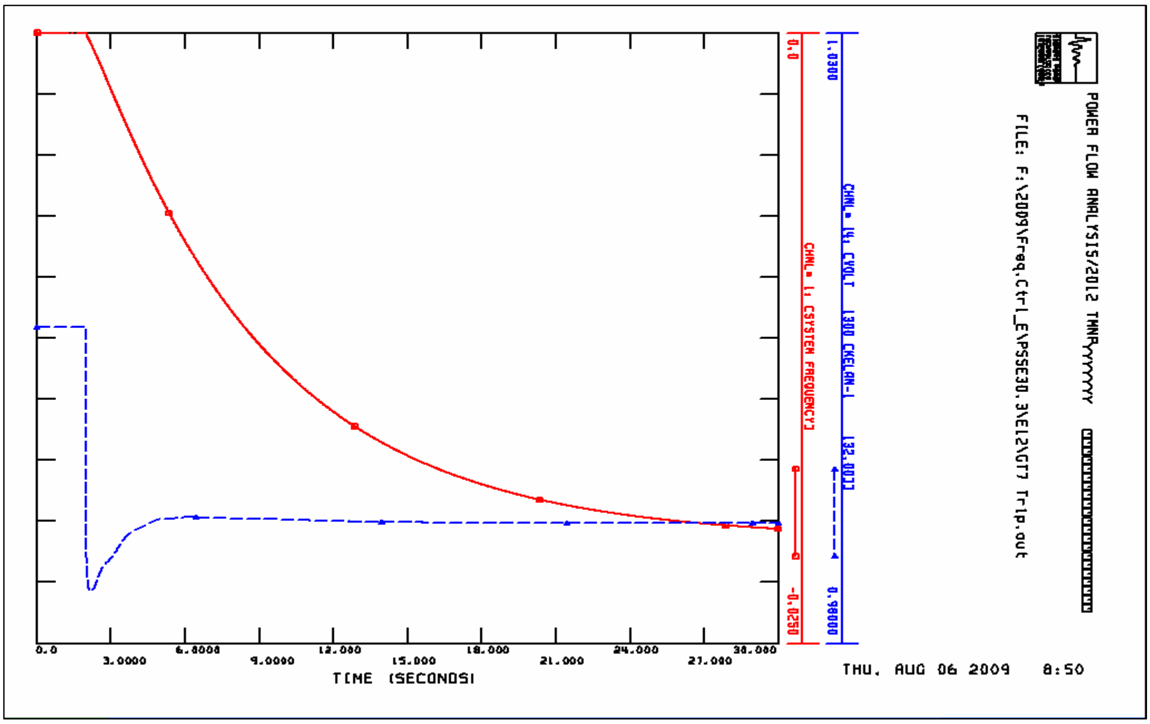


**Fig 4.9 Simulation of GT-7 unit (115 MW) trip: Transient variation in frequency WITHOUT governors in action**

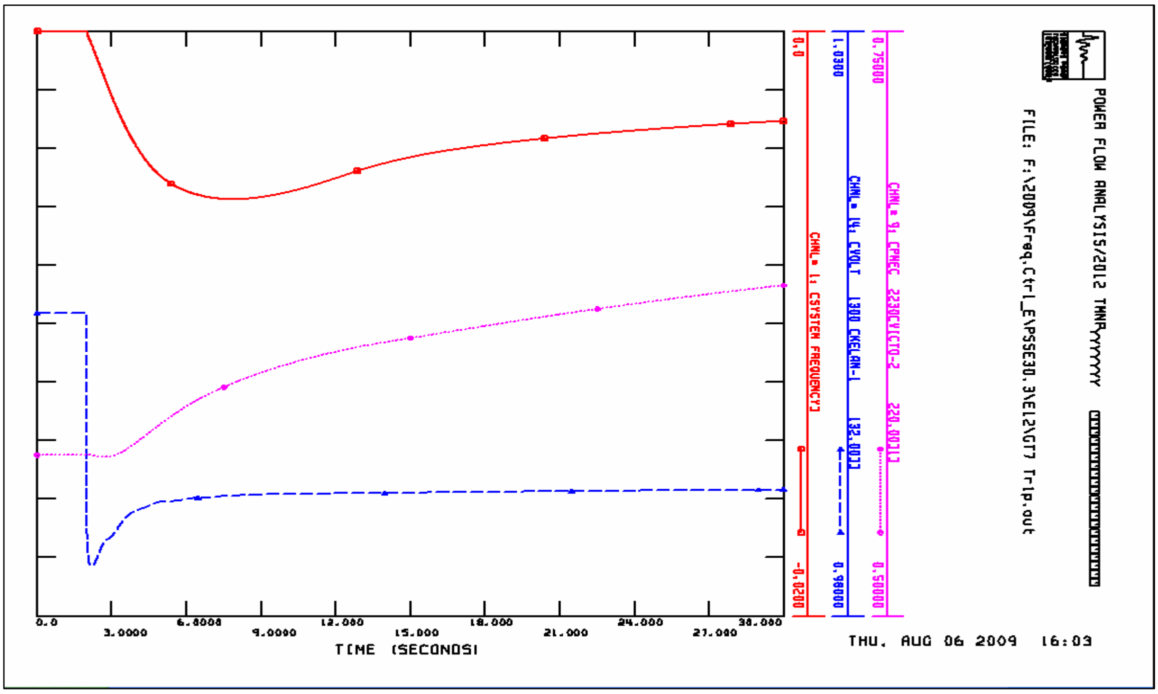


**Fig 4.10 Simulation of GT-7 unit (115 MW) trip: Transient variation in frequency WITH governors in action**

## 4.4 Frequency behavior of CEB power system: 2016 base case

The CEB power system planned for the year 2016 System can have a night peak load of 3726.7MW with the addition of 300MW unit at Trincomalee coal power plant.

The simulation results of trip of 300 MW coal unit at Trincomalee are given in Fig 4.11 with all governors in action. The frequency fall is less than 1%.

However with only Victoria governors in control frequency fall is close to 5% (Fig. 4.12). It shows that other machines should be brought in for secondary frequency control.

For off-peak case, (with load of 1490.7 MW) however it is observed from simulation that control of frequency is possible only with Victoria as other machines have margin to spare as shown in Fig 4.13.

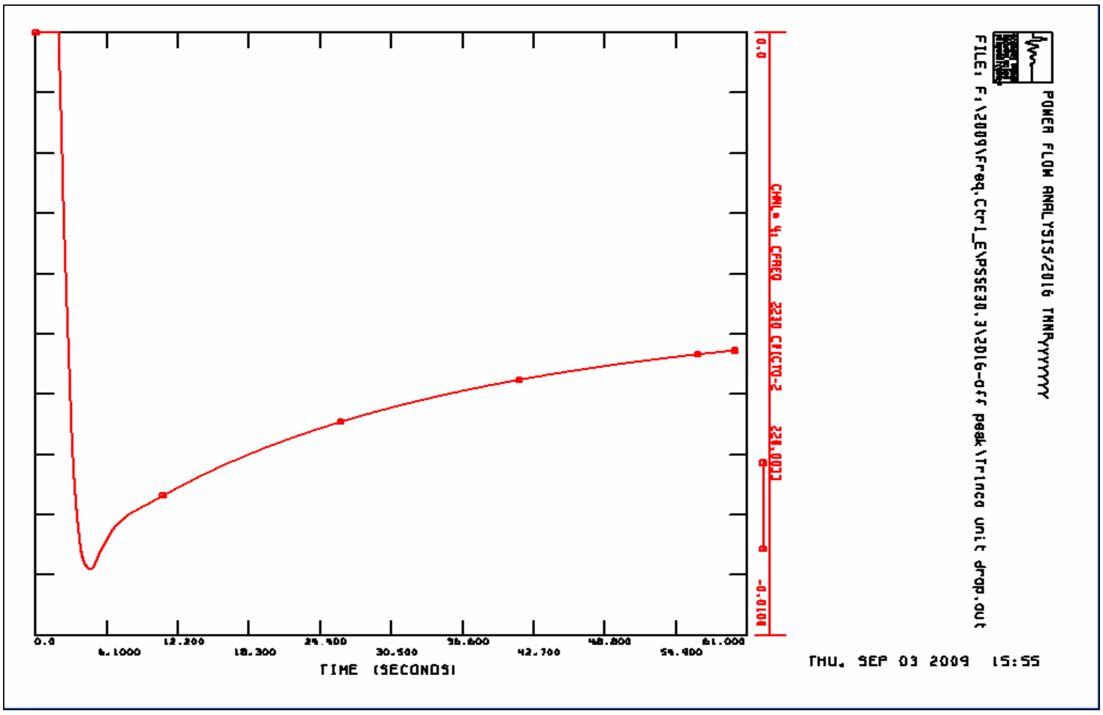


**Fig 4.11 Simulation of Trincomalee coal unit (300 MW) trip: Transient variation in frequency WITH governors in action: 2016 night peak load**

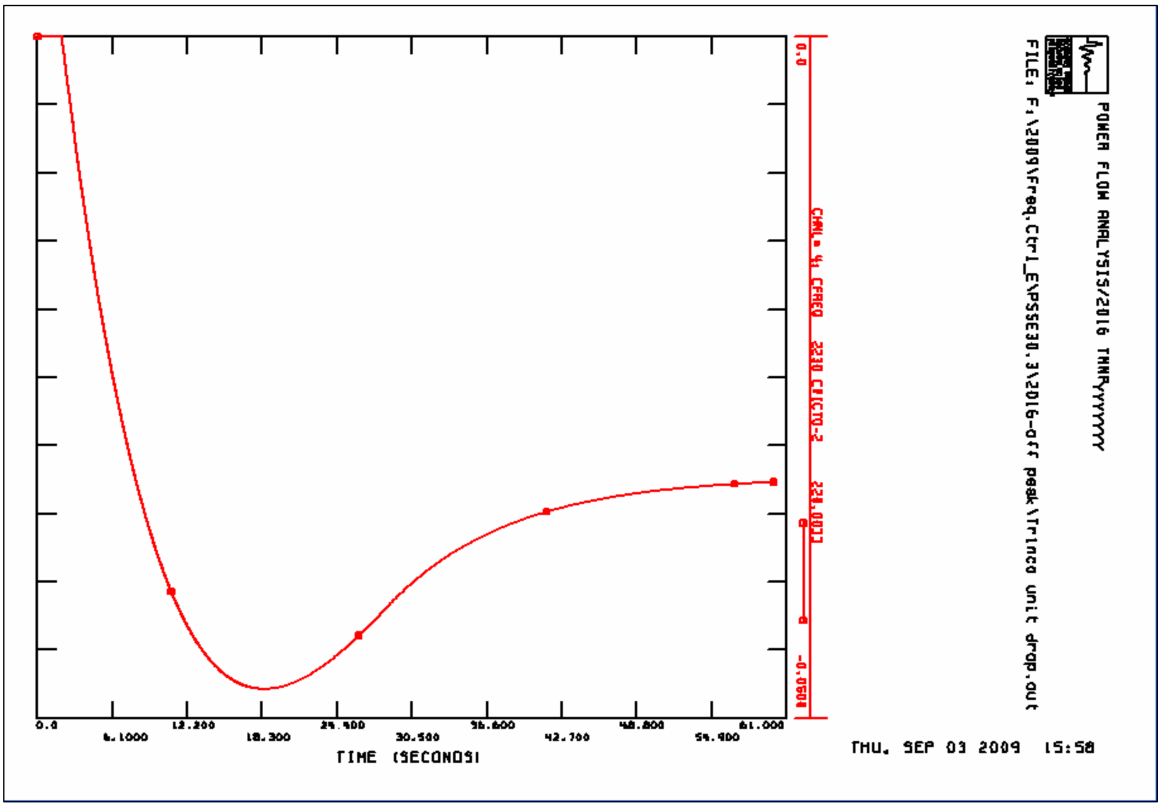


**Fig 4.12 Simulation of Trincomalee coal unit (300 MW) trip: Transient variation in frequency WITH ONLY Victoria governors in action**

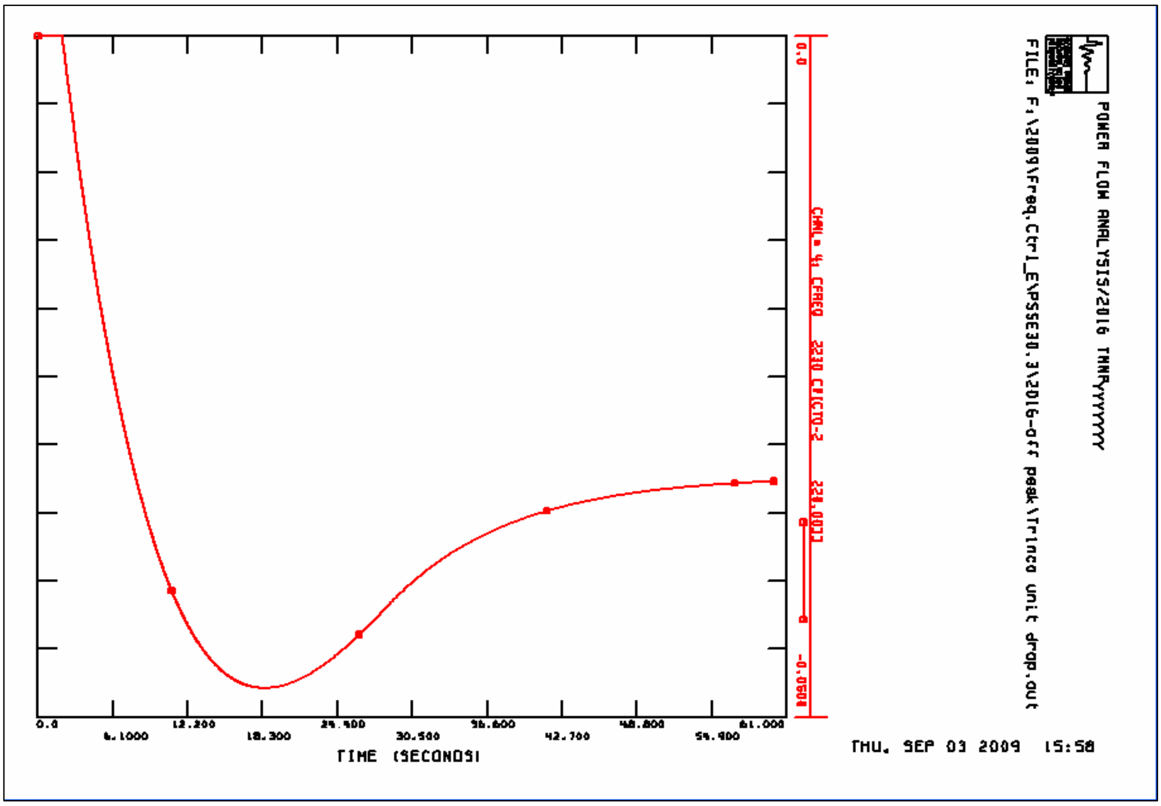


**Fig 4.13 Simulation of Trincomalee coal unit (300 MW) trip: Transient variation in frequency WITH ONLY Victoria governors in action: Off-peak load**

## 4.5 Frequency behavior of CEB power system: 2020 base case

The 2020 power system is characterized by the addition of more thermal power plants of 300 MW capacity each.

Trip of a coal power plant causes frequency variation as shown in Fig.4.14. There is no difficulty in controlling the frequency if one 300 MW unit trips. Without governors participating in control, however, the frequency fall cannot be arrested, as shown in Fig. 4.15 and load shedding has to be resorted to.

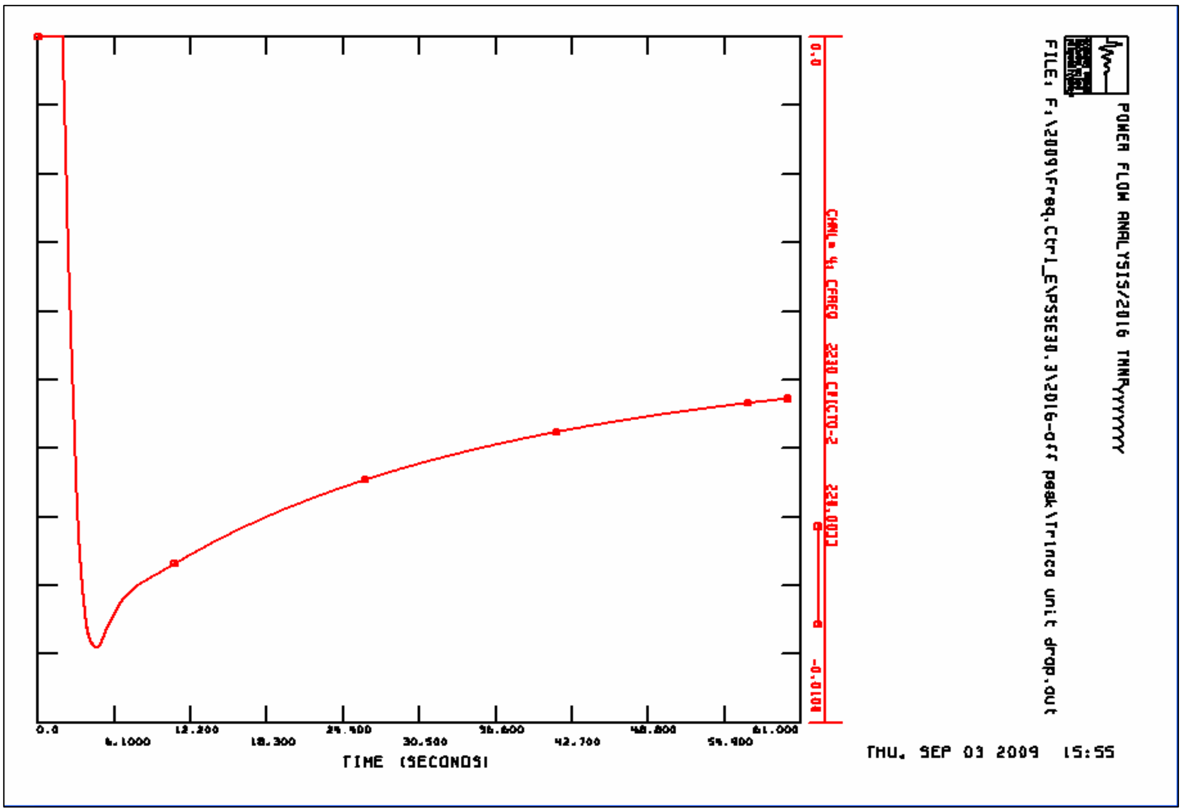


**Fig 4.14 Simulation of 300 MW coal unit trip: Transient variation in frequency WITH all governors in action**

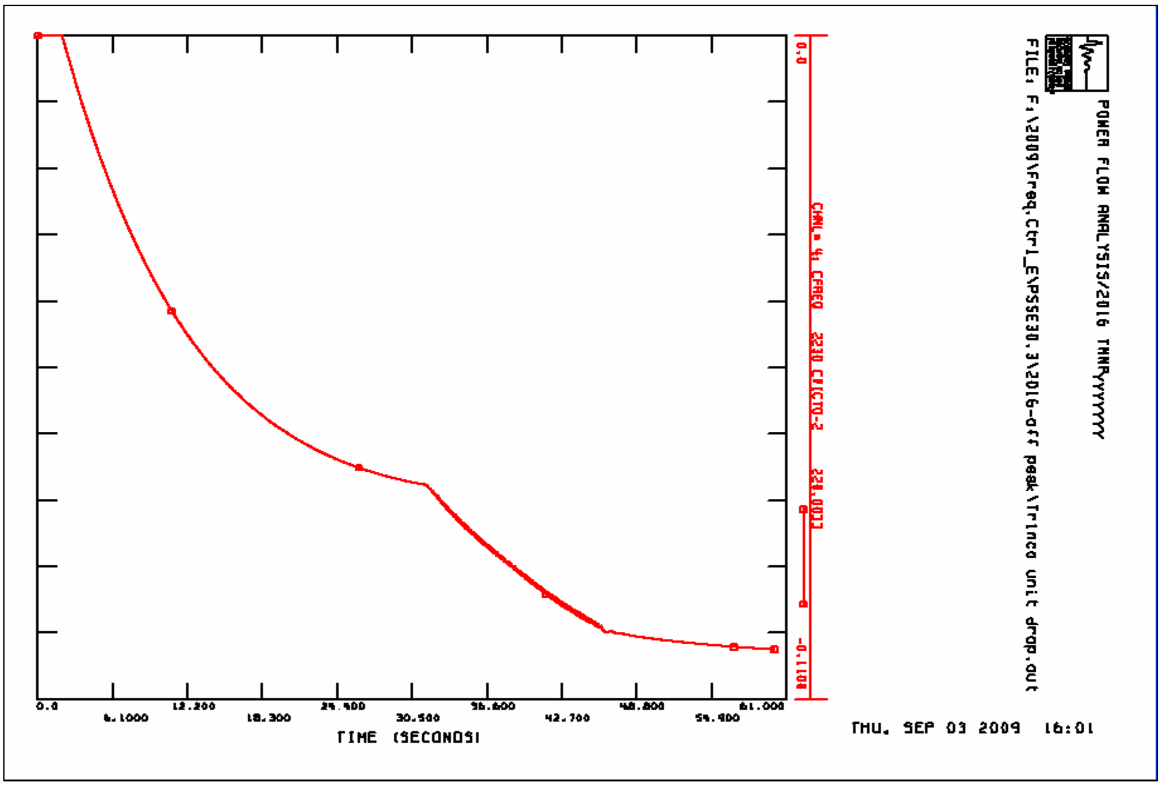


**Fig 4.15 Simulation of coal unit (300 MW) trip: Transient variation in frequency WITH OUT governors in action**

## 4.6 Concluding Observations

The simulation of CEB power system for various scenarios has been carried out using PSS/E available with CEB. Various cases have been considered like 2008, 2012, 2016 and 2020 for night peak and off-peak loadings.

In each base case trip of a large generating unit has been simulated and transient frequency variations have been observed.

It is observed with the control settings provided in the dynamic data base of PSS/E for various governors etc., the system can withstand the trip of one large generating unit like GT-7 (115 MW), coal unit (300 MW) etc.

It is possible that many of the governors may be in ‘blocked’ state and may not be participating in the frequency regulation. Also the data that is incorporated in the PSS/E dynamic data base may not exactly represent the physical system.

In view of the above, it is suggested that whenever a large generating unit trips feed forward action may be initiated to trip an equal amount of load without waiting for the frequency fall to be sensed.

It is also important to incorporate Load Frequency Control (LFC)/Automatic Generation Control (AGC) in the SCADA/Energy Management System (EMS) as discussed in another chapter.

# Chapter 5

# TUNING ASPECTS OF GOVERNORS

## 5.1 Introduction

The frequency behaviour of an interconnected power system depends on the system parameters like rotor inertia, time constants of various devices in the governing loop, time constants of the steam turbine cylinders and the penstock water inertia time and the settings of the individual governors which are adjustable.

It is important to tune the adjustable parameters in an optimum way otherwise an otherwise stable system may become unstable.

A study of the tuning aspects of the governing systems of CEB turbines is given in this chapter.

## 5.2 Droop

The power-frequency characteristic can be expressed in terms of 'Droop'. As shown in the figure below (for 4% droop) when power output changes from 100% to 0%, frequency changes from 50 Hz to 52 Hz i.e., it increases by 4%. For 5% droop, frequency increases by 5% to 52.5 % Hz.

Droop can be defined as the percentage drop in system frequency which would cause the Generating Unit under free governor action to change its output from zero to full load.

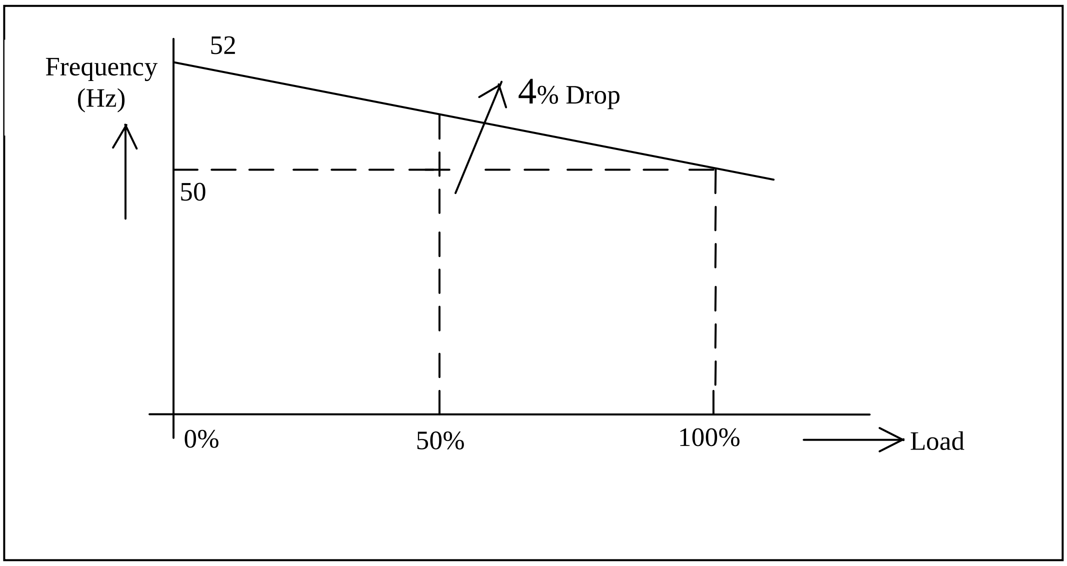


**Fig 5.1 Regulation or Droop Characteristic**

- Droop facilitates parallel operation of generating units in the interconnected mode.
- When a load disturbance occurs, the portion of load change shared by a generating unit depends on the droop.
- Droop also influences the stability of turbine speed control system.

- The overall power system frequency control is also affected by the droops of all connected turbine governors.

**Droop Value**

Droop relates the power output versus speed or frequency, which relationship depends on the various components of governing system, governor valve lift-steam flow characteristic. In the electro-hydraulic governors adjustable parameter is provided as droop that relates the gate (or) valve opening command signal. For practical purposes this adjustable parameter is considered as the 'droop'.

In hydro power plants this droop is referred as the 'permanent droop' as there is another parameter 'temporary droop'.

Normally, all turbine governors have a droop of between 3% and 6%.

In India 4% or 5 % is set. In many utilities in USA 5% droop value is set.

In the CEB power stations, the value of 5% is set, as per the 'dynamic data' given.

Therefore there is no change in droop value suggested.

It should however be remembered that the droop value in practice may change due to the changes in the characteristics of the governing system components especially the mechanical-hydraulic components. For old power stations or renovated power stations, the power – frequency relationship has to be checked by measurements.

## 5.3 Dead Band

The governing system action depends on speed sensing. There is a minimum value of speed which cannot be picked by the sensing mechanism and hence may remain uncorrected. This minimum value is called governor insensitivity or dead band. The characteristic is shown in Fig 5.2.

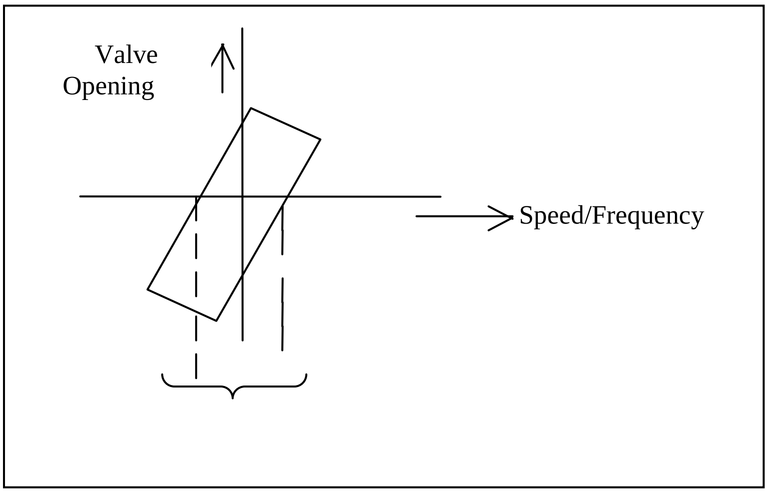


**Fig. 5.2 Dead Band Characteristic**

Sometimes due to wear and tear dead band increases over a period of time. This is detrimental to the frequency regulation. In control system analysis, it is well known that dead band or hysteresis in a closed loop causes instability or limit cycle oscillations. Governor hunting may occur. At the same time, governor should not react for very small changes in frequency, so dead band is introduced intentionally in the electronic governor which is an adjustable feature.

As per the NERC (North American Electric Reliability Council) of USA Operating Manual:

- Generators with nameplate ratings of 10 MW or ore must have governors should provide 5% droop.
- Dead band on all governors must be set to +/- 0.036 Hz i.e., 0.06 % of 60 Hz.

So for 50 Hz system, dead band should not be more than +/- 0.03 Hz or 30 mHz.

## 5.4 Tuning of Hydro Turbine Governor Parameters

The governors are provided with adjustable parameters that are to be properly tuned to achieve stable operation when the turbine generator unit is running in isolation and to obtain proper frequency regulation of the interconnected power system operation.

The performance depends on adjustable controller parameters and plant parameters fixed in design like rotor inertia constant, water inertia constant (in hydro turbine) and various other machine constants depending on the scheme.

The adjustable parameters, apart from droop, are:
- temporary droop
- reset time
- acceleration feedback gain (in hydro temporary droop governor)
- PID (proportional, integral and derivative) gains (in PID governor)

Proper tuning of hydro turbine governor parameters is very important as hydro power plants can get isolated from the rest of the system. To overcome the negative effect of ‘water inertia’, proper values are to be set to the temporary droop or PID governor for stable operation.

The following formulas may be used to tune the temporary droop governor for stable operation:
Temporary droop: $\mathbf{b_t = K_t (T_w/T_m)}$, where

$T_w$ = Water inertia time (sec.) and
$T_m$ = the rotor inertia time = 2 *H
H = inertia constant
$K_t$ = 2 to 2.5

Recovery time $\mathbf{T_r = K_r * T_w}$
Where $K_{r\,=}$ 4 to 6;

## 5.5 Tuning of Thermal power plant Governor Parameters

CEB power system has several Diesel generators operated by IPPs. Typical (Ace Power) diesel power plant has four 6.20 MW engines running on diesel cycle with Wartsila 18 V 32 LN engine and is PLC controlled.

In diesel generator governor droop value is provided as 5%.

In CEB power system there are Combined Cycle Power plants, like 163 megawatt (MW) combined cycle diesel power plant at Kelanitissa and 300 MW Kerawalapitiya Multi Fuel Combined Cycle Power Plant.

Gas turbine control and steam turbine control are adjusted using the standard Proportional Integral Derivative (PID) controller tuning techniques while commissioning. One typical standard technique is based on the minimization of a performance index (J) based on the magnitude of speed error (e(t)) as given below. Different performance indices $J_1$, $J_2$ and $J_3$ are given. In $J_3$, time (t) is also used.

$$J_1 = \int_0^\infty |e(t)| dt = \min,$$

$$J_2 = \int_0^\infty e^2(t) dt = \min,$$

$$J_3 = \int_0^\infty t \cdot e^2(t) dt = \min,$$

## 5.6 Concluding Observations

The generation in CEB is predominantly hydro. The thermal generation is mostly by private companies. Droop and dead band are two common parameters for all power generating units. In hydro, there are other adjustable parameters like temporary droop and recovery time which have to be adjusted according to the criterion given as they have a profound influence on the frequency stability.

The frequency trend observed at steady state in the CEB power system and the transient simulation studies indicate that the CEB power system frequency is quite stable. Simulation study of separate hydro, thermal and combined cycle plants also showed no oscillations in frequency. Few sample results are given in the following pages. Tuning is required only when renovation of old hydro power plants takes place and on the new generating units being added.

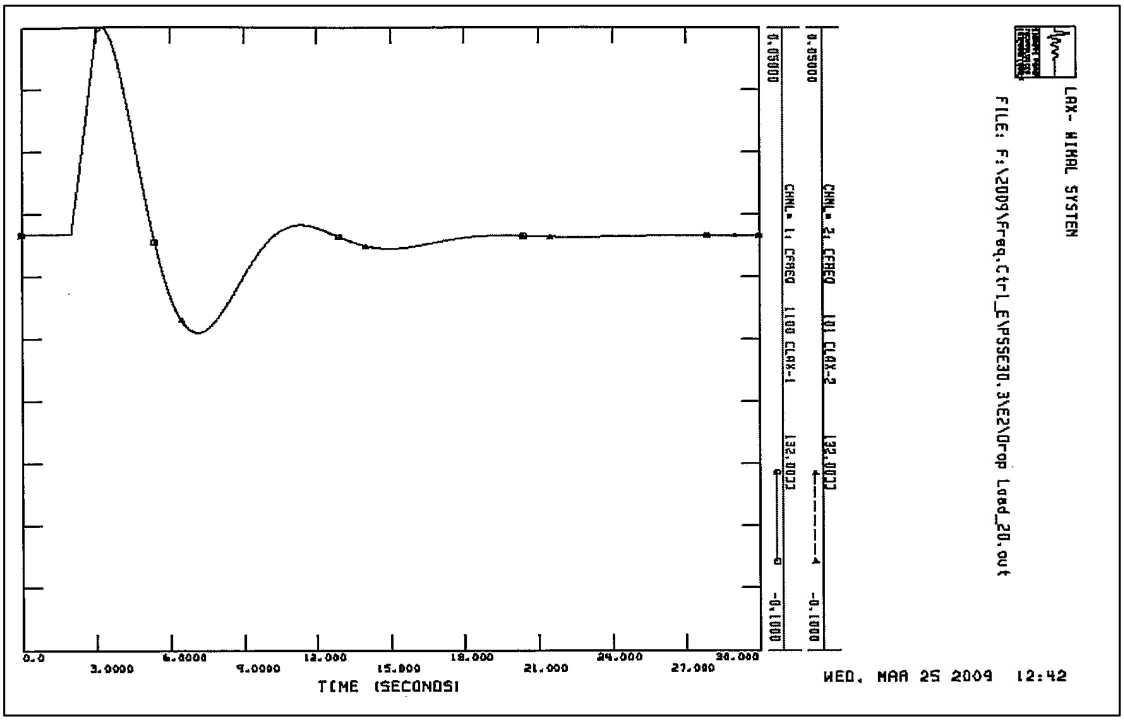

Fig 5.3 Frequency Variation following a sudden load drop of 50% and reconnection after 1 second

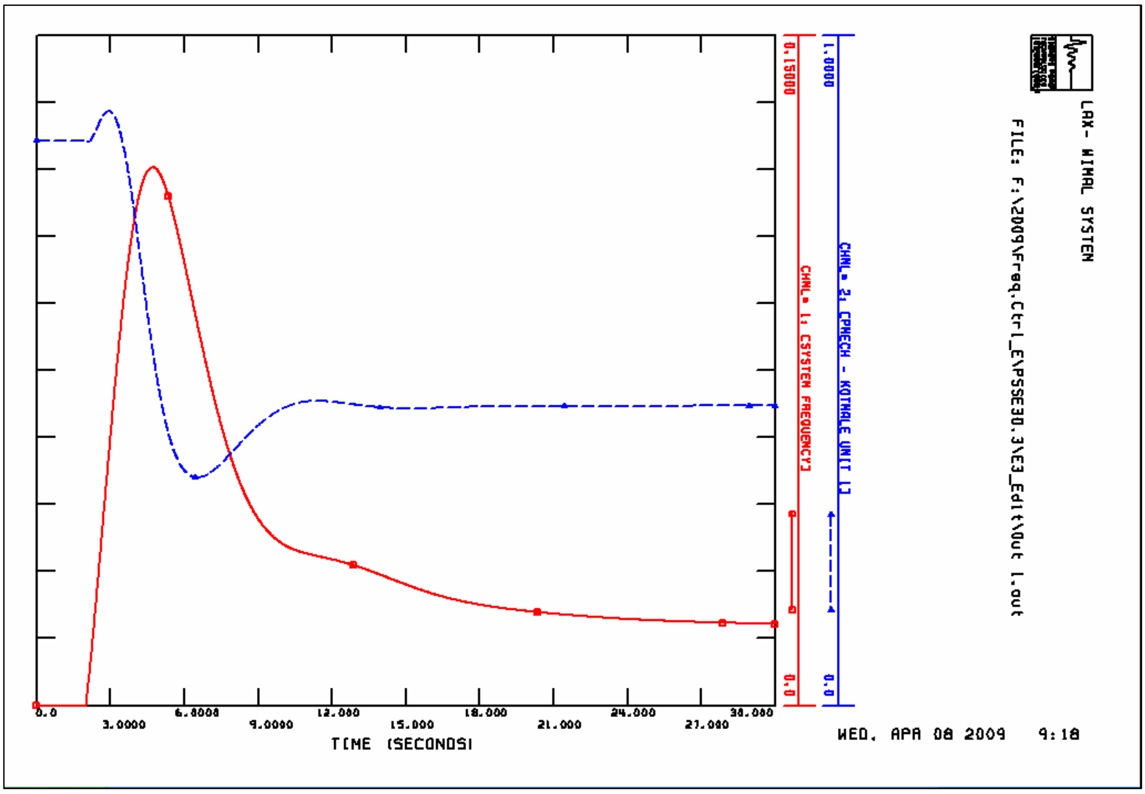

Fig 5.4 Effect of 50% load drop on Kotmale hydro machine

# Chapter 6

# FREQUENCY CONTROL STRATEGY: RECOMMENDATION FOR AUTOMATIC GENERATION CONTROL

## 6.1 Introduction

Frequency is constant when the generation and load are in balance. But load always changes in a power system so frequency also changes. Frequency of power supply has to be maintained close to the operating frequency viz., 50 Hz for various reasons. Most of the electrical equipment is designed for the specified frequency. The prime movers resonant frequencies should be avoided.

In this chapter, the current practice of frequency control and the future strategies to be adopted for frequency control are presented.

## 6.2 System Frequency Criteria

The grid codes or the operating guidelines specify the close range in which frequency is to be maintained.

CEB guidelines specify that frequency is to be maintained at 50 Hz +/- 1% i.e., 49.5 Hz to 50.5 Hz and when frequency falls less than 48.75 Hz load shedding is resorted to.

In India, the system frequency should be maintained within the frequency band of 49.0 Hz to 50.5 Hz, according to the Indian electricity Grid Code.

According to the UK grid code, "the frequency of the transmission system shall be nominally 50 Hz and shall normally be controlled within the limits of 49.5 Hz – 50.5 Hz, The system Frequency could rise to 52 Hz or fall to 47 Hz in exceptional circumstances. Design of Generators Plant and Apparatus must enable operation of that Plant and Apparatus within that range in accordance with the following:-

Frequency Range Requirement
47.5 Hz – 52 Hz Continuous operation is required
47 Hz – 47.5 Hz Operation for a period of least 20 seconds is required each time the frequency is below 47.5 Hz.

## 6.3 Frequency Variation and Control

Frequency is an indicator of balance of power generation and load. In an interconnected power system, the generation of entire 'control area' and the total load connected are to be in balance for the frequency to be constant. But the load in a power system is never at steady state and always varies though slowly. When ever such load variation occurs, the frequency varies and generation has to be adjusted.

The variation in frequency depends on the grid inertia. As shown in Fig 6.1 any mismatch in generation and load manifests as frequency change of the power system area. In a large power system, several such areas connected by tie lines exist.

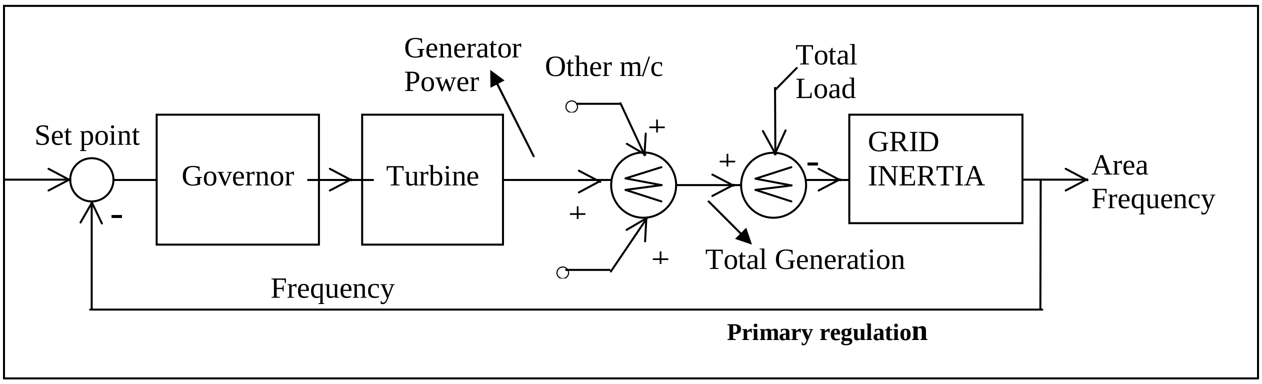


**Fig 6.1 Power System Frequency Control System**

Whenever frequency changes, the governors in all the machines sense the change in frequency (or speed) and act to adjust the generation by adjusting gate opening in hydro and valve opening in the case of thermal machines. Such regulation is called **primary regulation** as shown in the block diagram**.** The generating units which respond naturally are said to be in governor-free mode (or free governor mode-FGMO).

When a load change occurs, due to the nature of droop characteristic provided frequency does not get back to the original value before a disturbance with primary regulation alone. The set points have to be adjusted manually or automatically and the process is called **secondary regulation**. Automatic Load Frequency Control (ALFC) system performs the secondary regulation as shown in the block diagram in Fig 6.2.

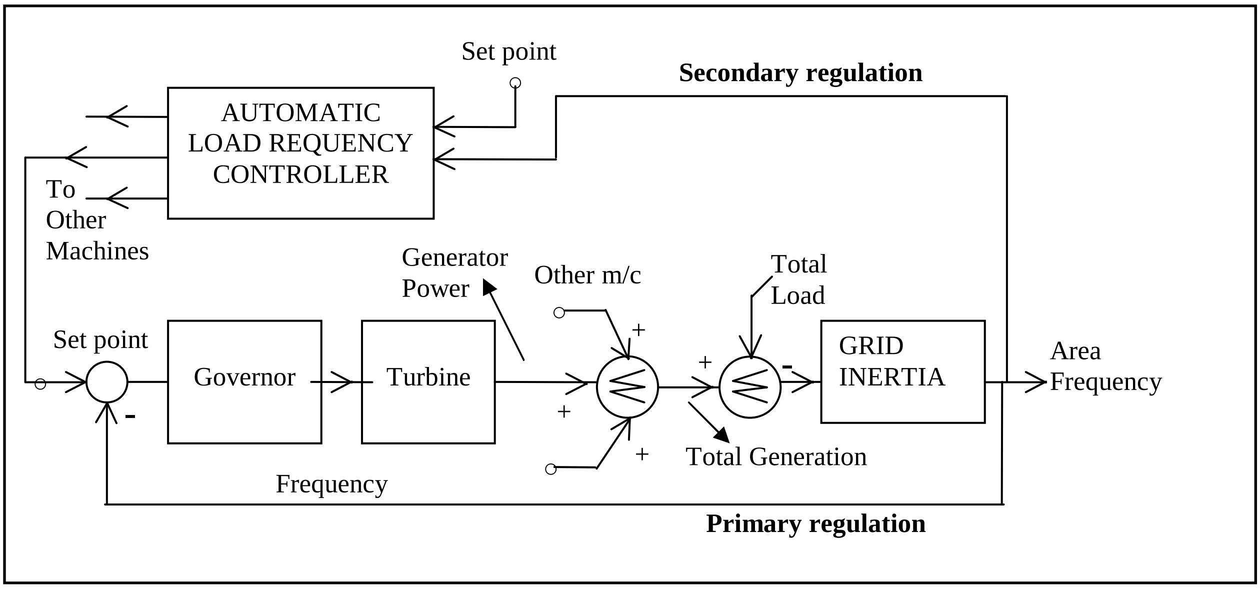


**Fig 6.2 Automatic Load Frequency Control System**

In the modern Energy Management Systems (EMS) automatic load frequency control system (ALFC) is part of Automatic Generation Control (AGC).

In power systems, where automatic control does not exist, manual control of set points is done on instructions from dispatch center.

## 6.4 Current Practice of Frequency Control in CEB

In Sri Lanka the frequency control is performed by the System Control Centre (SCC) of CEB. Automatic load frequency control by secondary regulation does not exist. The frequency control task is assigned to hydro power stations at Victoria (3 x 70 MW) and New Laxpana (2 x 50 MW). Sometimes Samanalawewa (2 x 60 MW) and Kotmale (3 x 67 MW) are also used. Other generating units generate power as per the dispatch instructions given by SCC.

When the frequency falls, the droop setting of the participating Victoria hydro machines with spare capacity is reduced to 1.6% due to which Victoria machines increase their generations. As noted earlier, the share of power in case of load change depends on the droop setting. The sharing of a machine with 5% droop will be less than the sharing of machines with 1.6% droop.

A machine should be in governor-free mode and it should have enough spare capacity, to respond to frequency fall. Similarly with higher dead band or insensitivity, the generating units cannot participate in frequency regulation.

Typical frequency variation for a disturbance is shown in Fig 6.3 as obtained from the PSS/E simulation study of 2008 base case CEB power system.

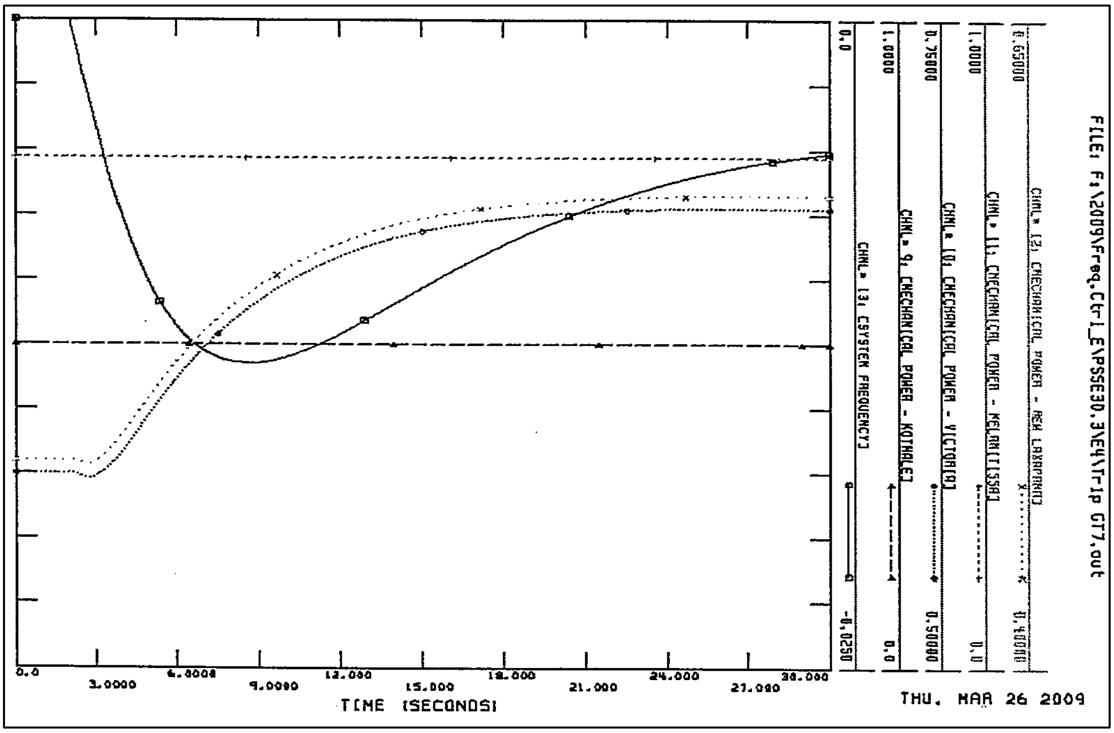


**Fig 6.3 Simulation of GT-7 trip (115 MW): Transient variation in frequency and power outputs**

When there is a disturbance like GT-7 trip, frequency started falling and with governors in action the power outputs have increased and frequency fall is arrested. When the generation matches with the new load frequency settles down at the corresponding value of frequency which is lower than the operating frequency. But if there is automatic load frequency controller it should have come back to the original value.

The current practice of frequency control where Victoria hydro machines are directed to participate in secondary frequency regulation by reducing permanent droop of their governors to 1.6% (from 5%) is also simulated and it was observed that the frequency does not come back to the original value as the correction to set points of governors has not been given. When the frequency falls below 47.5 Hz, load shedding is resorted to.

## 6.5 Suitable Method of Frequency Control for the Future Power System

It is necessary to incorporate an automatic mechanism for frequency regulation. If an automatic load frequency control system is provided frequency gets restored to the pre-disturbed value as shown by the typical frequency variation in a 60-Hz system.

In this response curve taken from published literature, a loss of generation has resulted in a frequency fall from 60.01 Hz to 59.209 Hz and due to governor actions (primary regulation), frequency starts increasing and it should have settled around 59.75 Hz as shown below.


**Fig 6.4 Typical frequency response of a 60-Hz power system with Automatic Generation Control (AGC) for a step load increase**

But **Automatic Generation Control (AGC)** system which includes **Load Frequency Control (LFC)** acts on the set points of the governors and frequency gets restored to the 60 Hz value as shown in the response curve (Fig. 6.3).

For a similar system, measured frequency variation when large generation is lost is shown in Fig. 6.4.

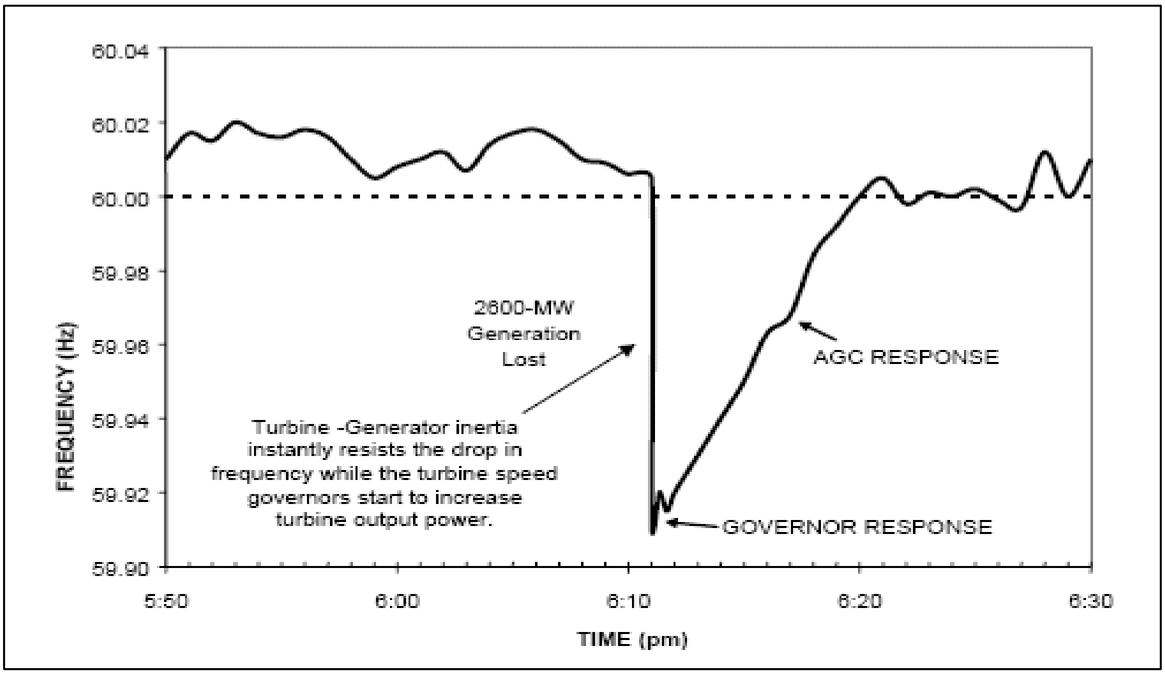


**Fig 6.5 Typical frequency response of a 60-Hz power system with Automatic Generation Control (AGC) for a generation loss**

The **primary control** (Immediate change corresponding to sudden change of load and frequency) and **secondary control** (Change in setting control power to maintain operating frequency) can be clearly seen on the steady state droop characteristic.

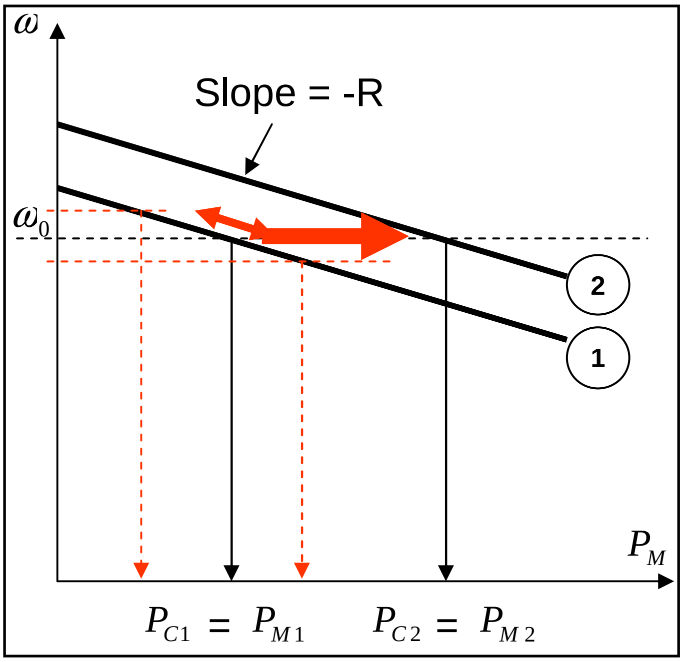


**Fig 6.6 Governor Set point change by Secondary Control on Droop characteristic**

In the sloping curve (1) when power level changes from $P_{c1}$ to $P_{c2}$, frequency falls. But the reference is shifted by the AGC so that the operating frequency corresponding to new power level $P_{c2}$ is original frequency $\omega_0$.

## 6.6 Implementation of Automatic Generation Control (AGC)

The AGC implemented in developed countries includes load frequency control (LFC), economic dispatch (ED) and interchange scheduling (IS). These are implemented as application programs in Energy Management System (EMS) software located in Energy Control Centers (ECC).

For CEB power system only LFC function can be applied as ED function mainly deals with optimal operation of thermal power plants. In Sri Lankan power system automatic control function can be implemented only in Hydro power stations.

The interchange scheduling (IS) is applicable to power system with many control areas. The CEB power system being small can be considered as a single area power system. When deregulation is implemented IS function will be necessary.

The implementation scheme for AGC is shown in Fig 6.7. The AGC function within SCADA/EMS will receive frequency, generations (MW) etc and signals through remote terminal units (RTUs).

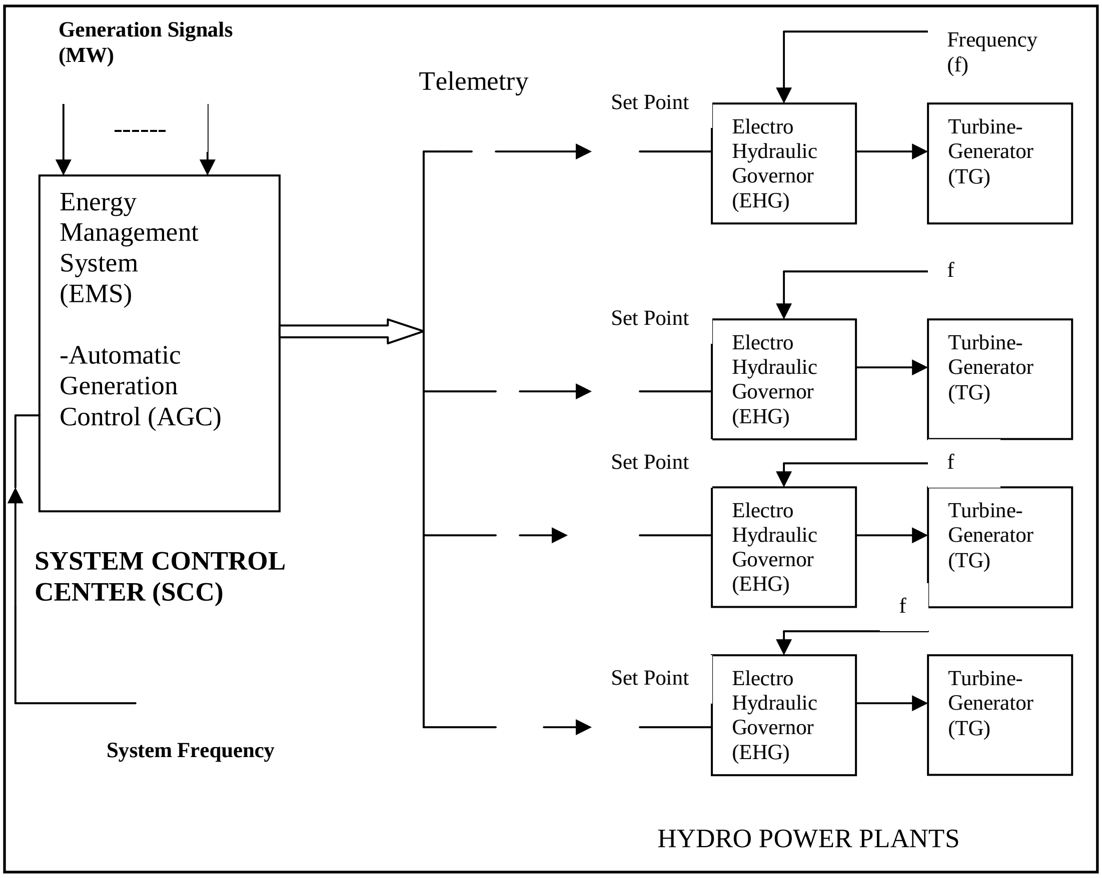


**Fig 6.7 Typical implementation scheme of Automatic Generation Control (AGC)**

When there is a frequency change, primary control action is performed by the governors of prime movers. After few seconds, Secondary Control function by Automatic generation controller (AGC) is initiated. AGC computes the set point changes required to restore the frequency to the set value and issues commands to participating generating units.

**Area Control Error (ACE)**

AGC acts on what is called Area Control Error (ACE) which is defined below:

$$ACE = \Delta \text{ Net Interchange} + \beta (\Delta f)$$

$\Delta$ Net Interchange = Interchange error = Scheduled – Actual

$\Delta f = \Delta \omega$ = frequency deviation

$\beta$ = frequency bias ( pu MW/ pu frequency)

The basic idea is when ACE> 0 generation is decreased and ACE<0 generation is increased.

The change in power reference settings ($\Delta$Pref ) is calculated using integral control ( or Proportional integral control) as:

$$\Delta P_{ref} = - K_i \int ACE \, dt$$

At steady state $\Delta P_{ref}$ must become constant and ACE=0. Then necessarily $P_{ref}=\Delta P_l$ (change in load). Integral control with stable gain $K_i$ guarantees zero error.

Where interchange scheduling is also involved, at a later stage in CEB power system, the scheme is shown in Fig 6.8.

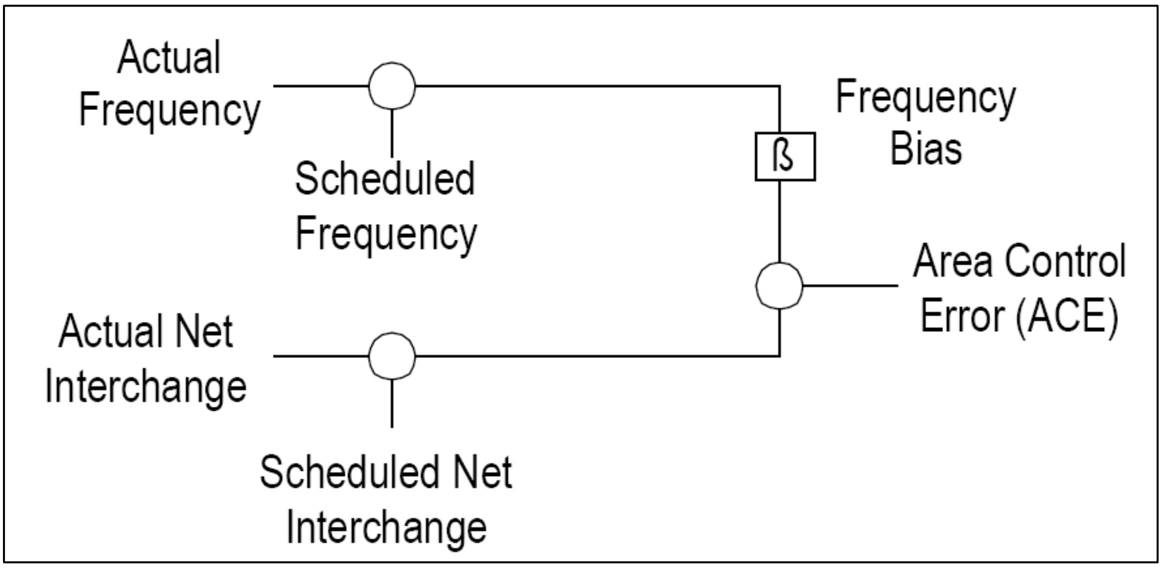


**Fig 6.8 Area Control error (ACE) in Automatic Generation Control (AGC) of multi-area system**

## 6.7 Frequency Control with Renewable Energy Sources

Apart from major hydro and thermal fired power stations, CEB power system has plans to enhance the share of non-centrally dispatched power sources like wind and small hydro. There is a pilot wind power project of 3 MW capacity and several proposals are under consideration. Sri Lanka has more than 110 MW of mini hydro connected to the grid, mostly owned by small power producers (SPPs).

**Penetration level of wind and mini hydro sources**

In any power system there is a maximum load deviation that can be sustained by the load frequency control system. It can be expressed approximately as:

$$\Delta P = P_{rated} \cdot \left( \frac{\Delta f_{max}}{f_{rated} \cdot S} + \frac{\Delta f_{max} \cdot D}{f_{rated}} \right)$$

Where $\Delta P$ = maximum load deviation
$P_{rated}$ = rated power
$\Delta f_{max}$ = maximum permissible frequency deviation from the rated value
$f_{rated}$ = rated frequency (50 Hz)
S = governor's droop parameter
D = load damping constant

[Source: Vladimir Chuvychin, Antans Sauhats, Vadims Strelkovs, Ref. 10.]

For typical values of Prated = 100; Δfmax = 0.2 Hz; D = 1.6; S = 0.05, the value of ΔP is 8.6%. The system can sustain a maximum load change of 8.6% keeping the steady state frequency deviation within maximum permissible value of 0.2 Hz.
So the penetration level possible is 8.6%.

Penetration levels of 20% are already reached in Denmark.

However wind penetration affects the load frequency control, apart from voltage control due to the intermittent nature of wind energy and also due to the absence of inertial response. Supplementary control systems are to be introduced in the LFC or AGC and sufficient reserve capacities are to be ensured for stable operation.

In CEB power system, penetration level of more than 10% is not expected in the next few years. However for future power system scenarios beyond 2016, it is suggested that advanced control schemes using storage devices be used for frequency regulation.

A possible AGC scheme for future power system is given in Fig. 6.9 where Automatic Storage Control (ASC) like advanced batteries and flywheels and Automatic Load Control (ALC) devices based on power electronics devices can be used for frequency regulation under AGC.

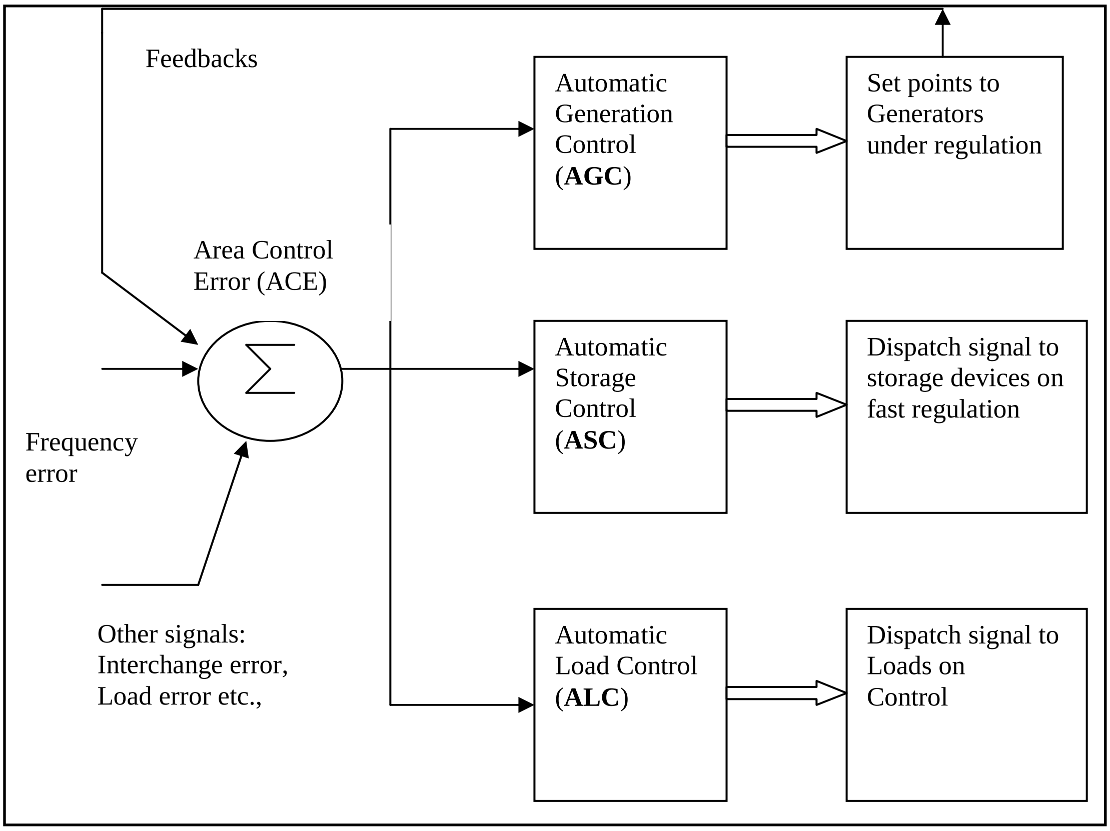


**Fig 6.9 Frequency regulation scheme with generation control storage control and load control**

## 6.8 Recommendations

The frequency control practice suggested for future power system up to 2020 is to incorporate Automatic Generation Control (AGC) which is also referred as Load Frequency Control (LFC).

It is understood that CEB is upgrading the System Control Center in which Fichtner has prepared the feasibility report suggesting the incorporation of Load Frequency Control in the SCADA / Energy Management System (EMS).

AGC function may only act on the hydro power plants with electronic governors and sufficient spare capacity should be available.

When the penetration levels of wind, mini hydro and other power systems increase, it is recommended to enhance the Automatic Generation Control (AGC) system by including Automatic Storage Control (ASC) with batteries and fly wheel and also Automatic Load Control (ALC) using power electronics devices.

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# Chapter – 7

# VOLTAGE CONTROL: LOAD FLOW AND DYNAMIC SIMULATION STUDY

## 7.1 Load Flow Studies:

The following Load Flow Studies are performed on the base-case CEB System for *a typical Day: (24th June, 2009] :*

(i) Day – Peak : Hydro Max
(ii) Day – Peak: Thermal Max
(iii) Off – Peak: Hydro Max
(iv) Off – Peak: Thermal Max
(v) Morning – Peak: Hydro Max
(vi) Morning – Peak: Thermal Max
(vii) Night – Peak: Hydro Max
(viii) Night – Peak: Thermal Max

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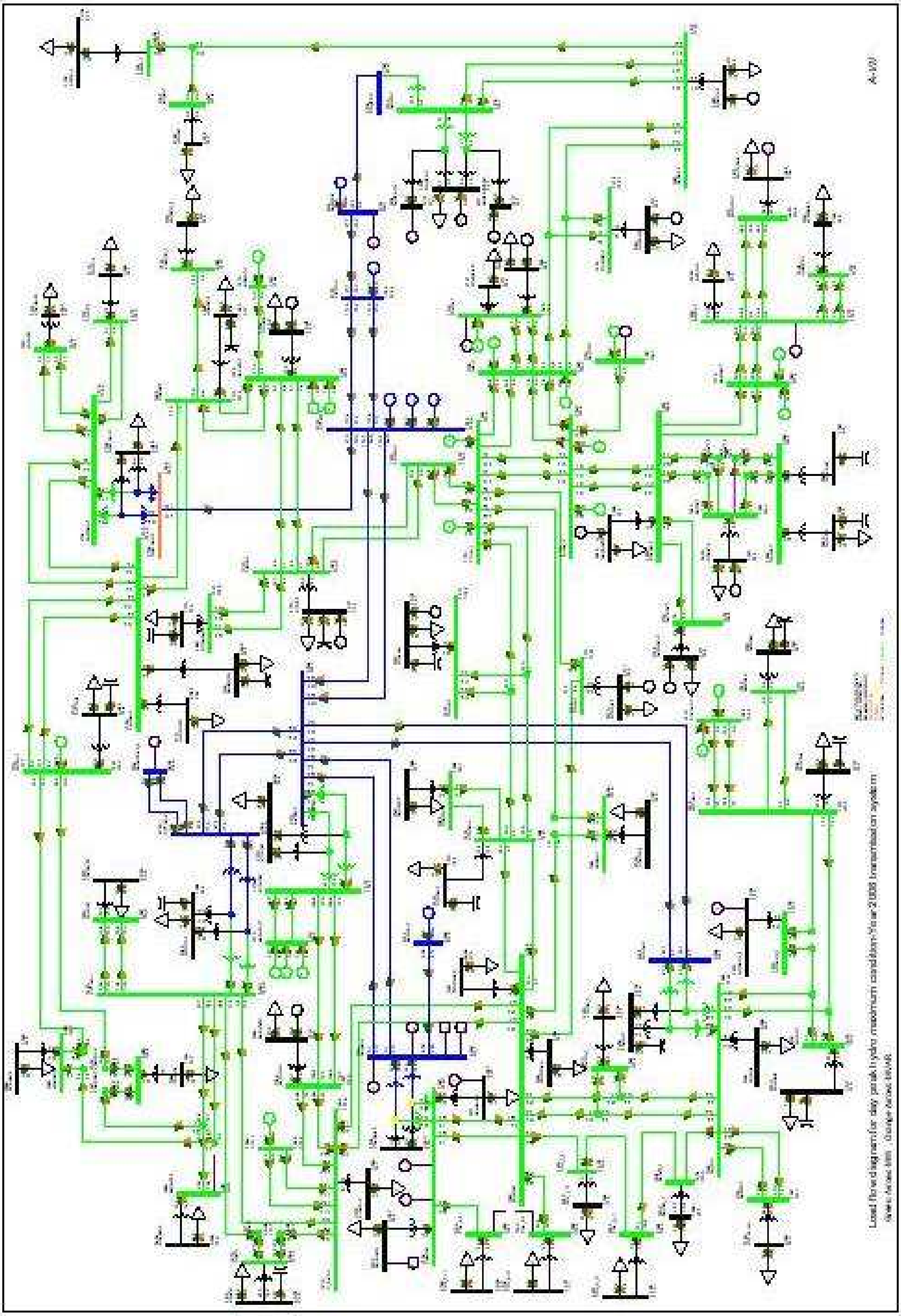
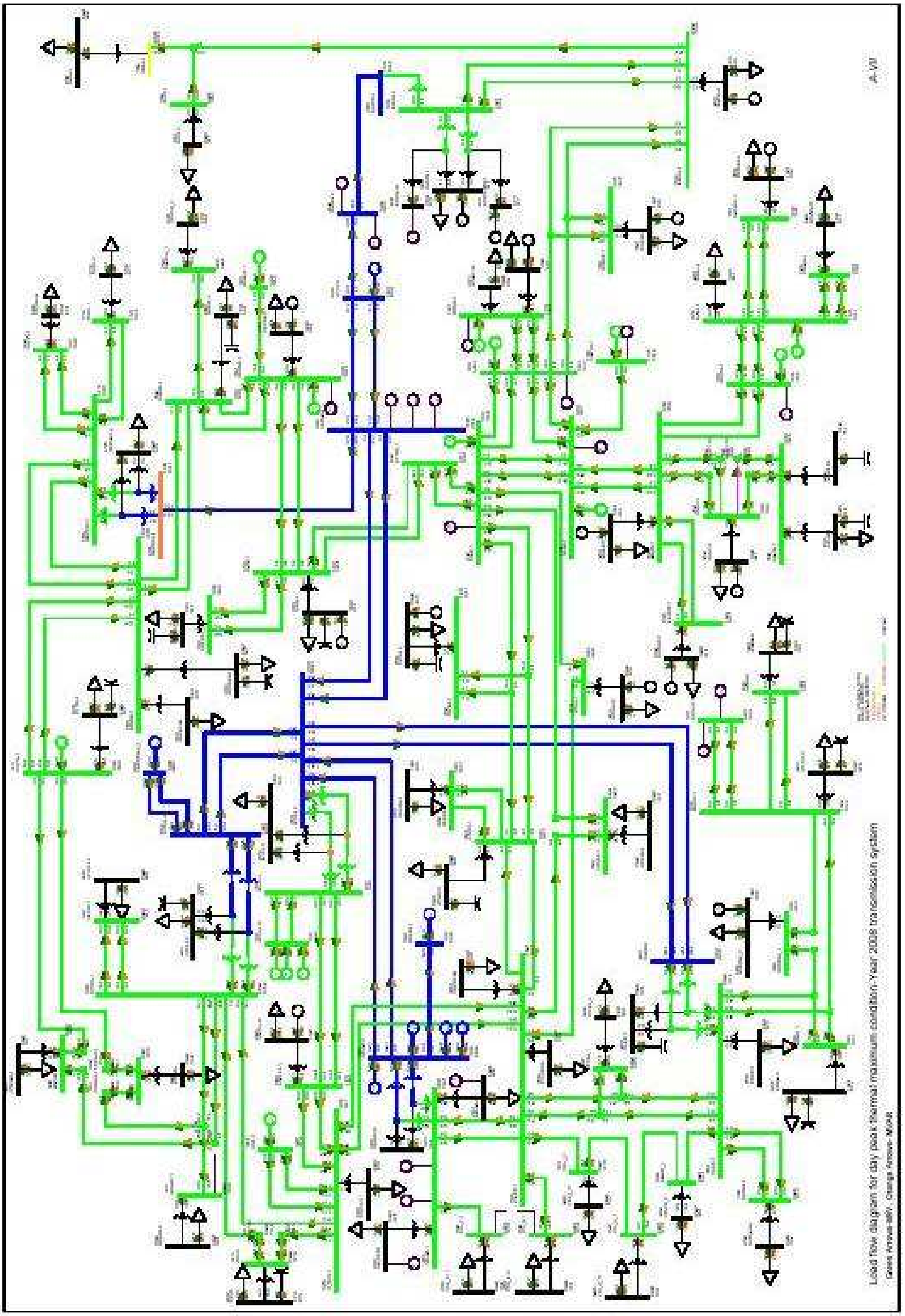
| Inconvenience caused by the following eight illegible images is highly regretted. Legible images will be incorporated in subsequent reprints. |

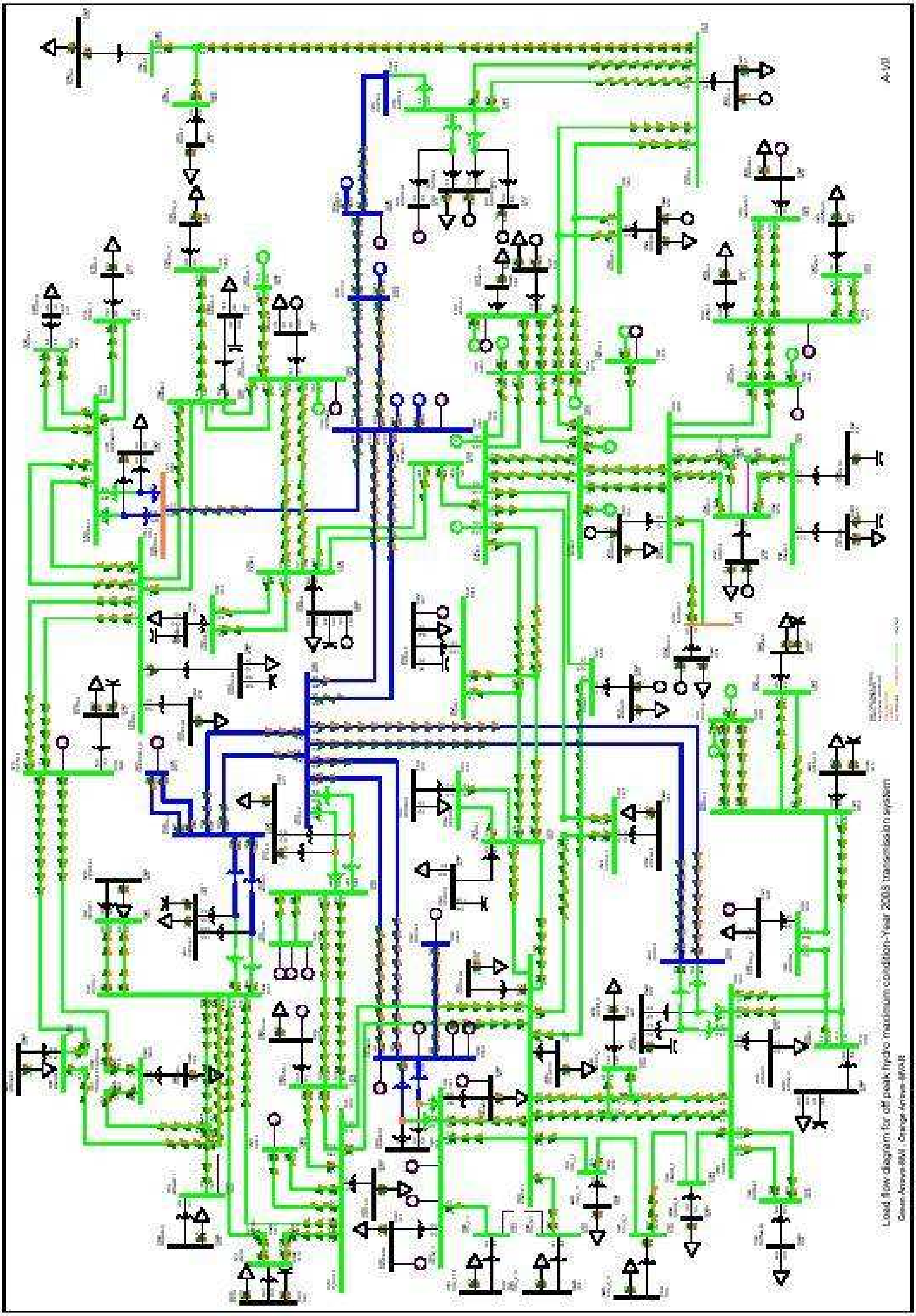
(i) Day – Peak : Hydro Max



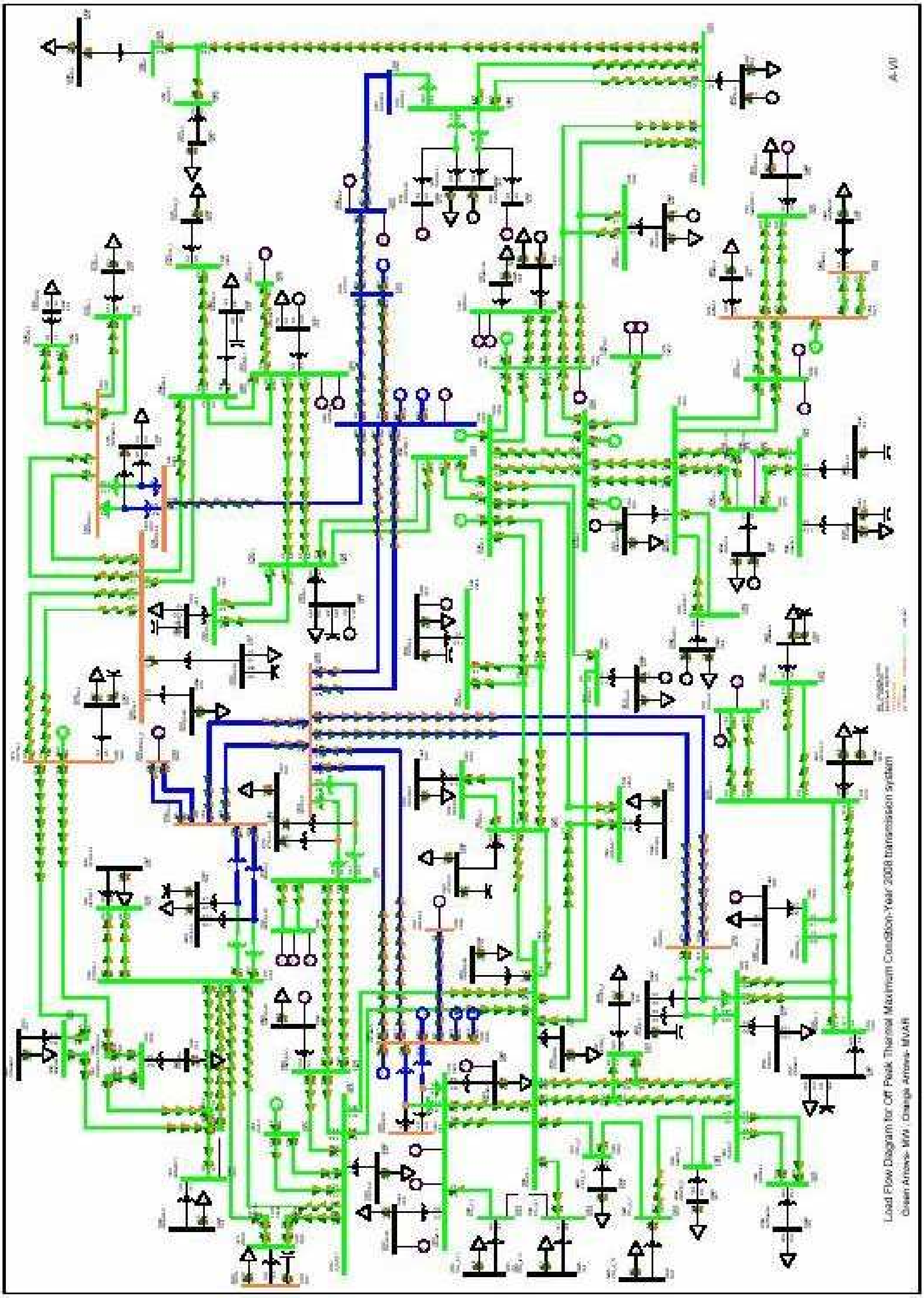
(ii) Day – Peak: Thermal Max



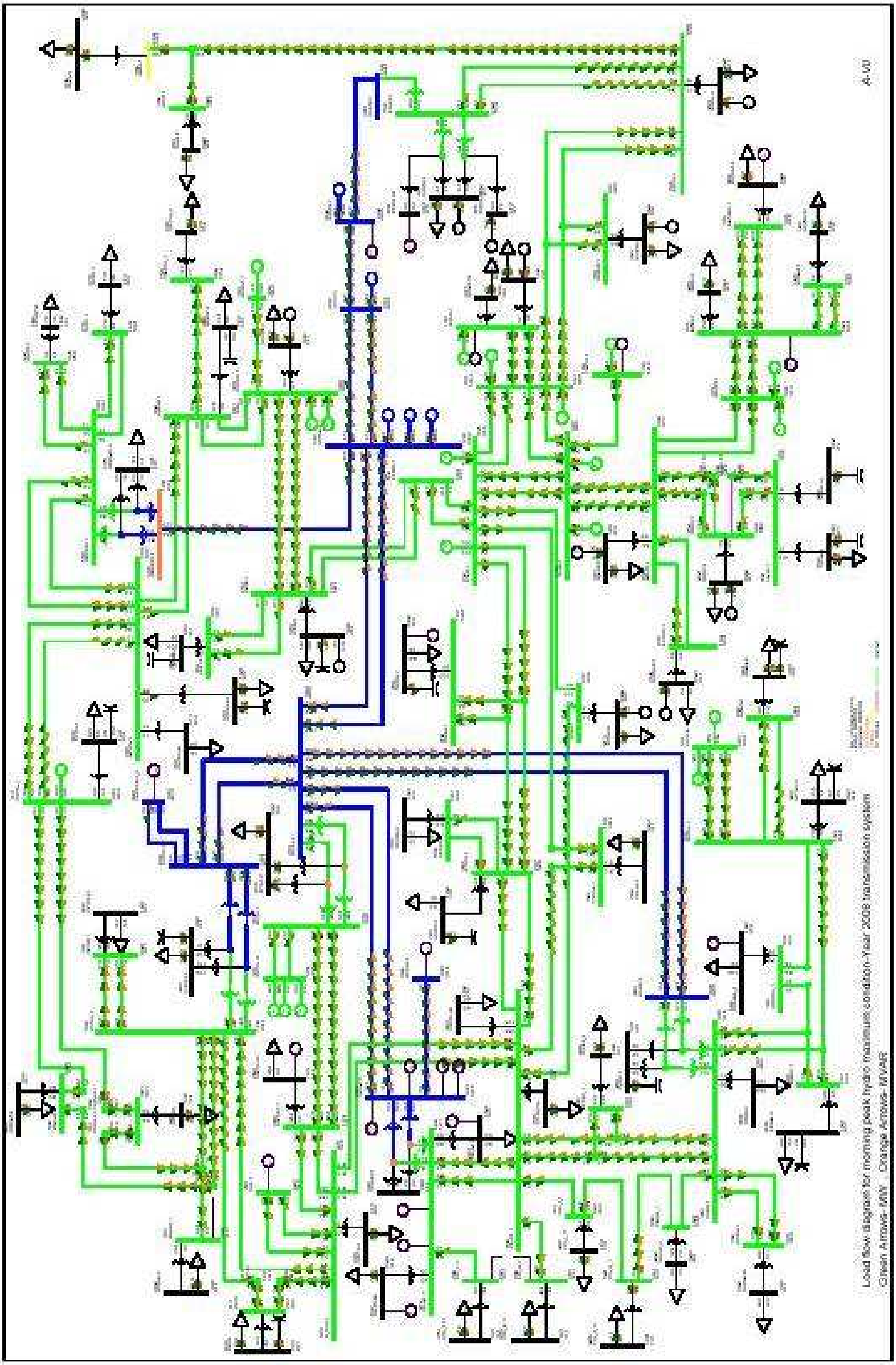
(iii) Off – Peak: Hydro Max



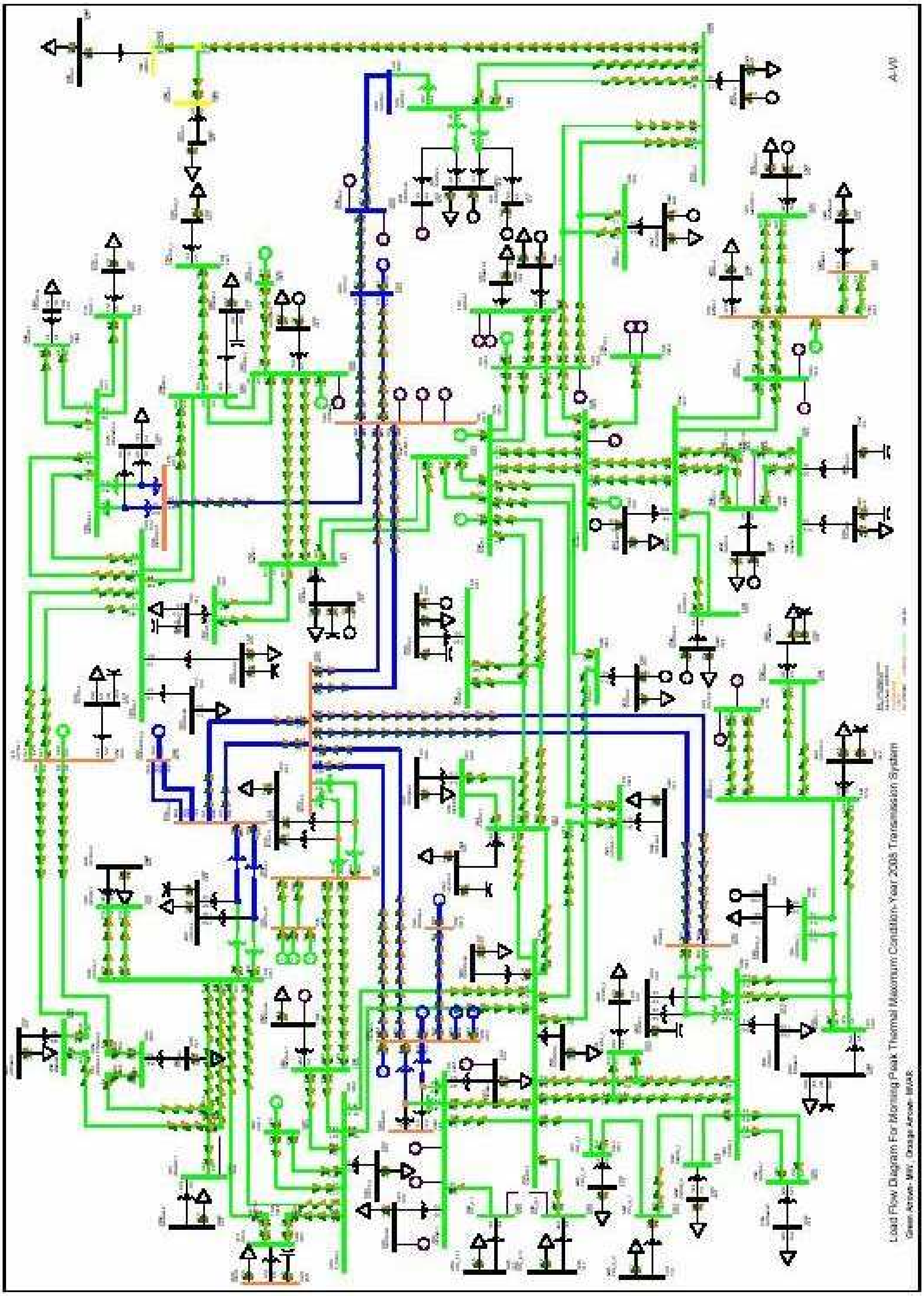
(iv) Off – Peak: Thermal Max



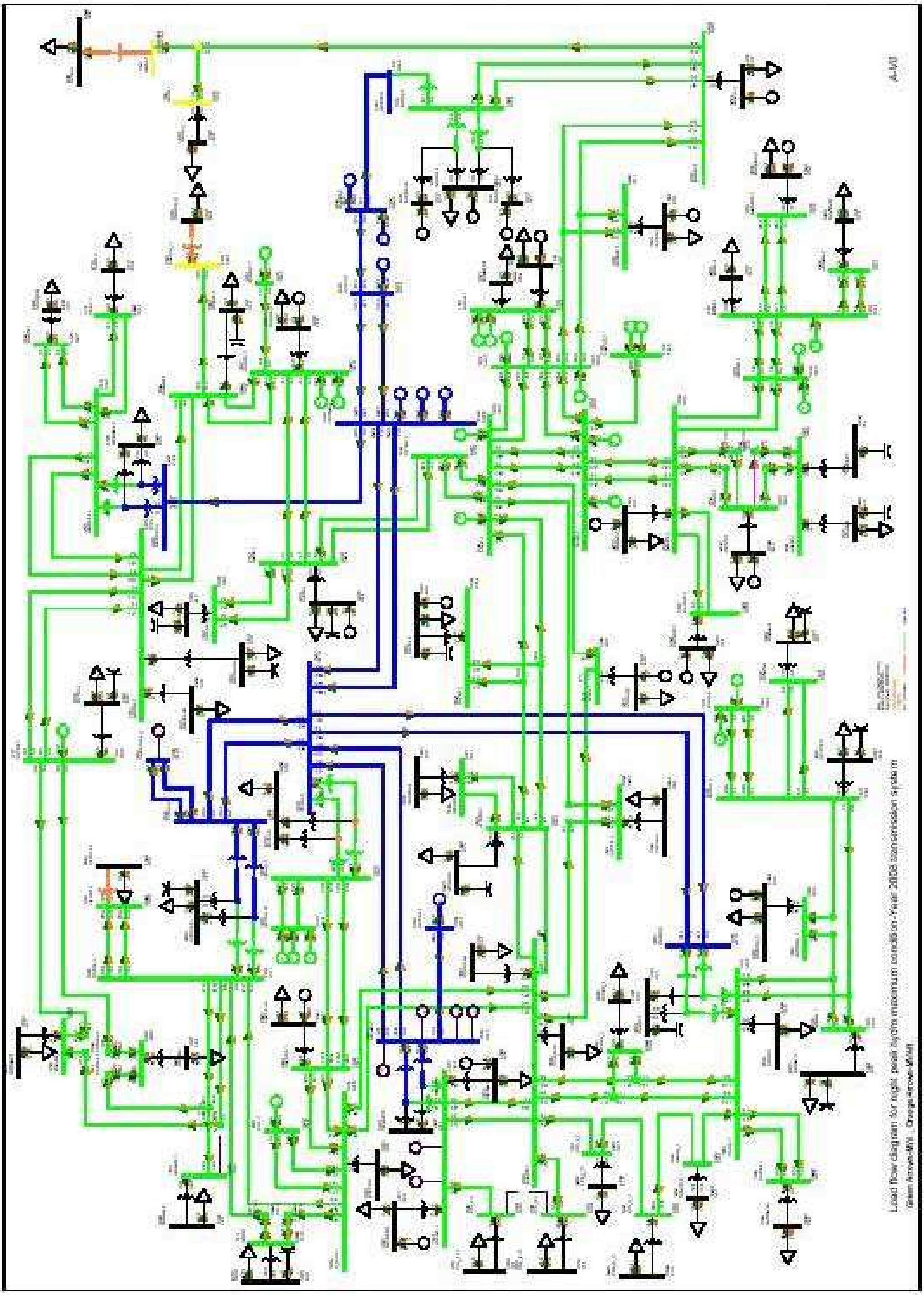
(v) Morning – Peak: Hydro Max



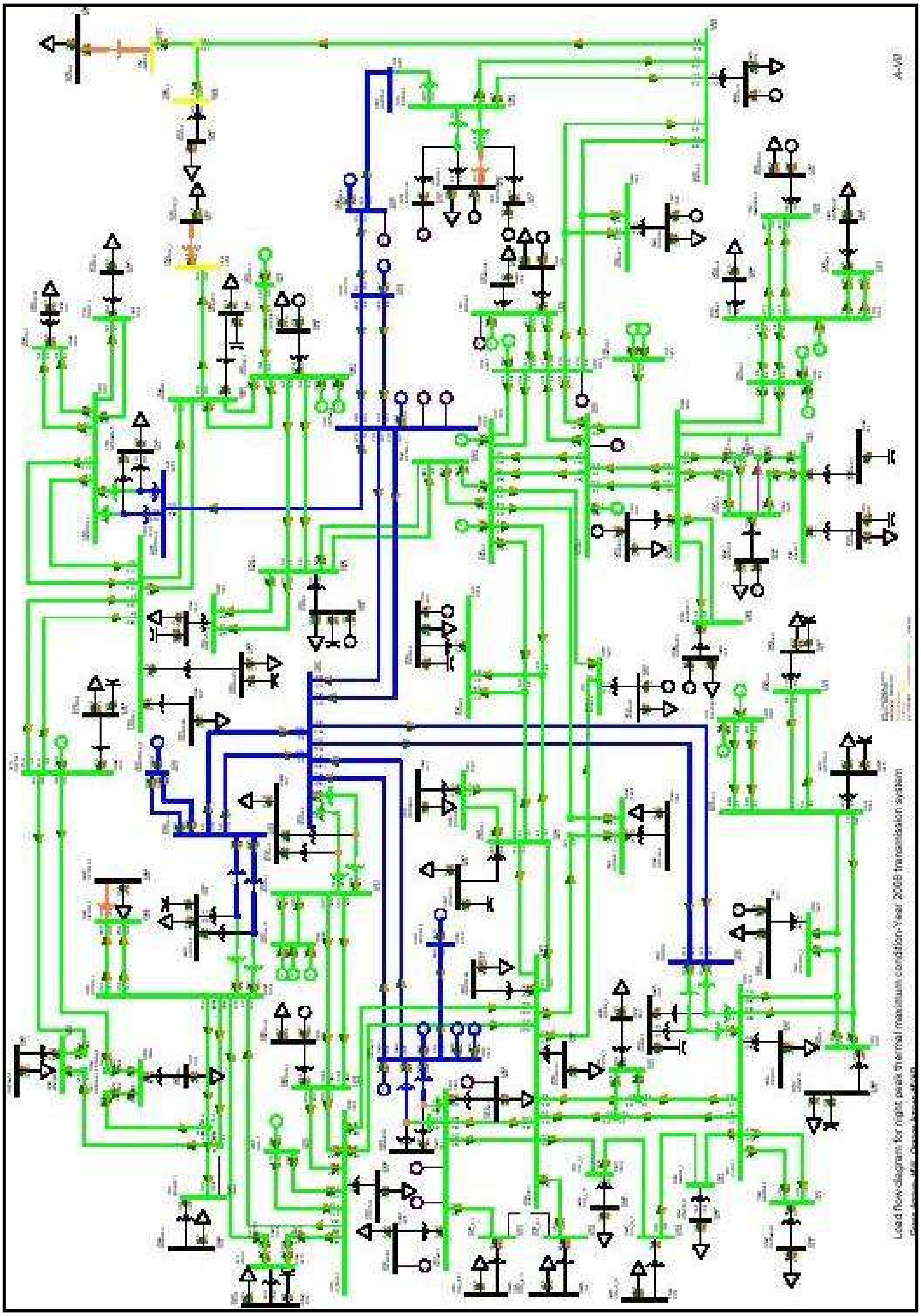
(vi) Morning – Peak: Thermal Max



(vii) Night – Peak: Hydro Max



(viii) Night – Peak: Thermal Max



**Existing Planning Criteria in CEB:**

In order to ensure quality and a reliable supply of electricity, CEB plans to operate the transmission network as given below:

***Voltage:***

(i) Normal operating range :

220KV: +/ - 5%; 132KV: + / - 10%; 33KV: + / - 1%

(ii) Single Contingency Condition :

220KV: - 10% to + 5%; 132KV: + / - 10%; 33KV: + / - 1%

However, at present, it is observed that the CEB transmission network experiences the following variations in system parameters:

(iii) Normal operating range :

220KV: + / - 10%; 132KV: + / - 10%

(iv) Short term variations :

220KV: - 16% to + 12% for 5 seconds;
132KV: - 16% to + 12% for 5 seconds.

**Minimum System Voltages (during a typical month):**

Lowest Recorded during the month:

132KV level: 107KV at 2000 hrs.
220KV level: 195KV at 2100 hrs.

Lowest Recorded on the Day of the Maximum Night Peak:

(a) At the time of Day Peak: 1100 hrs.

level: 113KV; 220KV level: 210KV.

(b) At the time of Night Peak: 1930 hrs.

132KV level: 108KV; 220KV level: 211KV.

## 7.2 Dynamic Simulation Studies

The following Simulation Studies are performed:

### (A) Tuning of Excitation AVR Parameters :

#### (i) Sample Example – 1 :

A small sample system with two generating units, three buses, two loads and six lines is considered for simulation using PSS/E software modules. Following the disconnection of one of the load buses , variations of bus terminal voltages are obtained and plotted, for different values of AVR gain constant , K (K = 200, 150, 100, 80).

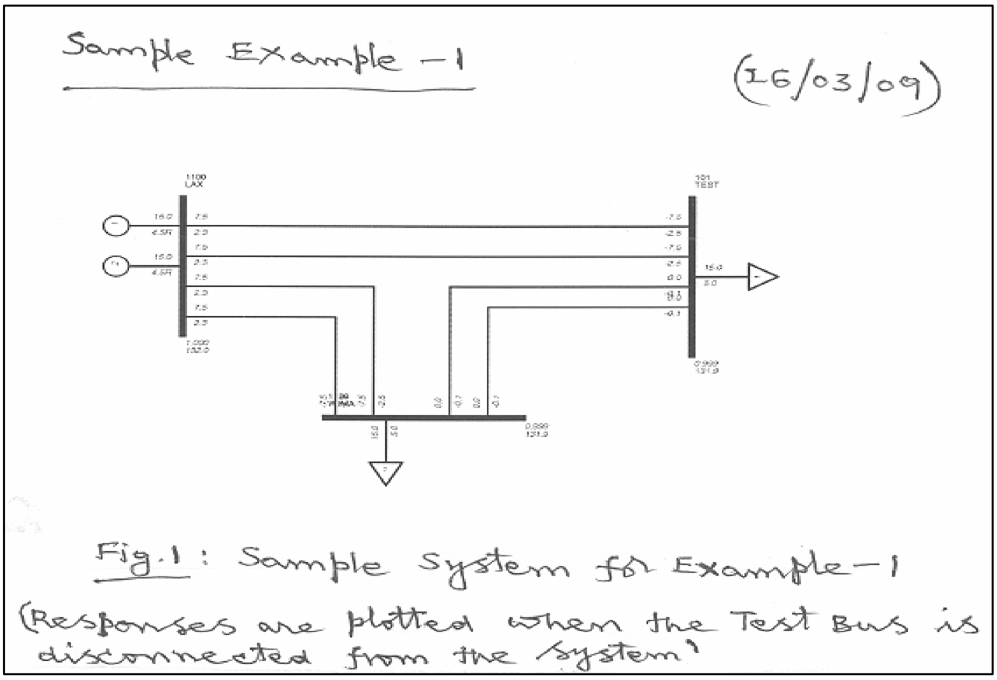



Fig.1 : Sample System for Example – 1
(Responses are plotted when the Test Bus is disconnected from the system)

***Observation:*** As the value of K is reduced, the transient peak value of voltage variation response has gradually increased with slow rate of transient decay.

#### (ii) Sample Example – 2 :

A small partial network of CEB system corresponding to Mahaweli Complex with 2 generating units (three units at Kotmale are combined into one equivalent machine and one unit at Victoria), 4 buses, 2 loads, and 5 lines (220 kv) is considered for simulation using PSS/E software modules. Disturbance is simulated by disconnecting the Rantembe bus from the network and the variations of terminal voltages of each of the two units are obtained and plotted, for different values of AVR gain constant, K (K= 200, 150, 100, 80) with the ratio of time constants ($T_A$ / $T_B$) = 0.1 and K=100 with ($T_A$ / $T_B$) = 0.

26/03/09

## Sample Example -2

Testing for Mahaweli Complex

Disturbance-Disconnecting the Rantembe Bus from the network and observe the behavuoir of Terminal Voltage of each machine for 5s.

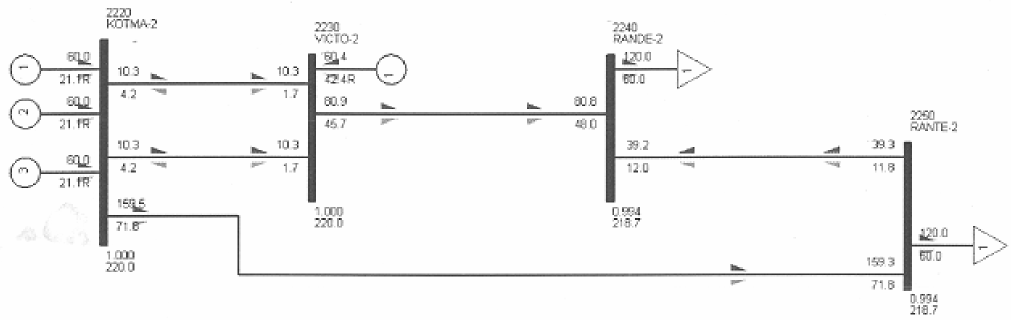



Fig.2: Sample system for Example -2.

***Observation:*** With ($TA/T_B$) taken as 0.1, and as the value of K is reduced, the rate of decay from the transient peak is slow. With ($TA/T_B$) changed from 0.1 to 0.0, the voltage variation response has become more oscillatory and takes more time to reach steady-state value.

**(iii) Simulations using MATLAB – Semolina on Sample Example :**

SMIB like Sample Example is considered for the study using the parameters similar to those of CEB system components. Machine is represented by:

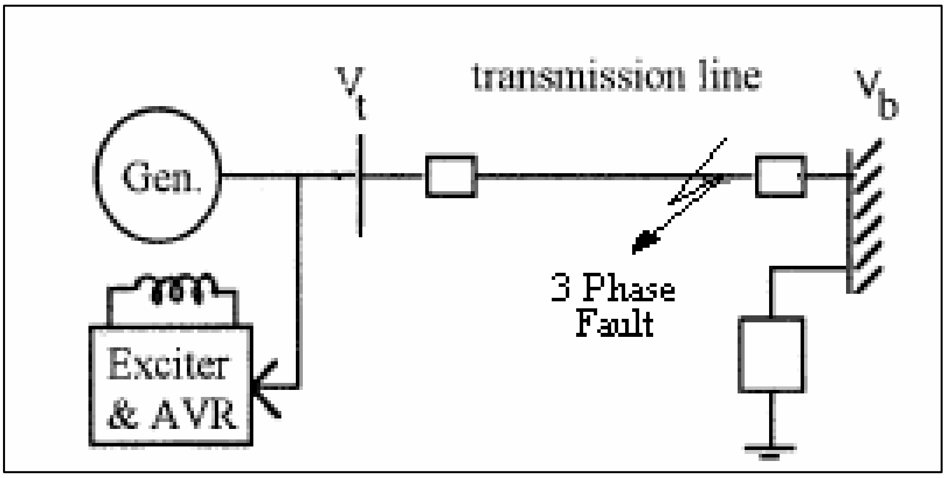
(a) Salient-pole type, corresponding to Hydro plant, and (b) Round-rotor type, corresponding to Thermal plant. The following two types of Excitation Systems are considered: (i) SEXS Model, and (ii) Excitation System Model available in MATLAB, which is similar to the standard model of IEEE Type 1 system.

Variations of the following parameters are considered: (a) AVR Gain, $K_{A,}$ and (b) Feedback gain, $K_{f.}$ The following responses are obtained and plotted:

Rotor Angle deviation, Speed deviation, Active Power, Reactive Power, and Terminal Voltage.

## a. Simulation Studies with 'SEXS'

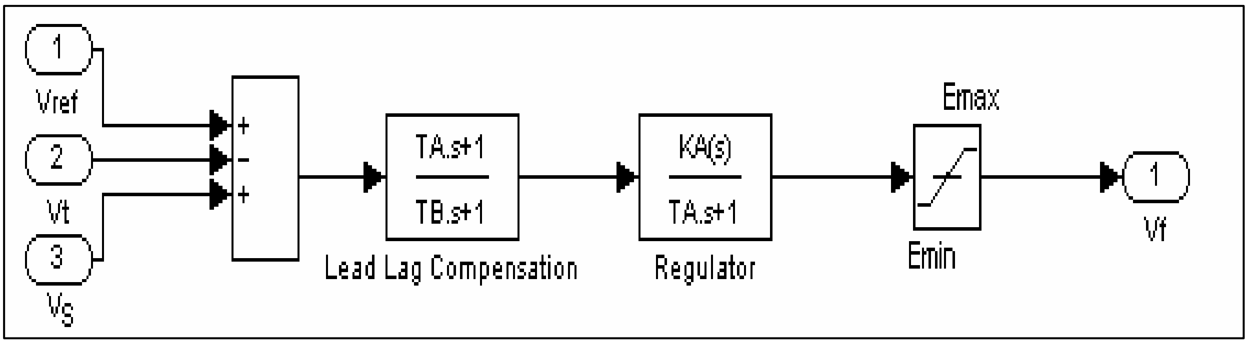
The following is the line diagram of Synchronous generator connected to infinite bus. The transient responses have been obtained for variation in $K_A$ from 50 to 400 of SEXS type excitation system.




**Machine Data:**

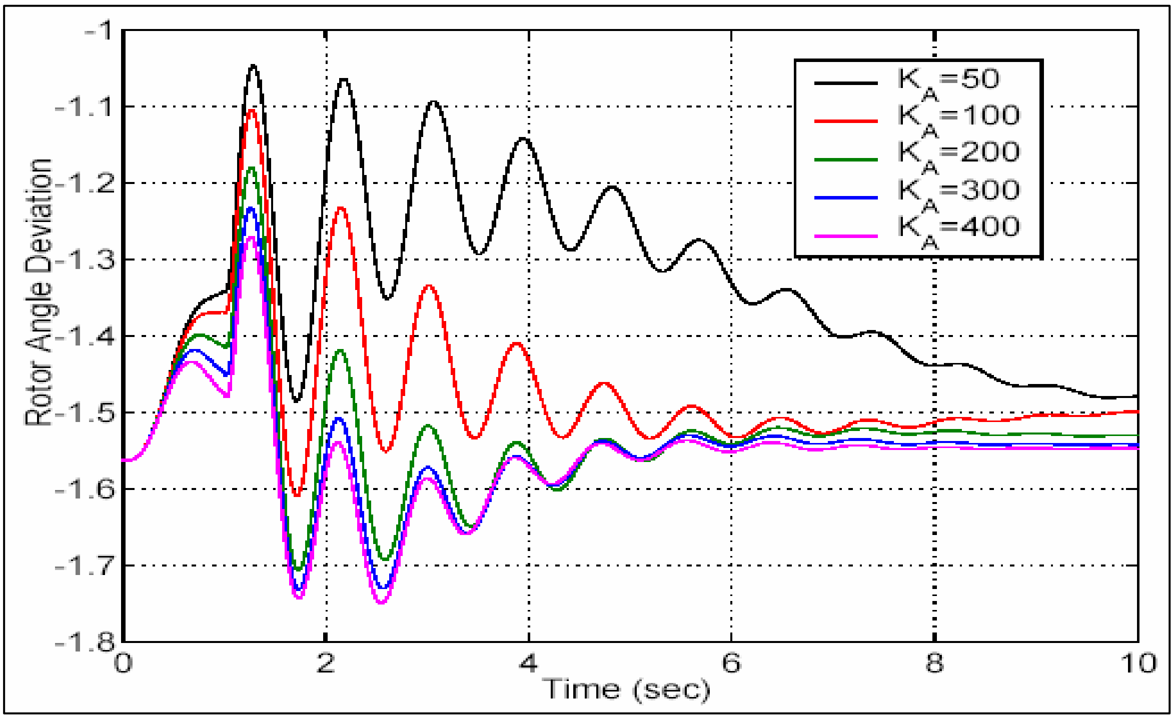
| M/C Data | VICTO | KELAN |
|---|---|---|
| $T'_{do}$ (>0) (sec) | 6.7 | 6.85 |
| $T''_{do}$ (>0) (sec) | 0.051 | 0.032 |
| $T''_{qo}$ (>0) (sec) | 0.11 | 0.16 |
| Inertia, H | 4.3 | 4.5 |
| Speed damping, D | 0.5 | 0.5 |
| $X_d$ | 1.03 | 1.75 |
| $X_q$ | 0.63 | 1.72 |
| $X'_d$ | 0.29 | 0.27 |
| $X''_d = X''_q$ | 0.165 | 0.16 |
| $X_l$ | 0.1 | 0.1 |
| S(1.0) | 0.03 | 0.03 |
| S(1.2) | 0.25 | 0.4 |

**'SEXS'(Simplified Excitation System)**

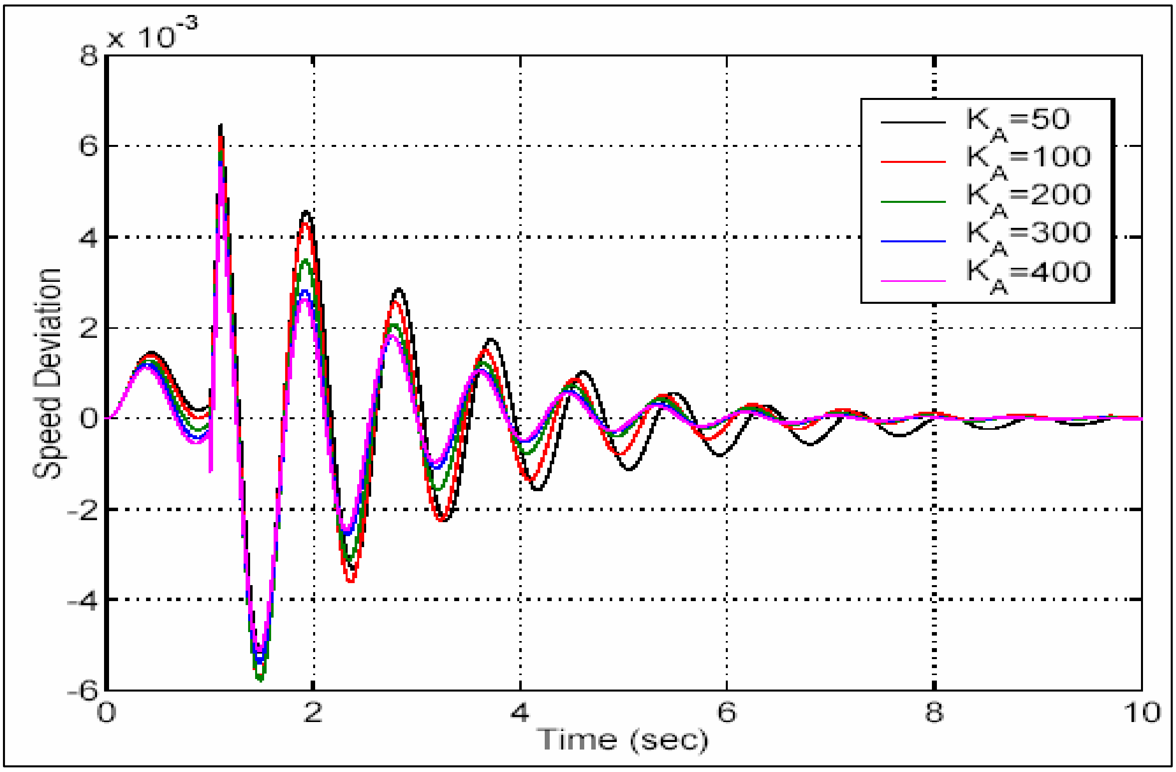


**Data:** Lead lag compensation
$T_A = 1$
$T_B = 10$
Regulator
$K_A$ varied from 50 to 400
$T_A = 0.05$

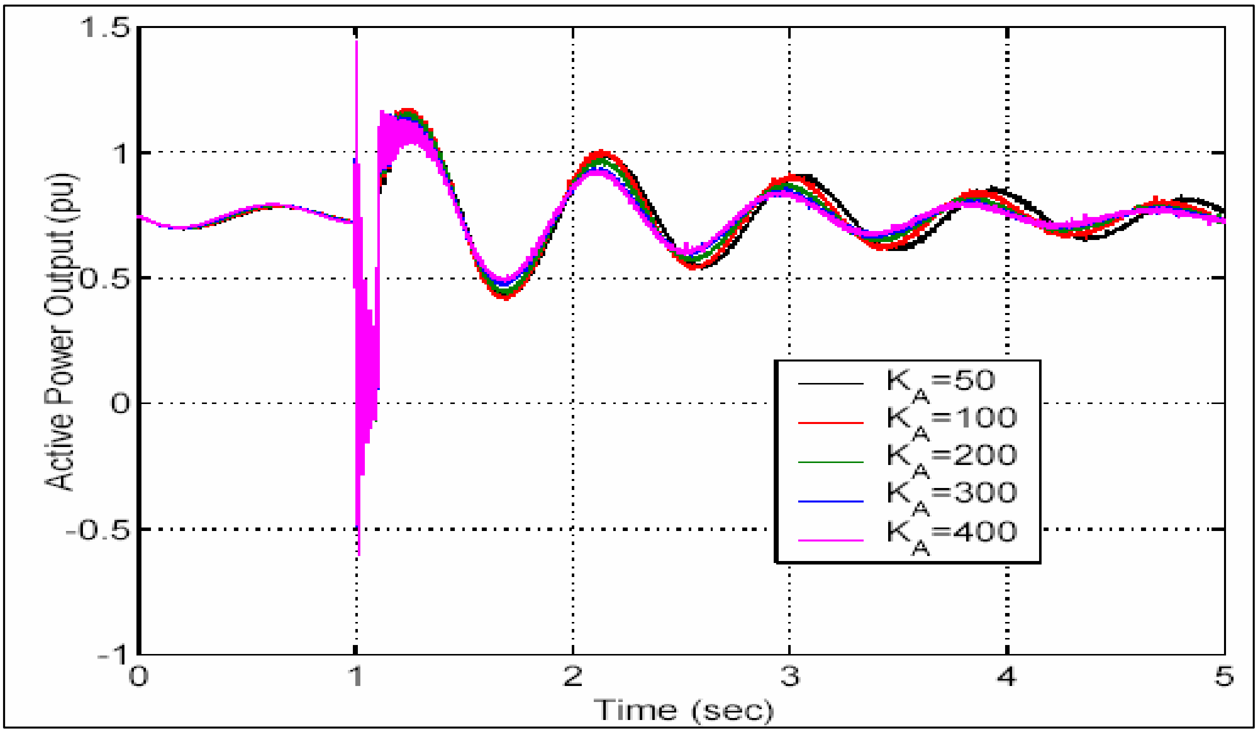
**Kelanitissa (Thermal): SEXS Model**



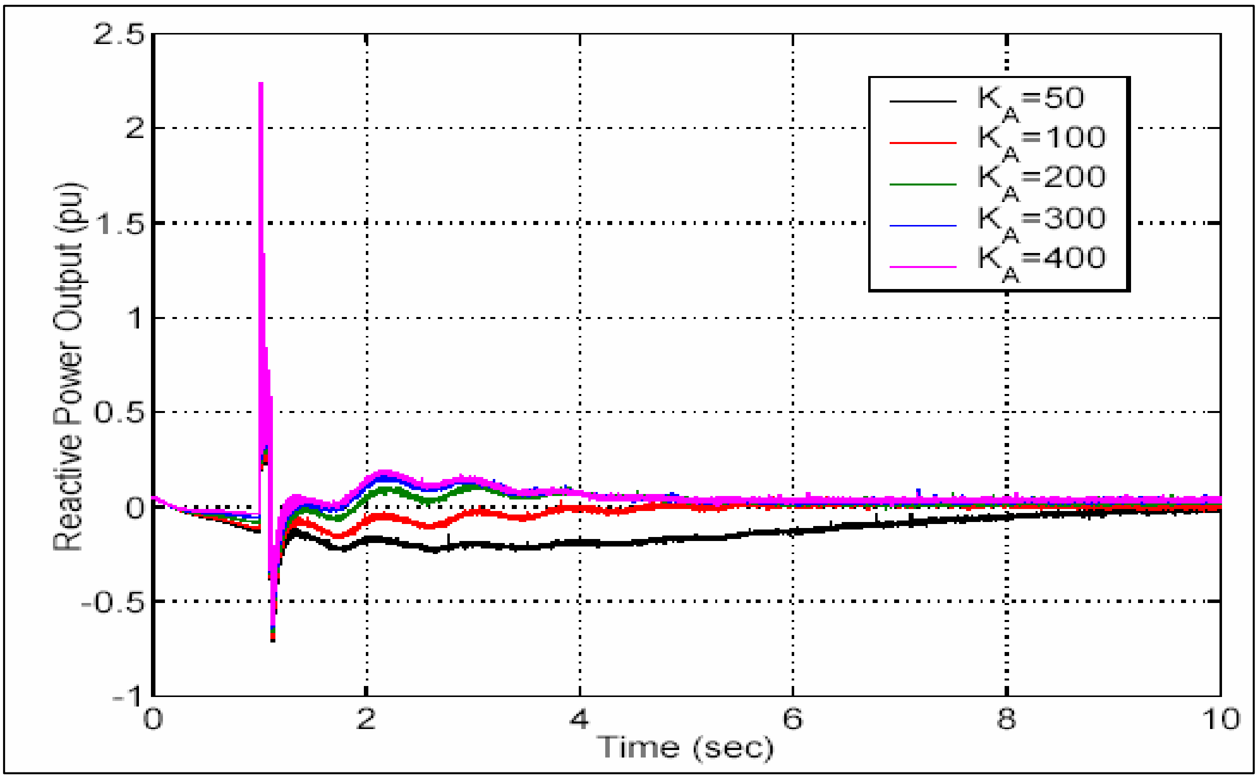

**Kelanitissa (Thermal): SEXS Model**



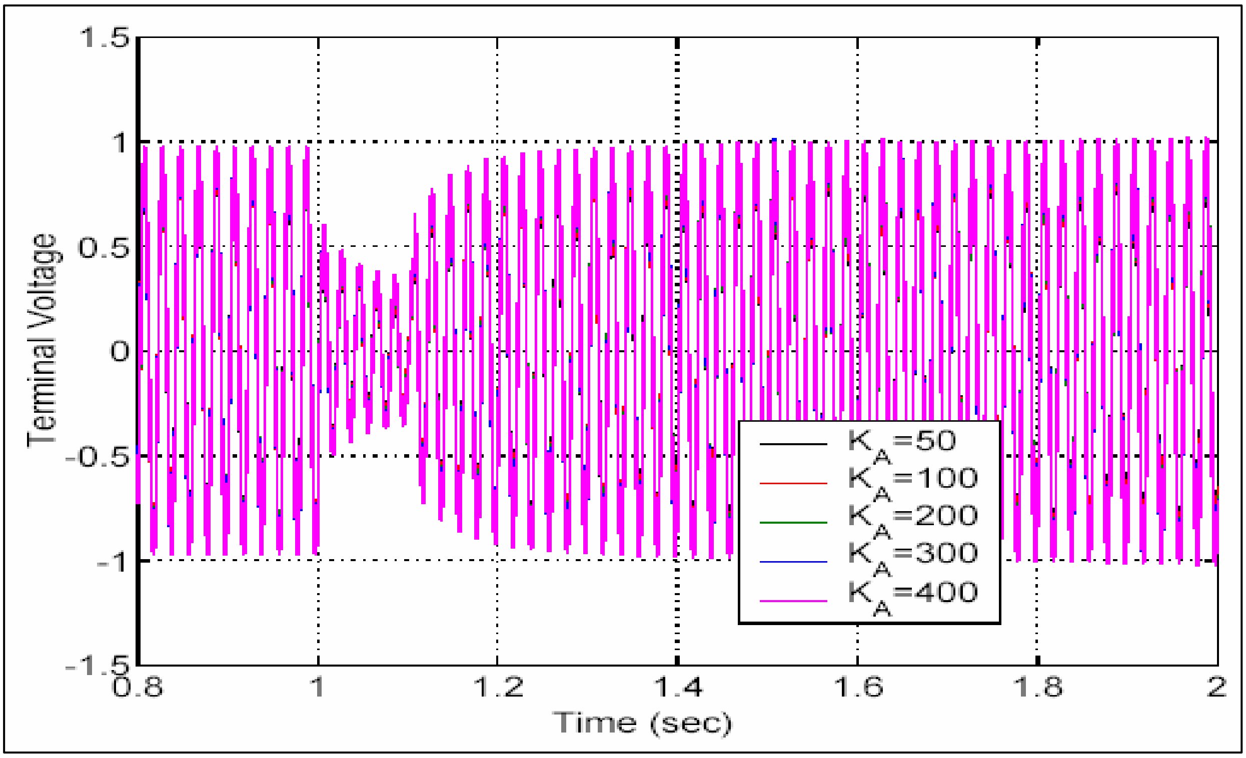
**Kelanitissa (Thermal): SEXS Model**



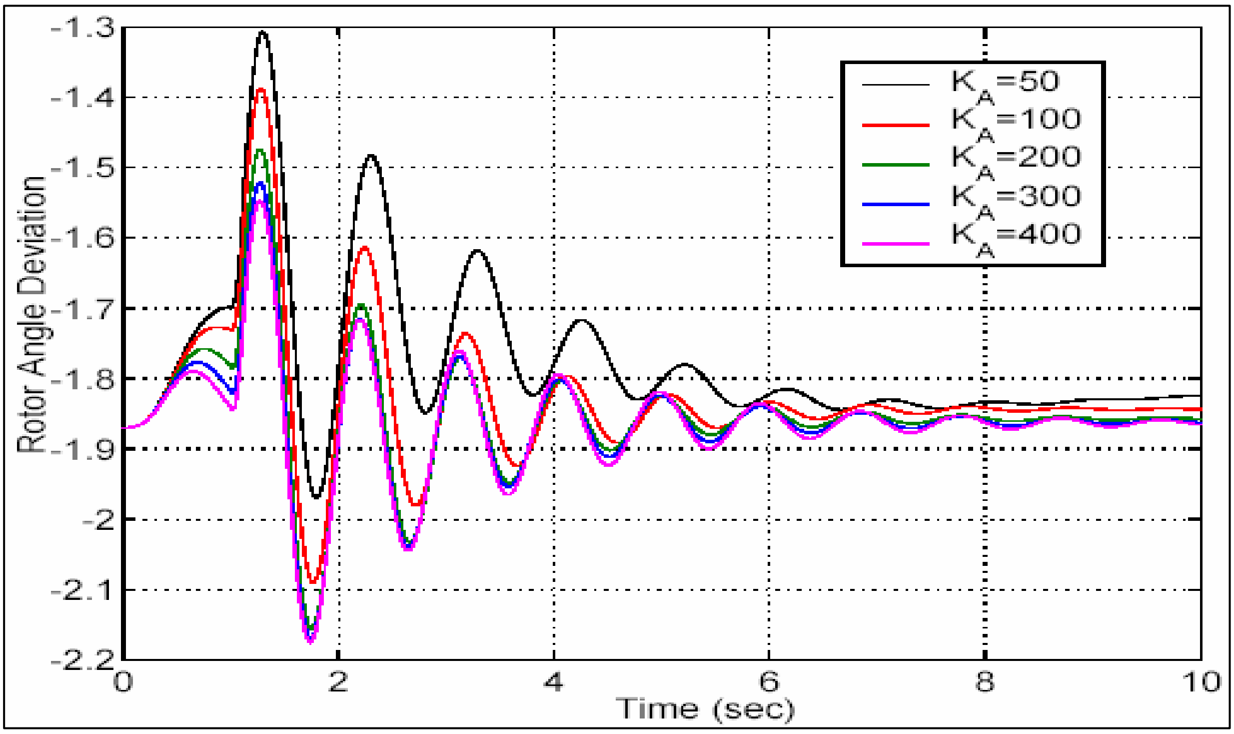

**Kelanitissa (Thermal): SEXS Model**



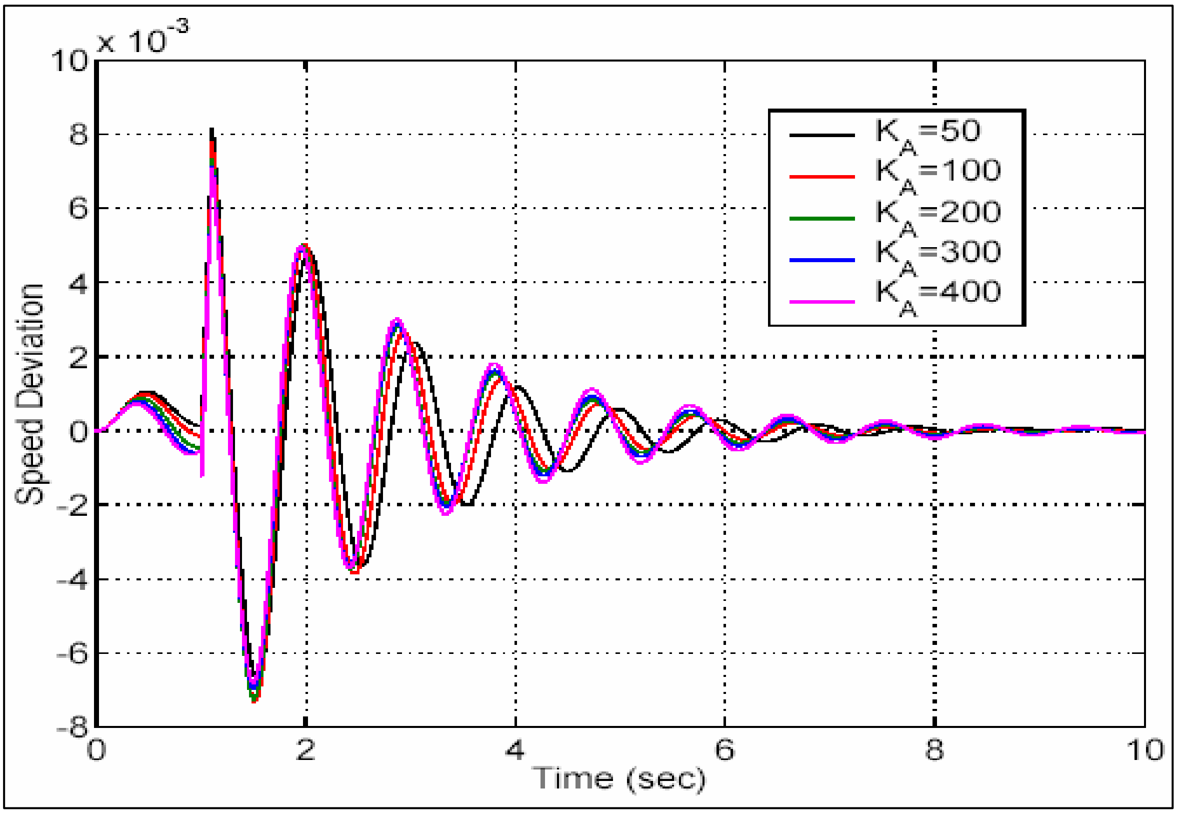
**Kelanitissa (Thermal): SEXS Model**



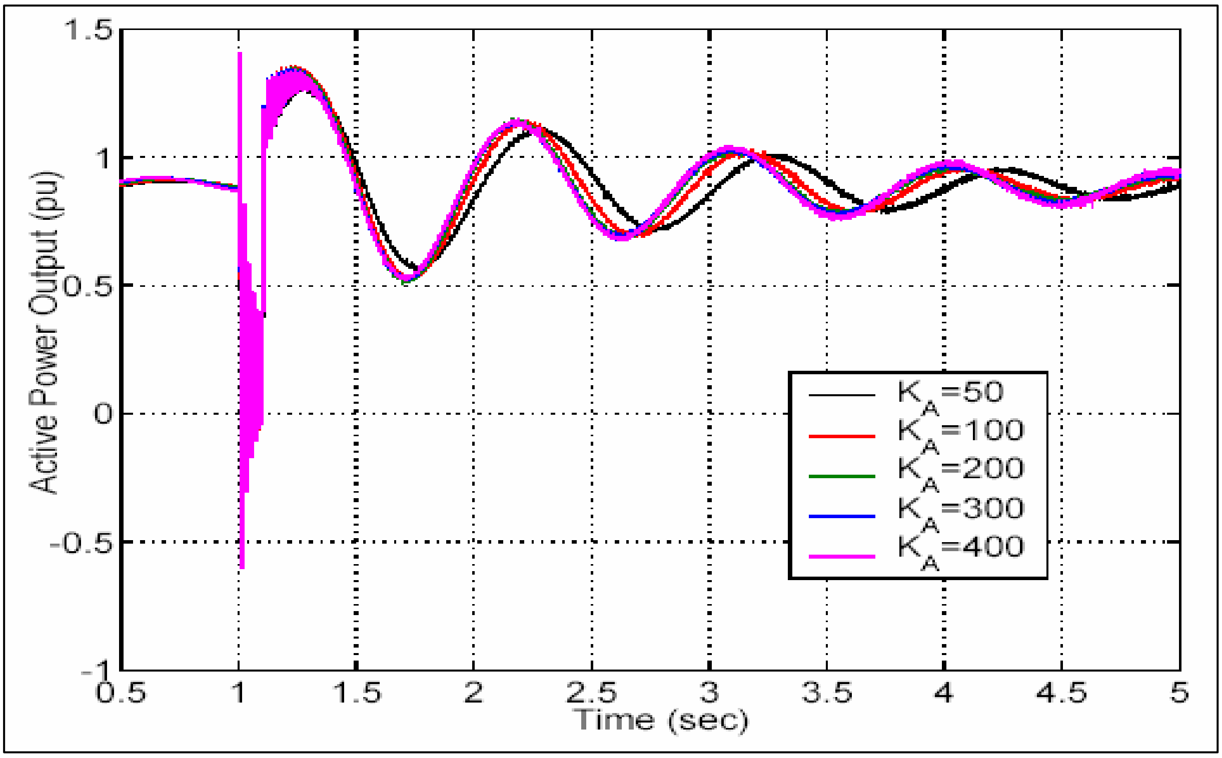

**Victoria (Hydro): SEXS Model**



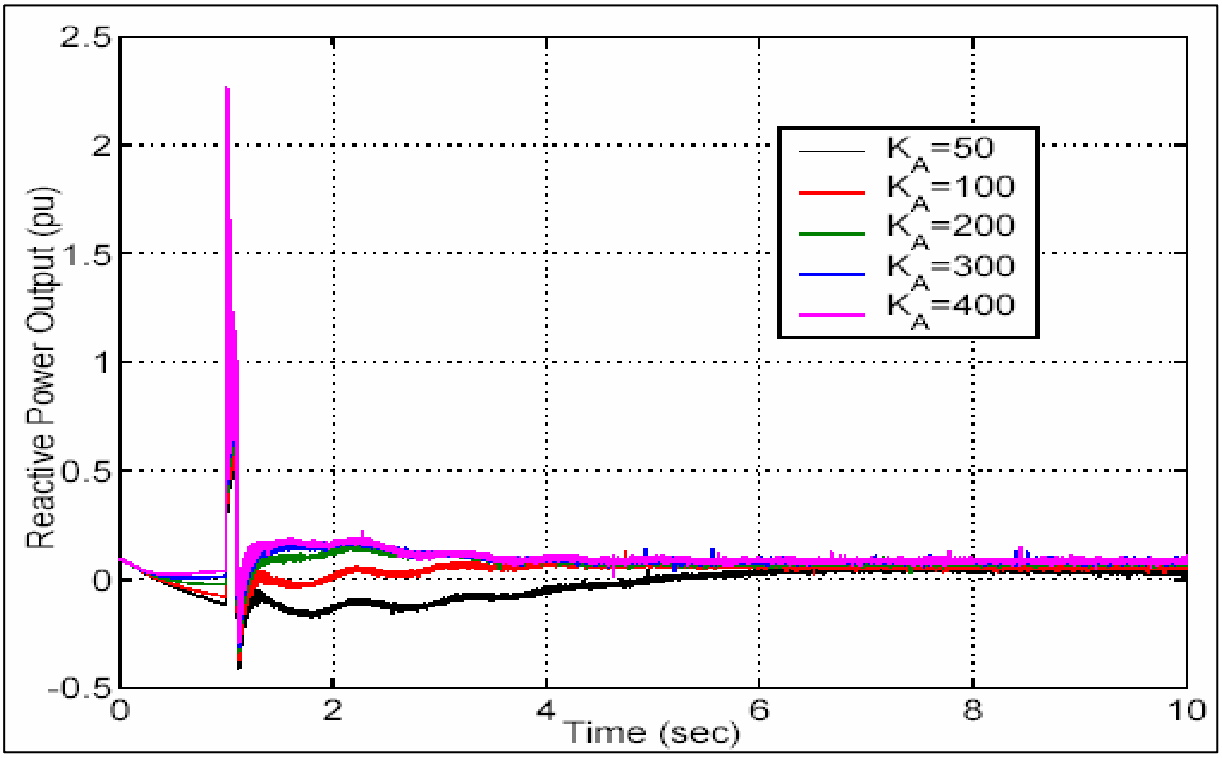
**Victoria (Hydro): SEXS Model**



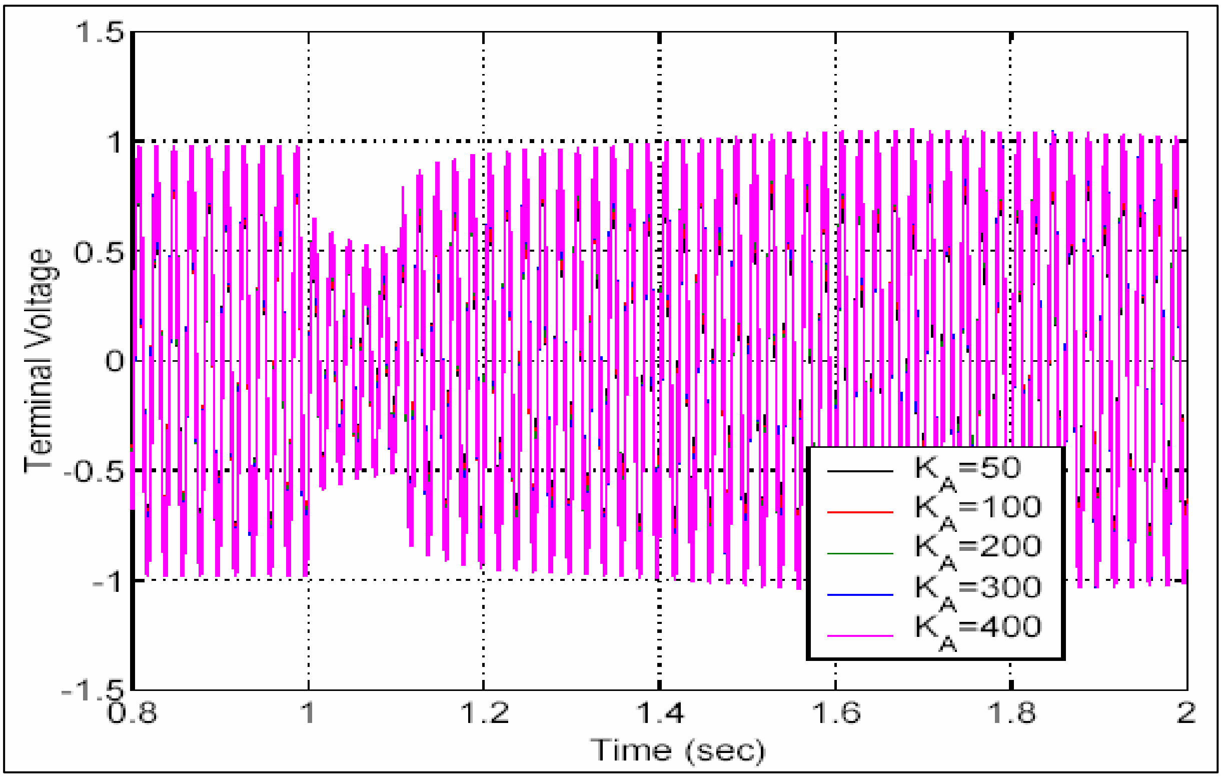

**Victoria (Hydro): SEXS Model**



**Victoria (Hydro): SEXS Model**

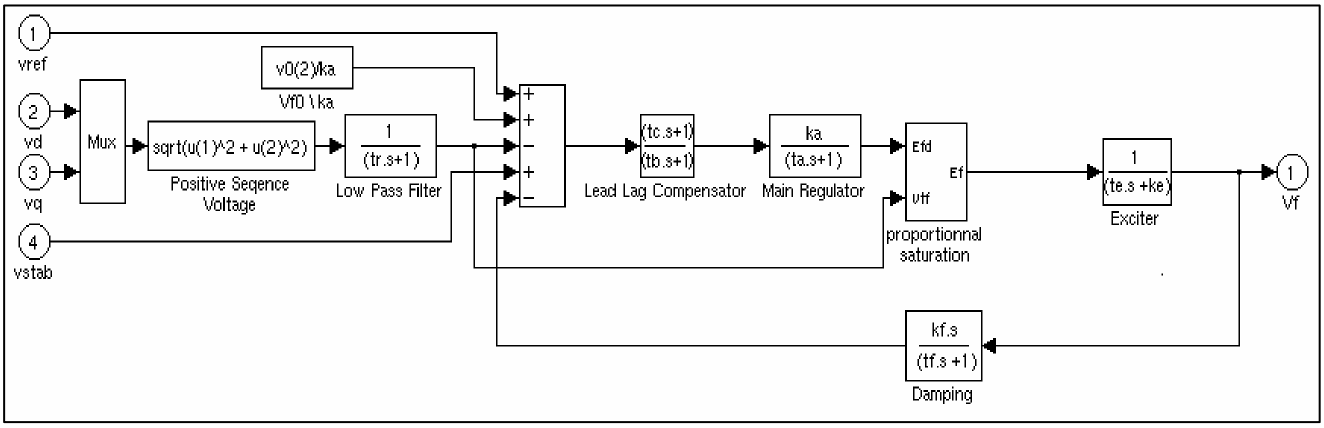



**Victoria (Hydro): SEXS Model**



## Simulation Studies with 'IEEE Type 1 like'

## IEEE Type 1 Excitation System

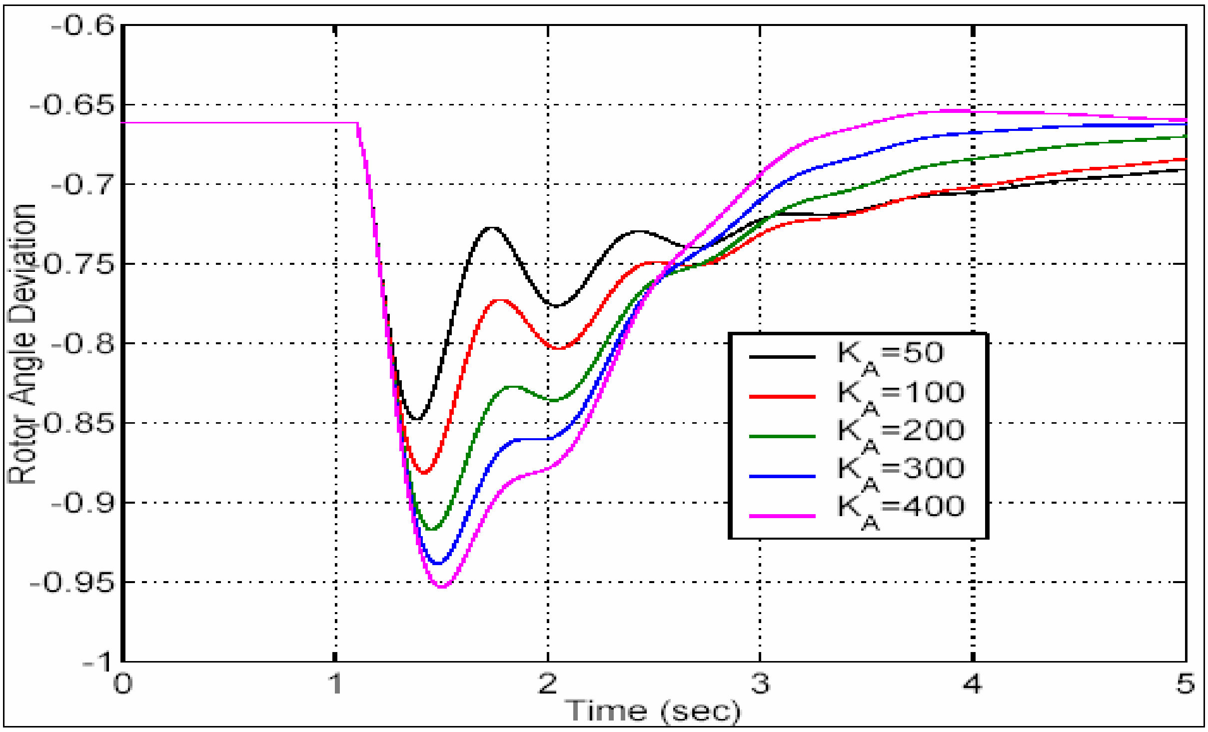



### Excitation System Data

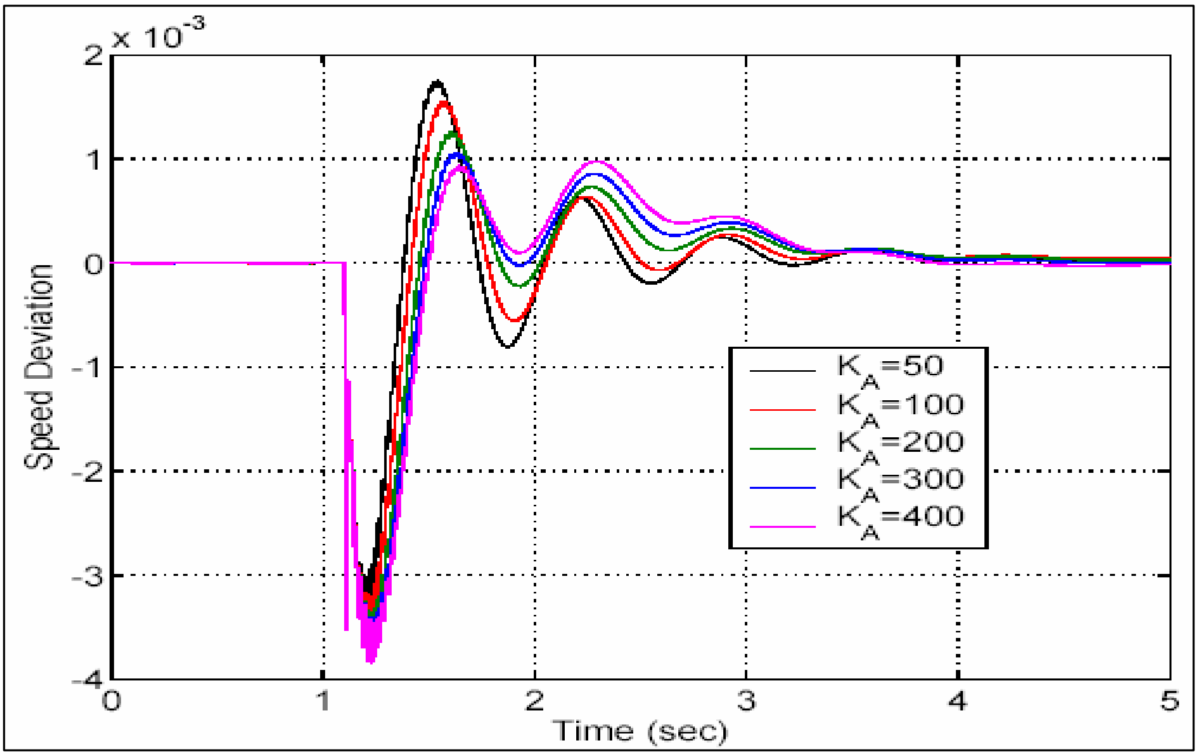
$t_r$= 0.02s
$t_c$=$t_b$=0;
$K_a$=varied from 50 to 400
$T_a$= 0.001 s
$K_f$= varied between 0.0001 to 0.05
$T_f$=0.1s
$K_e$=1; $T_e$=0;

**Ref:** "Recommended Practice for Excitation System Models for Power System Stability Studies", IEEE Standard 421.5-1992, August, 1992.

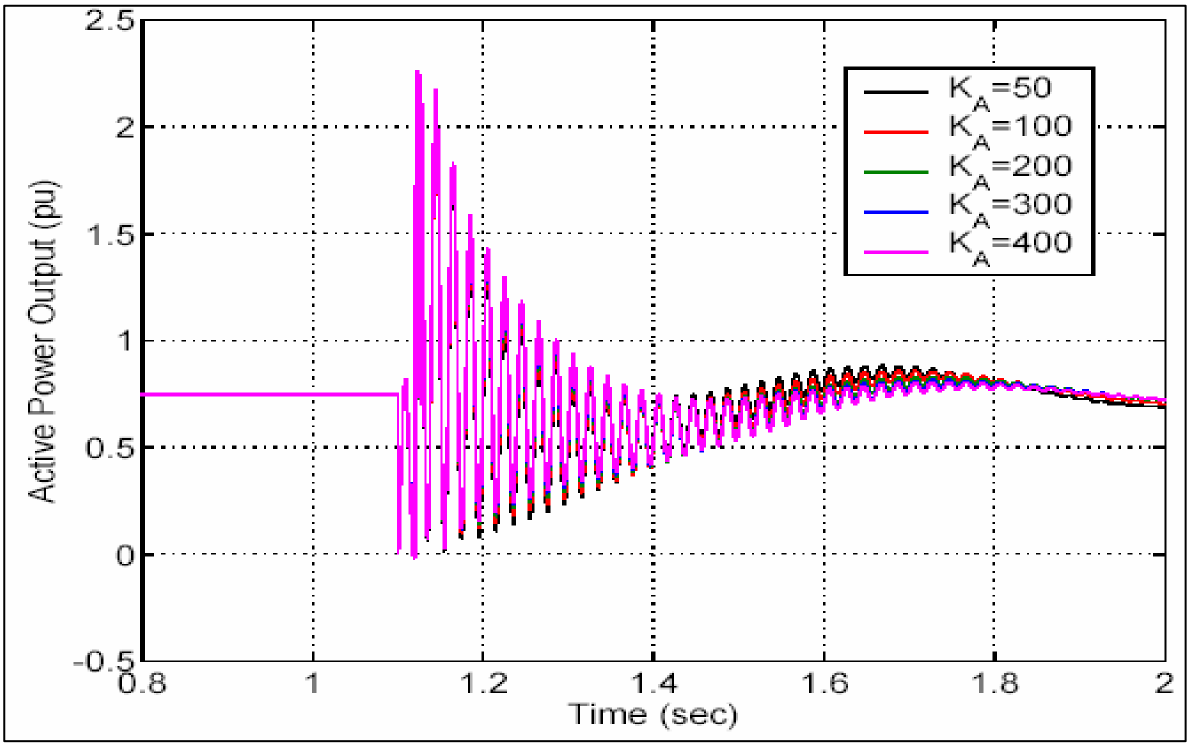
**Kelanitissa (Thermal) : IEEE Type 1 like Excitation Model**



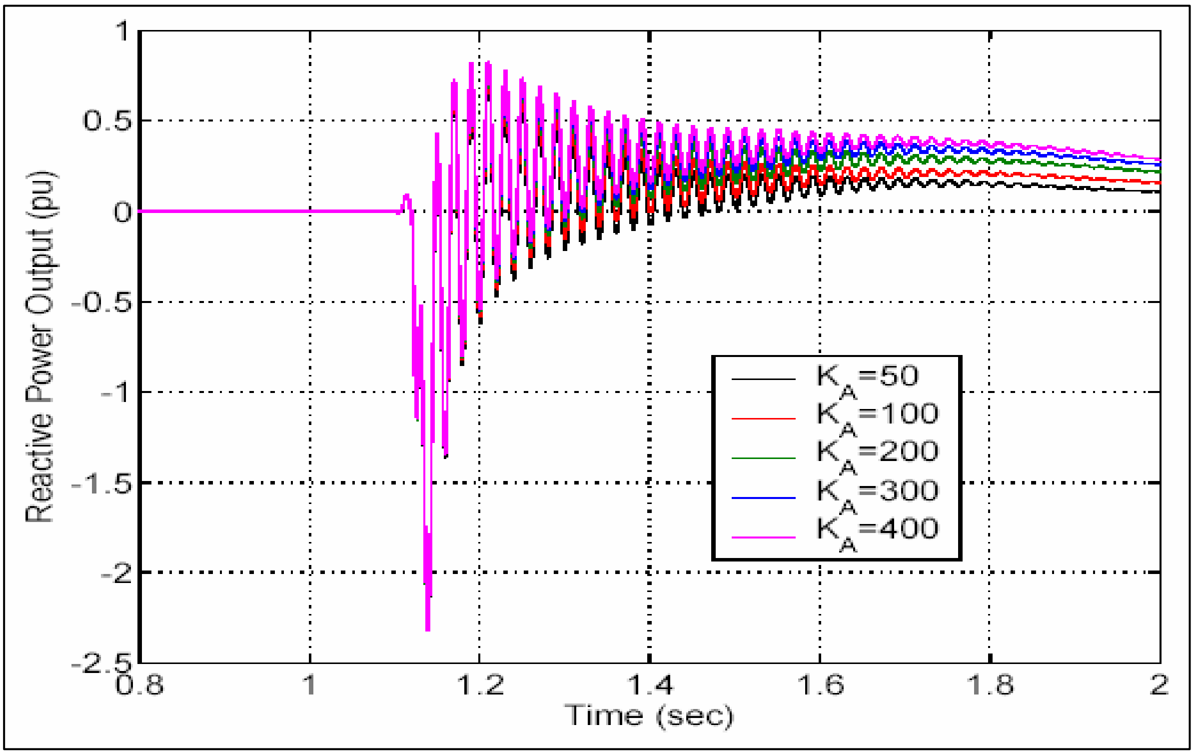
**Kelanitissa (Thermal) : IEEE Type 1 like Excitation Model**



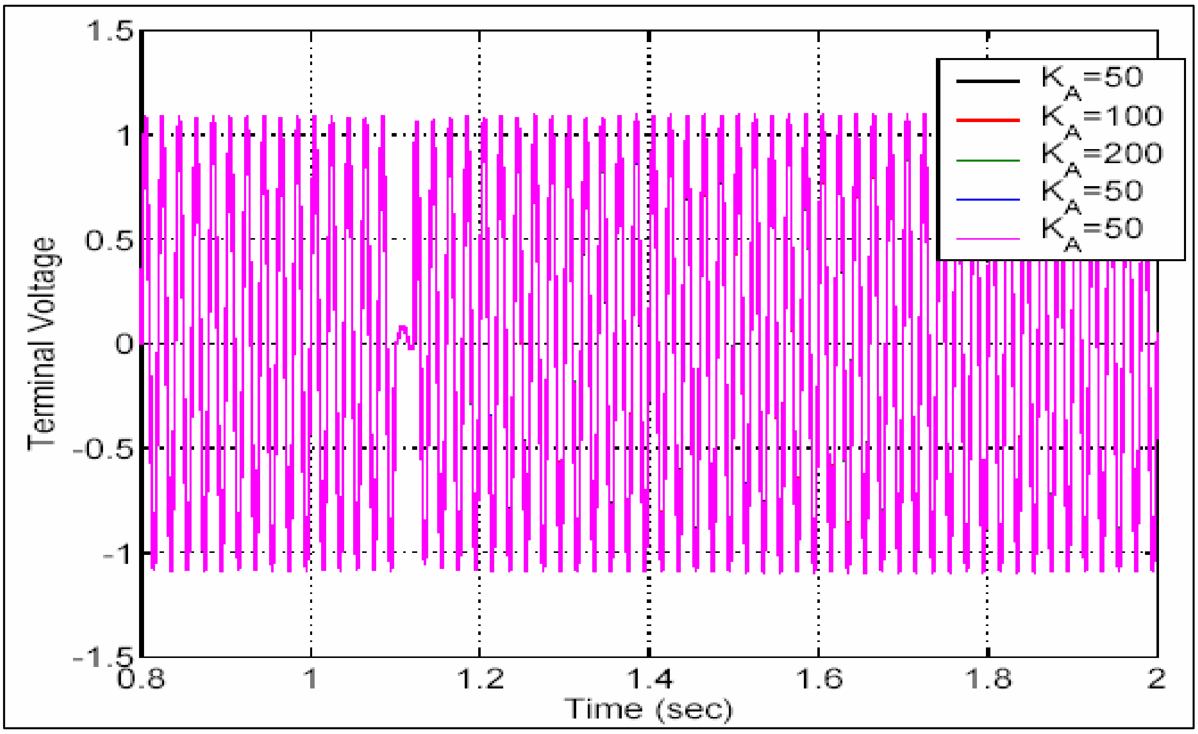

**Kelanitissa (Thermal) : IEEE Type 1 like Excitation Model**



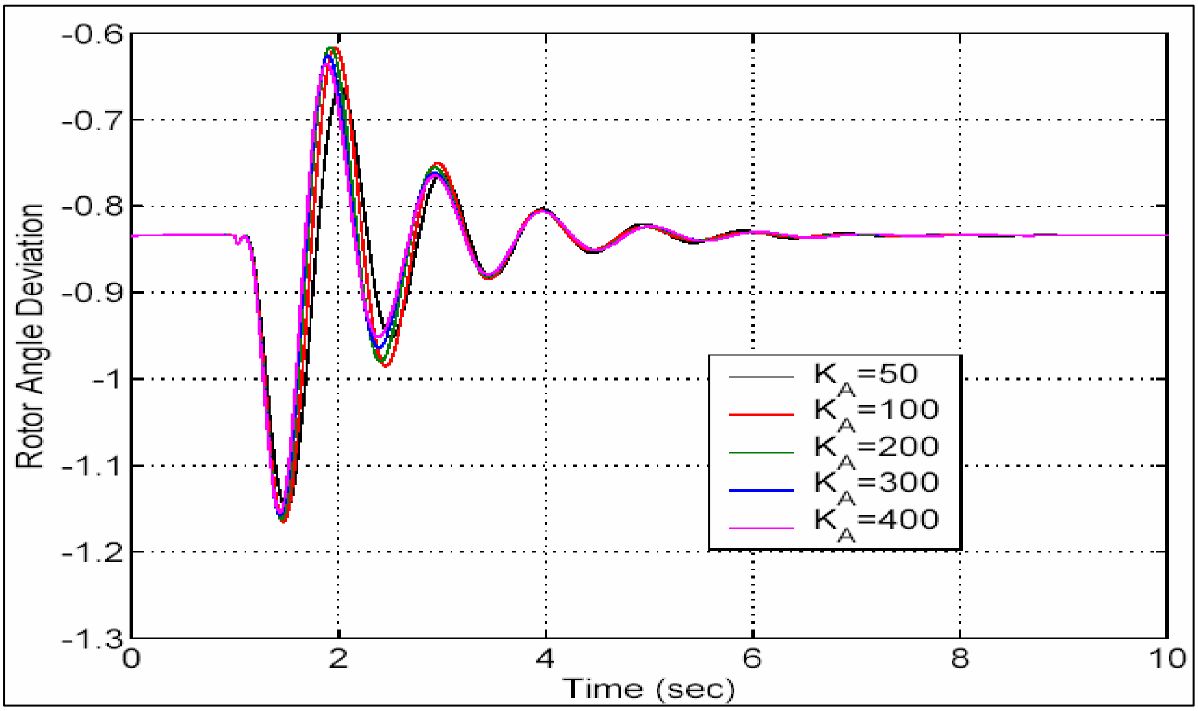
**Kelanitissa (Thermal) : IEEE Type 1 like Excitation Model**



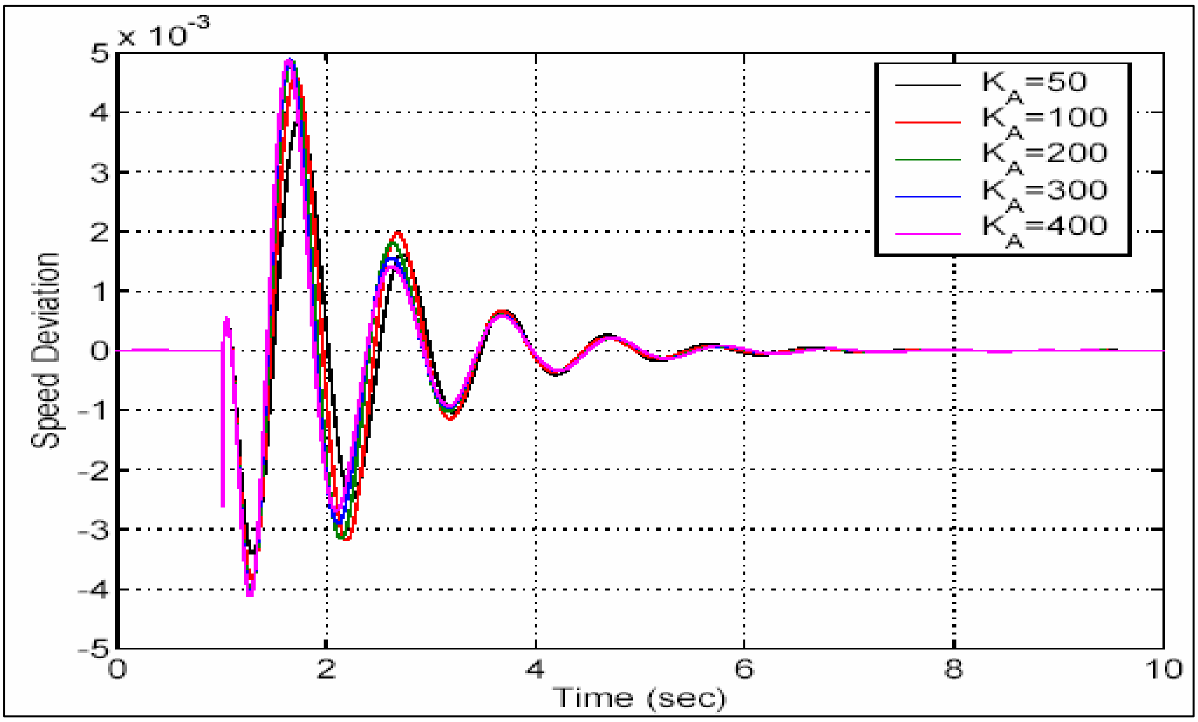

**Kelanitissa (Thermal) : IEEE Type 1 like Excitation Model**



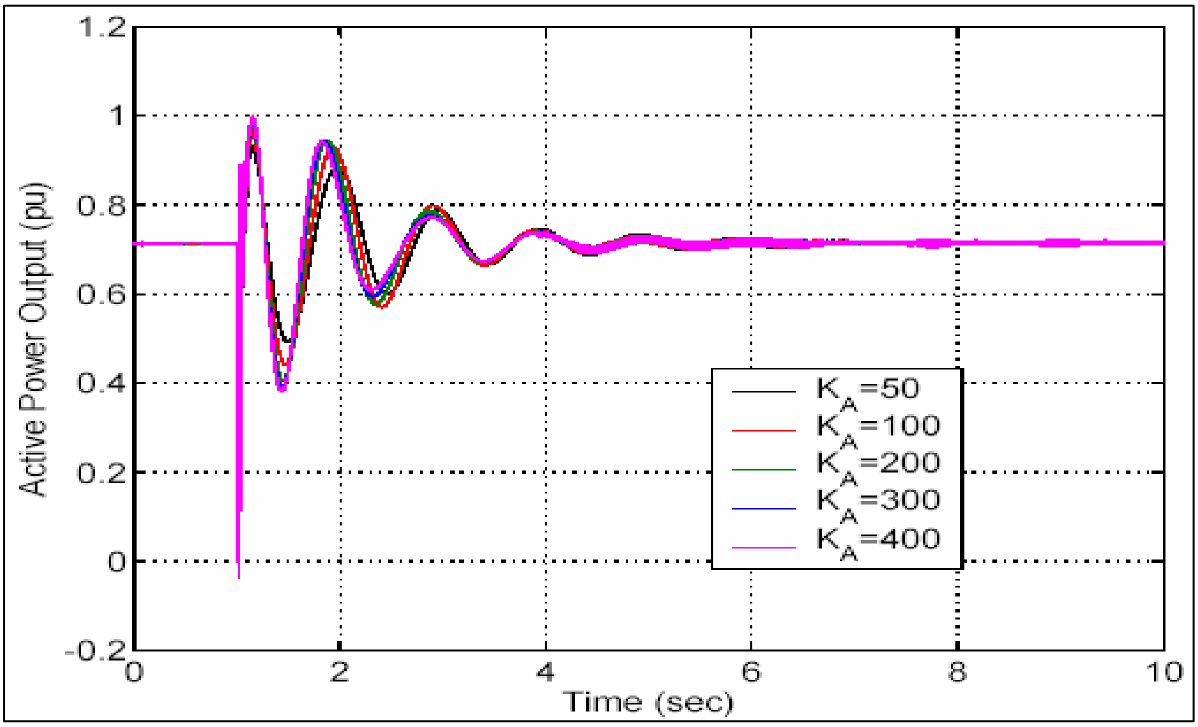
**Victoria (Hydro) : IEEE Type 1 like Excitation Model**



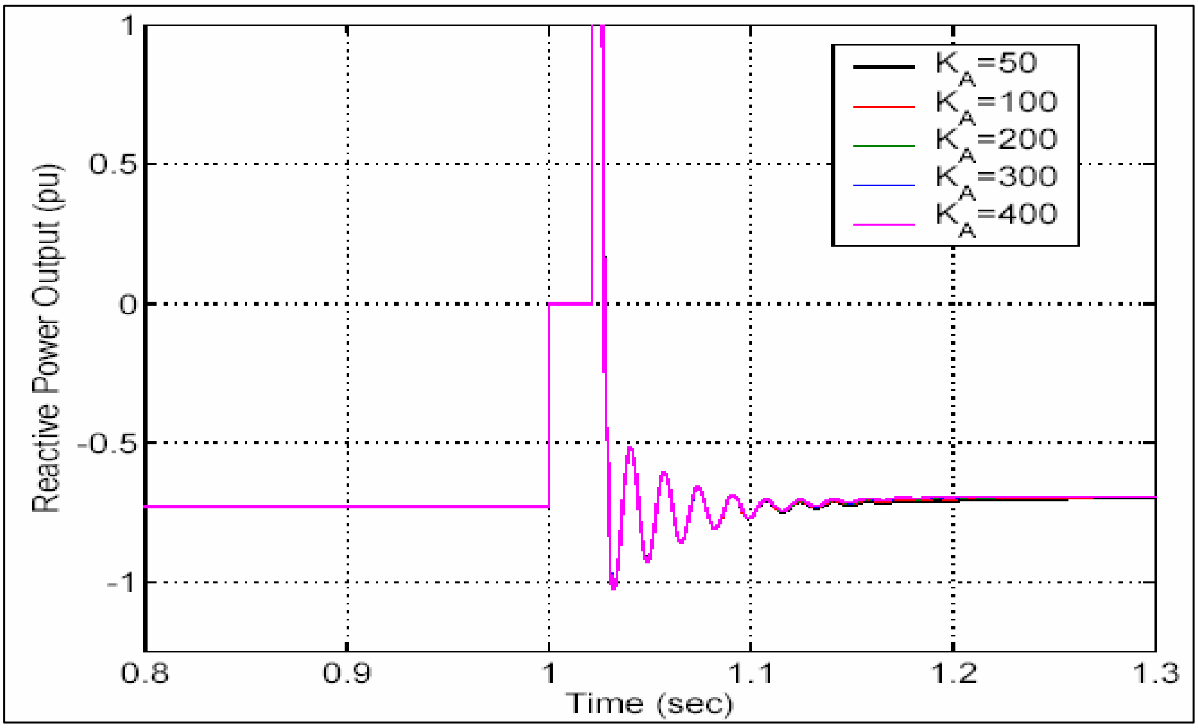

**Victoria (Hydro) : IEEE Type 1 like Excitation Model**



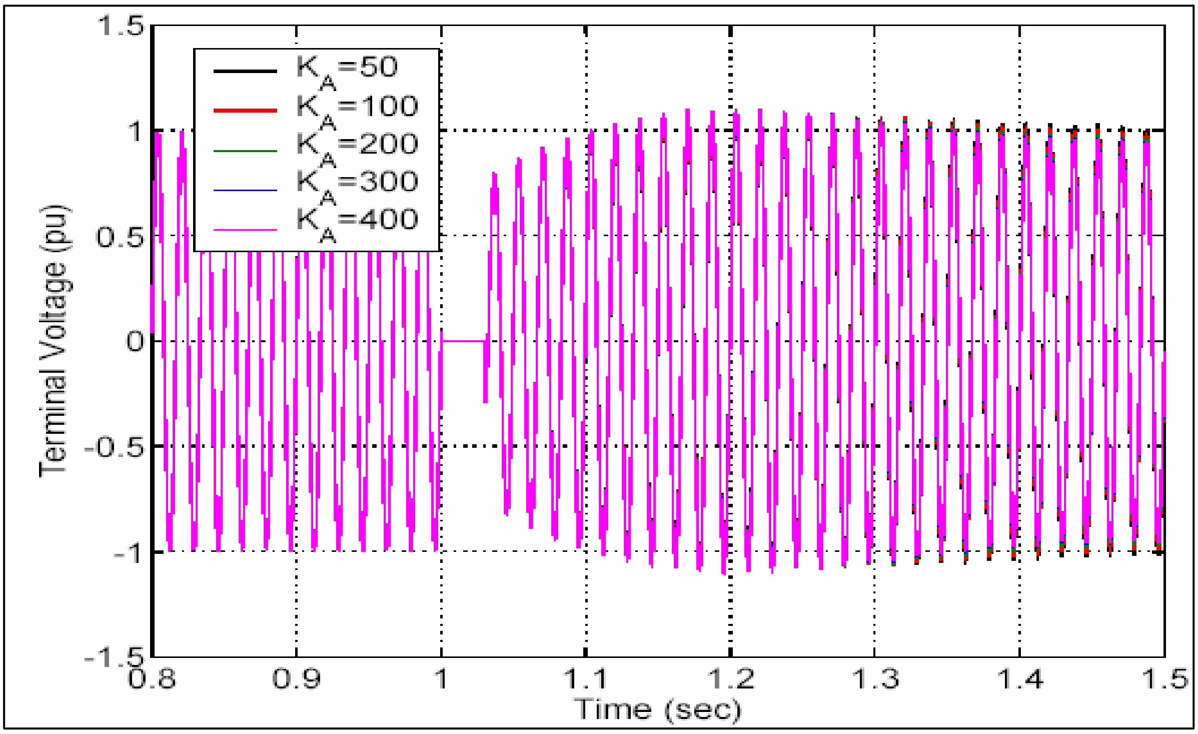
**Victoria (Hydro) : IEEE Type 1 like Excitation Model**




**Victoria (Hydro) : IEEE Type 1 like Excitation Model**

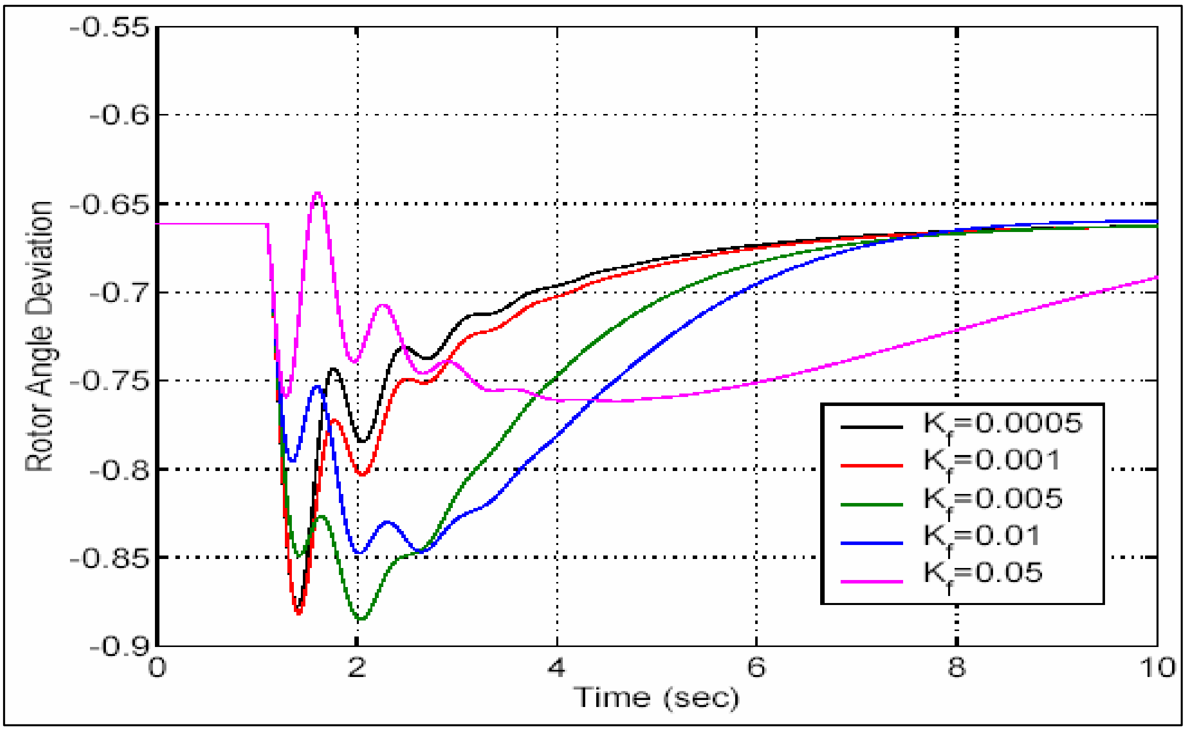


**Victoria (Hydro) : IEEE Type 1 like Excitation Model**

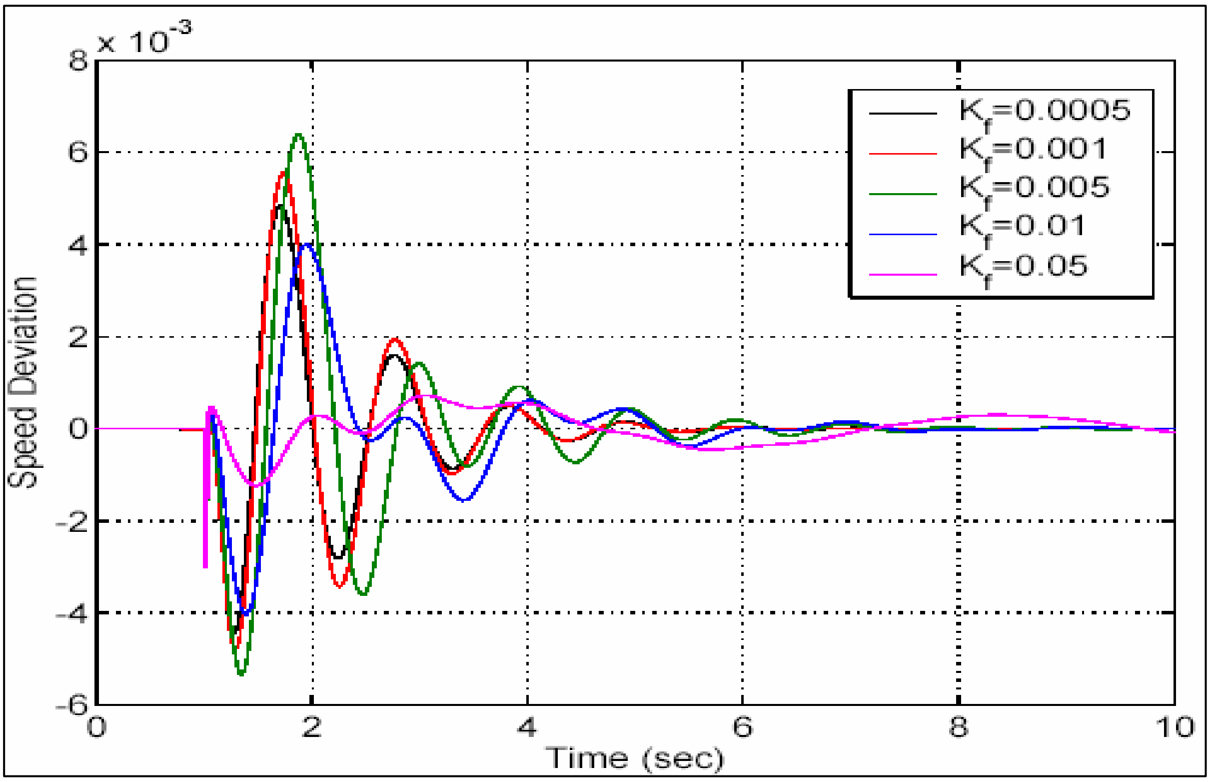



**Kelanitissa (Thermal) : IEEE Type 1 like Excitation Model (Variation of $K_f$ )**
Even response plots are obtained by varying the value of $K_A$ (100, 200, 400), sample plots are shown here.

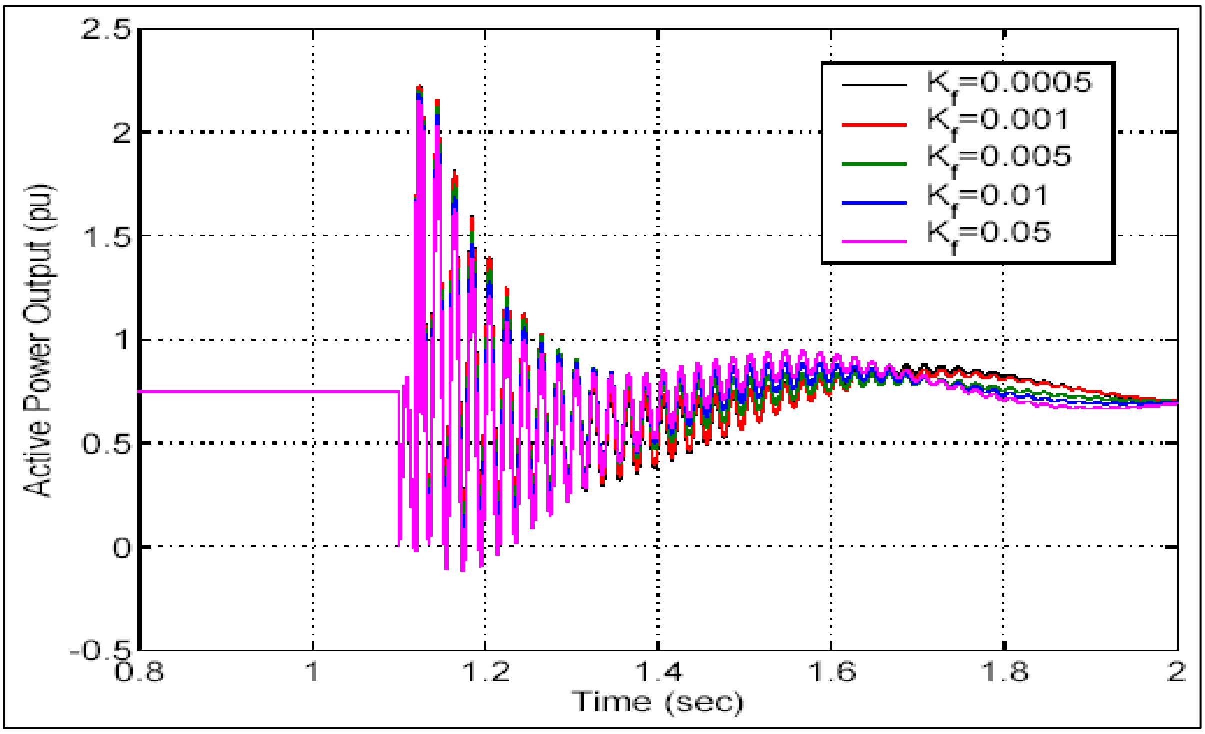
**$K_A$ = 100**



**$K_A$ = 100**

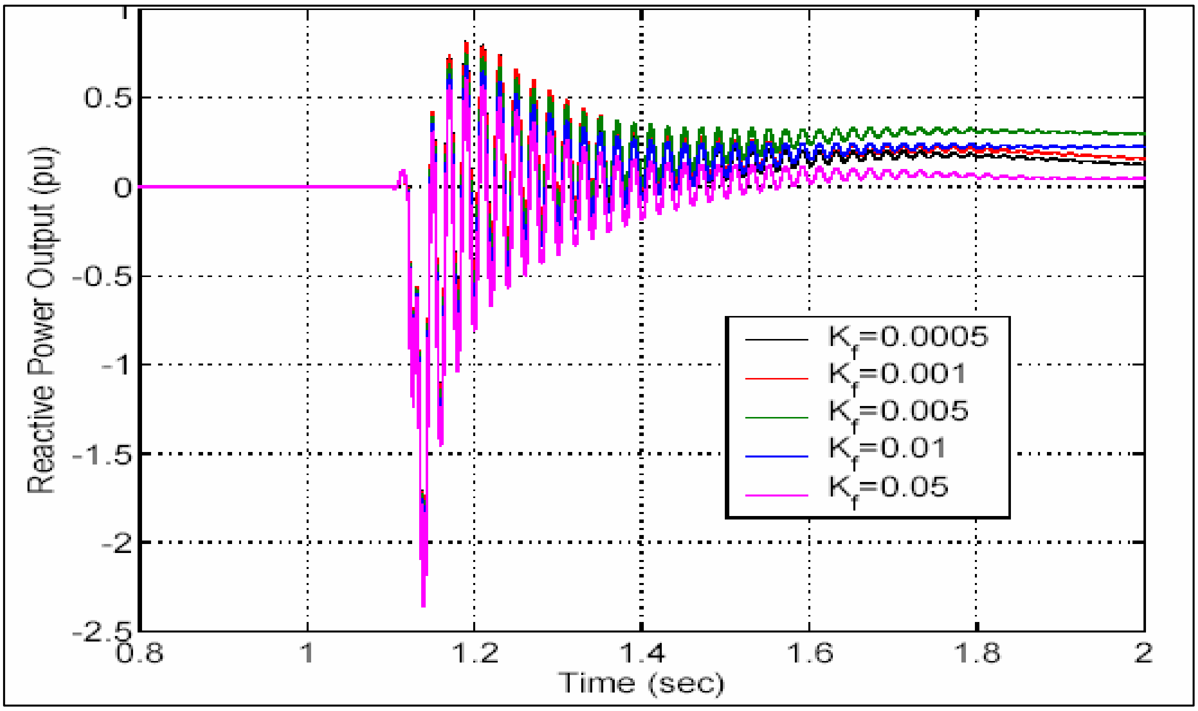


x 10^-3
8
6
4
2
0
-2
-4
-6
Speed Deviation
0
2
4
6
8
10
Time (sec)
Kf=0.0005
Kf=0.001
Kf=0.005
Kf=0.01
Kf=0.05

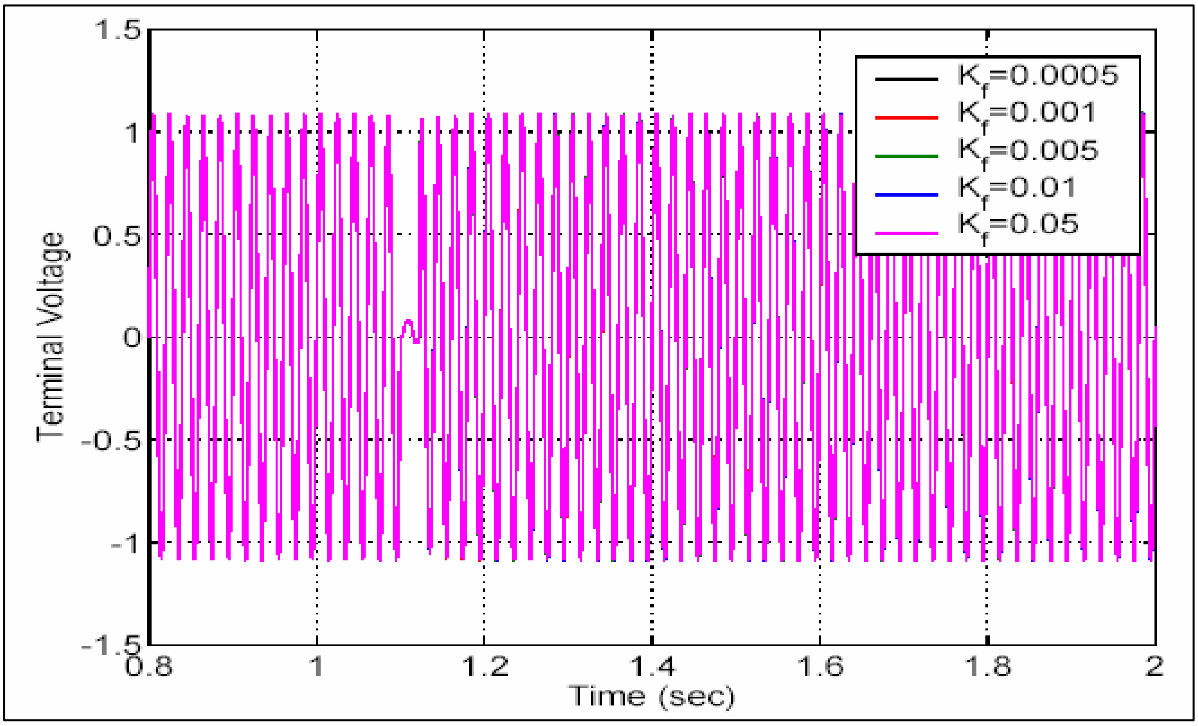



2.5
2
1.5
1
0.5
0
-0.5
Active Power Output (pu)
0.8
1
1.2
1.4
1.6
1.8
2
Time (sec)
Kf=0.0005
Kf=0.001
Kf=0.005
Kf=0.01
Kf=0.05

**$K_A$ = 100**



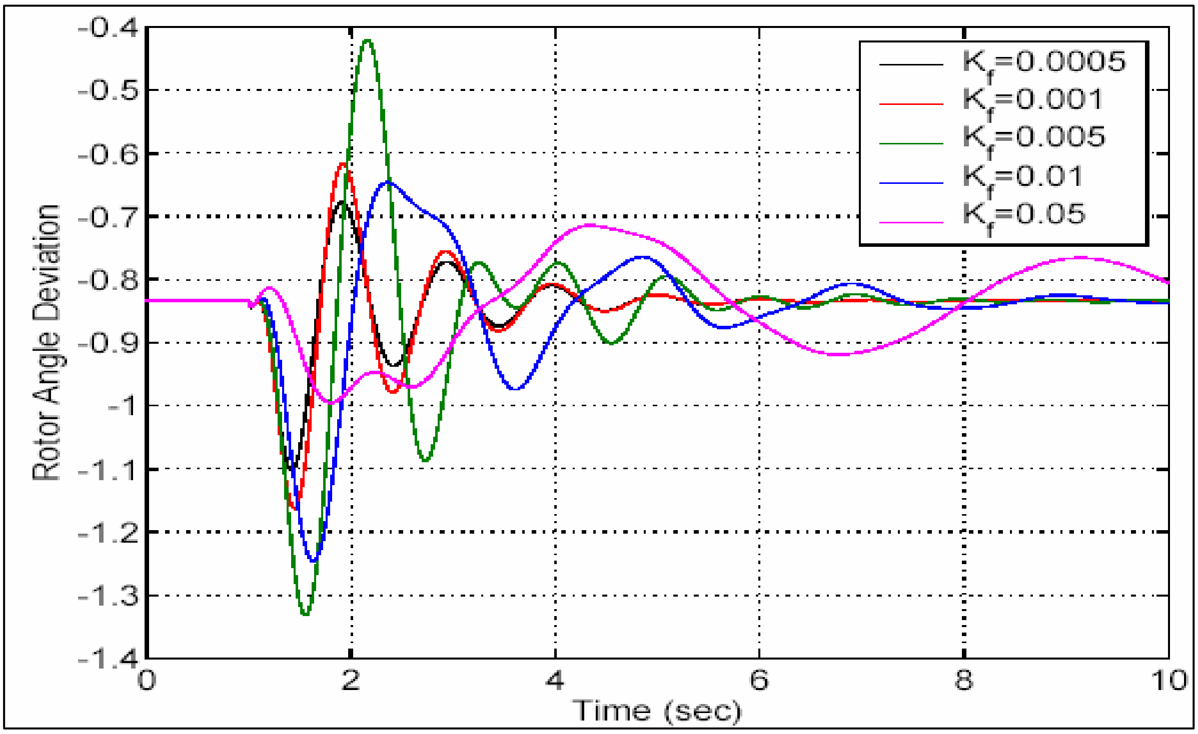

**$K_A$ = 100**



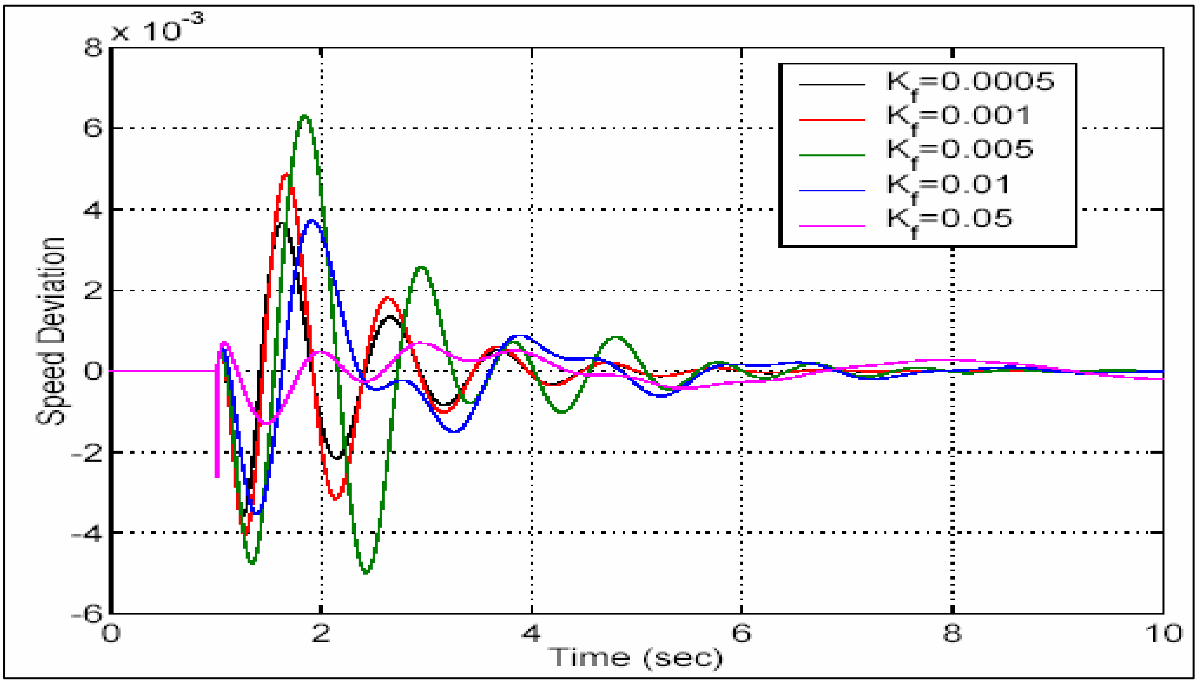

**Victoria (Hydro) : IEEE Type 1 like Excitation Model (Variation of $K_f$)**

Even response plots are obtained by varying the value of $K_A$ (100, 200, 400), sample plots are shown here.

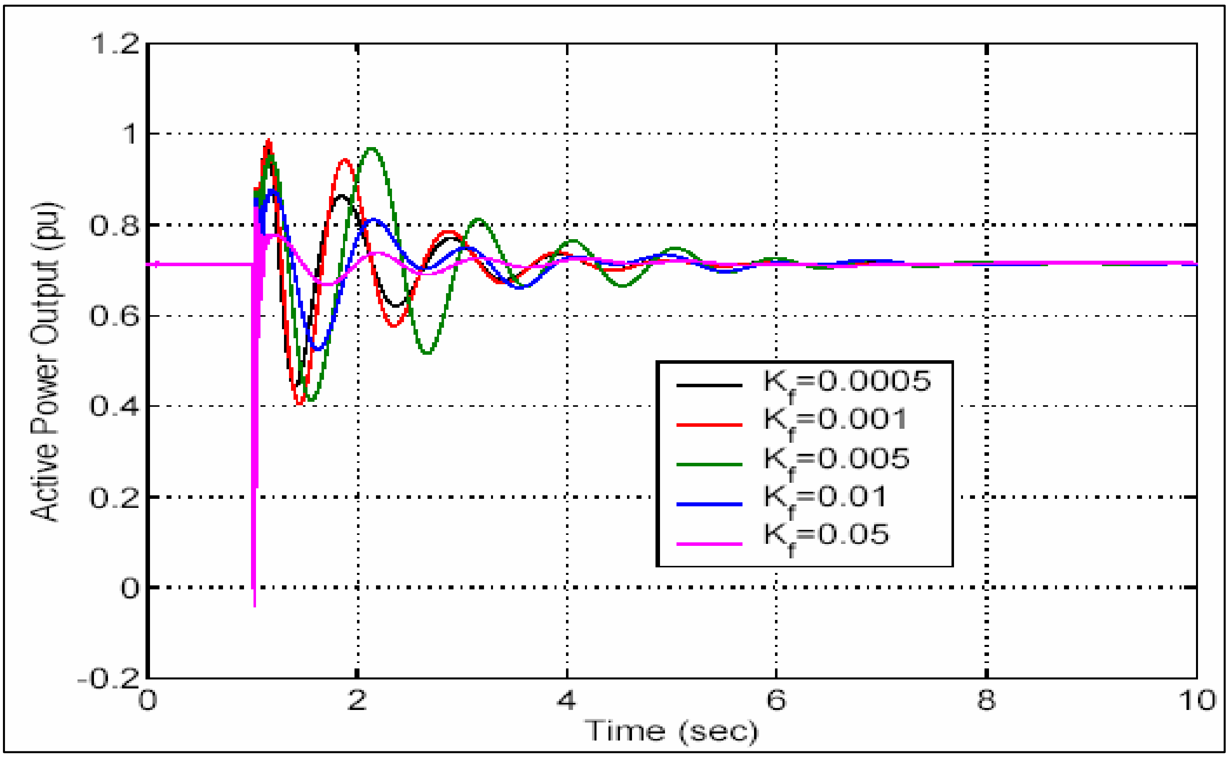
$K_A = 200$

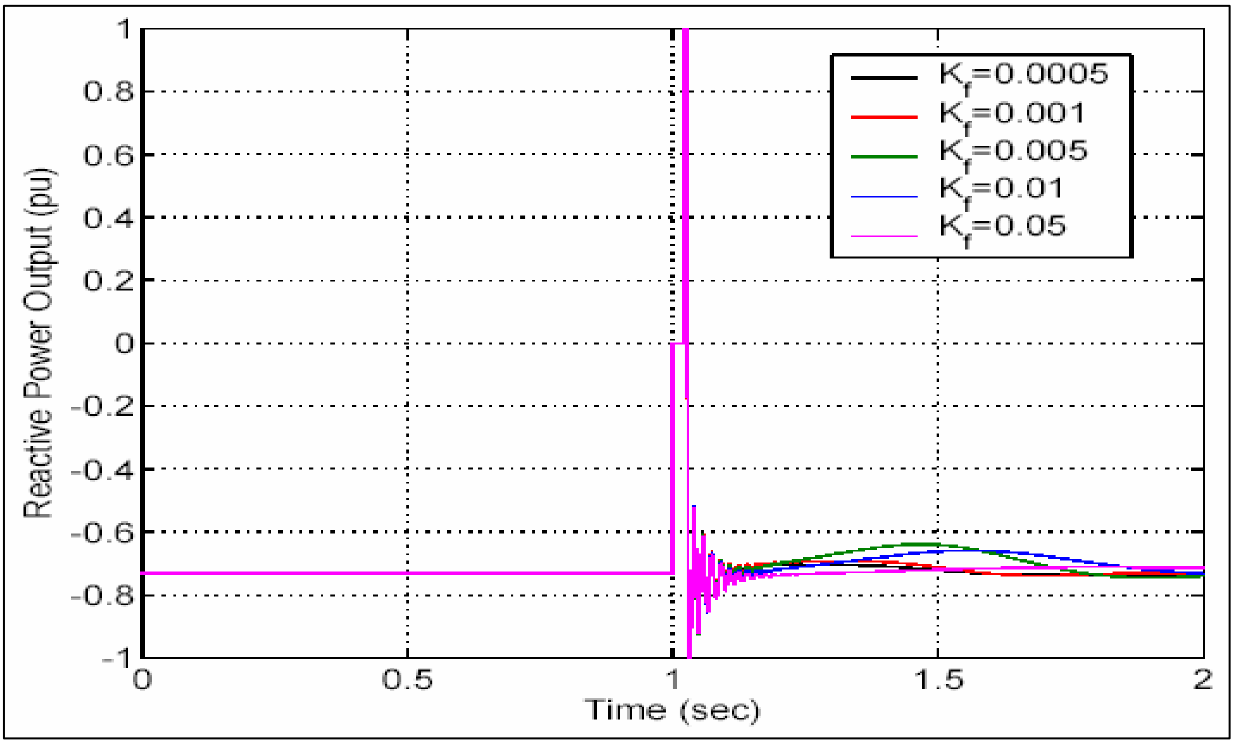


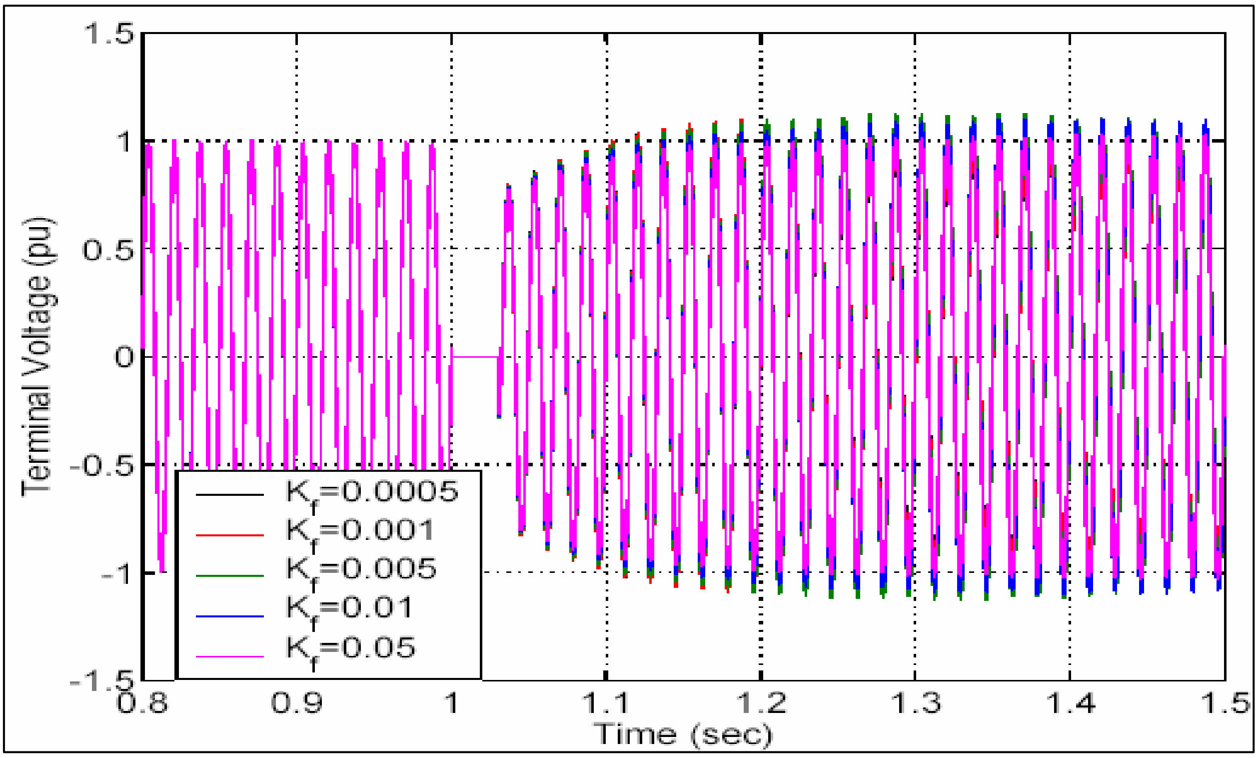

$K_A = 200$




$K_A = 200$


Active Power Output (pu)
Time (sec)
K_f=0.0005
K_f=0.001
K_f=0.005
K_f=0.01
K_f=0.05


Reactive Power Output (pu)
Time (sec)
K_f=0.0005
K_f=0.001
K_f=0.005
K_f=0.01
K_f=0.05




**Some Observations:**

(a) For SEXS Type model with the chosen parameters,

(i) It is found that damping is poor for Kelanitissa (Thermal) machine compared to Victoria (Hydro) machine for the plots of rotor angle deviations, for lower values of $K_A$. Also, it is found that lower values of $K_A$ leads to more oscillations on Kelanitissa machine than Victoria machine, from the plots of rotor angle deviation.

(ii) From the plots of speed deviation, active power output, reactive power output, and terminal voltage, it is found that the nature of oscillations is similar for Kelanitissa and Victoria machines, including the effect of $K_A$.

Also, fewer oscillations are observed in the plots of Reactive power output compared to Active power output for both types of machines.

(b) For IEEE Type model with the chosen parameters,

(i) It is found from the plots of rotor angle deviation that for higher values of $K_A$, the transient dip is more and settling times are lower.
From the plots of rotor angle deviations, variation of $K_A$ is found to be less effective for Victoria machine compared to Kelanitissa machine.

(ii) From the plots speed deviations, it is found that the general nature of plots is similar for Kelanitissa and Victoria machines.

(iii) From the plots of Active power output, it is found that the settling time is less for Kelanitissa machine compared to Victoria machine.

(iv) From the plots of Reactive power output, it is found that oscillations are more for higher values of $K_A$ for both types of machines.

(c) IEEE Type model representation appears to result in improved response plots for both types of machines.

(d) For IEEE Type model with the chosen parameters for both types of machines,

(i) Effect of feedback gain $K_f$, is found to be more visible for higher values of $K_A$ in the plots of rotor angle deviations and lower values of $K_f$ result in lower settling times. Also, nature of rotor angle deviation varies with the value of $K_f$ for a chosen value of $K_A$.

(ii) Effect of $K_f$ on the nature of the plots of speed variation, active and reactive power outputs appears to be marginal.

(iii) Nature of rotor angle deviations appear to be different for Kelanitissa machine and Victoria machine, when $K_f$ is varied for chosen values of $K_A$ .

### 7.3 Dynamic Simulation Studies conducted on Base Case (Year 2008) CEB System:

#### (a) Detailed Sample study:

Disturbance has been simulated by considering a Three-phase fault at the Kotmale end of the Kotmale–Biyagama 220 KV Line. Two cases of reclosing conditions with time sequences as indicated below are considered:

(a) Successful Reclosing :
Fault ...(160ms)… CBs trip …(500ms)… CBs close and clearing fault.

(b) Unsuccessful Reclosing :
Fault ...(160ms)… CBs trip …(500ms)… CBs close …(160ms)… CBs trip.

Following time responses of Behaviours of Four Generators (Kotmale, Victoria, Kelanitissa and New Laxapana) are obtained and plotted, using PSS/E modules: Terminal Voltage, and Power Output (P&Q).

The above simulations are obtained for both the cases (i) with all governors in operation, and (ii) with governors at Victoria, Kotmale, Randenigala and Samanalawewa are in operation, and (iii) without governors.

#### (b) Simulation of Three-phase Faults on 220/132 KV Lines:

(1) Disturbance is simulated by tripping *both circuits* of 220 KV lines and the responses are obtained and plotted using PSS/E modules, similar to those (with governors) of the above item, for the following cases of study:

(i) *Kelanitissa – Biyagama* (Case of Successful Recloser) : Response plots of variations in Terminal Voltage, Active Power, and Reactive Power, at two buses.

Also, (Case of Unsuccessful Recloser): Response plots of variations in Terminal Voltage, Active Power, and Reactive Power, at two buses.

(ii) *Biyagama – Pannipitiya* (Case of Successful Recloser): Response plots of variations in Terminal Voltage, Active Power, and Reactive Power, at four buses.

Also, (Case of Unsuccessful Recloser): Response plots of variations in Terminal Voltage, [Active Power], and Reactive Power, at four buses.

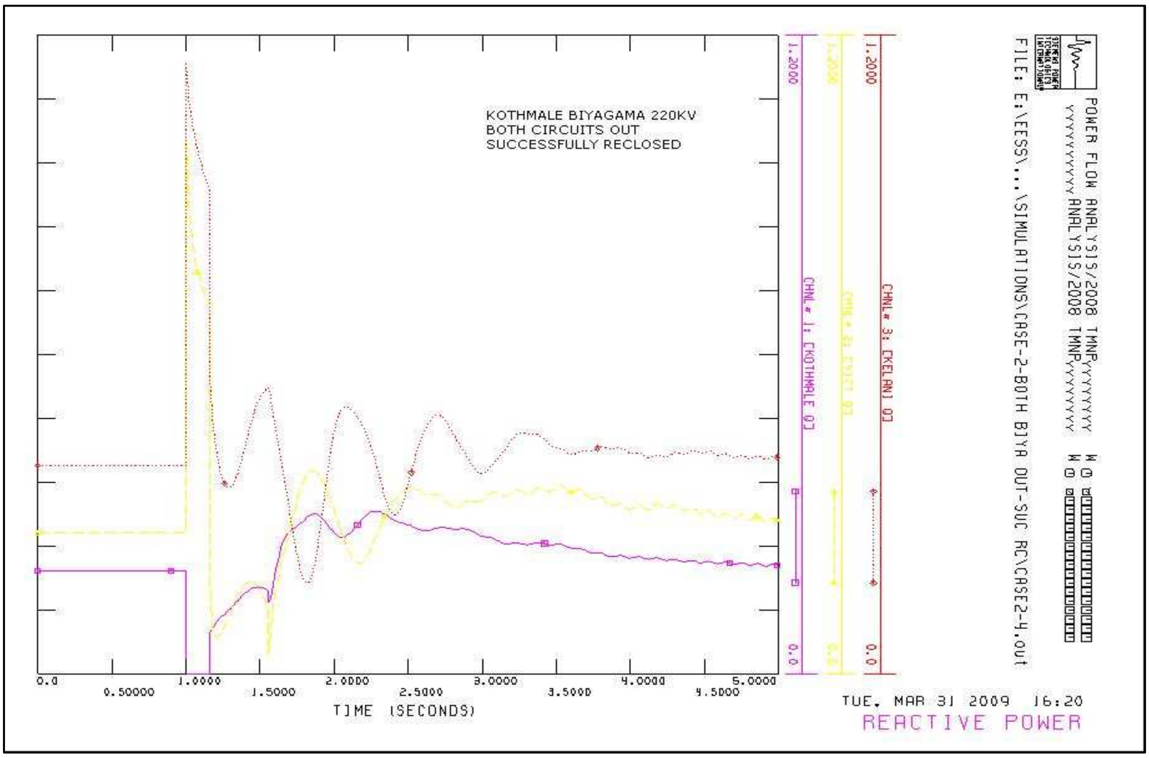
(iii) Biyagama – Kotugoda (Case of Successful Recloser): Response plots of variations in Terminal Voltage, [Active Power], and Reactive Power, at four buses.

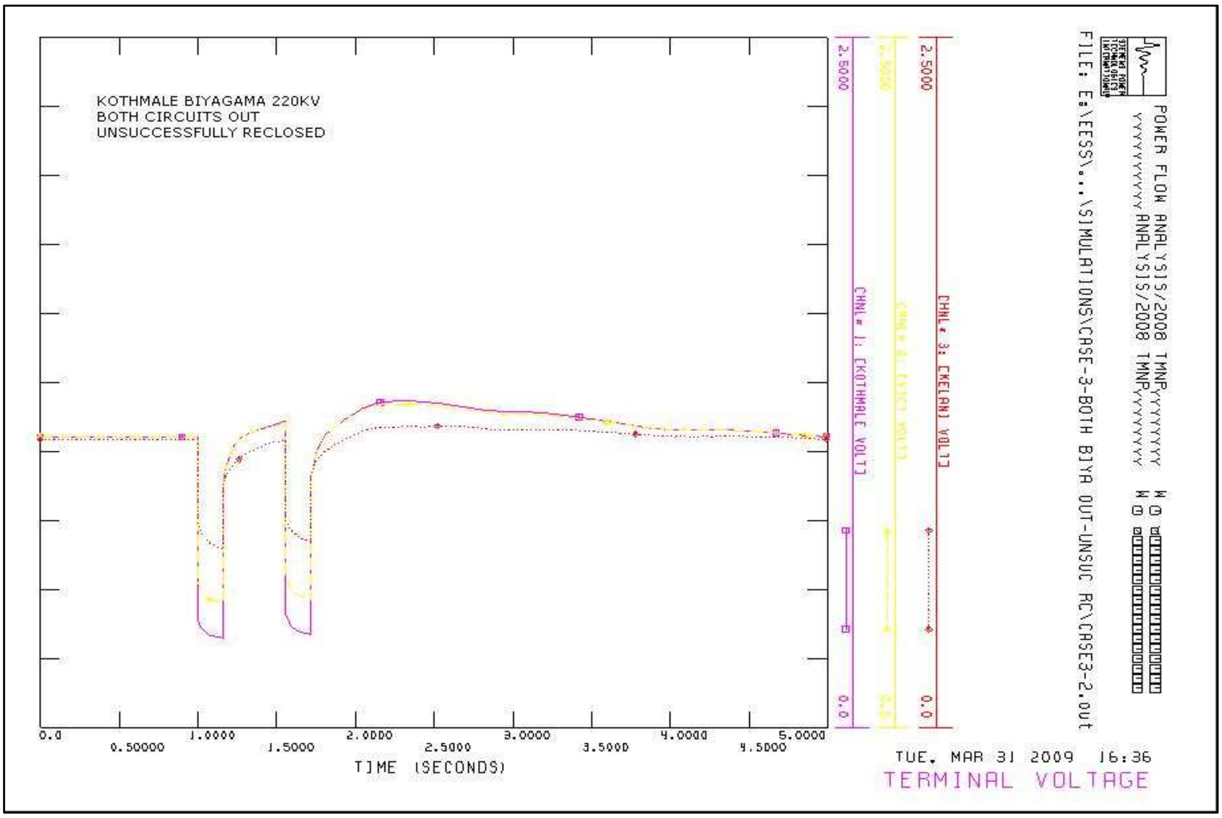
Also, (Case of Unsuccessful Recloser): Response plots of variations in Terminal Voltage, Active Power, and Reactive Power, at four buses.

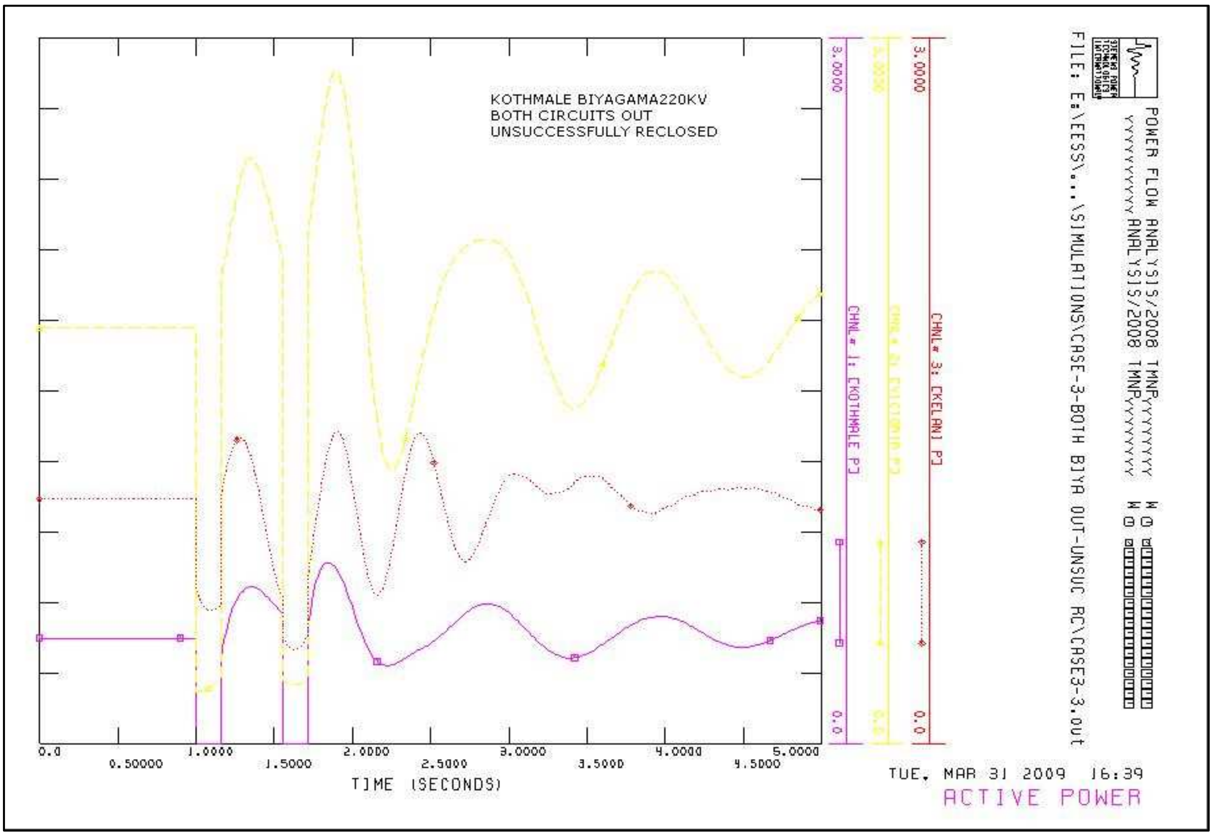
(iv) *Kotmale – Biyagama* (Case of Successful Recloser): Response plots of variations in Terminal Voltage, and Reactive Power, at three buses.

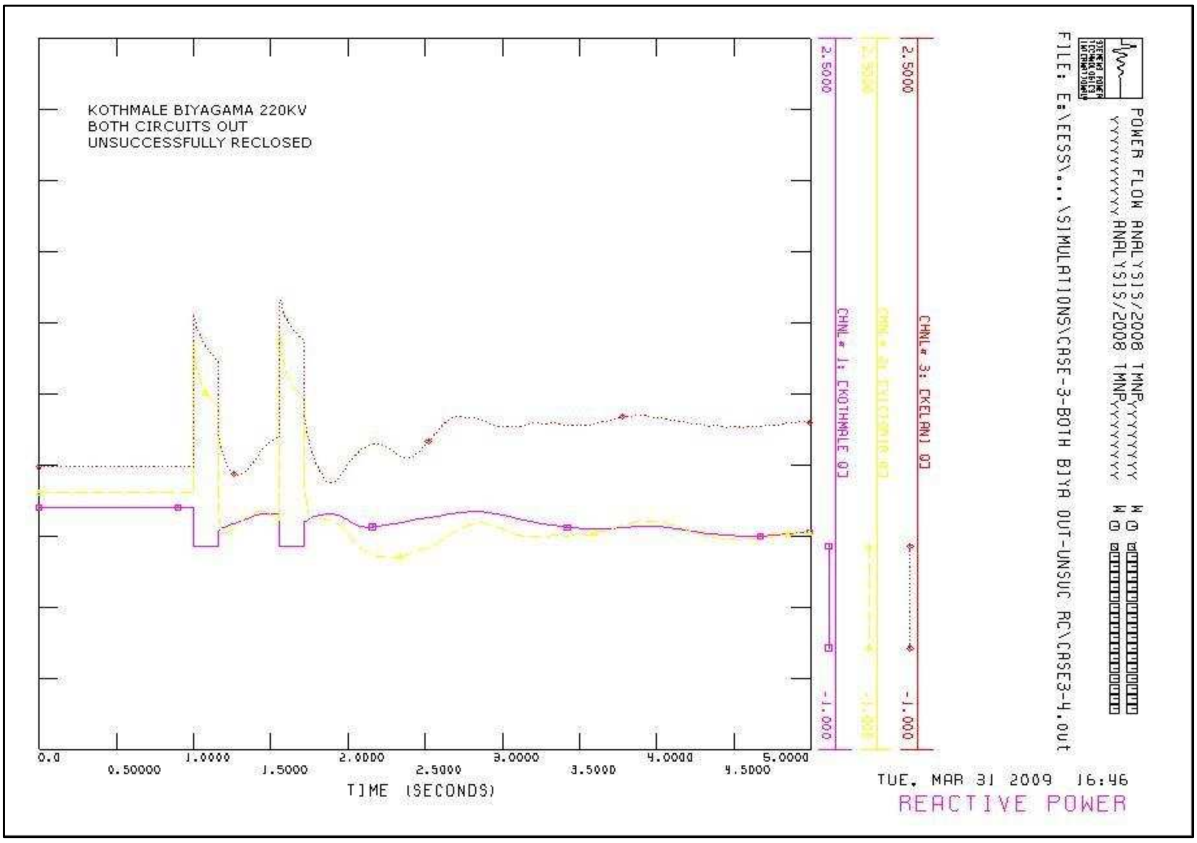
Also, (Case of Unsuccessful Recloser): Response plots of variations in Terminal Voltage, Active Power, and Reactive Power, at three buses.

Even though Response Plots are obtained for all the above mentioned 4 Cases, sample Response Plots for the Case (iv) Kotmale – Biyagama are shown here :




KOTHMALE BIYAGAMA 220KV
BOTH CIRCUITS OUT
UNSUCCESSFULLY RECLOSED
0.0
0.50000
1.0000
1.5000
2.0000
2.5000
3.0000
3.5000
4.0000
4.5000
5.0000
TIME (SECONDS)
TUE, MAR 31 2009 16:36
TERMINAL VOLTAGE


KOTHMALE BIYAGAMA220KV
BOTH CIRCUITS OUT
UNSUCCESSFULLY RECLOSED
0.0
0.50000
1.0000
1.5000
2.0000
2.5000
3.0000
3.5000
4.0000
4.5000
5.0000
TIME (SECONDS)
TUE, MAR 31 2009 16:39
ACTIVE POWER



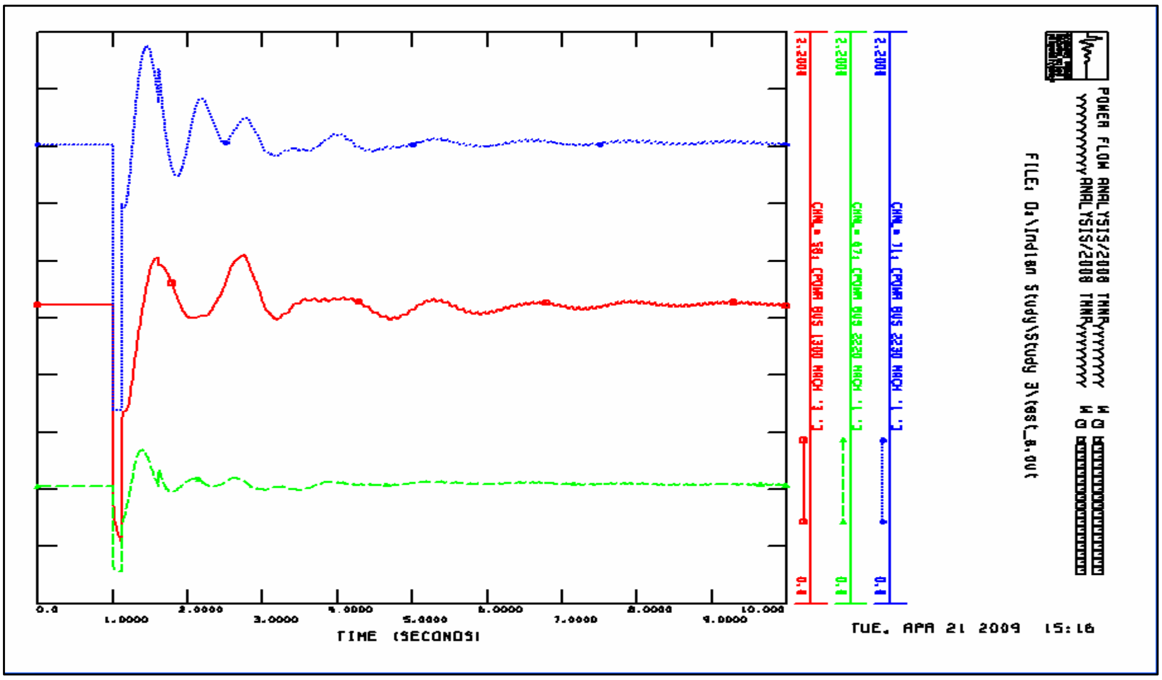

**(c) Simulation of Three-phase Faults on 220/132 KV Lines, *with machines equipped with Excitation System Model SEXS :***

(1) Disturbance is simulated by tripping <u>*one circuit* of 220 KV lines</u> (with thermal maximum at night peak) and the responses are obtained and plotted using PSS/E modules, similar to those (with governors) of the above item (a), for the following cases of study: (with Successful Recloser)

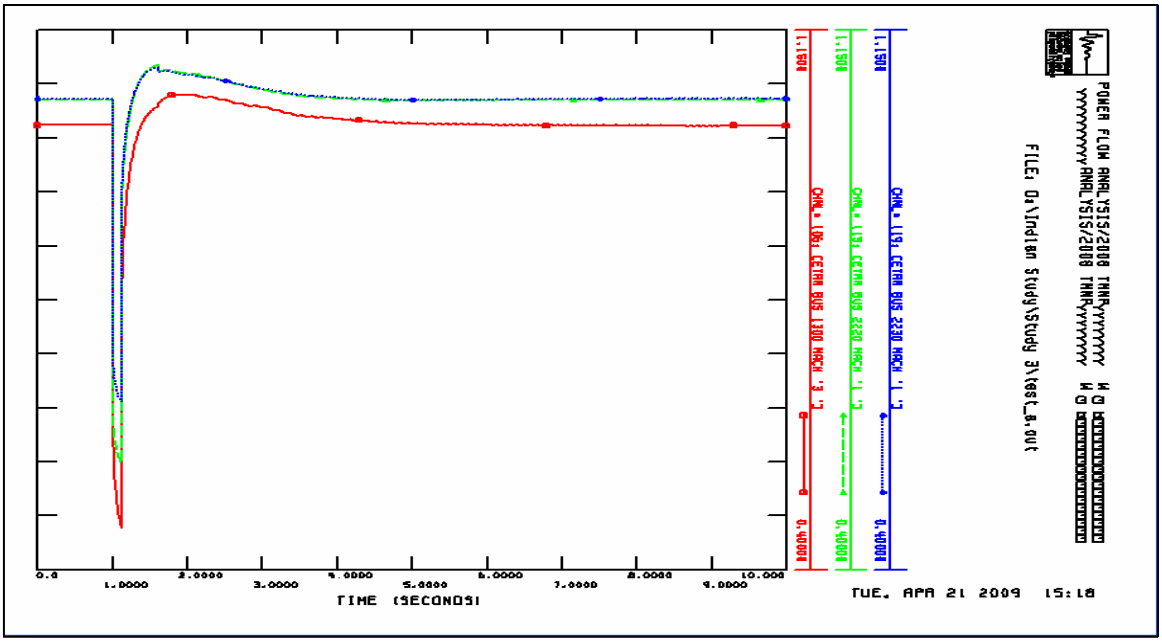
- (i) *Kotmale – Biyagama* at Biyagama end: Response plots of variations in Terminal Voltage, and Power output, at three buses.
- (ii) *Kelanitissa GIS – Biyagama* at Biyagama end: Response plots of variations in Terminal Voltage, and Power output, at two buses.
- (iii) *Pannipitiya – Biyagama* at Pannipitiya end: Response plots of variations in Terminal Voltage, and Power output, at four buses.
- (iv) *Kotugoda – Biyagama* at Kotugoda end: Response plots of variations in Terminal Voltage, and Power output, at two buses.
- (v) *Kotmale – New Anuradhapura* at New Anuradhapura end: Response plots of variations in Terminal Voltage, and Power output, at three buses.

(i) *Kotmale – Biyagama* at Biyagama end: Response plots of variations in Terminal Voltage, and Power output, at three buses.

**Power Output Variation**

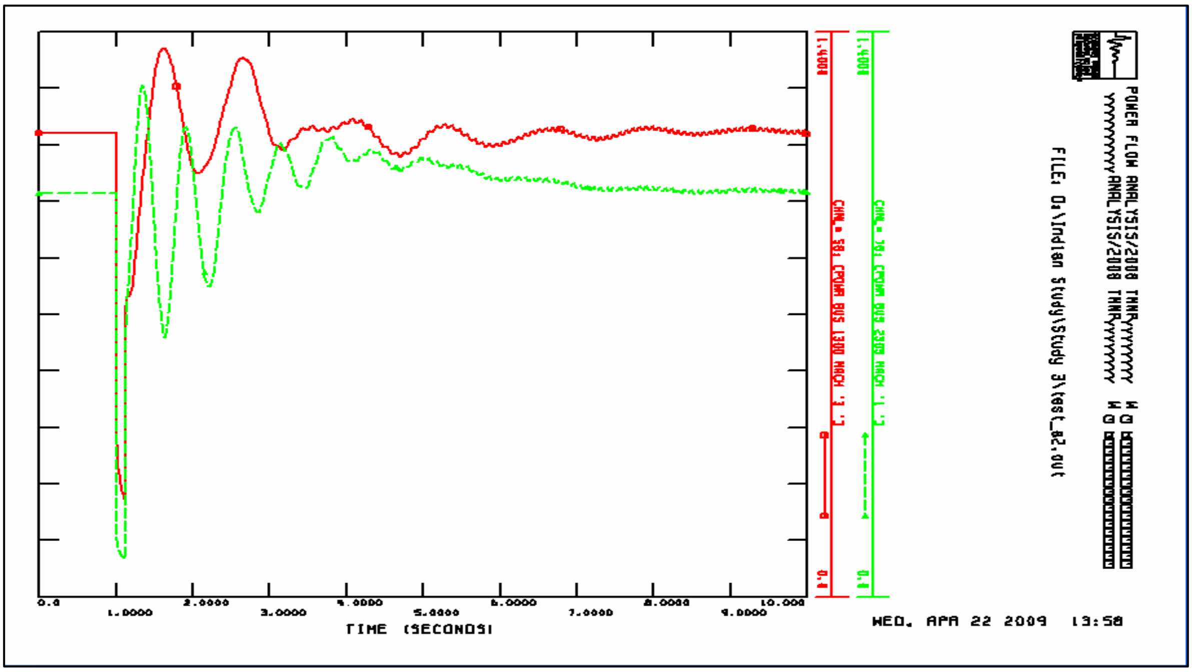



**Terminal Voltage Variation**

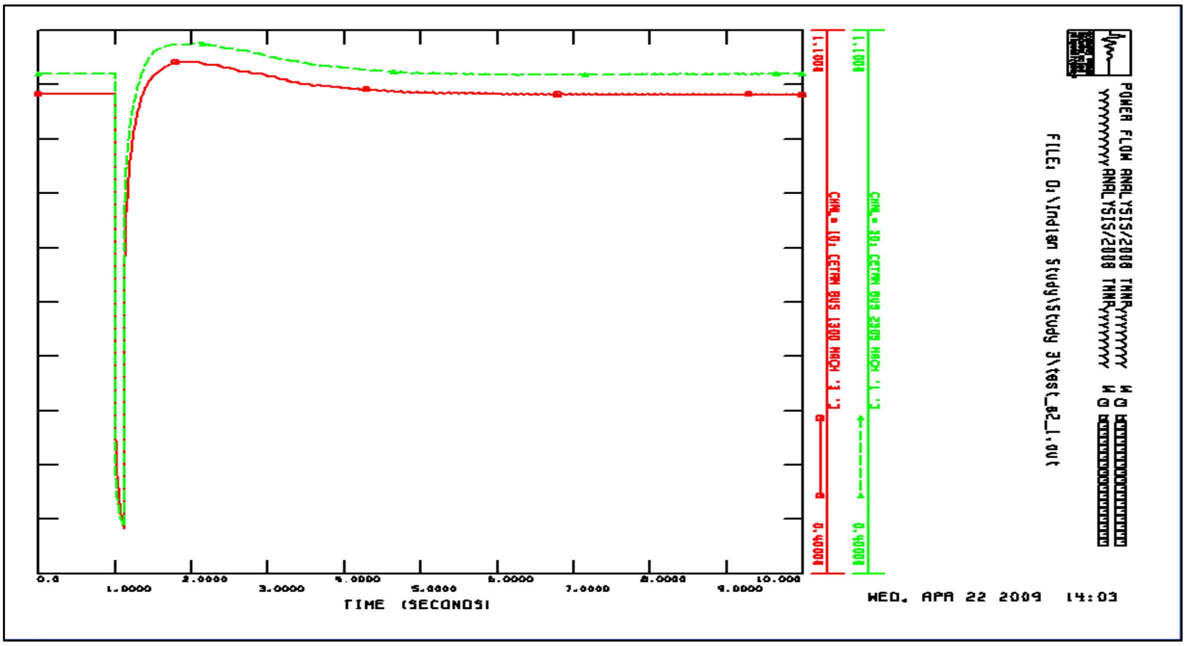


(ii) Simulation of 3 Ø fault on one cct of Kelanitissa GIS -Biyagama 220kV transmission Line at Biyagama end. Successful reclosing assumed.

**Power Output Variation**

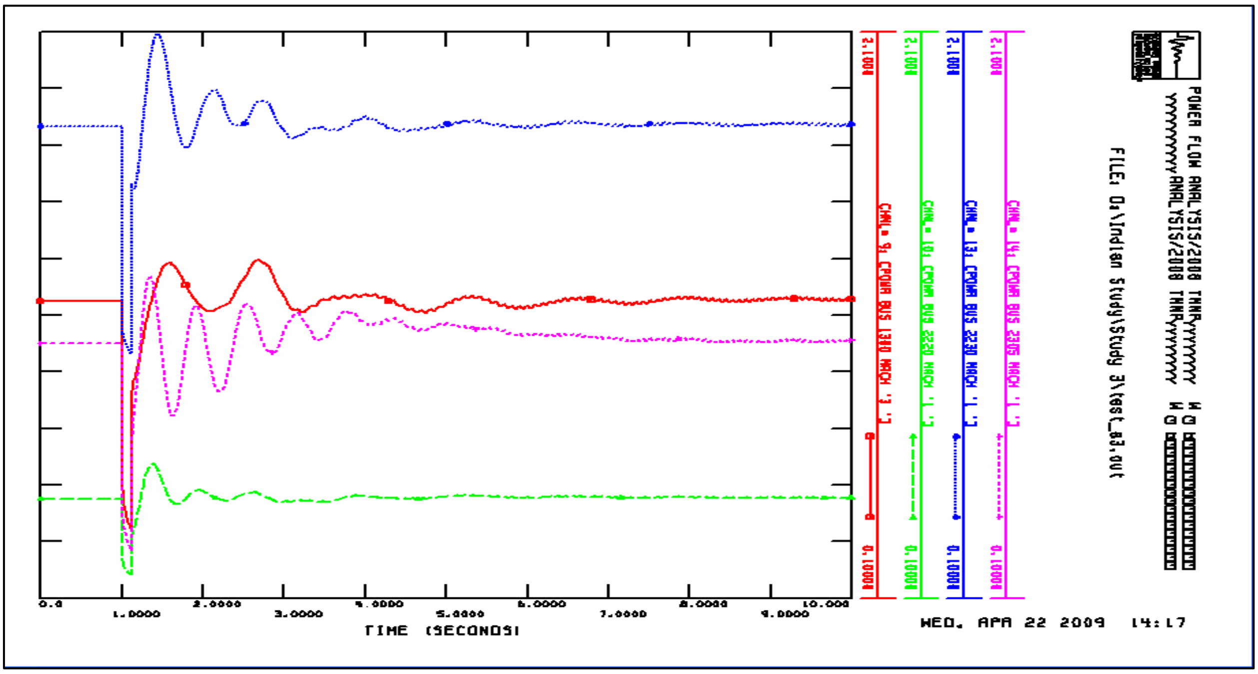



**Terminal Voltage Variation**

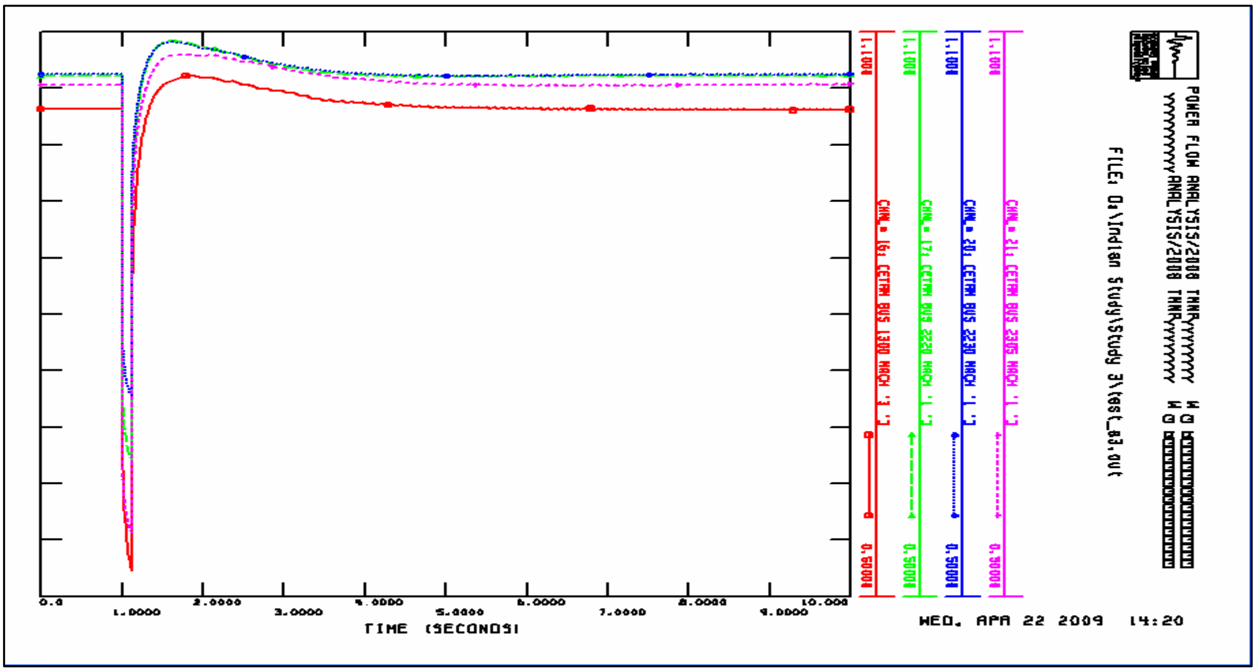


(iii) Simulation of 3 Ø fault on one cct of Pannipitiya -Biyagama 220kV transmission Line at Pannipitiya end. Successful reclosing assumed.

**Power Output Variation**

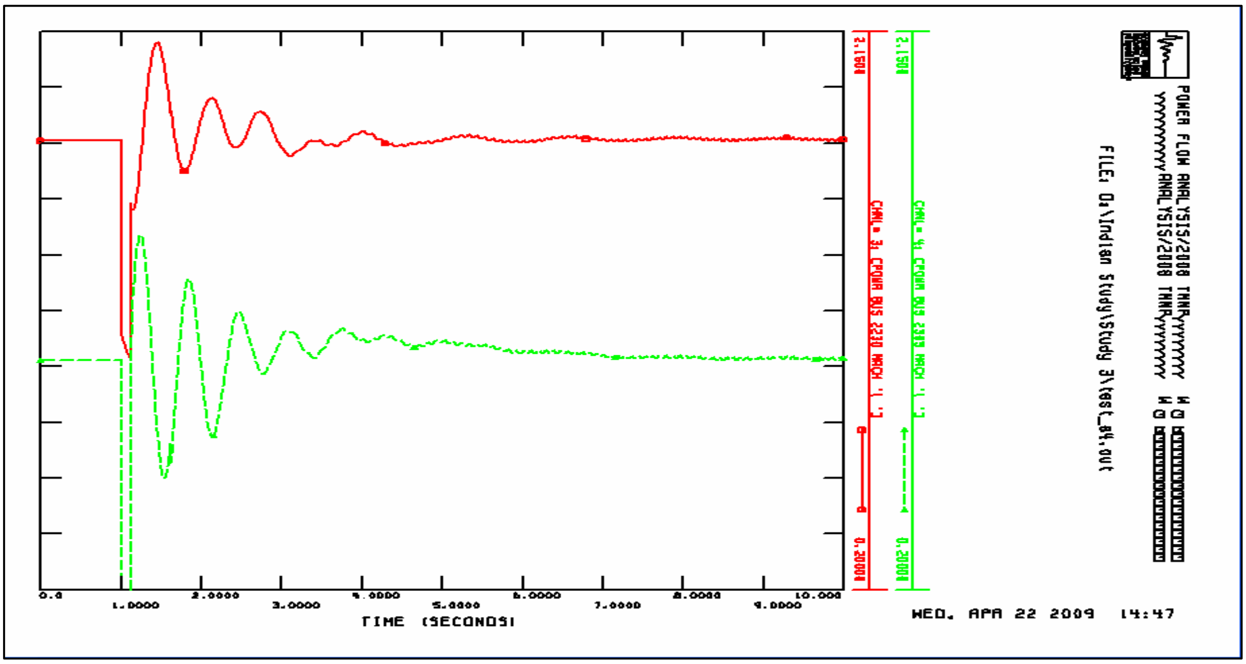



**Terminal Voltage Variation**

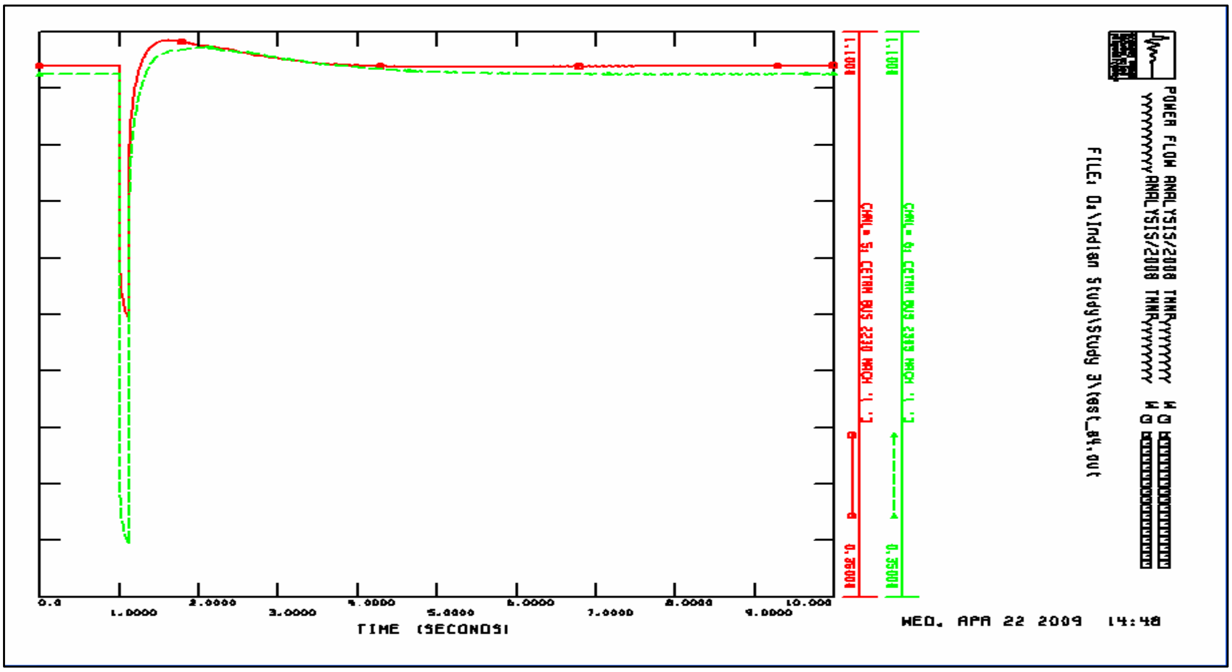


(iv) Simulation of 3 Ø fault on one cct of Kotugoda-Biyagama 220kV transmission Line at Kotugoda end. Successful reclosing assumed.

**Power Output Variation**

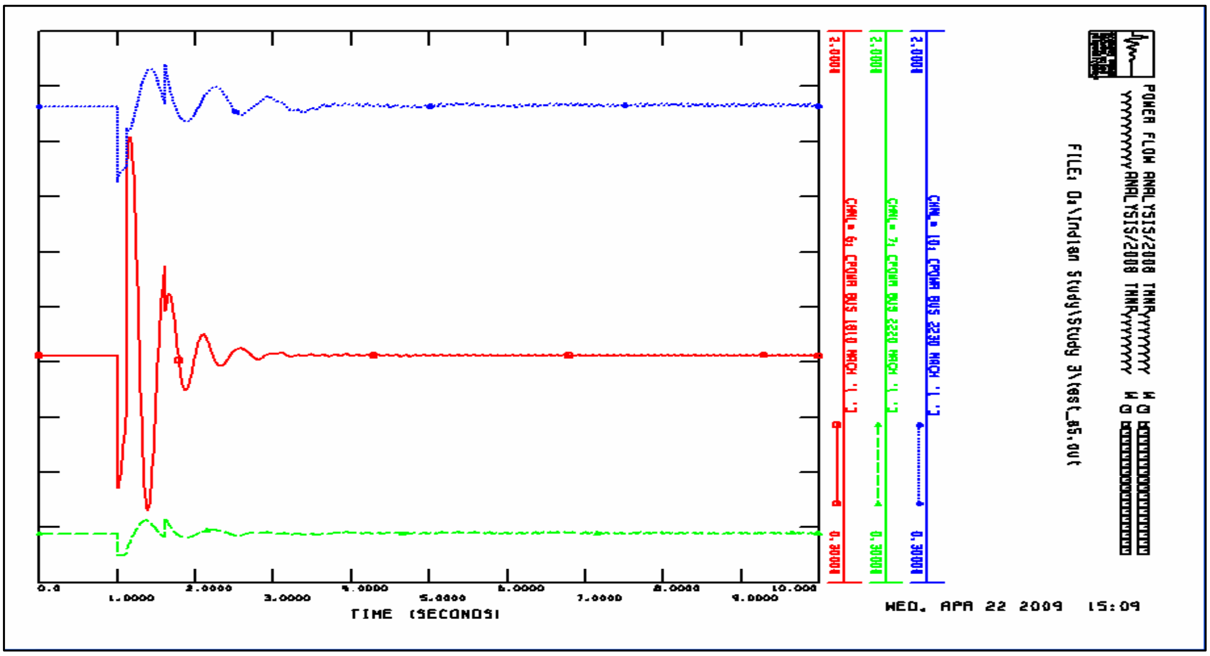



**Terminal Voltage Variation**

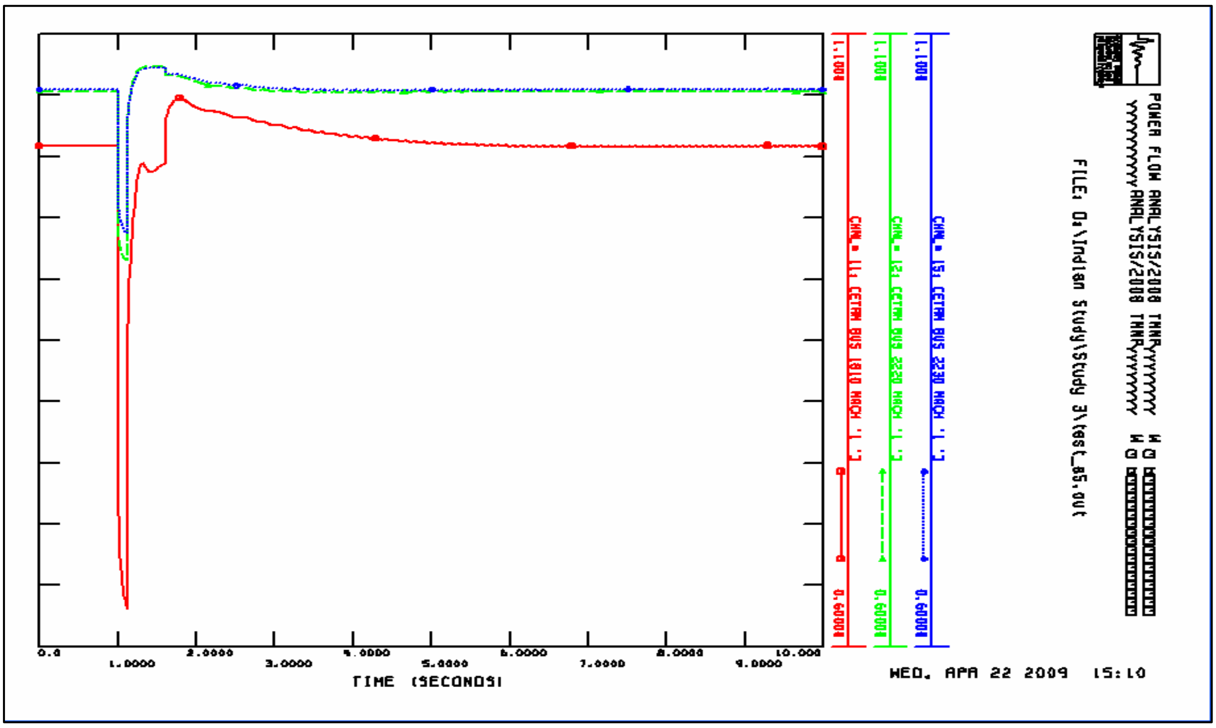


(v) Simulation of 3 Ø fault on one cct of Kotmale-New Anuradhapura 220kV transmission Line at New Anuradhapura end. Successful reclosing assumed.

**Power Output Variation**




**Terminal Voltage Variation**

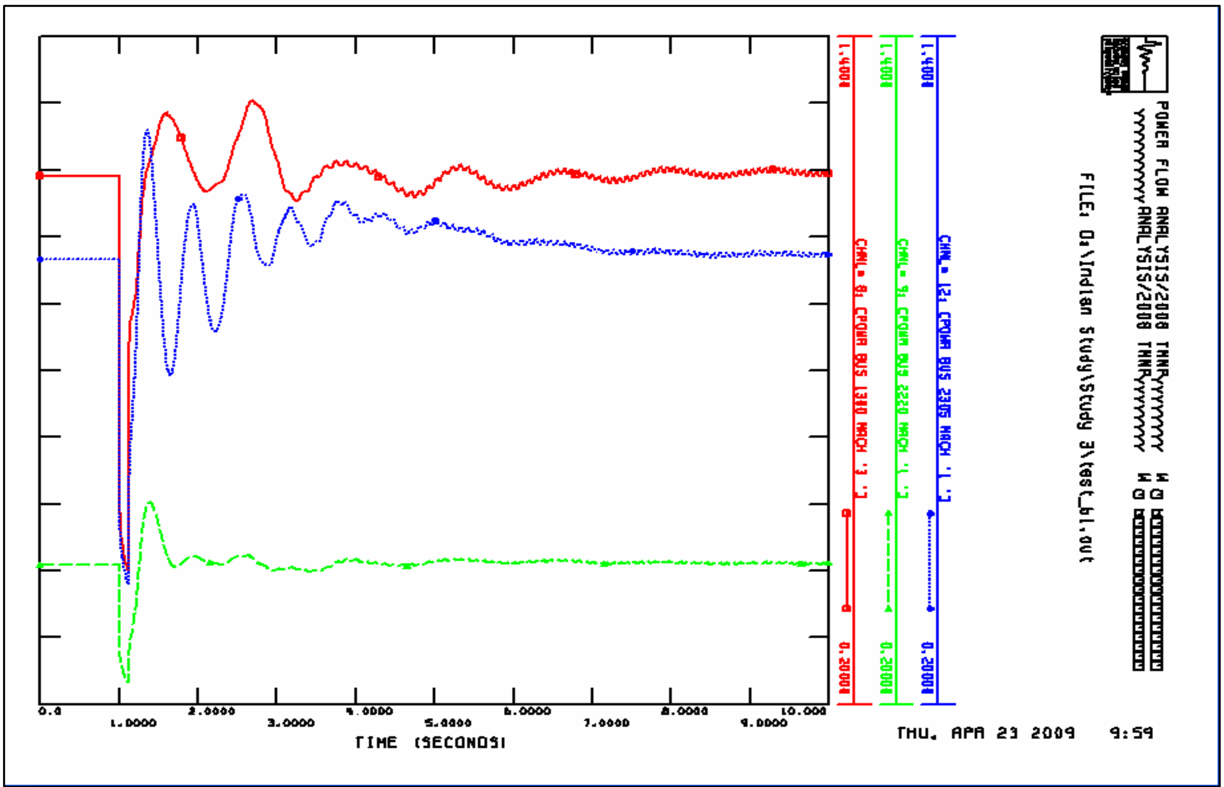


(2) Disturbance is simulated by tripping <u>*one circuit*of 132 KV lines</u> (with thermal maximum at night peak) and the responses are obtained and plotted using PSS/E modules, similar to those (with governors) of the above item (a), for the following cases of study: (with Successful Recloser)

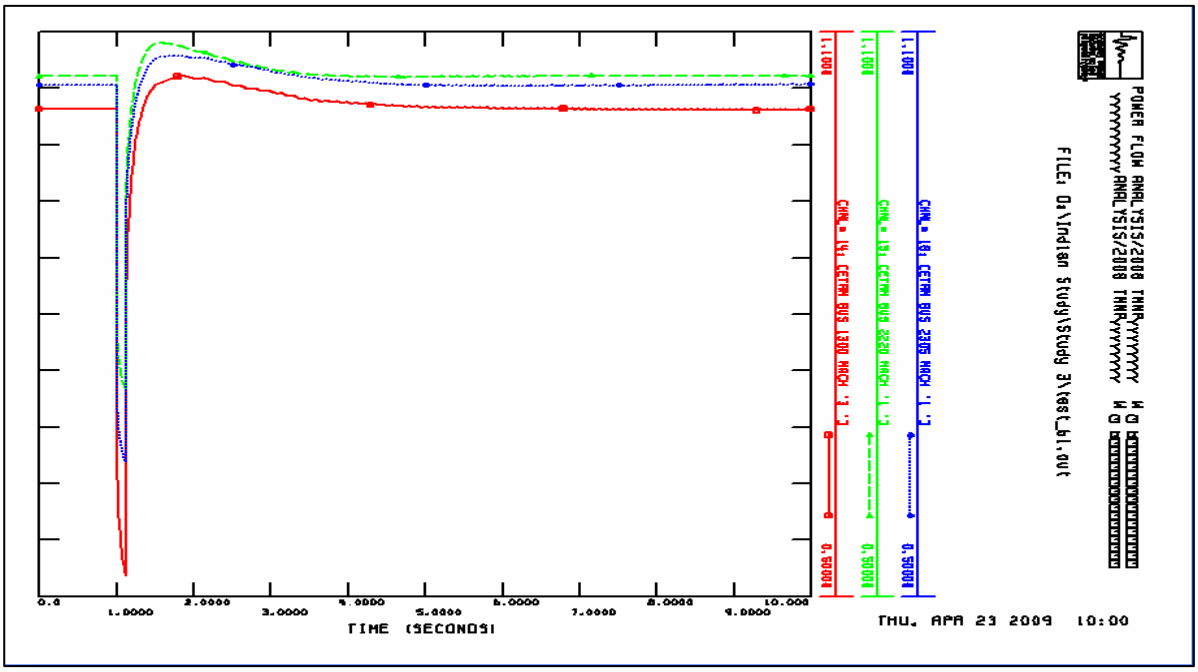
(i) *Biyagama – Sapugaskanda* at Biyagama end: Response plots of variations in Terminal Voltage, and Power output, at three buses.
(ii) *New Laxapana – Balangoda* at Balangoda end: Response plots of variations in Terminal Voltage, and Power output, at three buses.
(iii) *Polpitiya – Kiribathkubura* at Polpitiya end: Response plots of variations in Terminal Voltage, and Power output, at three buses.
(iv) *Kelaniya – Kolonnawa* at Kelaniya end: Response plots of variations in Terminal Voltage, and Power output, at three buses.
(v) *Kolonnawa – Kelanitissa* at Kolonnawa end: Response plots of variations in Terminal Voltage, and Power output, at three buses.

(i) Simulation of 3 Ø fault on one cct of Biyagama-Sapugaskanda 132kV transmission Line at Biyagama end. Successful reclosing assumed.

**Power Output Variation**

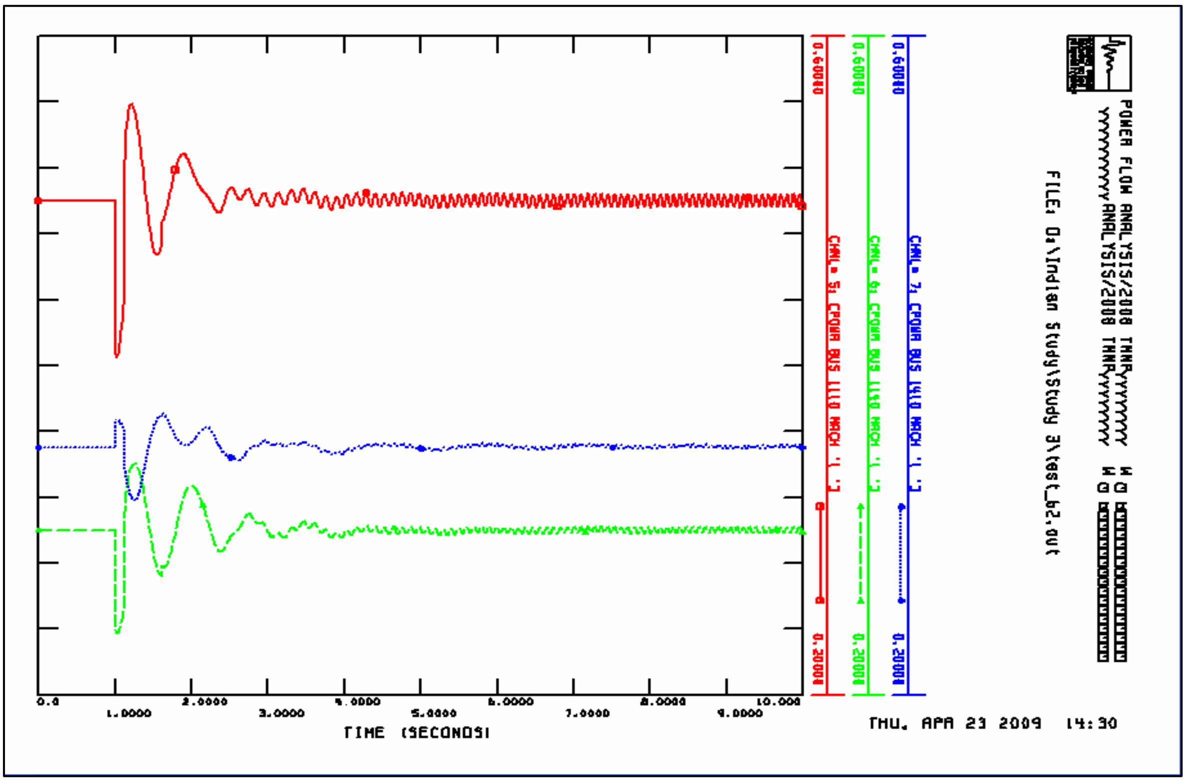


**Terminal Voltage Variation**

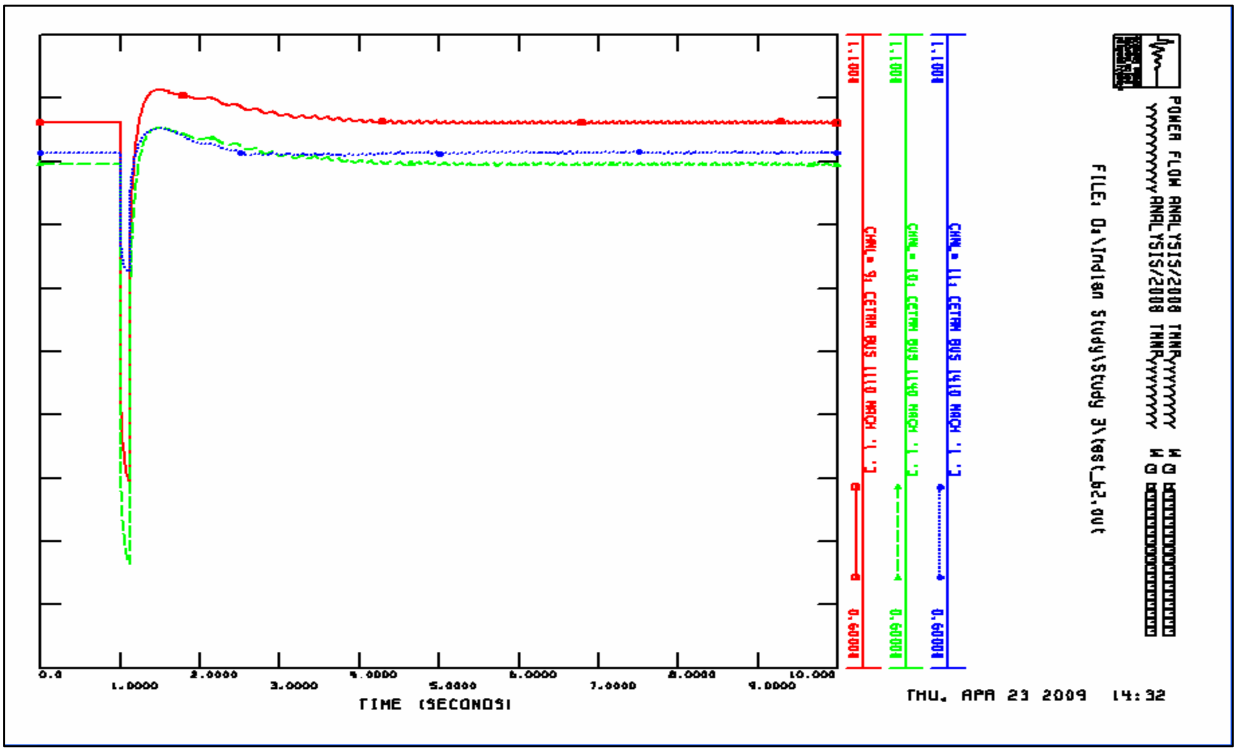



(ii) Simulation of 3 Ø fault on one cct of New Laxapana-Balangoda 132kV transmission Line at Balangoda end. Successful reclosing assumed.

**Power Output Variation**

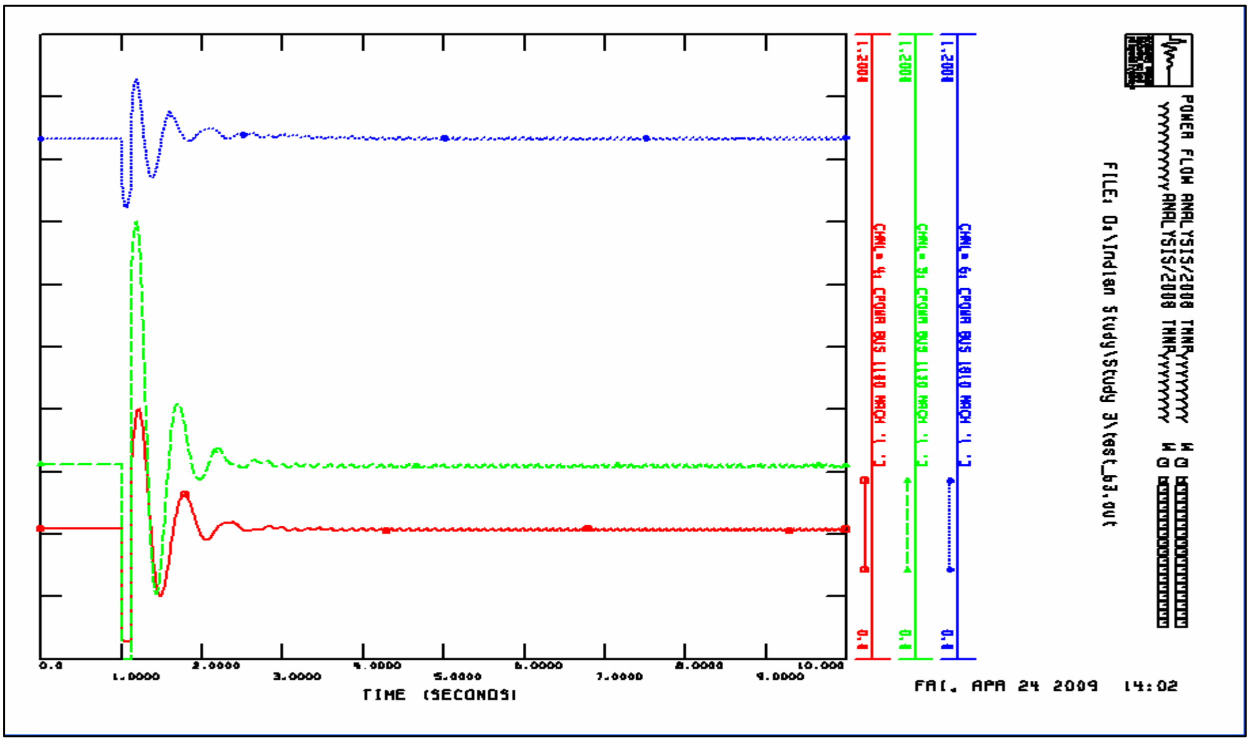


**Terminal Voltage Variation**

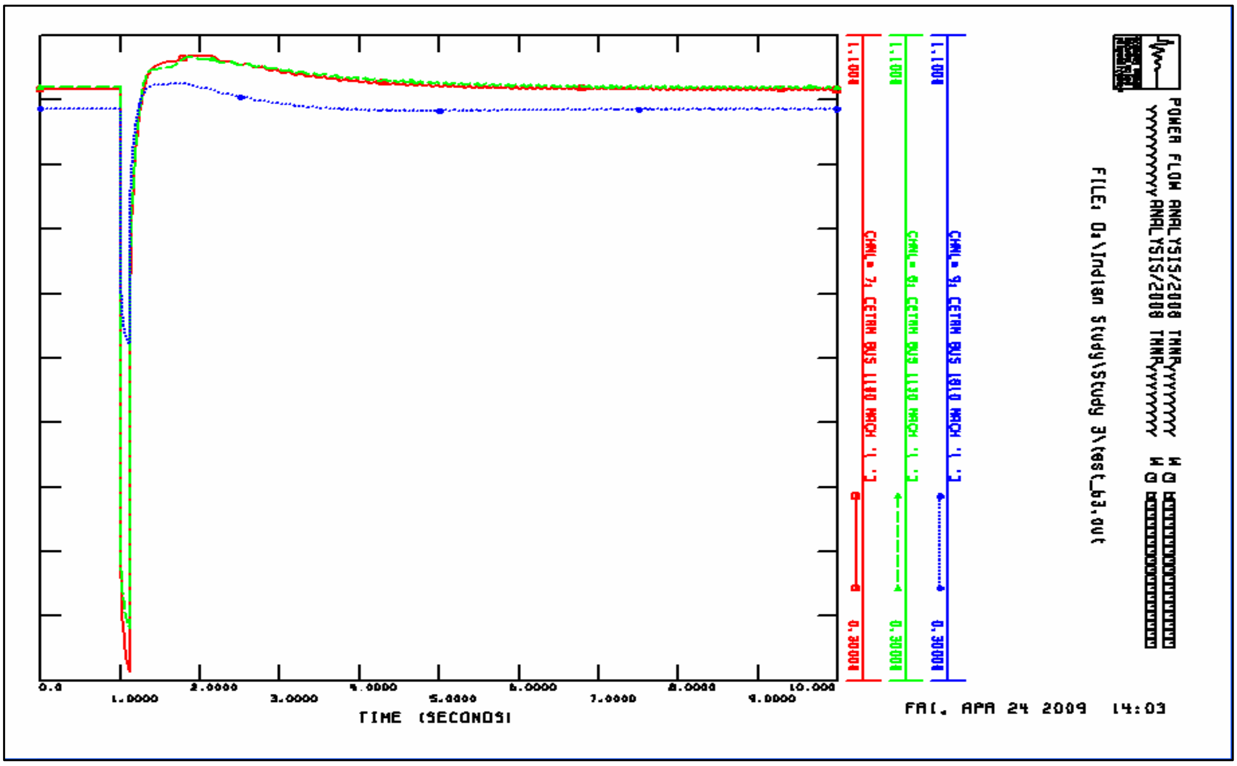



(iii) Simulation of 3 Ø fault on one cct of Polpitiya-Kiribathkubura 132kV transmission Line at Polpitiya end. Successful reclosing assumed.

**Power Output Variation**

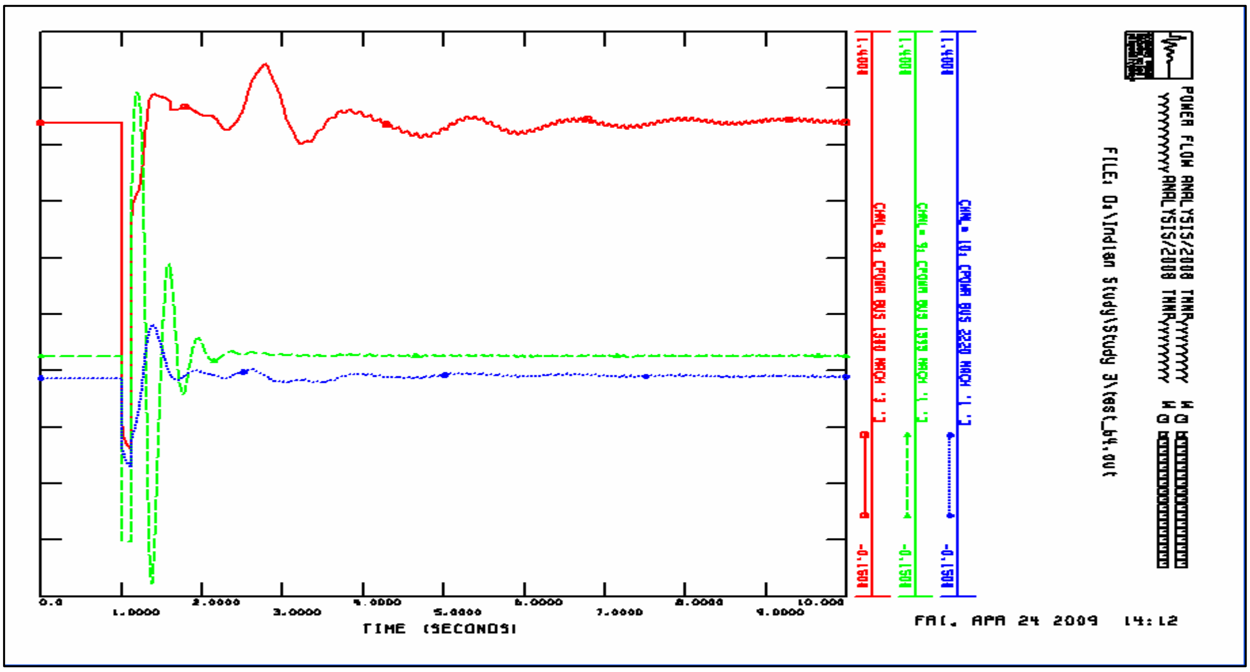


**Terminal Voltage Variation**

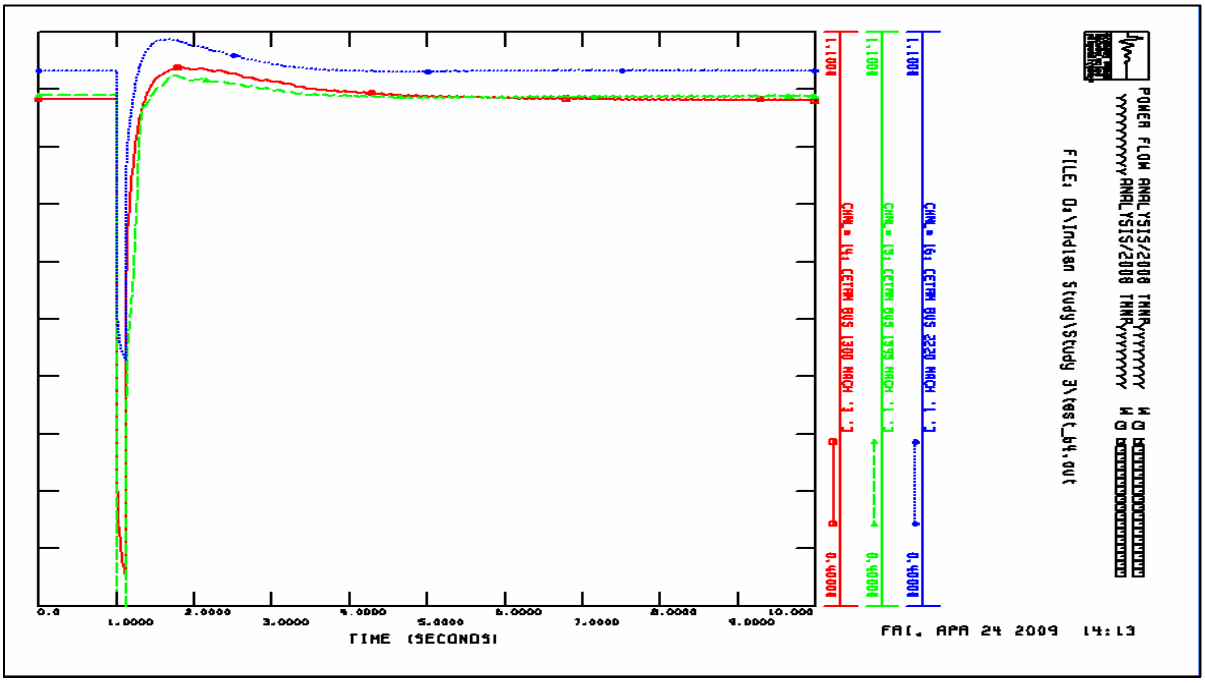



(iv) Simulation of 3 Ø fault on one cct of Kelaniya-Kolonnawa 132kV transmission Line at Kelaniya end. Successful reclosing assumed.

**Power Output Variation**

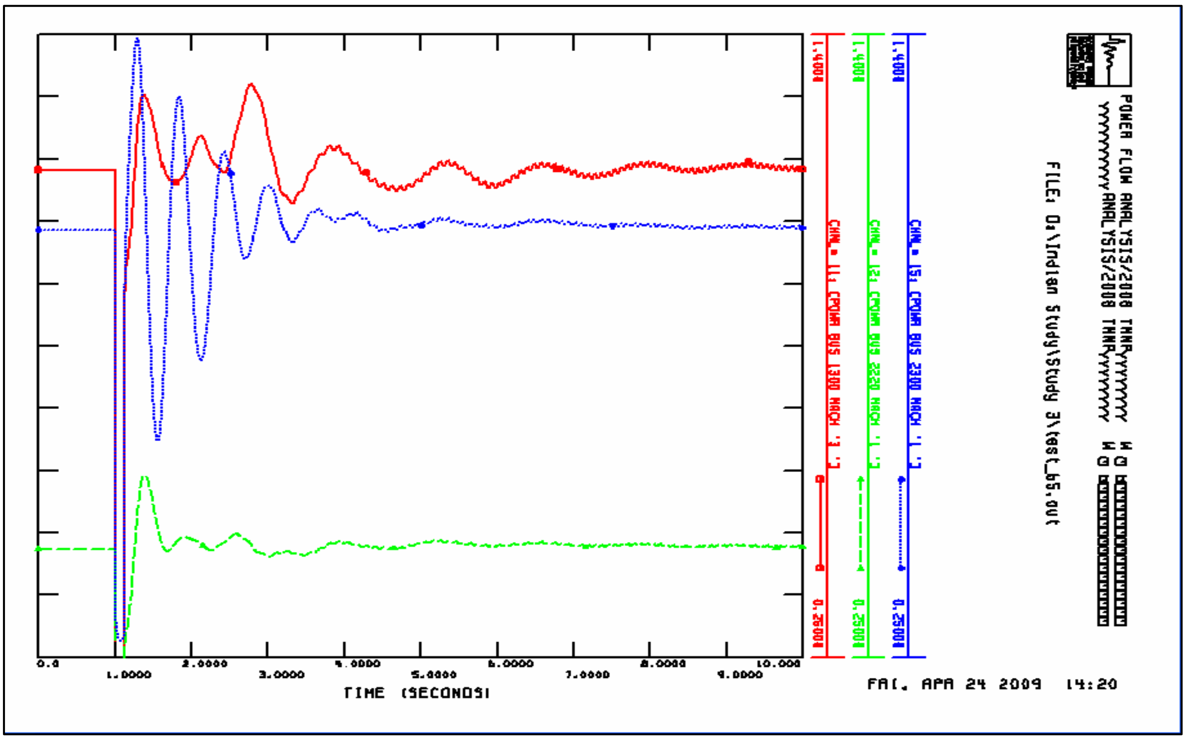


**Terminal Voltage Variation**

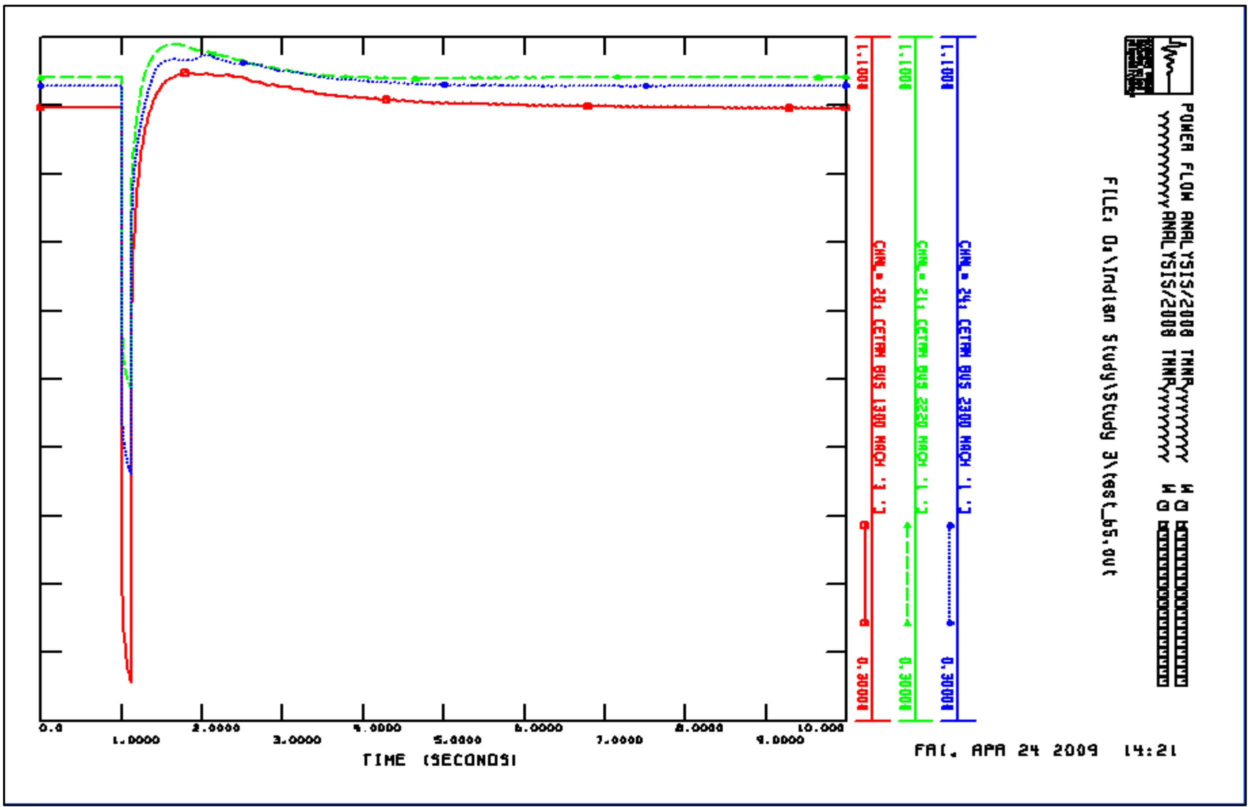



(v) Simulation of 3 Ø fault on one cct of Kolonnawa-Kelanitissa 132kV transmission Line at Kolonnawa end. Successful reclosing assumed.

**Power Output Variation**



**Terminal Voltage Variation**




**(d) Simulation of Three-phase Faults on 220/132 KV Lines, *with machines equipped with Excitation System Model IEEE T1 :***

(1) Disturbance is simulated by tripping <u>*one circuit* of 220 KV lines</u> (with thermal maximum at night peak) and the responses are obtained and plotted using PSS/E modules, similar to those (with governors) of the above item (a), for the following cases of study: (with Successful Recloser)

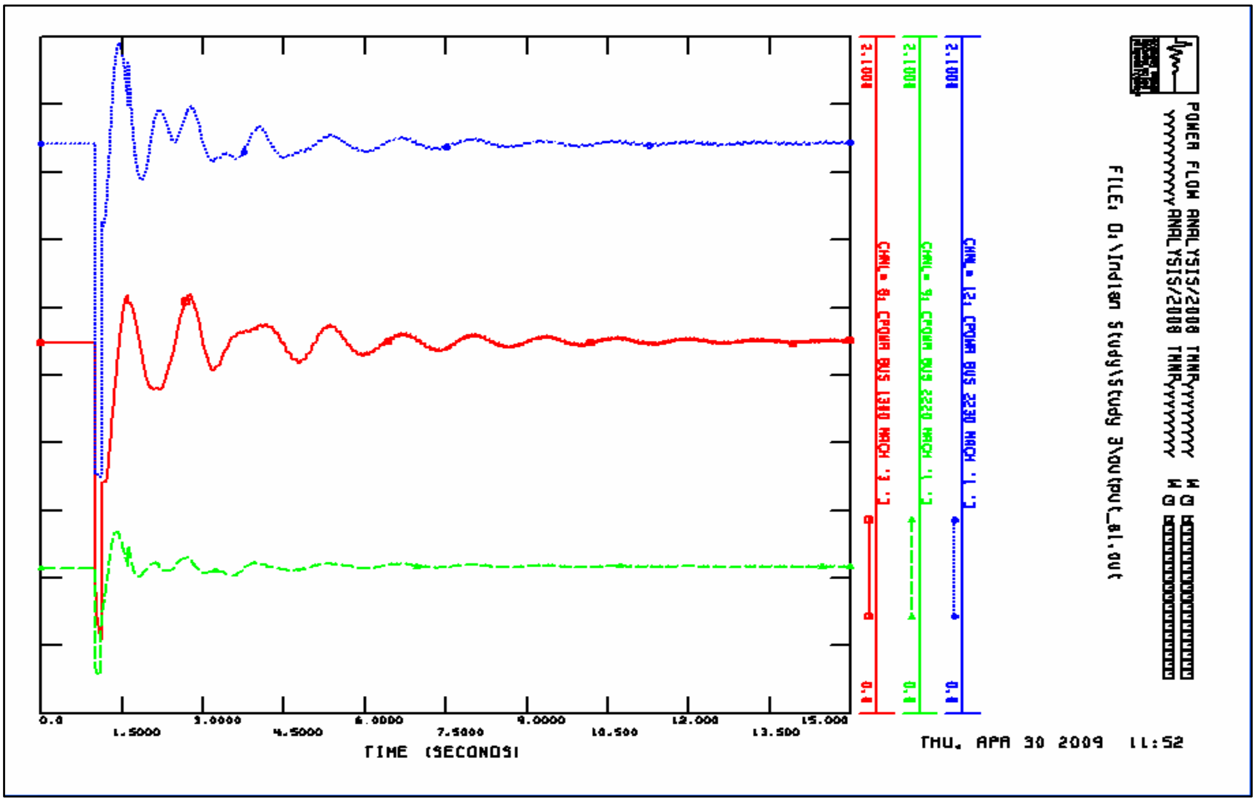
(i) *Kotmale – Biyagama* at Biyagama end: Response plots of variations in Terminal Voltage, and Power output, at three buses.

(ii) *Kelanitissa GIS – Biyagama* at Biyagama end : Response plots of variations in Terminal Voltage, and Power output, at two buses.

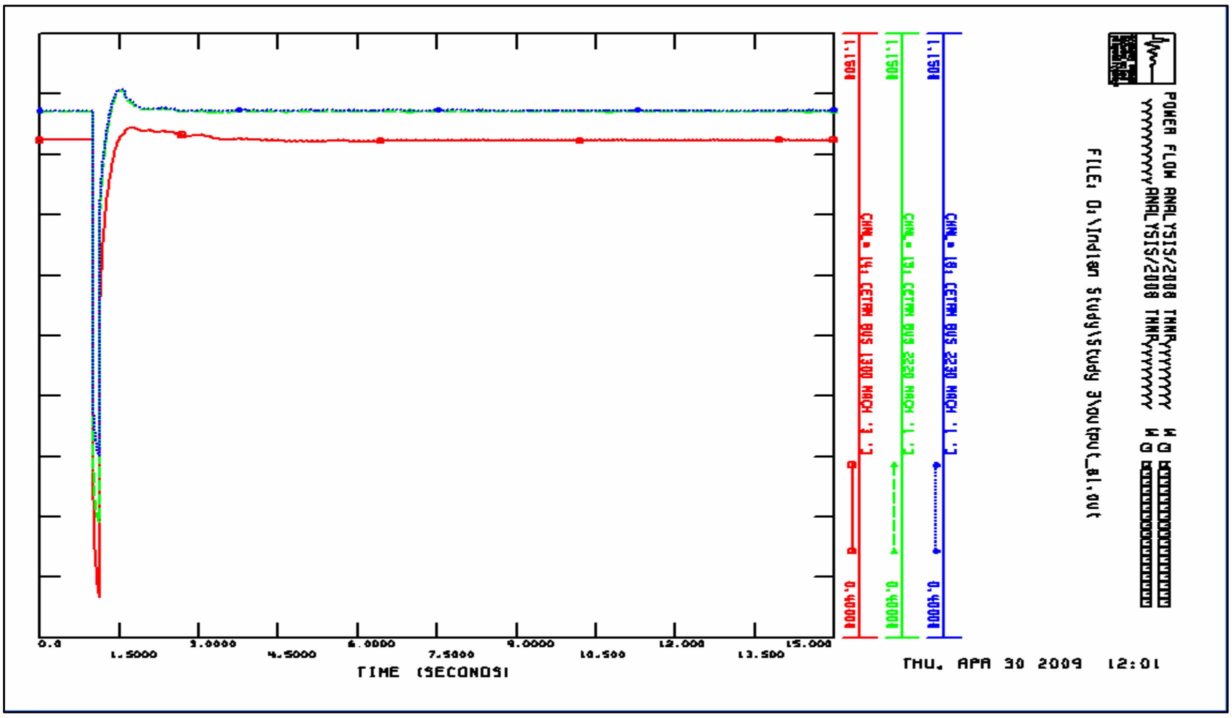
(iii) *Pannipitiya – Biyagama* at Pannipitiya end : Response plots of variations in Terminal Voltage, and Power output, at four buses.

(i) Simulation of 3 Ø fault on one cct of Kotmale-Biyagama 220kV transmission Line at Biyagama end. Successful reclosing assumed.

**Power Output Variation**

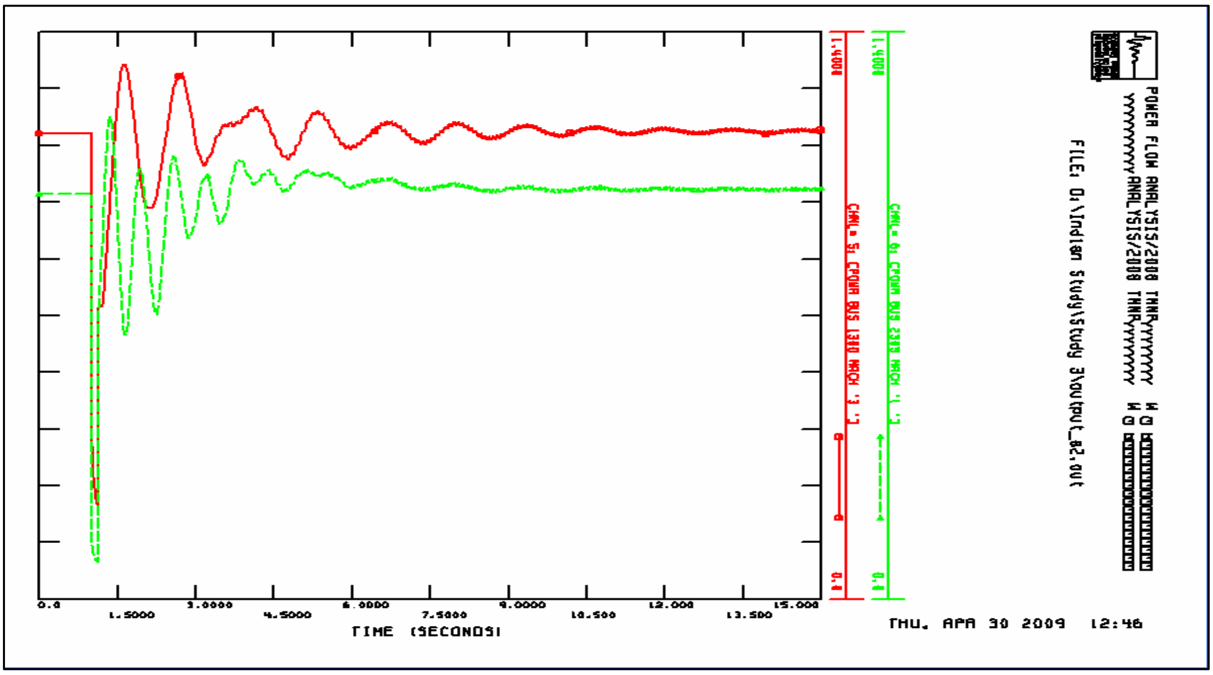



**Terminal Voltage variation**

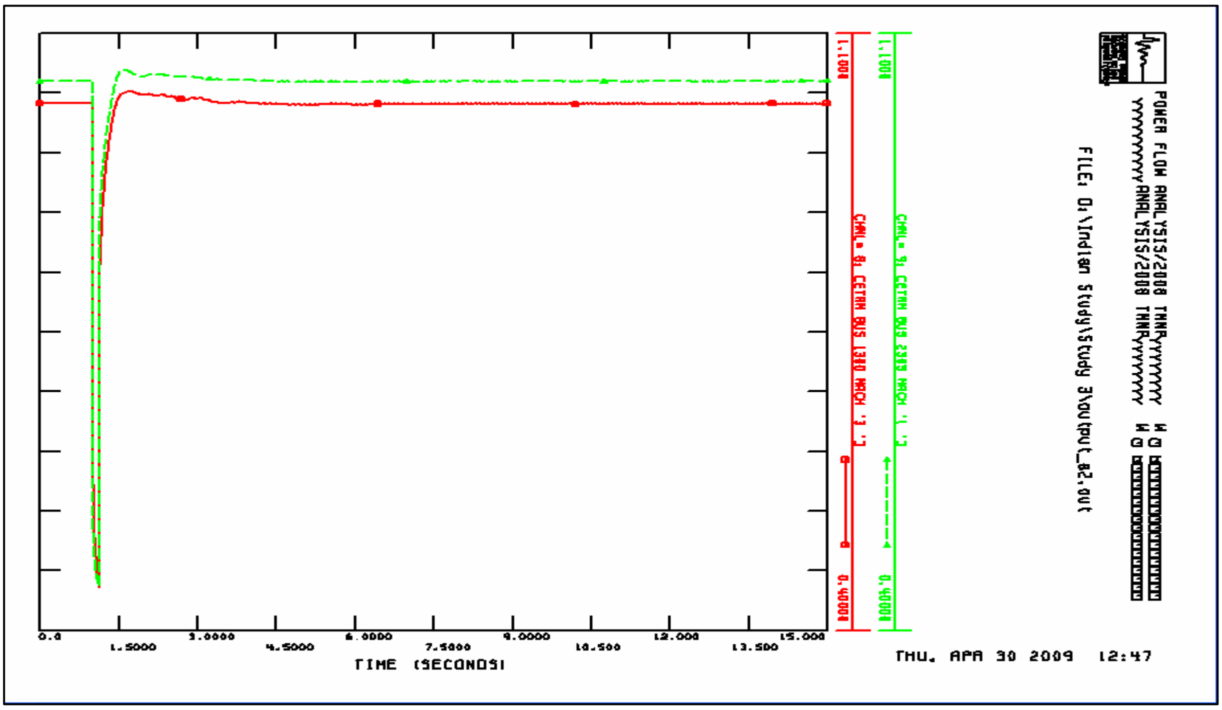


(ii) Simulation of 3 Ø fault on one cct of Kelanitissa GIS -Biyagama 220kV transmission Line at Biyagama end. Successful reclosing assumed.

**Power Output Variation**

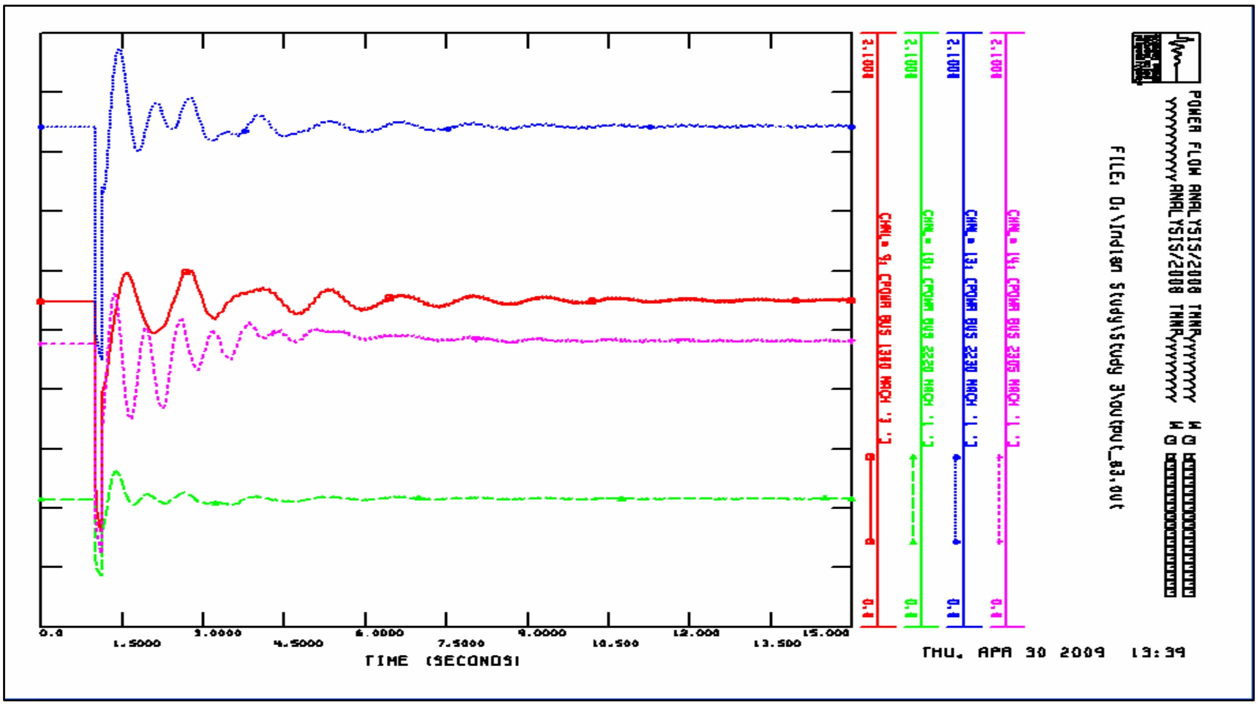



**Terminal Voltage Variation**

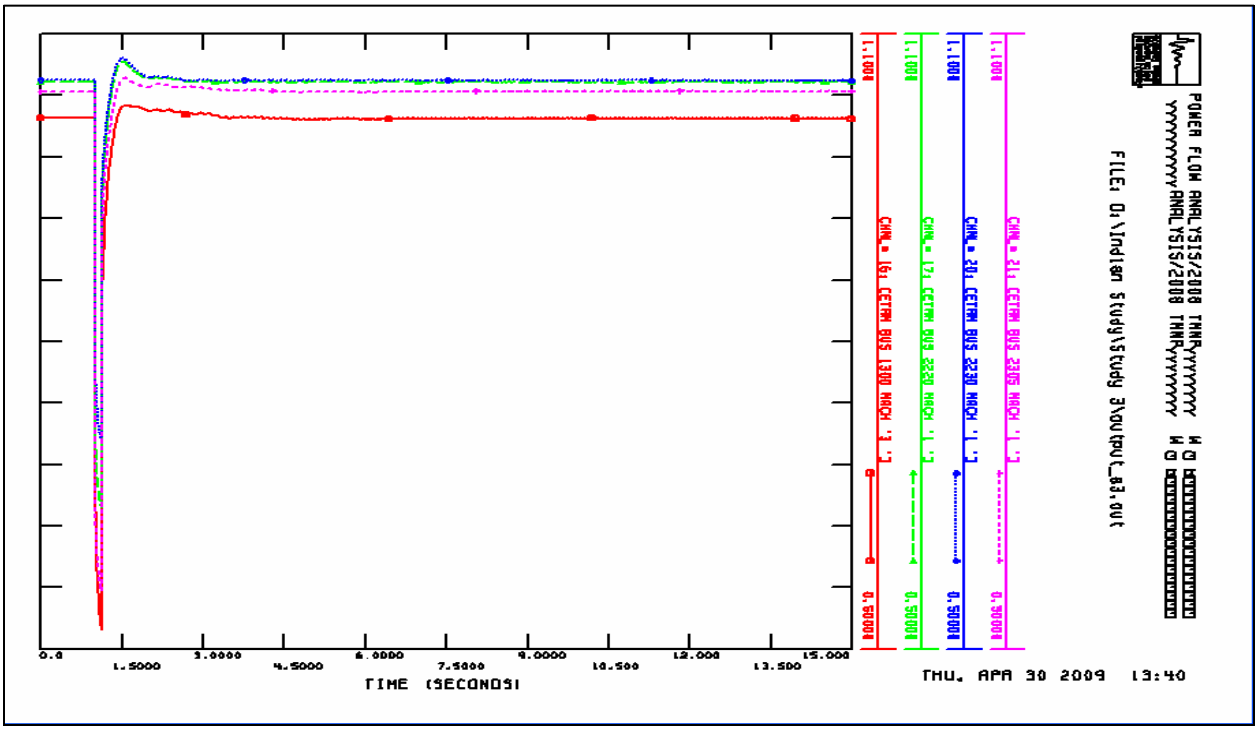


(iii) Simulation of 3 Ø fault on one cct of Pannipitiya -Biyagama 220kV transmission Line at Pannipitiya end. Successful reclosing assumed.

**Power Output Variation**



**Terminal Voltage Variation**



(2) Disturbance is simulated by tripping <u>*one circuit* of 132 KV lines</u> (with thermal maximum at night peak) and the responses are obtained and plotted using PSS/E modules, similar to those (with governors) of the above item (a), for the following cases of study: (with Successful Recloser)

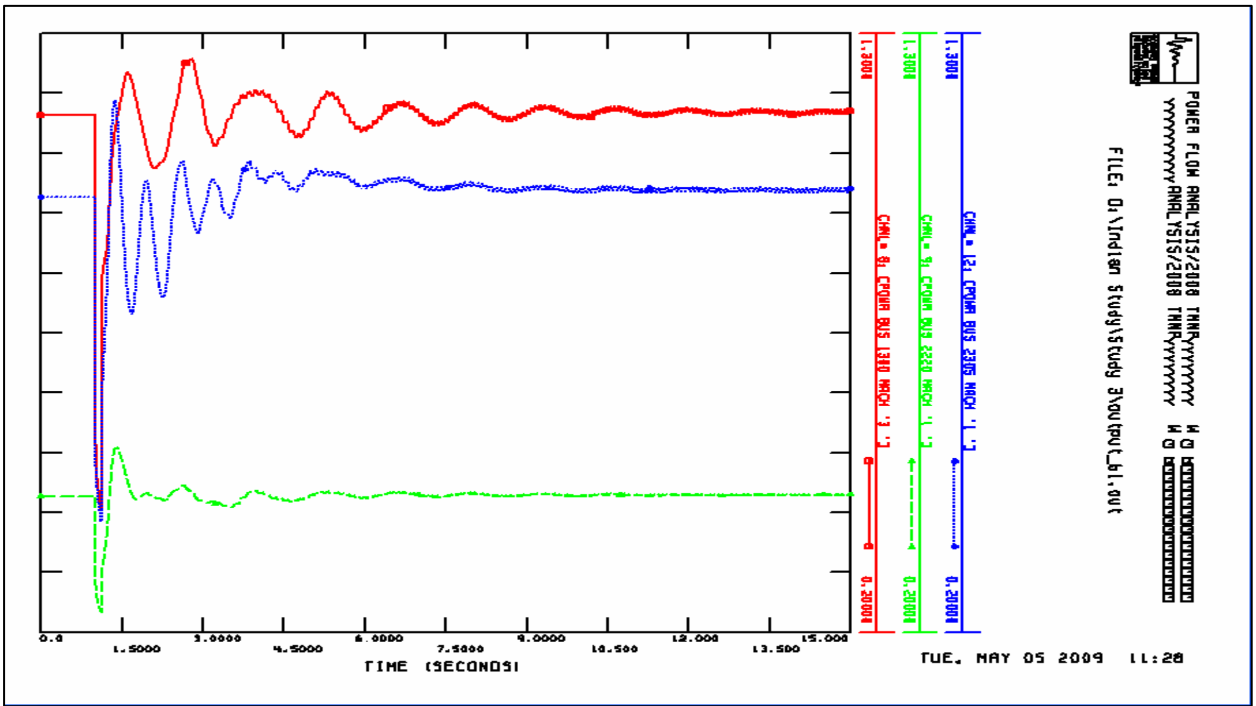
   (i) *Biyagama – Sapugaskanda* at Biyagama end: Response plots of variations in Terminal Voltage, and Power output, at three buses.

   (ii) *New Laxapana – Balangoda* at Balangoda end: Response plots of variations in Terminal Voltage, and Power output, at three buses.

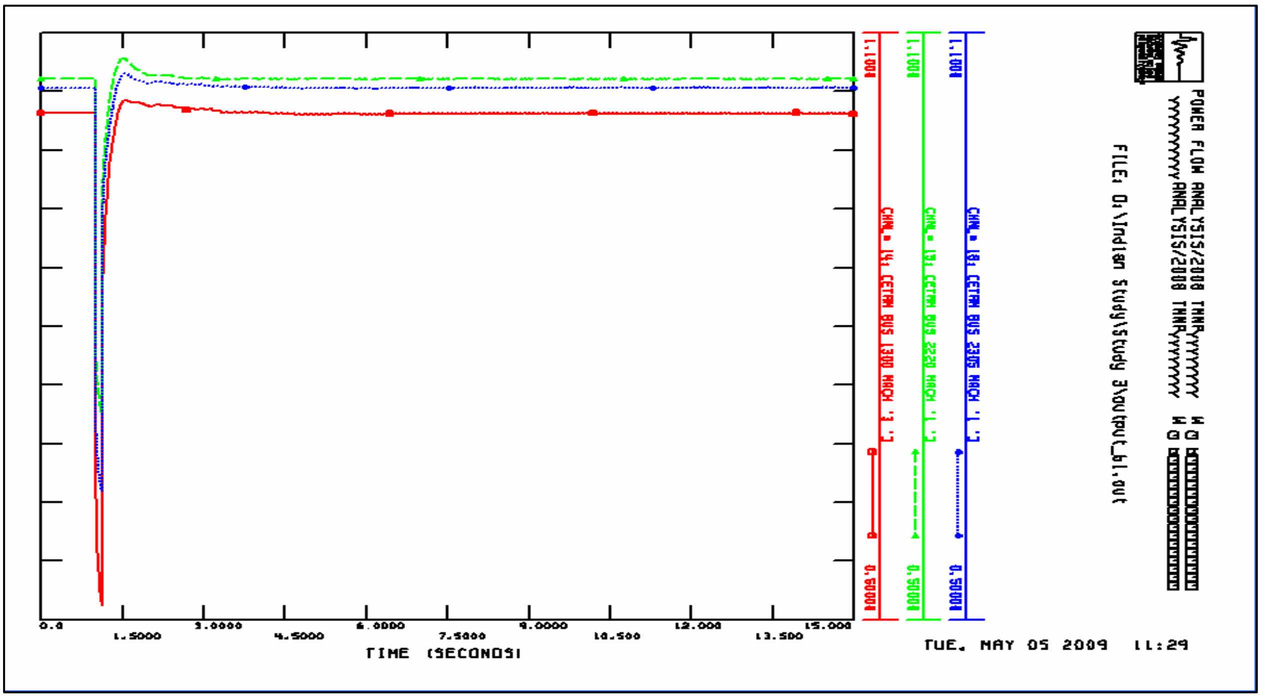
   (iii) *Polpitiya – Kiribathkubura* at Polpitiya end: Response plots of variations in Terminal Voltage, and Power output, at three buses.

(i) Simulation of 3 Ø fault on one cct of Biyagama-Sapugaskanda 132kV transmission Line at Biyagama end. Successful reclosing assumed.

**Power Output Variation**

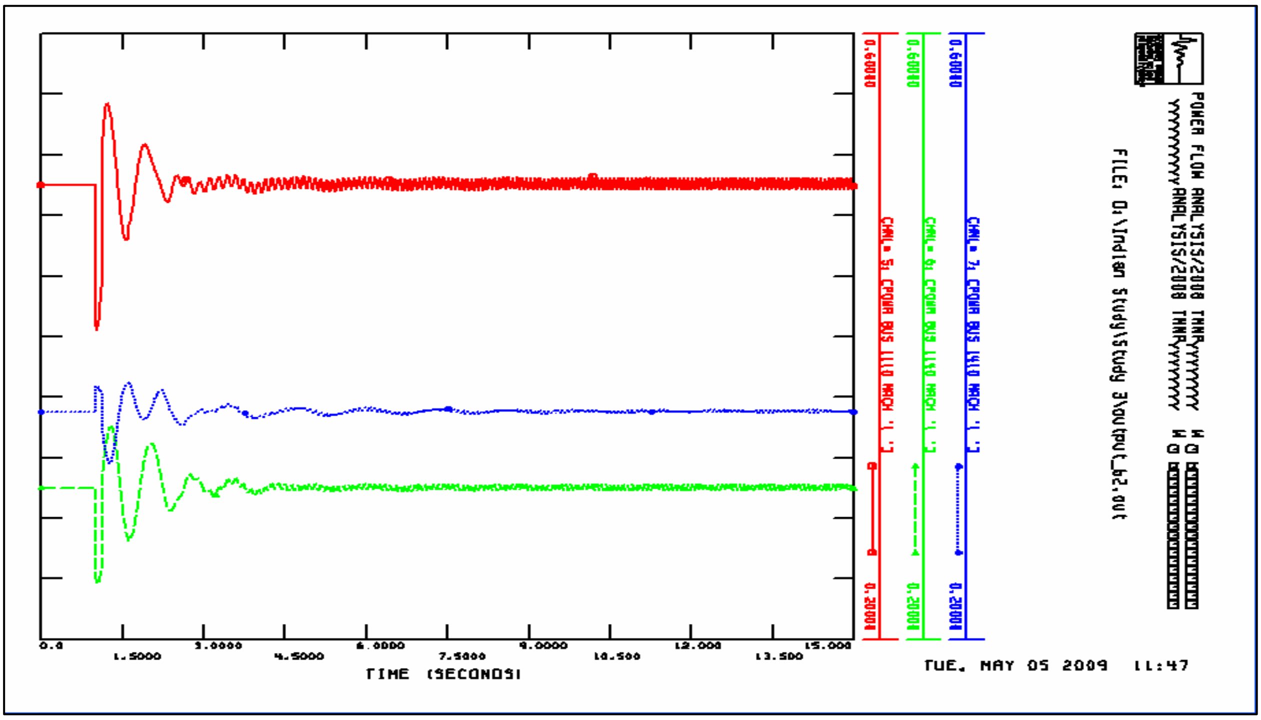


**Terminal Voltage Variation**

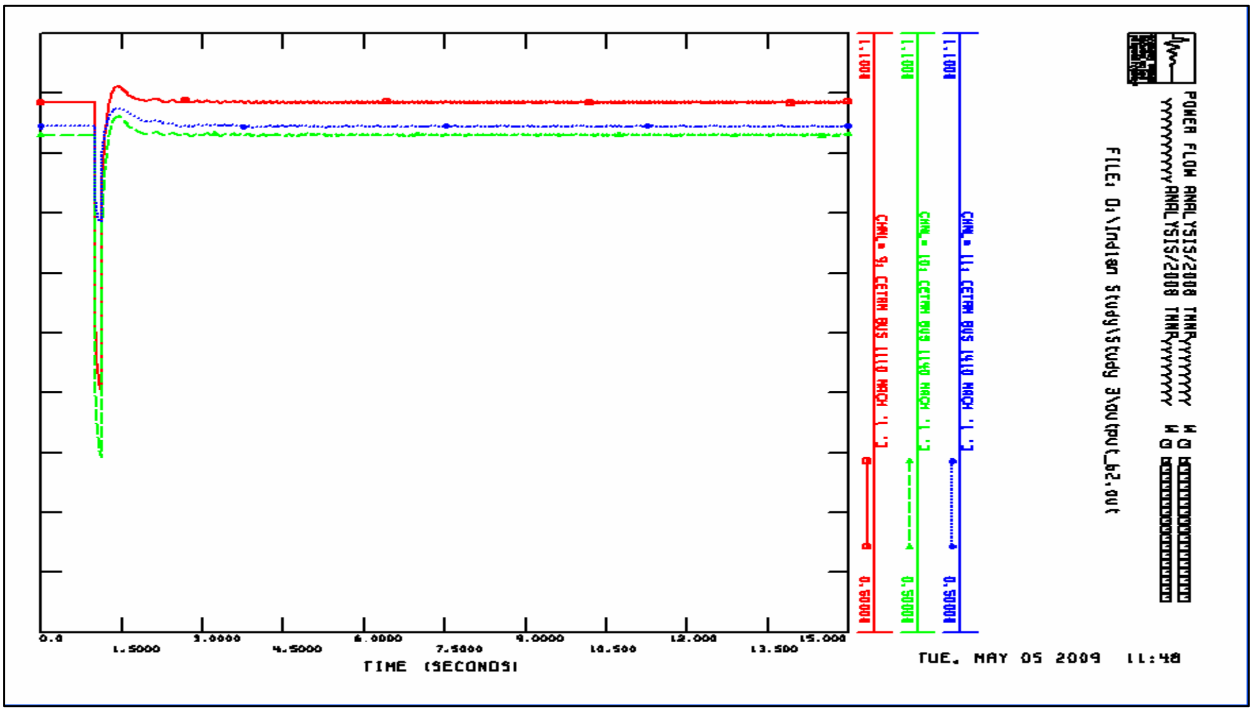



(ii) Simulation of 3 Ø fault on one cct of New Laxapana-Balangoda 132kV transmission Line at Balangoda end. Successful reclosing assumed.

**Power Output Variation**

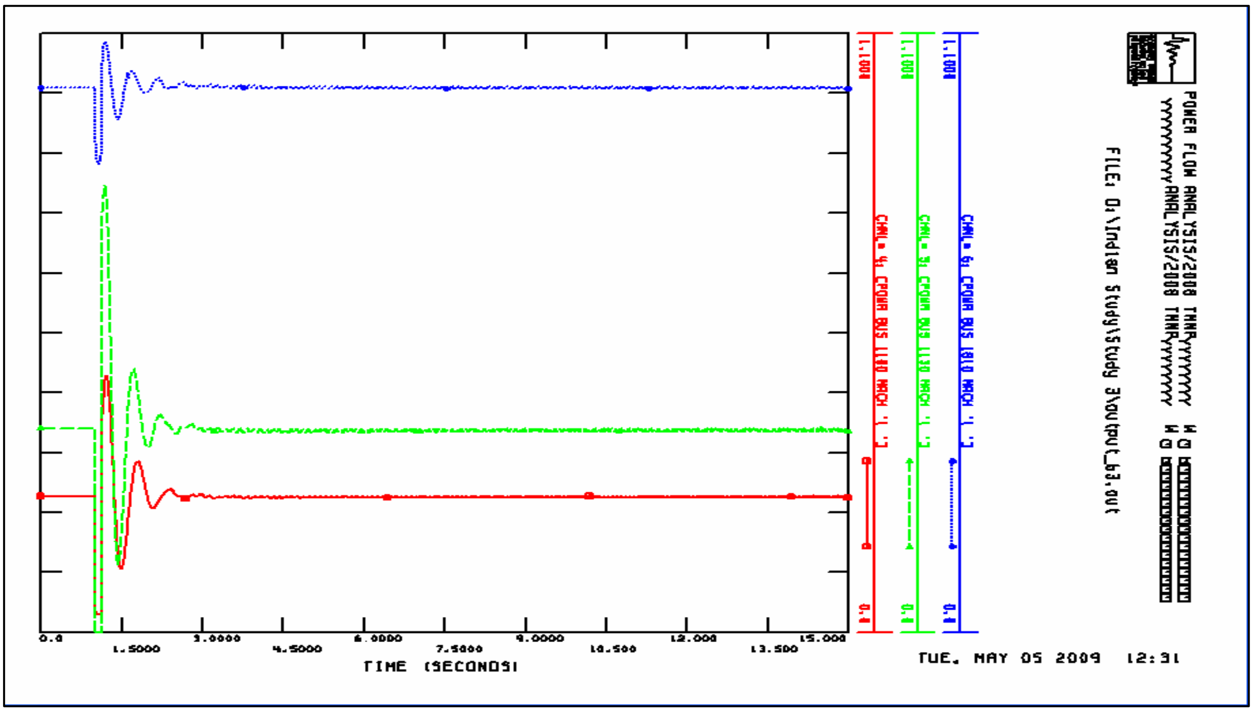


## Terminal Voltage Variation

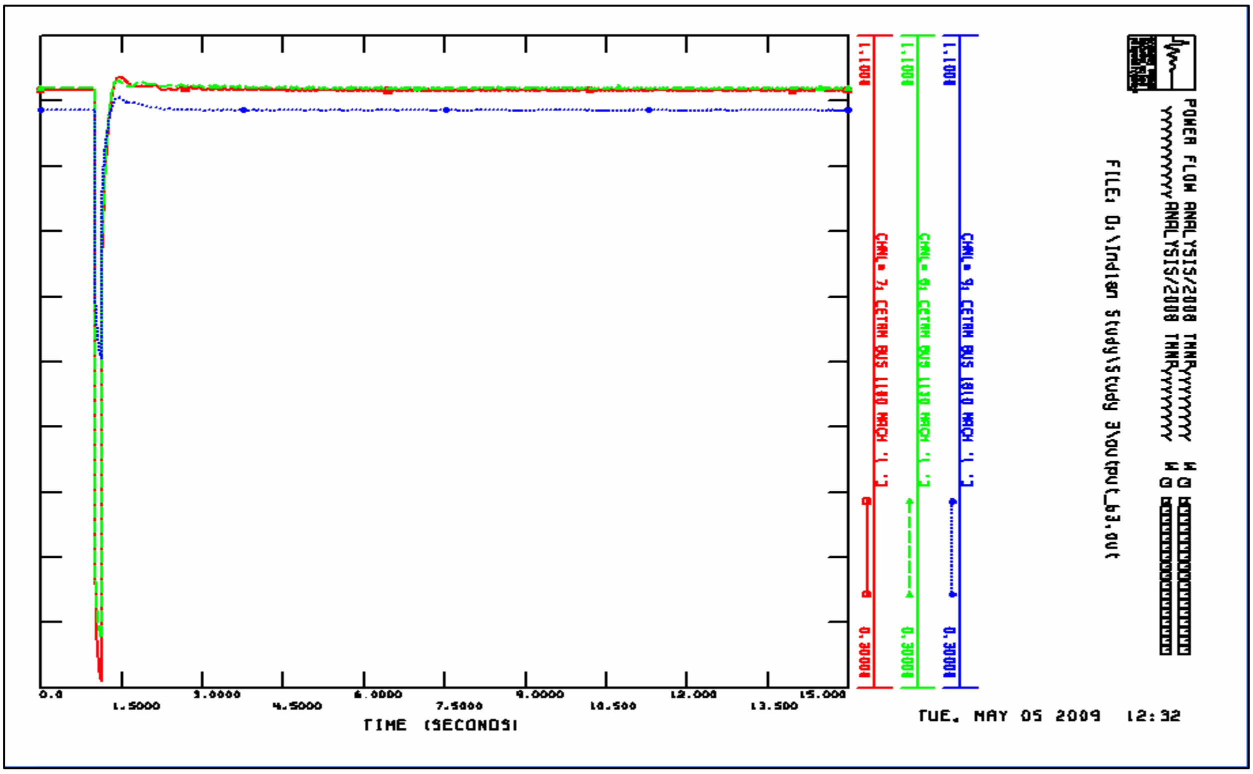


(iii) Simulation of 3 Ø fault on one cct of Polpitiya-Kiribathkubura 132kV transmission Line at Polpitiya end. Successful reclosing assumed.

## Power Output Variation



**Terminal Voltage Variation**




**(e) Simulation of Three-phase Faults on 220 / 132 KV Lines,** ***with machines equipped with Excitation System Model IEEE T1 and Power System Stabilizer (PSS) of STAB 1 Type Model :***

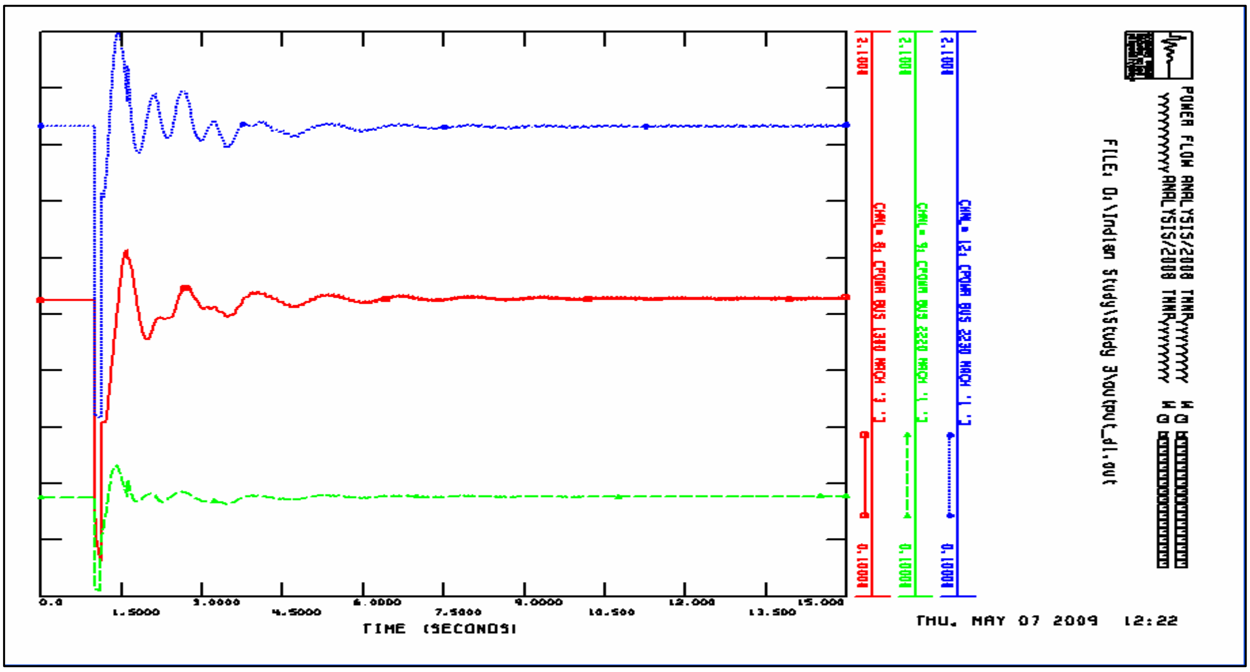
It is simulated that the following Generating Stations are considered for installation of PSS: Kelanitissa GT 7, Victoria, Kotmale, Randenigala, Rantembe, Kerawalapitia, and Kukule.

(1) Disturbance is simulated by tripping *one circuit* of 220 KV lines (with thermal maximum at night peak) and the responses are obtained and plotted using PSS/E modules, similar to those (with governors) of the above item (a), for the following cases of study: (with Successful Recloser)

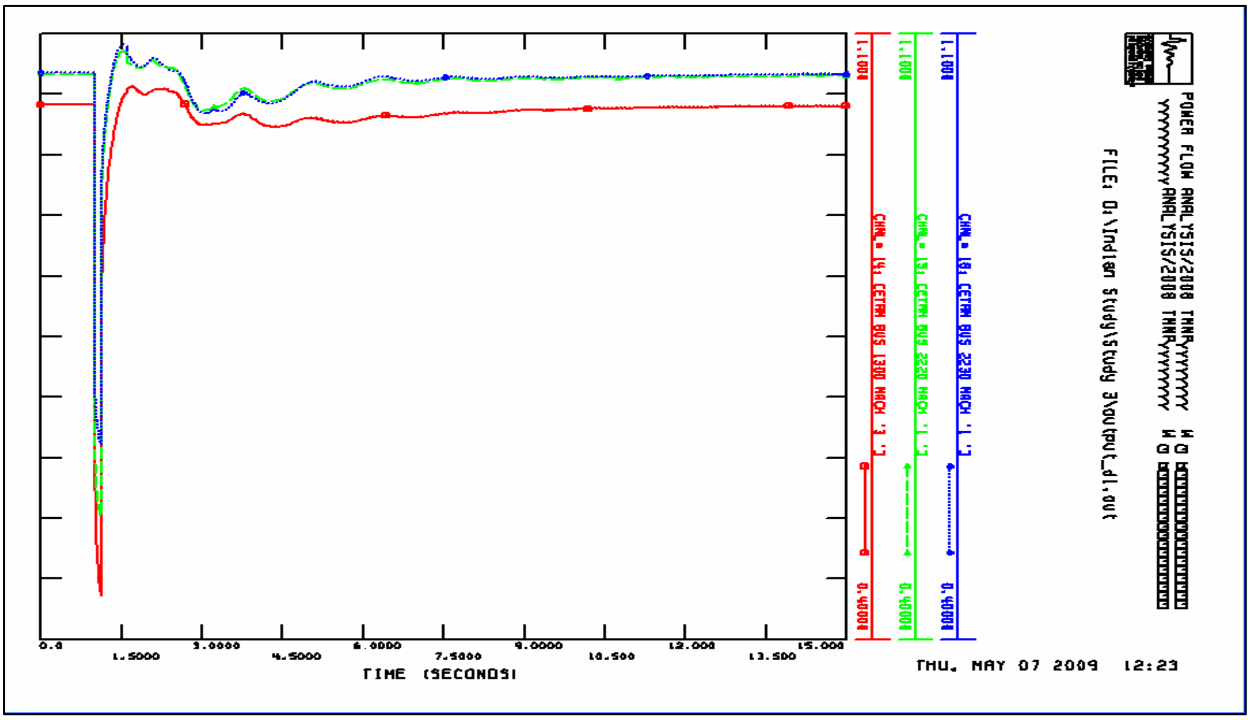
- (i) *Kotmale – Biyagama* at Biyagama end: Response plots of variations in Terminal Voltage, and Power output, at three buses.
- (ii) *Kelanitissa GIS – Biyagama* at Biyagama end: Response plots of variations in Terminal Voltage, and Power output, at two buses.
- (iii) *Pannipitiya – Biyagama* at Pannipitiya end: Response plots of variations in Terminal Voltage, and Power output, at four buses.

(i) Simulation of 3 Ø fault on one cct of Kotmale-Biyagama 220kV transmission Line at Biyagama end. Successful reclosing assumed.

**Power Output Variation**

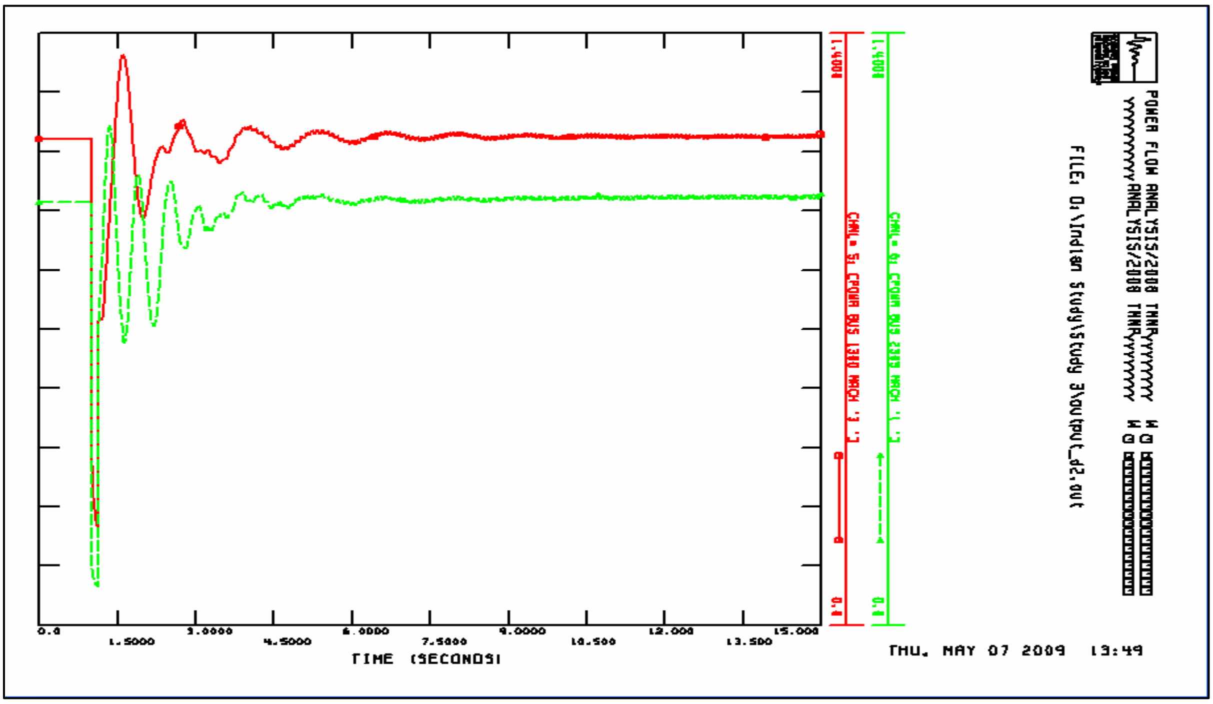


**Terminal Voltage Variation**

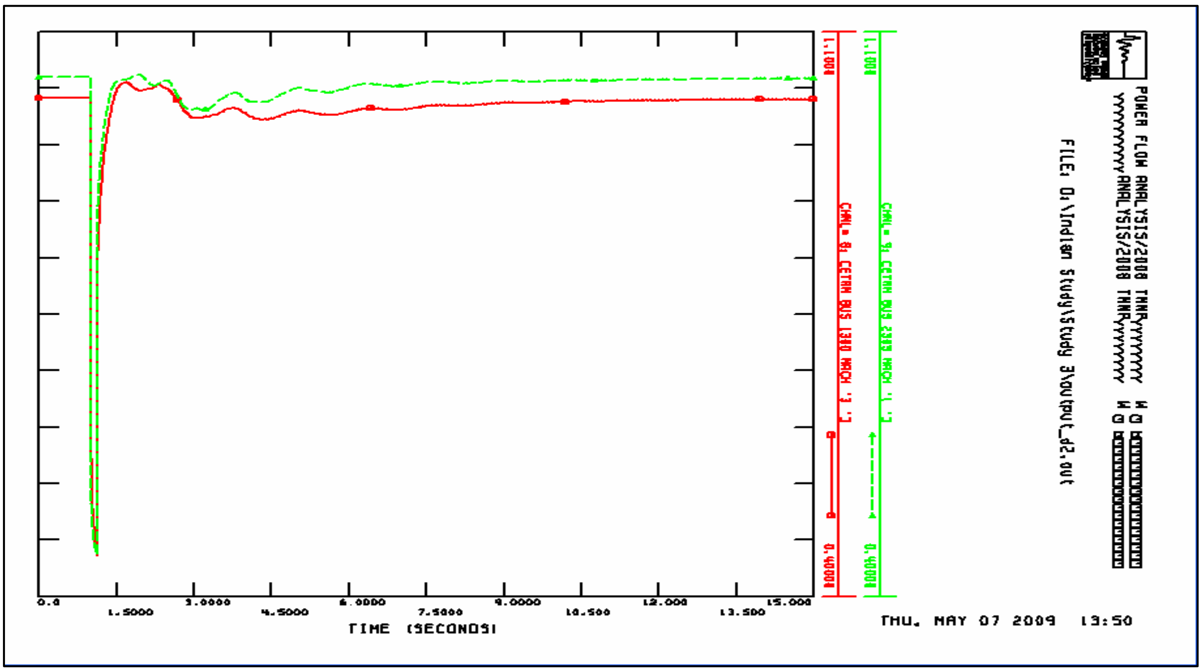


(ii) Simulation of 3 Ø fault on one cct of Kelanitissa GIS-Biyagama 220kV transmission Line at Biyagama end. Successful reclosing assumed.

**Power Output Variation**

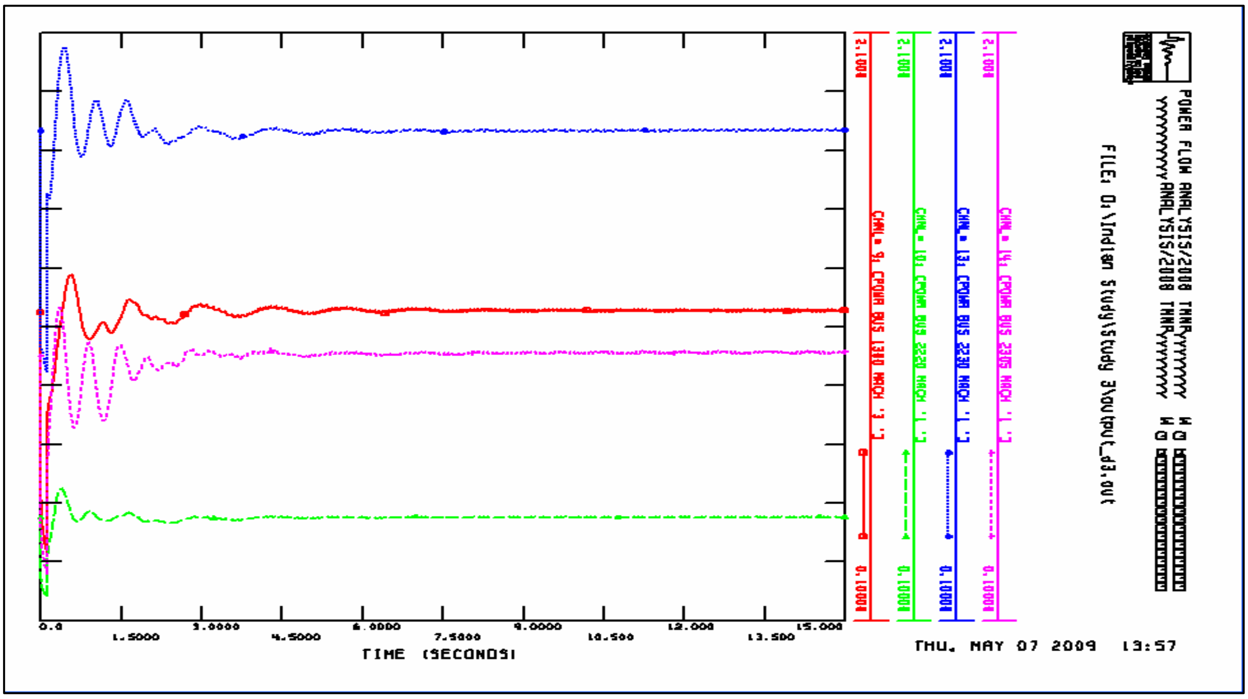



**Terminal Voltage Variation**

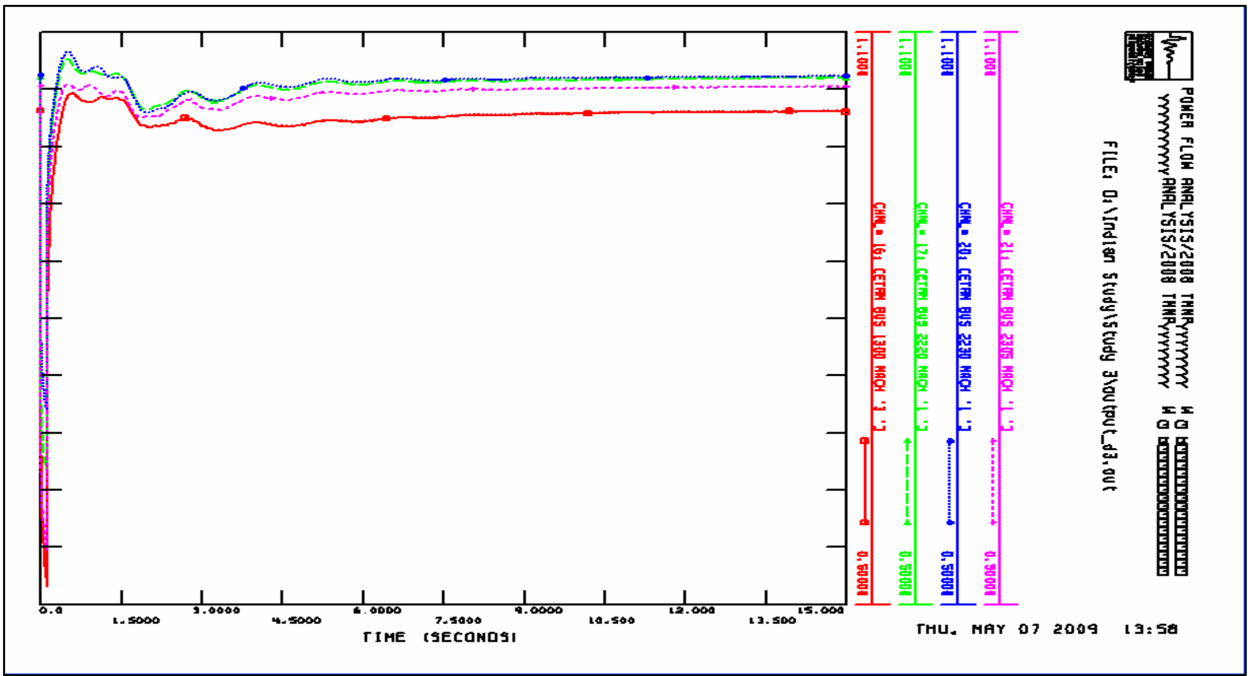


(iii) Simulation of 3 Ø fault on one cct of Pannipitiya -Biyagama 220kV transmission Line at Pannipitiya end. Successful reclosing assumed.

**Power Output Variation**




**Terminal Voltage Variation**

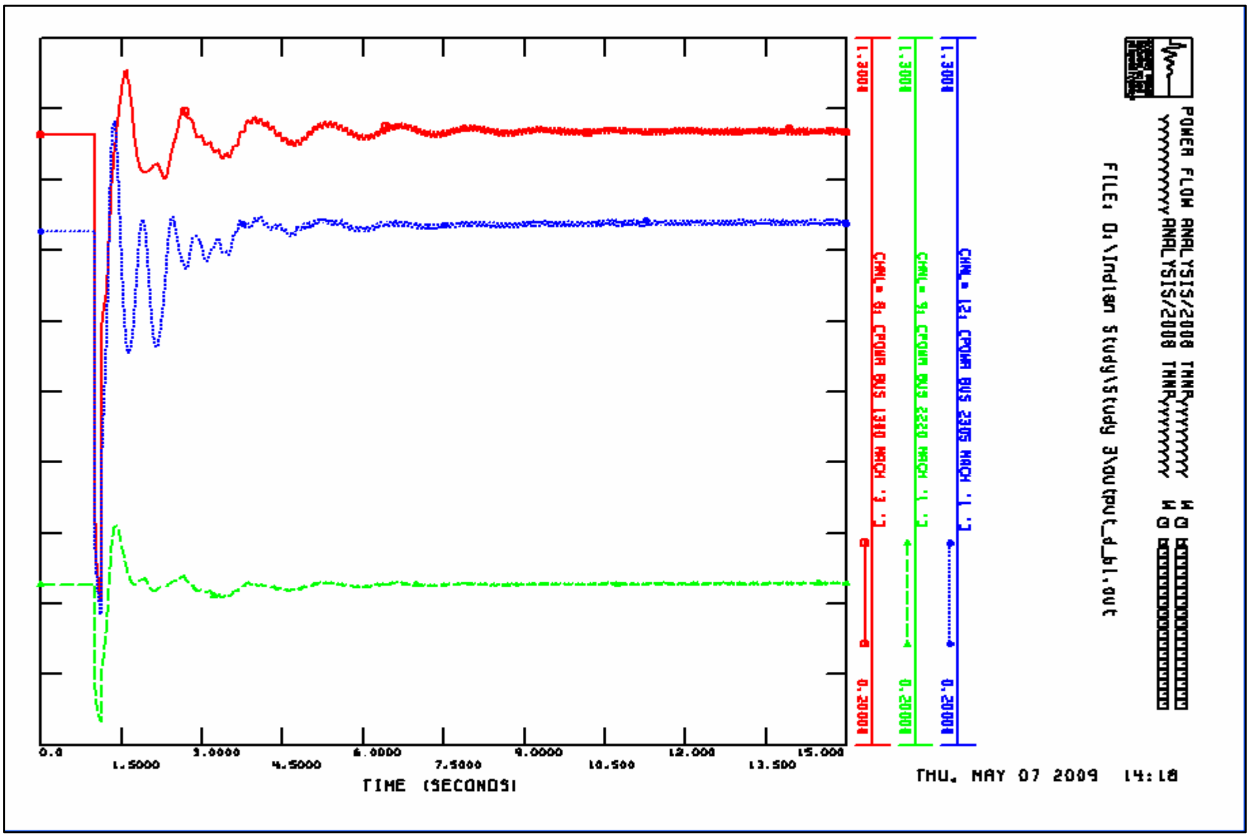


(2) Disturbance is simulated by tripping *one circuit* of 132 KV lines (with thermal maximum at night peak) and the responses are obtained and plotted using PSS/E modules, similar to those (with governors) of the above item (a), for the following cases of study: (with Successful Recloser)

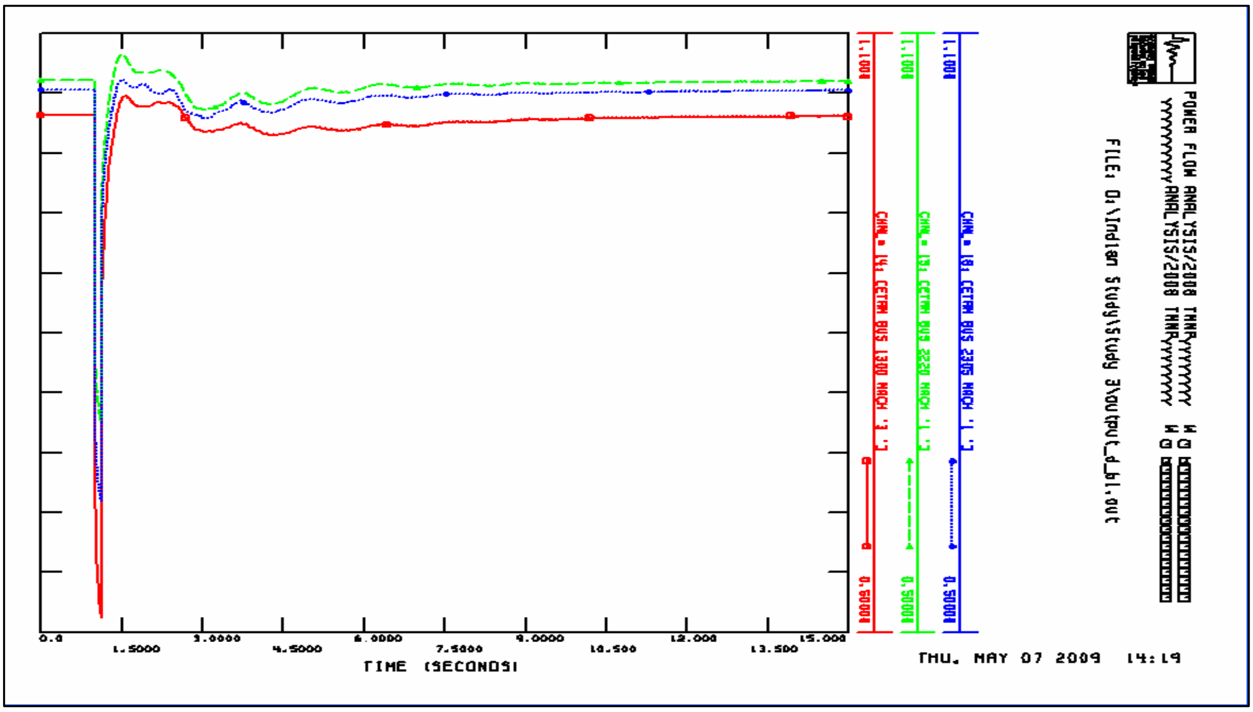
(i) *Biyagama – Sapugaskanda* at Biyagama end: Response plots of variations in Terminal Voltage, and Power output, at three buses.
(ii) *New Laxapana – Balangoda* at Balangoda end: Response plots of variations in Terminal Voltage, and Power output, at three buses.
(iii) *Polpitiya – Kiribathkubura* at Polpitiya end: Response plots of variations in Terminal Voltage, and Power output, at three buses.

(i) Simulation of 3 Ø fault on one cct of Biyagama-Sapugaskanda 132kV transmission Line at Biyagama end. Successful reclosing assumed.

**Power Output Variation**

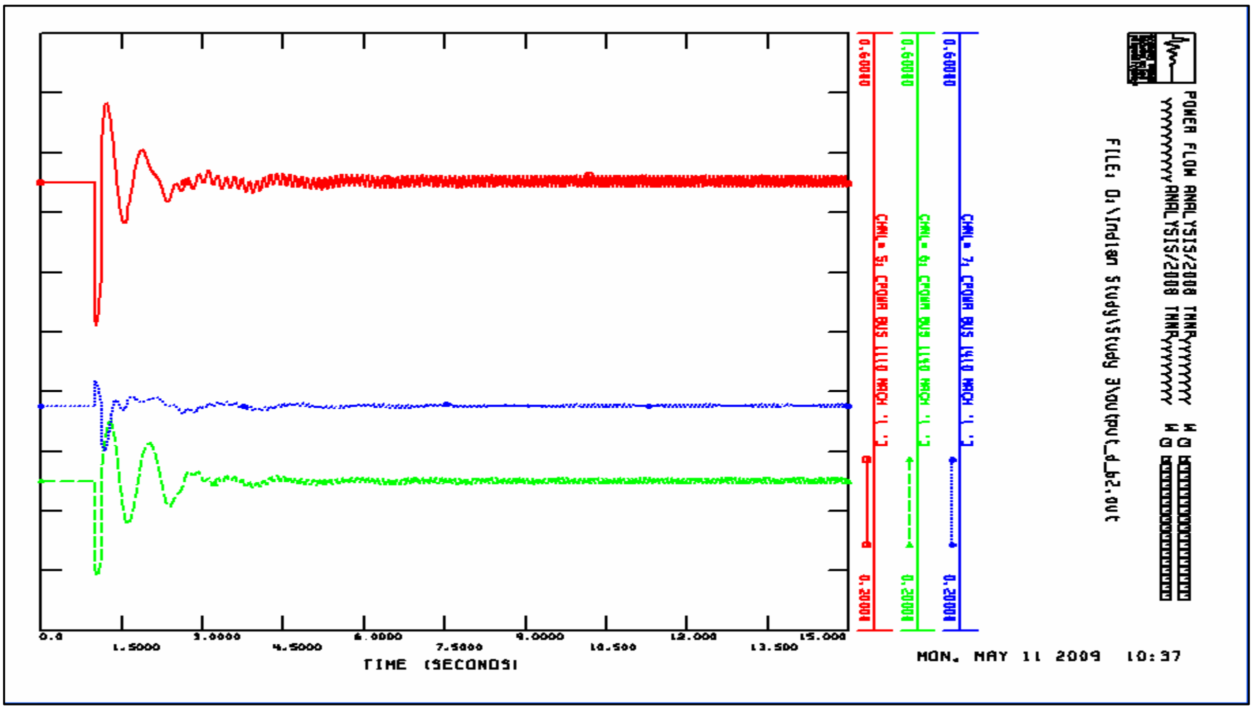


**Terminal Voltage Variation**

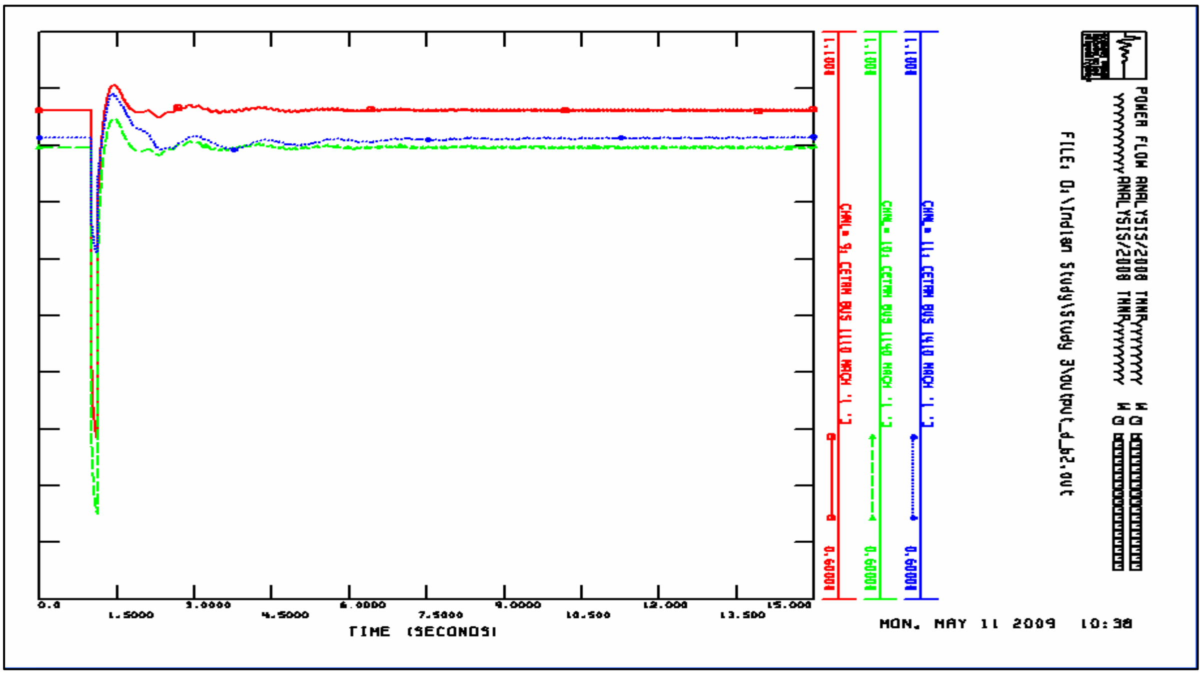



(ii) Simulation of 3 Ø fault on one cct of New Laxapana-Balangoda 132kV transmission Line at Balangoda end. Successful reclosing assumed

**Power Output Variation**

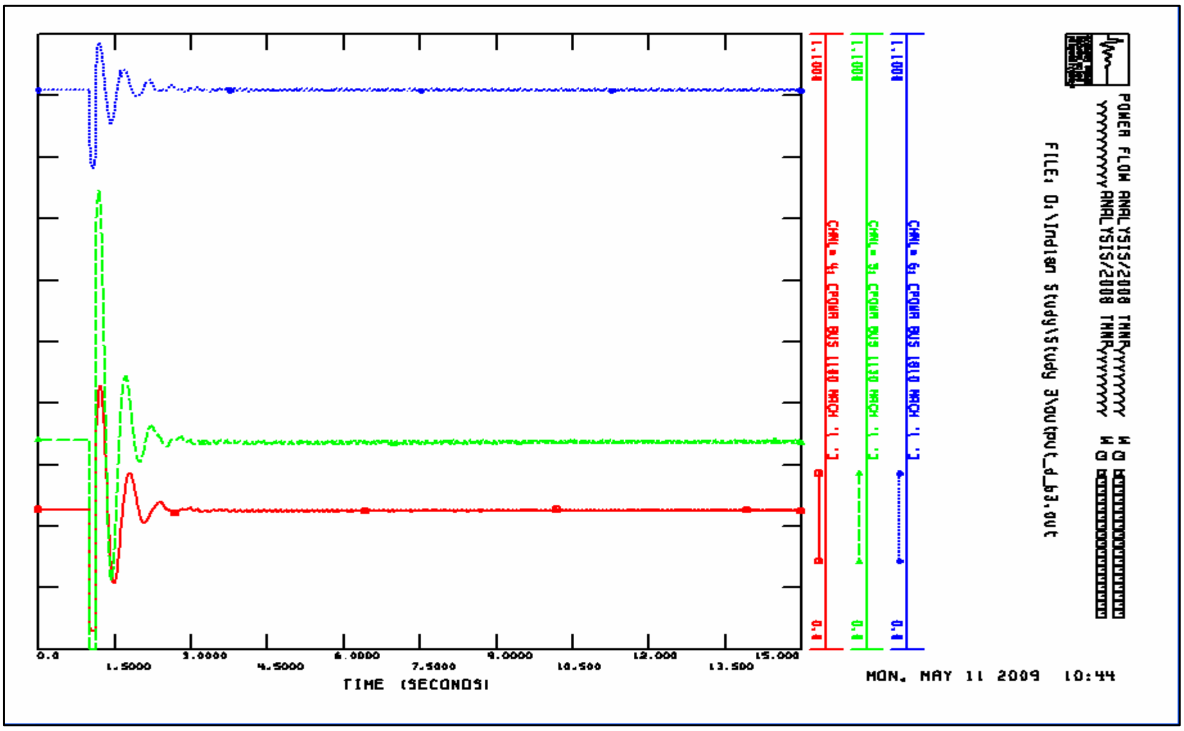


**Terminal Voltage Variation**

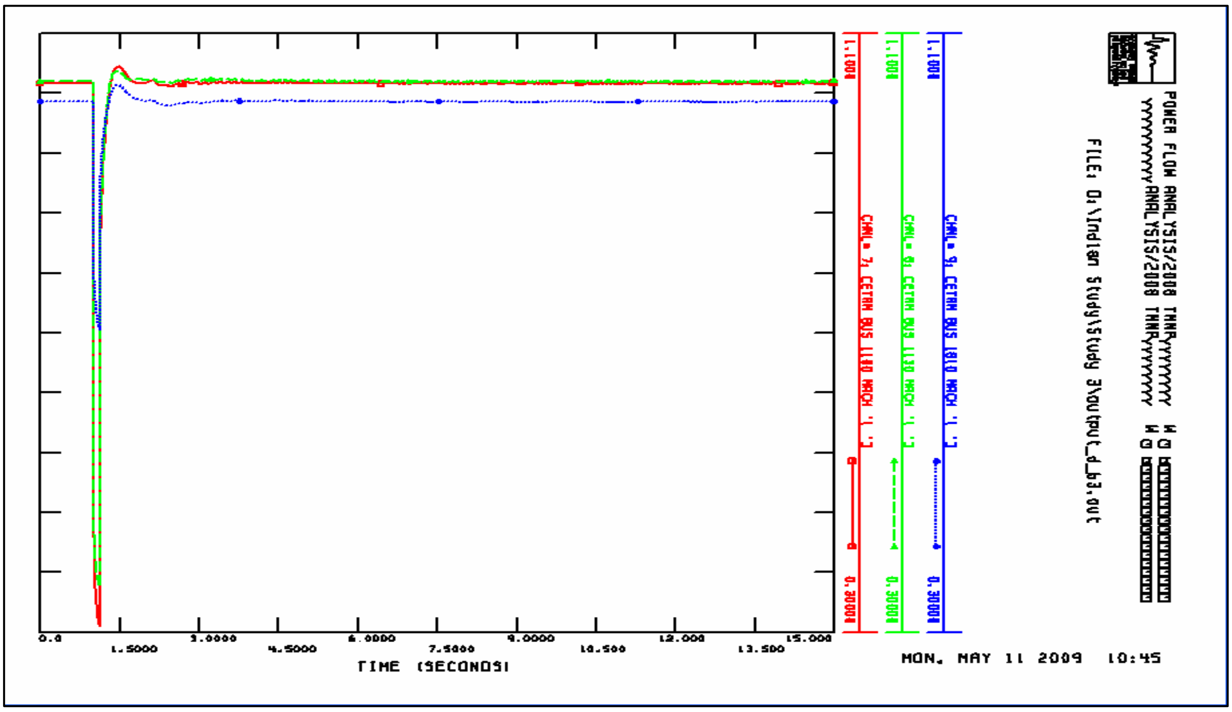



(iii) Simulation of 3 Ø fault on one cct of Polpitiya-Kiribathkubura 132kV transmission Line at Polpitiya end. Successful reclosing assumed

**Power Output Variation**



**Terminal Voltage Variation**



<u>**Some Observations**</u> :

**(a) With SEXS Type Excitation System Model :**

(i) Simulation Study on Kotmale – Biyagama 220KV line:
For the Case of tripping of one circuit with successful recloser, Response plots of Terminal Voltage variations at the bus Nos. 2230 and 2220 are similar except for initial transient dip, with more dip at bus No. 2220.

Nature of variation remains the same for all the three buses (1300, 2220, 2230), with marginally larger initial transient dip at bus 1300. Marginally higher voltages (more than rated pu voltages) following the voltage dips are exhibited for the case of tripping one circuit compared to tripping both circuits with successful recloser. In the case of tripping both circuits with unsuccessful recloser, increase in voltages, following the failure of recloser operation, is found to be more at Kotmale and Victoria buses compared to Kelanitissa bus.

For the Case of tripping both circuits, with successful recloser, larger initial transient dip occurs at bus No.2220 and lower at Kelanitissa bus. For unsuccessful recloser case, Kelanitissa bus exhibits marginally higher voltages.

(ii) For the case of tripping one circuit, it is found that the behaviours of variation for terminal voltage and power output remain similar, in all the cases of 220 KV line fault simulations studied. Marginal differences in the nature of behaviours are observed between 220 KV and 132 KV line faults.

**(b) With IEEE T1 Type Excitation System Model:**

Simulation Cases studied by tripping one circuit of either 220 KV or 132 KV lines, with successful recloser: From the plots of terminal voltage variations, following varying initial transient voltage dips, the increase in voltage is found to be lower with IEEE T1 model representation compared to SEXS model representation.

It is recommended to incorporate IEEE T1 Type Excitation System Model (based on the availability of data) instead of simpler model of SEXS Type, for the purpose of obtaining near actual results.

**(c) Machines equipped with IEEE T1 Type Excitation System Model and PSS of STAB 1 Type Model:**

(i) From the plots of terminal voltage variation, it is found that oscillatory behaviours are observed with larger settling times compared to the cases without PSS. However, it is noticed that relatively less oscillatory behaviours are found on some 132 KV buses compared to 220KV buses.

(ii) From the response plots obtained in the simulation cases studied both on 220KV and 132 KV lines, it is found necessary to identify effective locations for equipping PSS on the machines, instead of random selection of locations for PSS.

(iii) Undamped or poorly damped oscillations are often exhibited in modern interconnected power systems. The use of PSS with generating units for excitation control is well established as a means of improving damping in the system. Proper choice of the location of PSS is essential to get the maximum benefit from the point of view of improving dynamic stability. While it would be advantageous to install PSS on all the machines, the application of stabilizers on older units can be ineffective and uneconomical in practice. For satisfactory system damping, it is sufficient to equip relatively few machines with PSS. It is suggested to use eigenvalue analysis and the observation of mode shapes for the purpose.

## 7.4 Simulation of Three- phase Faults on 220 / 132 KV Lines:

**Response Plots of Rotor Angles**

Disturbance is simulated by tripping *both circuits* (or) one circuit of 220 KV/132 KV lines and the response plots of Rotor Angles are obtained and plotted using PSS/E modules, similar to those (with governors) of the above items, for the following cases of study:

(i) *Kelanitissa – Biyagama, (Both circuits of 220 KV Lines out):* Cases of Successful Recloser and Unsuccessful Recloser

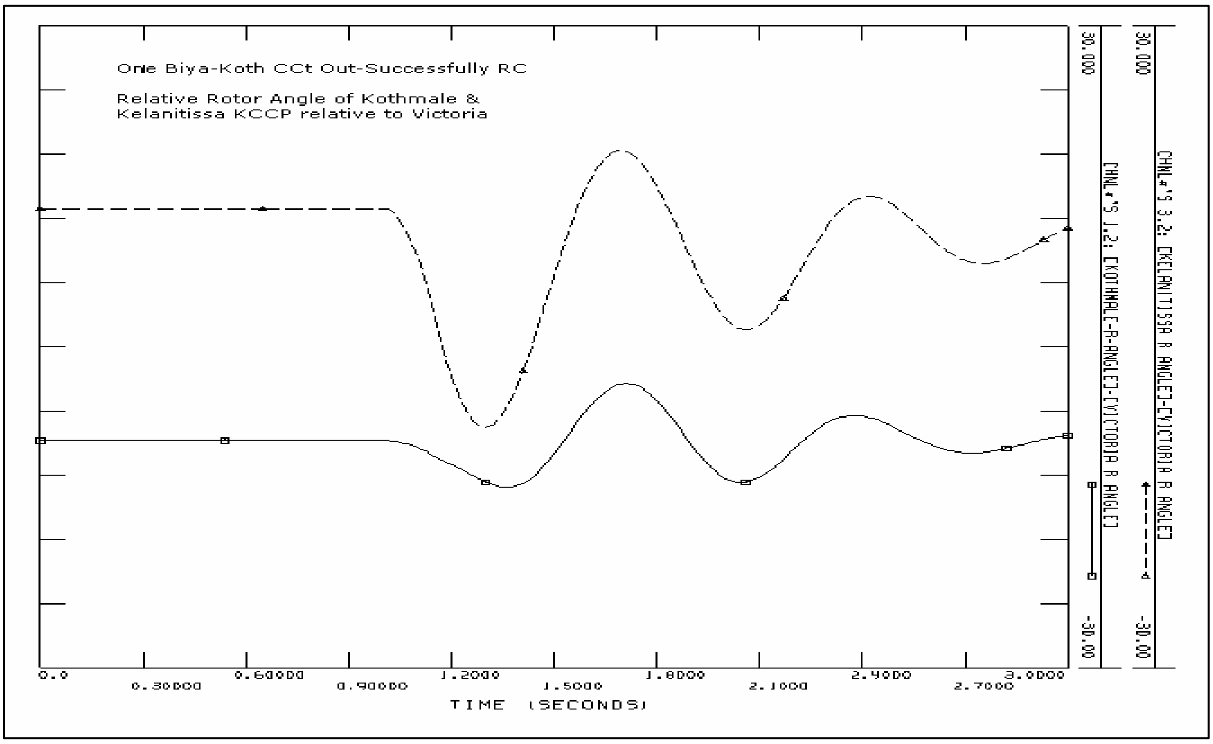
(ii) *Biyagama – Pannipitiya, (Both circuits of 220 KV Lines out):* Cases of Successful Recloser and Unsuccessful Recloser

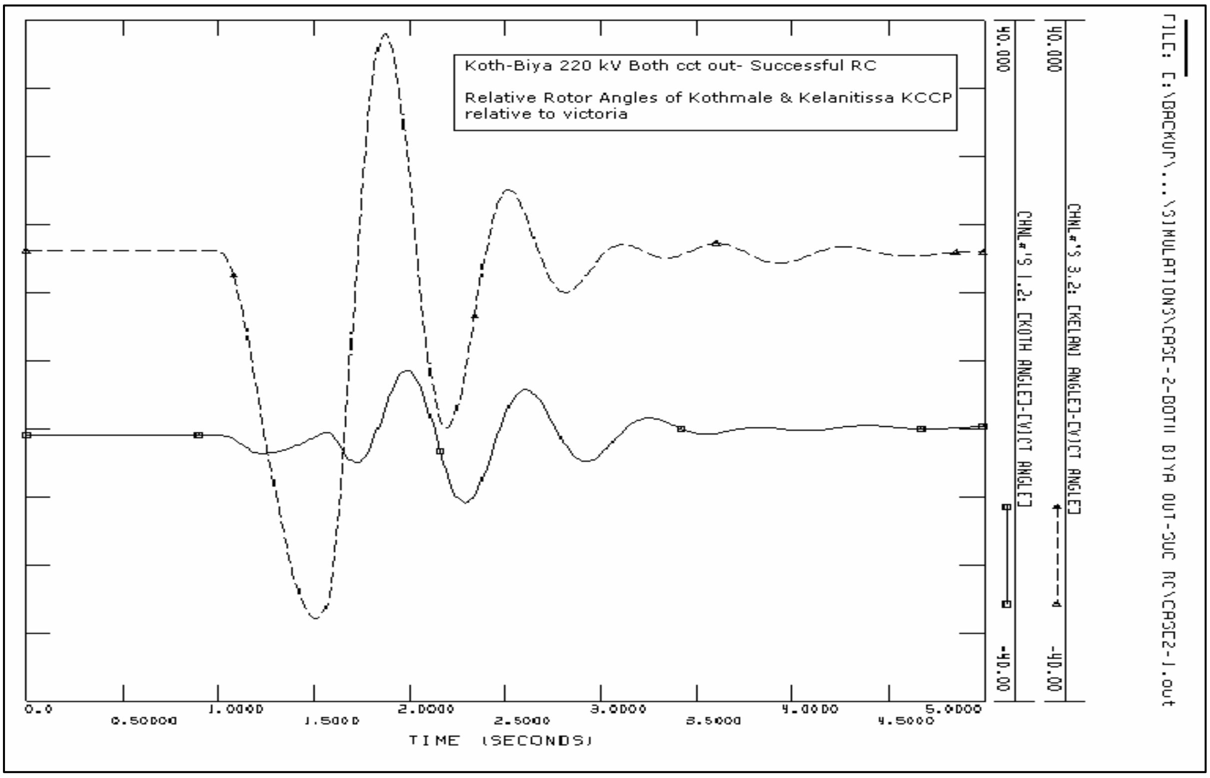
(iii) Biyagama – Kotugoda, *(Both circuits of 220 KV Lines out):* Cases of Successful Recloser and Unsuccessful Recloser

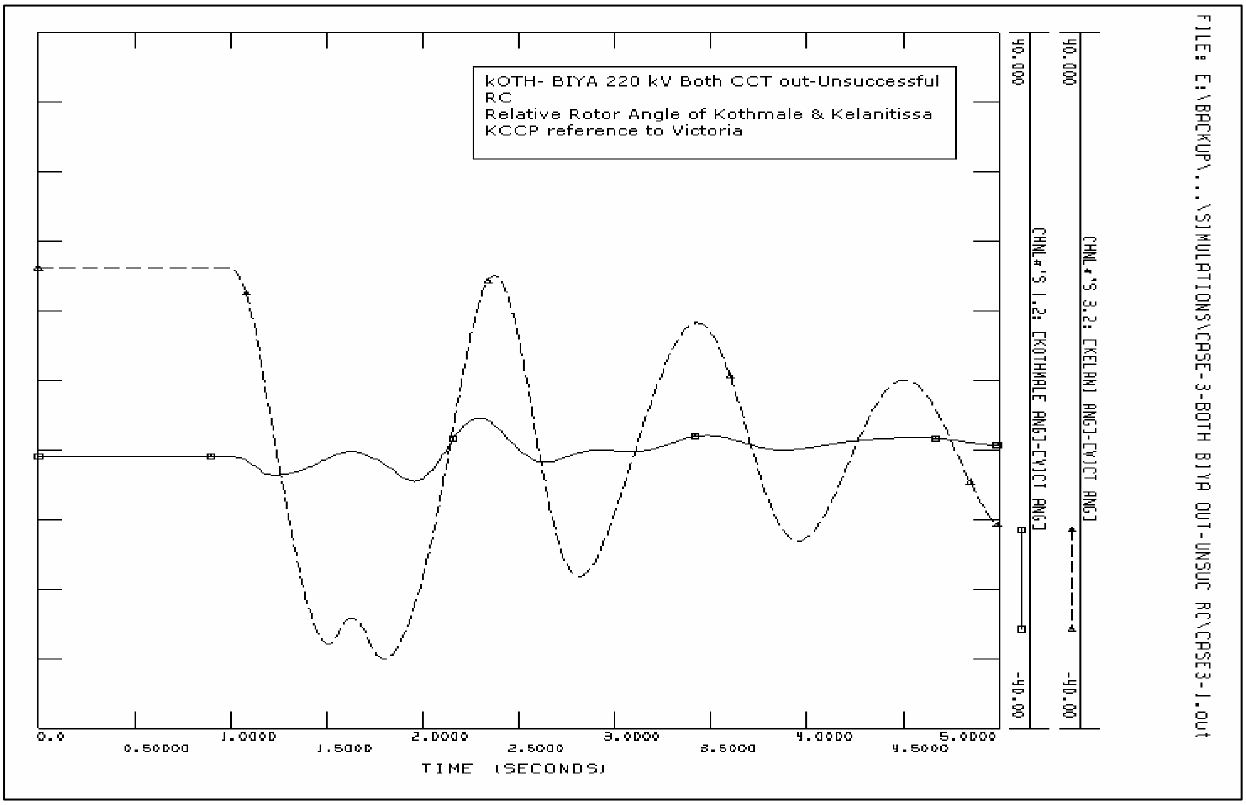
(iv) *Kotmale – Biyagama, (One circuit of 220 KV Lines):* Case of Successful Recloser

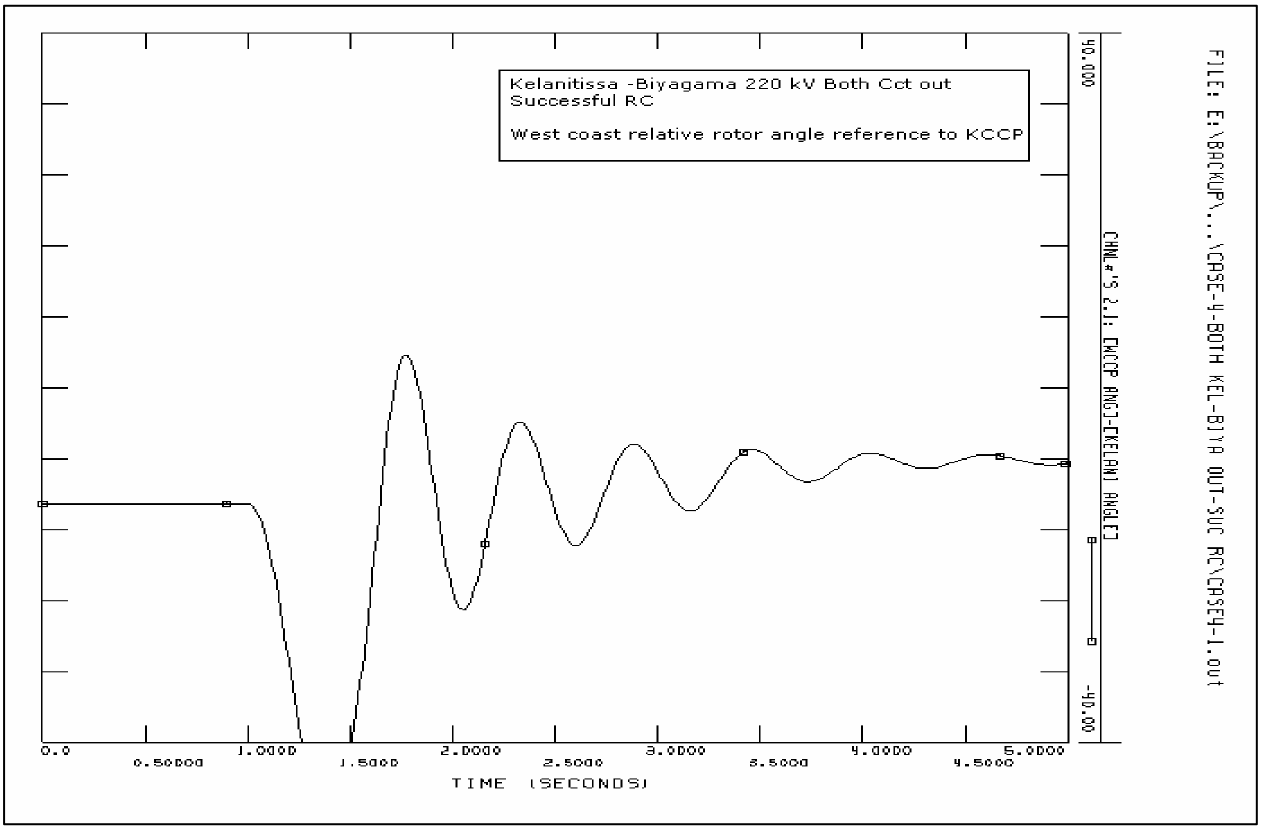
(v) *Kotmale – Biyagama (Both circuits of 220 KV Lines out):* Cases of Successful Recloser & Unsuccessful Recloser

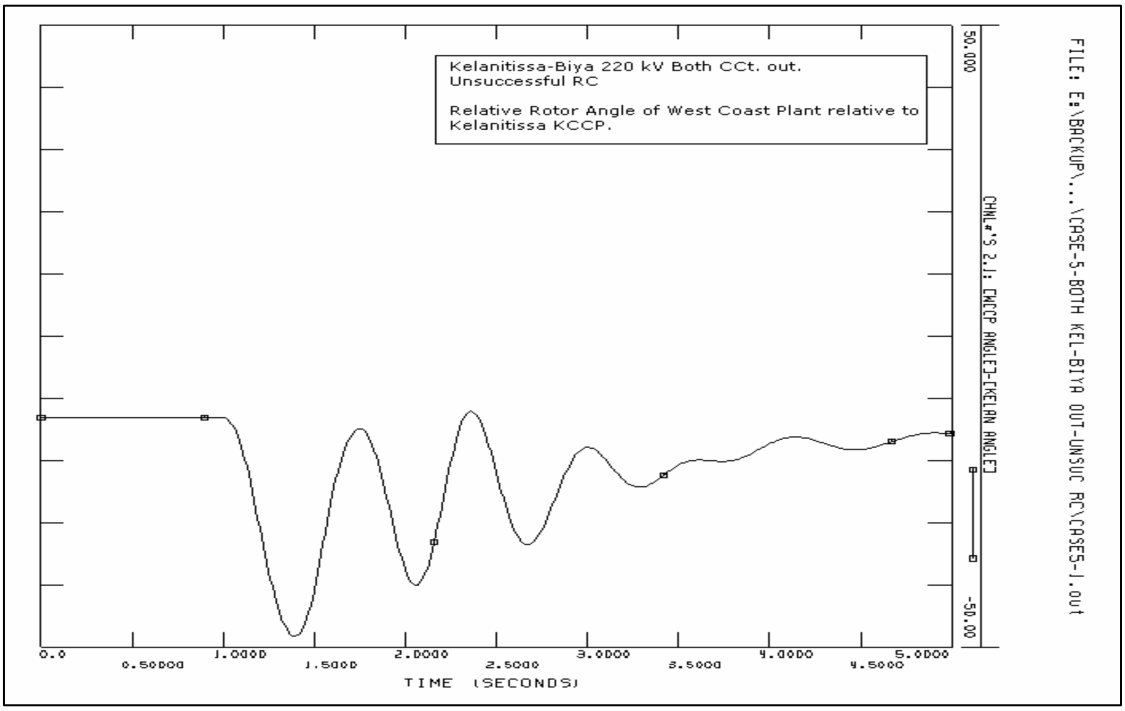
*(vi) Biyagama – Sapugaskanda, (Both circuits of 132 KV Lines out):* Cases of Successful Recloser & Unsuccessful Recloser

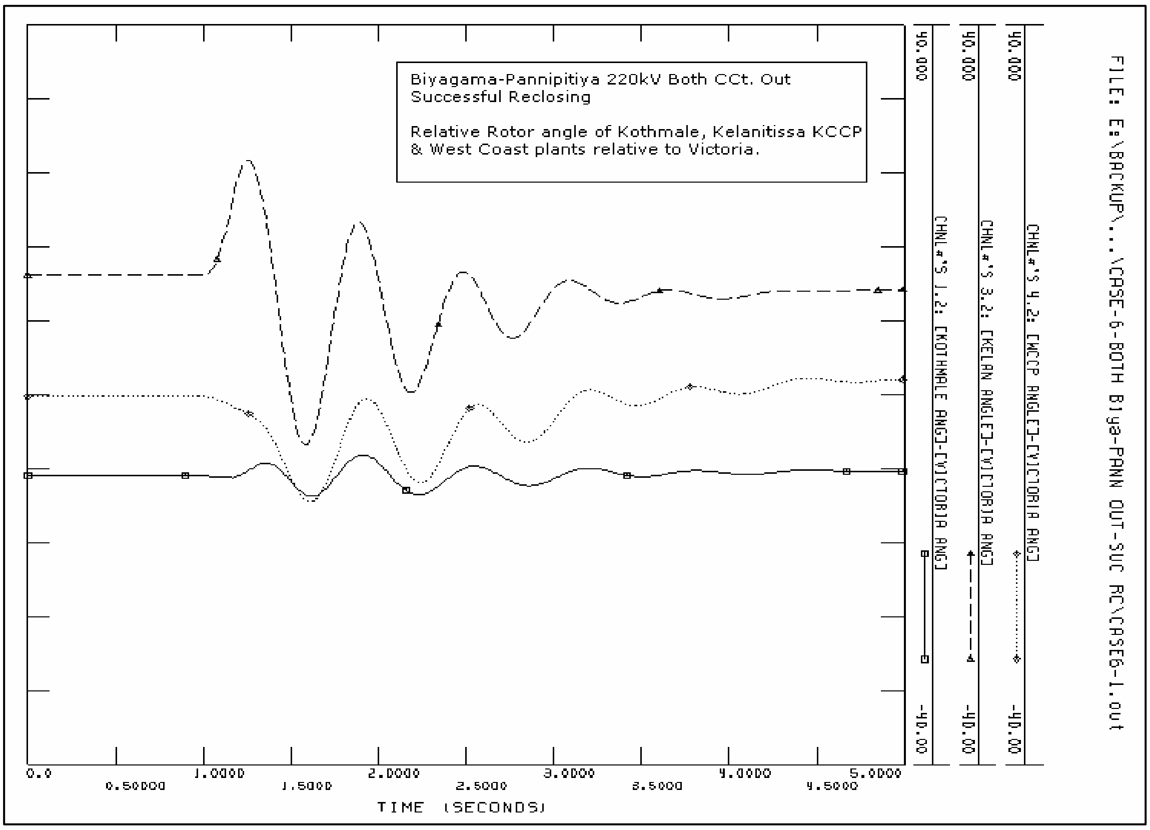


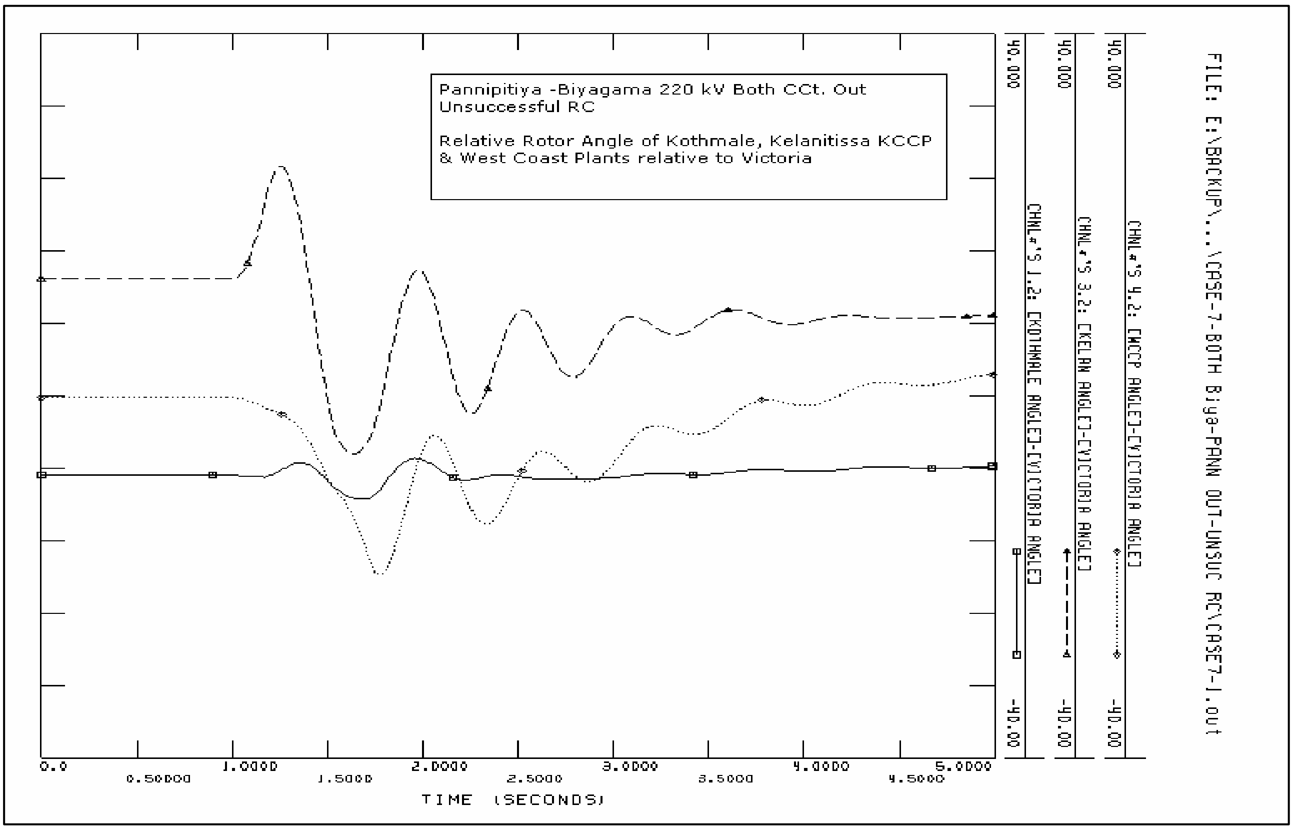



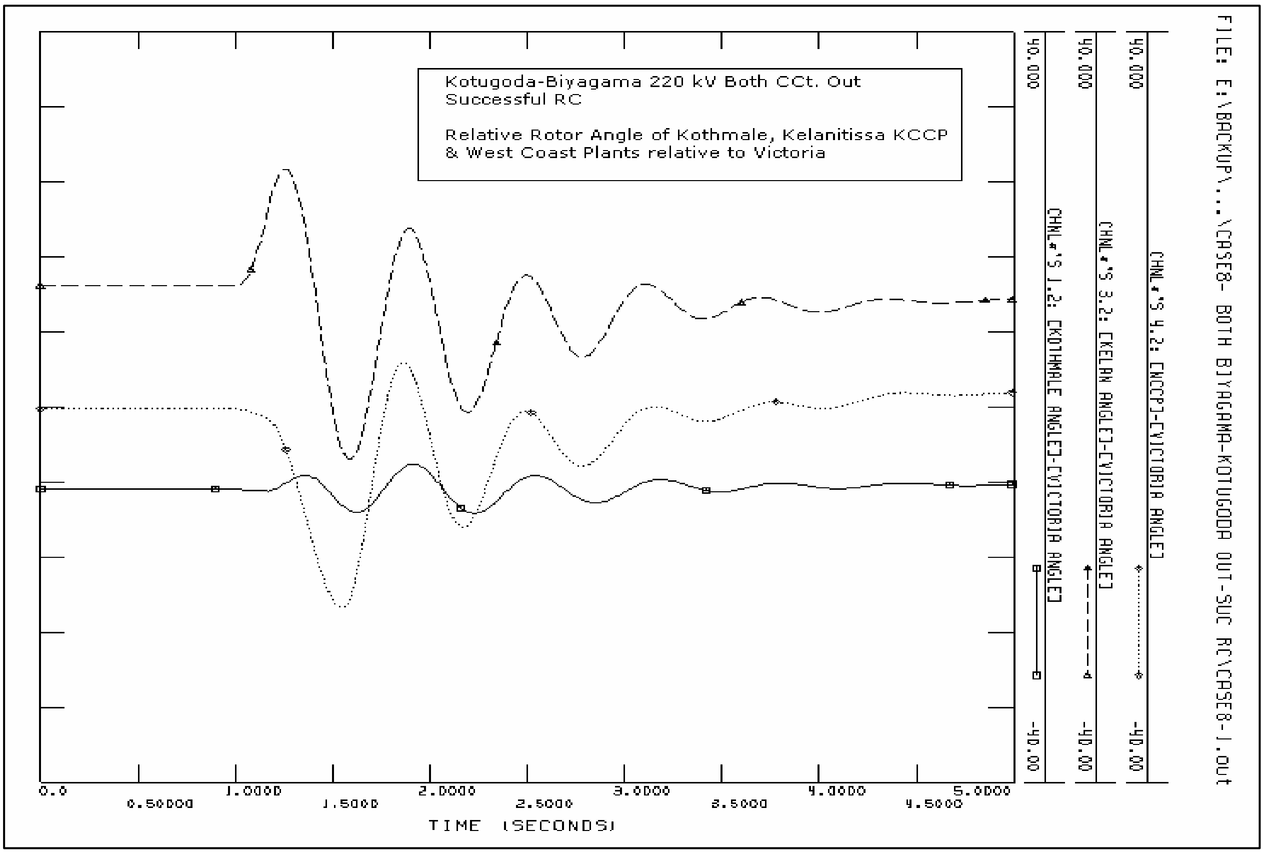

kOTH- BIYA 220 kV Both CCT out-Unsuccessful RC
Relative Rotor Angle of Kothmale & Kelanitissa
KCCP reference to Victoria
FILE: E:\BACKUP\...\SIMULATIONS\CASE-3-BOTH BIYA OUT-UNSUC RC\CASE3-1.out
CHNL#'S 1,2: [KOTHMALE ANG]-[VICT ANG]
CHNL#'S 3,2: [KELANI ANG]-[VICT ANG]
40.000
-40.00
0.0
0.50000
1.0000
1.5000
2.0000
2.5000
3.0000
3.5000
4.0000
4.5000
5.0000
TIME (SECONDS)

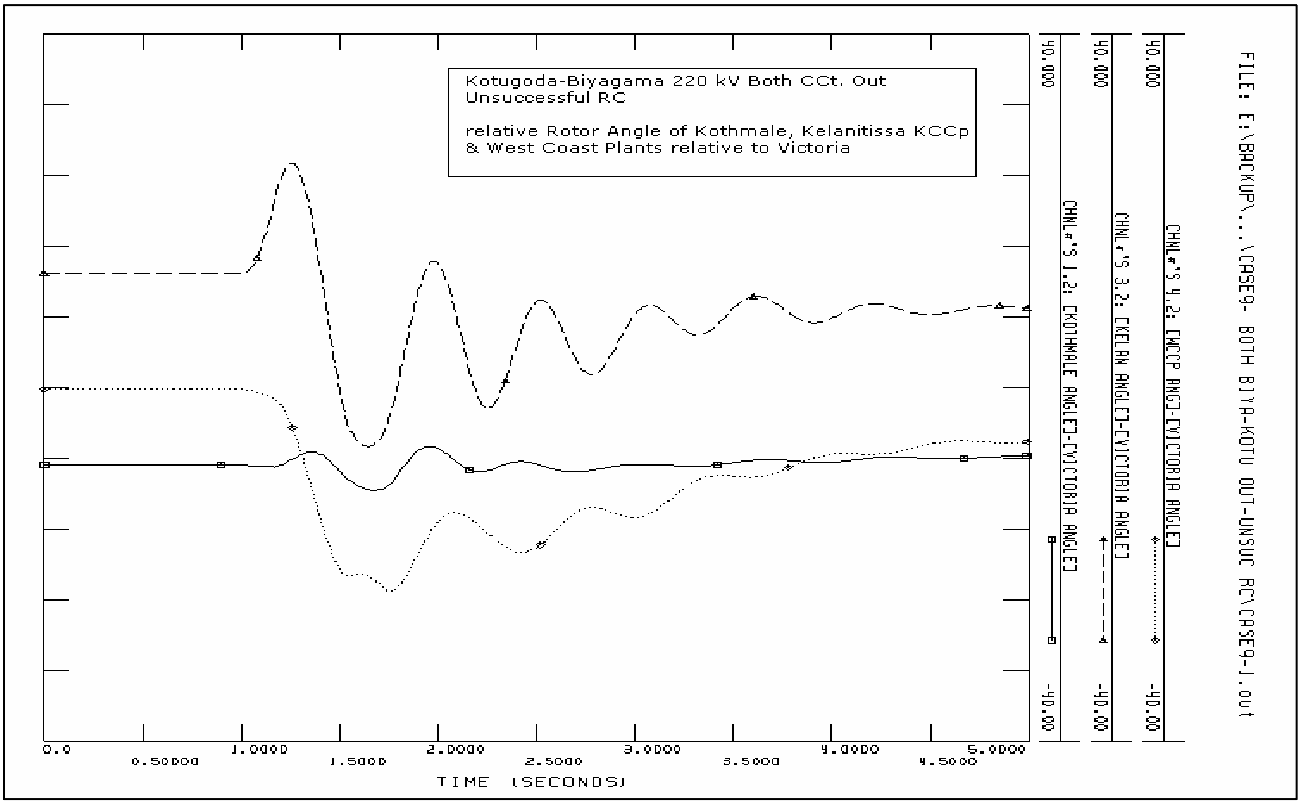

Kelanitissa -Biyagama 220 kV Both Cct out
Successful RC
West coast relative rotor angle reference to KCCP
FILE: E:\BACKUP\...\CASE-4-BOTH KEL-BIYA OUT-SUC RC\CASE4-1.out
CHNL#'S 2,1: [WCCP ANG]-[KELANI ANGLE]
40.000
-40.00
0.0
0.50000
1.0000
1.5000
2.0000
2.5000
3.0000
3.5000
4.0000
4.5000
5.0000
TIME (SECONDS)

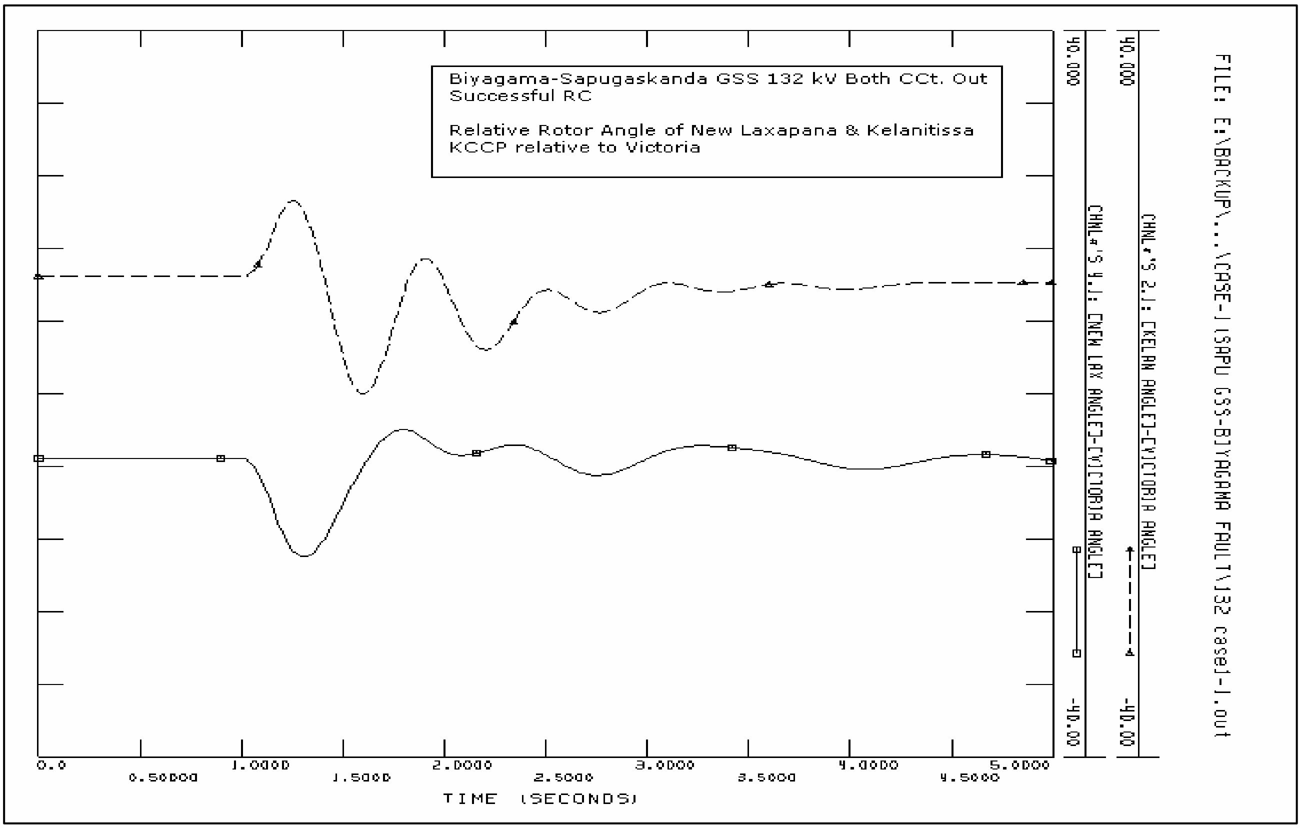

Kelanitissa-Biya 220 kV Both CCt. out.
Unsuccessful RC
Relative Rotor Angle of West Coast Plant relative to Kelanitissa KCCP.
50.000
-50.00
CHNL#'S 2.1: [WCCP ANGLE]-[KELAN ANGLE]
FILE: E:\BACKUP\...\CASE-5-BOTH KEL-BIYA OUT-UNSUC RC\CASE5-1.out
0.0
0.50000
1.0000
1.5000
2.0000
2.5000
3.0000
3.5000
4.0000
4.5000
5.0000
TIME (SECONDS)

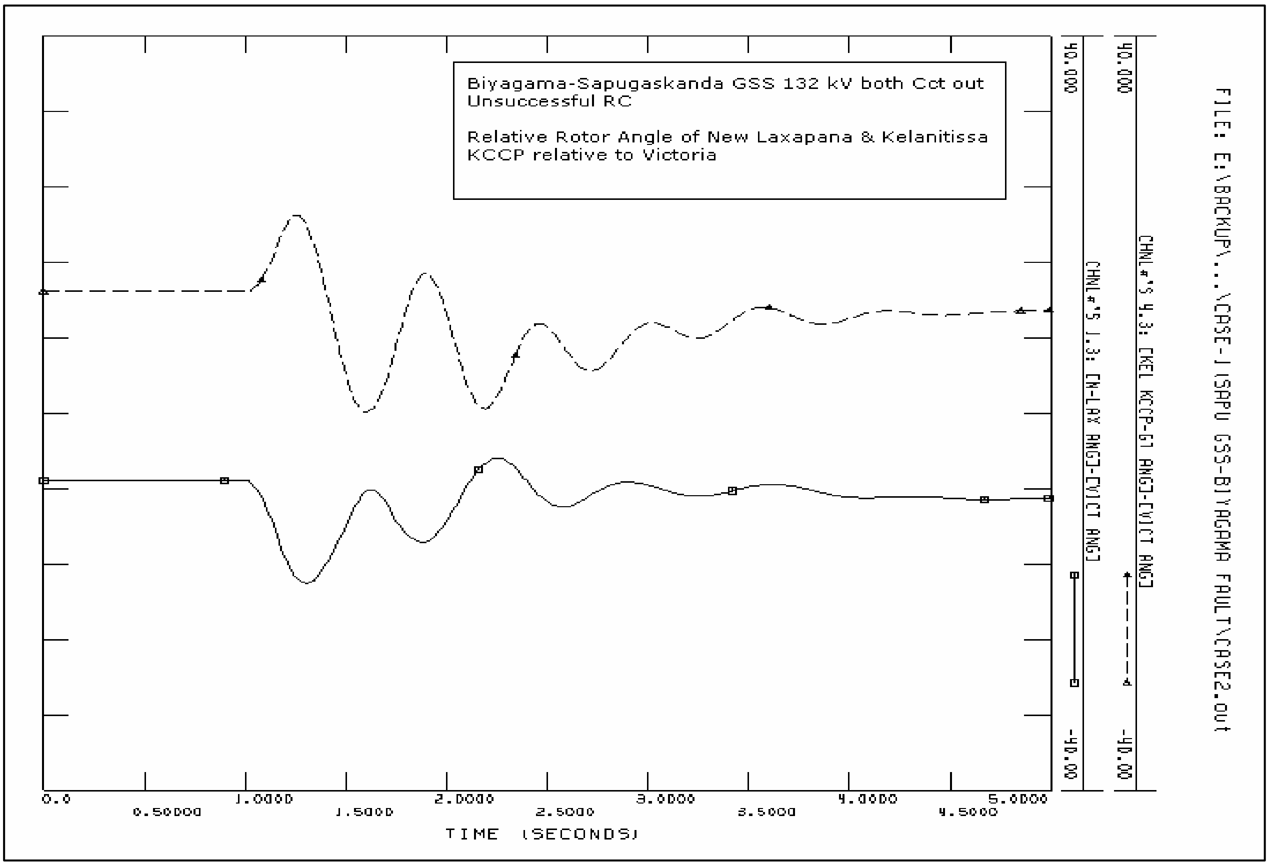

Biyagama-Pannipitiya 220kV Both CCt. Out
Successful Reclosing
Relative Rotor angle of Kothmale, Kelanitissa KCCP & West Coast plants relative to Victoria.
40.000
-40.00
CHNL#'S 1.2: [KOTHMALE ANG]-[VICTORIA ANG]
CHNL#'S 3.2: [KELAN ANGLE]-[VICTORIA ANG]
CHNL#'S 4.2: [WCCP ANGLE]-[VICTORIA ANG]
FILE: E:\BACKUP\...\CASE-6-BOTH Biya-PANN OUT-SUC RC\CASE6-1.out
0.0
0.50000
1.0000
1.5000
2.0000
2.5000
3.0000
3.5000
4.0000
4.5000
5.0000
TIME (SECONDS)


Pannipitiya -Biyagama 220 kV Both CCt. Out
Unsuccessful RC
Relative Rotor Angle of Kothmale, Kelanitissa KCCP
& West Coast Plants relative to Victoria
FILE: E:\BACKUP\...\CASE-7-BOTH Biyg-PANN OUT-UNSUC RC\CASE7-1.out
CHNL#'S 4.2: [WCCP ANGLE]-[VICTORIA ANGLE]
CHNL#'S 3.2: [KELAN ANGLE]-[VICTORIA ANGLE]
CHNL#'S 1.2: [KOTHMALE ANGLE]-[VICTORIA ANGLE]
40.000
-40.00
0.0
0.50000
1.0000
1.5000
2.0000
2.5000
3.0000
3.5000
4.0000
4.5000
5.0000
TIME (SECONDS)


Kotugoda-Biyagama 220 kV Both CCt. Out
Successful RC
Relative Rotor Angle of Kothmale, Kelanitissa KCCP
& West Coast Plants relative to Victoria
FILE: E:\BACKUP\...\CASE8- BOTH BIYAGAMA-KOTUGODA OUT-SUC RC\CASE8-1.out
CHNL#'S 4.2: [WCCP]-[VICTORIA ANGLE]
CHNL#'S 3.2: [KELAN ANGLE]-[VICTORIA ANGLE]
CHNL#'S 1.2: [KOTHMALE ANGLE]-[VICTORIA ANGLE]
40.000
-40.00
0.0
0.50000
1.0000
1.5000
2.0000
2.5000
3.0000
3.5000
4.0000
4.5000
5.0000
TIME (SECONDS)


Kotugoda-Biyagama 220 kV Both CCt. Out
Unsuccessful RC
relative Rotor Angle of Kothmale, Kelanitissa KCCp
& West Coast Plants relative to Victoria
FILE: E:\BACKUP\...\CASE9- BOTH BIYA-KOTU OUT-UNSUC RC\CASE9-1.out
CHNL#'S 4.2: [KCCP ANG]-[VICTORIA ANGLE]
CHNL#'S 3.2: [KELAN ANGLE]-[VICTORIA ANGLE]
CHNL#'S 1.2: [KOTHMALE ANGLE]-[VICTORIA ANGLE]
40.000
-40.00
0.0
0.50000
1.0000
1.5000
2.0000
2.5000
3.0000
3.5000
4.0000
4.5000
5.0000
TIME (SECONDS)


Biyagama-Sapugaskanda GSS 132 kV Both CCt. Out
Successful RC
Relative Rotor Angle of New Laxapana & Kelanitissa
KCCP relative to Victoria
FILE: E:\BACKUP\...\CASE-1\SAPU GSS-BIYAGAMA FAULT\132 case1-1.out
CHNL#'S 2.1: [KELAN ANGLE]-[VICTORIA ANGLE]
CHNL#'S 9.1: [NEW LAX ANGLE]-[VICTORIA ANGLE]
40.000
-40.00
0.0
0.50000
1.0000
1.5000
2.0000
2.5000
3.0000
3.5000
4.0000
4.5000
5.0000
TIME (SECONDS)




## Observations and Recommendations :

All cases of rotor angle deviations exhibit stable responses for the studies performed.

# Chapter – 8

## Voltage Control: VAR Scheduling

The following studies are performed to analyze the issue of VAR Scheduling :

**(A)** Study the voltage variation of busbar voltages in the vicinity after setting 33kV winding of the auto transformer mode to full load

**(B)** **VAR Scheduling considered :**

**Base Case Voltage Control Element Status:**
(Scenario: Thermal Maximum Night Peak)

- All Tap Changer Controls removed
- All AVR Controls removed
- Existing VAR compensator status
- Base case voltage violations
- Switched Shunt Capacitor Compensation Requirement Identified
- Tap Changer Controller Requirement Identified
- AVR Set Points Considered

**Options considered for study:**

- Changing AVR set points.
- Tap change control.
- Switched Shunt Controls.
- With all three controls

(No voltage above or below 5% has been observed)

**(C)** **AVR Setpoint Variation:**

Kotmale Vshedu=<1.03 pu, 1.04, 1.05
Barge Vshedu=1.02pu, 1.025, 1.03
Upper Kotmale Vshedu=1.04pu, 1.045, 1.05

**(D)** **TAP Positions**

**(i)** **2012 – Galle GSS :**

Matara GSS – 15% load increase at minimum tap position
Galle GSS – 15% load increase at nominal tap position
Galle GSS – 15% load increase at maximum tap position
Galle GSS – 20% load increase at minimum tap position

Galle GSS – 20% load increase at nominal tap position
Galle GSS – 20% load increase at maximum tap position
Galle GSS – 25% load increase at minimum tap position
Galle GSS – 25% load increase at nominal tap position
Galle GSS – 25% load increase at maximum tap position
Galle GSS – 5% load decrease from 1.25% Load at minimum tap position
Galle GSS – 5% load decrease from 1.25% Load at nominal tap position
Galle GSS – 5% load decrease from 1.25% Load at maximum tap position
Galle GSS – 10% load decrease from 1.25% Load at minimum tap position
Galle GSS – 10% load decrease from 1.25% Load at nominal tap position
Galle GSS – 10% load decrease from 1.25% Load at maximum tap position

**(ii)** **2012 - Ratmalana GSS :**

**(iii)** **2012 - Trincomalee GSS**

**(iv)** **2016 – Galle GSS:**

**(v)** **2016 - Ratmalana GSS :**

**(vi)** **2016 - Trincomalee GSS :**

**(E)** **AVR Setpoints and Tap Positions :**

***Kotmale PP and Ratmalana GSS:***

Kotmale Vshedu=<1.03 and Ratmalana GSS at minimum tap position
Kotmale Vshedu=<1.03 and Ratmalana GSS at nominal tap position
Kotmale Vshedu=<1.03 and Ratmalana GSS at maximum tap position
Kotmale Vshedu=1.05 and Ratmalana GSS at minimum tap position
Kotmale Vshedu=1.05 and Ratmalana GSS at nominal tap position
Kotmale Vshedu=1.05 and Ratmalana GSS at maximum tap position

**(F)** **Shunt Capacitors :**

***( i ) CEB System Year – 2012 :***
Without & with Ampara Capacitor
Without & with Pannipitiya Capacitor
Without & with Galle Capacitor
Without & with Matugama Capacitor

***( ii ) CEB System Year – 2016 :***
Without & with Ampara Capacitor
Without & with Pannipitiya Capacitor
Without & with Galle Capacitor
Without & with Matugama Capacitor

**(A)** **<u>Study the voltage variation of busbar voltages in the vicinity after setting 33kV winding of the auto transformer to full load</u>**

In PSS/E simulation, it is observed that the model auto transformer tap changers are working correctly. For example, extracts of some results for the year 2008 Night Peak Scenario are mentioned:

**Kotogoda inter-bus transformer - with OLTC**

*33kV winding loading - 119% (without 50 Mvar BSC):*
220kV Voltage - 0.978 p.u. ; 33kV Voltage - 0.981 p.u

*33kV winding loading - 93% (with 50 Mvar BSC):*
220kV Voltage - 0.997 p.u. ; 33kV Voltage - 1.009 p.u

**Kotogoda inter-bus transformer - without OLTC**

*33kV winding loading - 119% (without 50 Mvar BSC):*
220kV Voltage - 0.987 p.u. ; 33kV Voltage - 0.878 p.u

*33kV winding loading - 94% (with 50 Mvar BSC):*
220kV Voltage - 0.996 p.u. ; 33kV Voltage - 0.971 p.u

**Rantambe inter-bus transformer (OLTC at its nominal tap)**

220kV Voltage - 1.038 p.u. ; 132kV Voltage - 1.008 p.u

In the case of Kotugoda inter-bus transformer without OLTC the 220kV voltage is within limits (+5% ~ -5%), but the 33kV voltage is low as 0.878 p.u. This situation can be eliminated by activating the OLTC or using 50 Mvar BSC (already exists).

Normally in the PSS/E simulations, voltage problems are observed in Galle Region and Ampara area, but not at busses near to the three winding auto transformers.

Also, dynamic simulation studies are performed by considering several loading scenarios of Biyagama inter-bus transformer (33kV winding) and the effect of capacitors to improve the situation. Some results of these studies are indicated here:

**<u>Simulation 01</u>**

Set initial load at Biyagama 33kV winding to 80% of its nominal rating
Solve Load Flow
Put all exciters out of service

**<u>Simulation 02</u>**

Set initial load at Biyagama 33kV winding to 28% of its nominal rating
Solve Load Flow
Put all exciters out of service

**Simulation 03**

Set initial load at Biyagama 33kV winding to 28% of its nominal rating
Set all transformers to their nominal tap
Fixed all switched shunts
Solve Load Flow
Put all exciters out of service

**Simulation 04**

Set initial load at Biyagama 33kV winding to 28% of its nominal rating
Set all transformers to their nominal tap
Fixed all switched shunts
Solve Load Flow
Put all exciters out of service
Add 50 Mvar capacitors at t= 5 sec.

Biyagama 33kV busbar voltage variations

| Simulation | | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| ΔV (p.u) | With exit. | -0.024 | -0.081 | Not done | +0.082 |
| | Without exit. | -0.031 | -0.101 | -0.082 | +0.003 |

# Figure 8.1 : Network

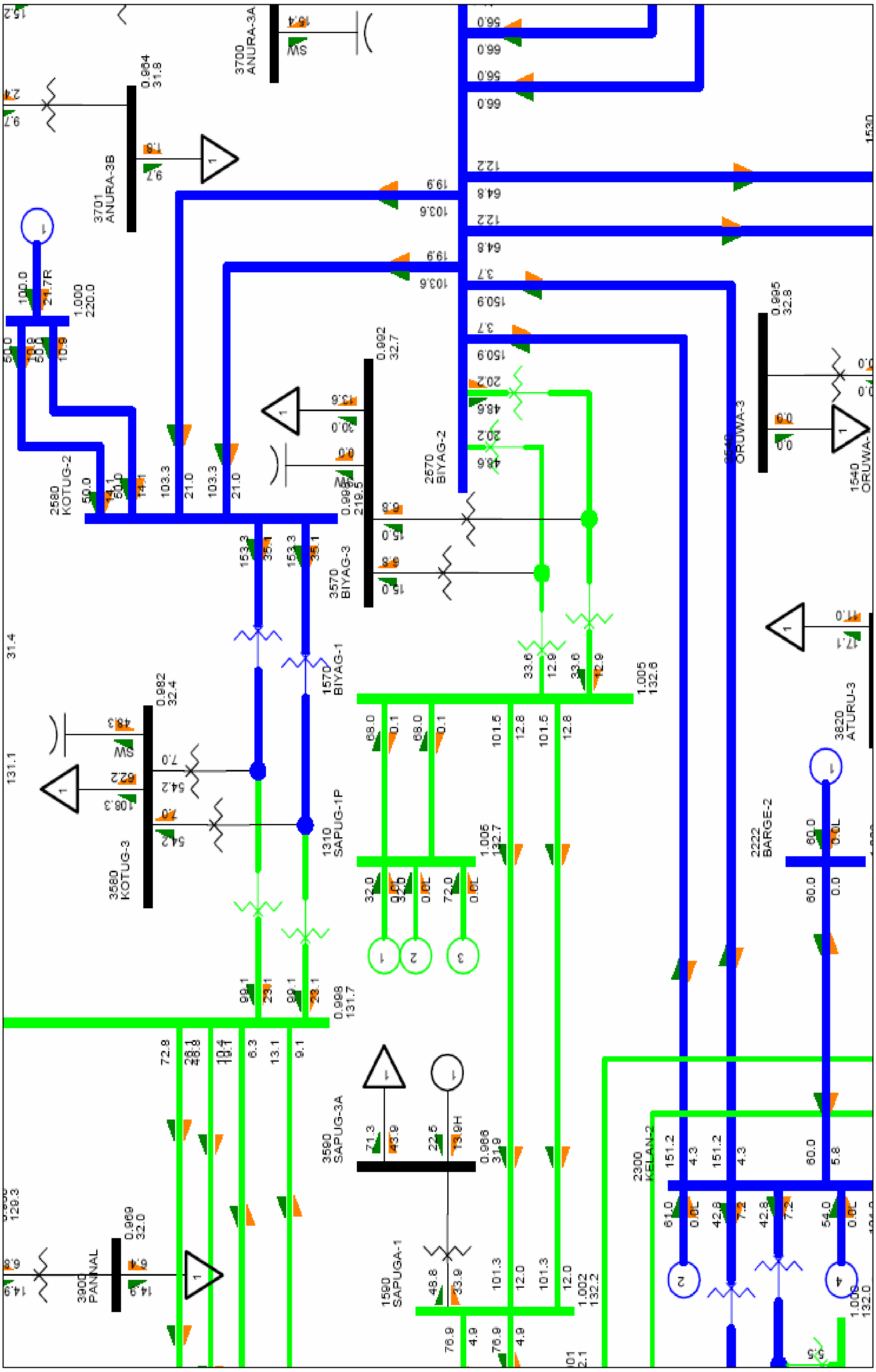


**Figure 8.2: Voltage variation following an approximately 21.6% (up to full load) load variation at Biyalama 33kV winding**

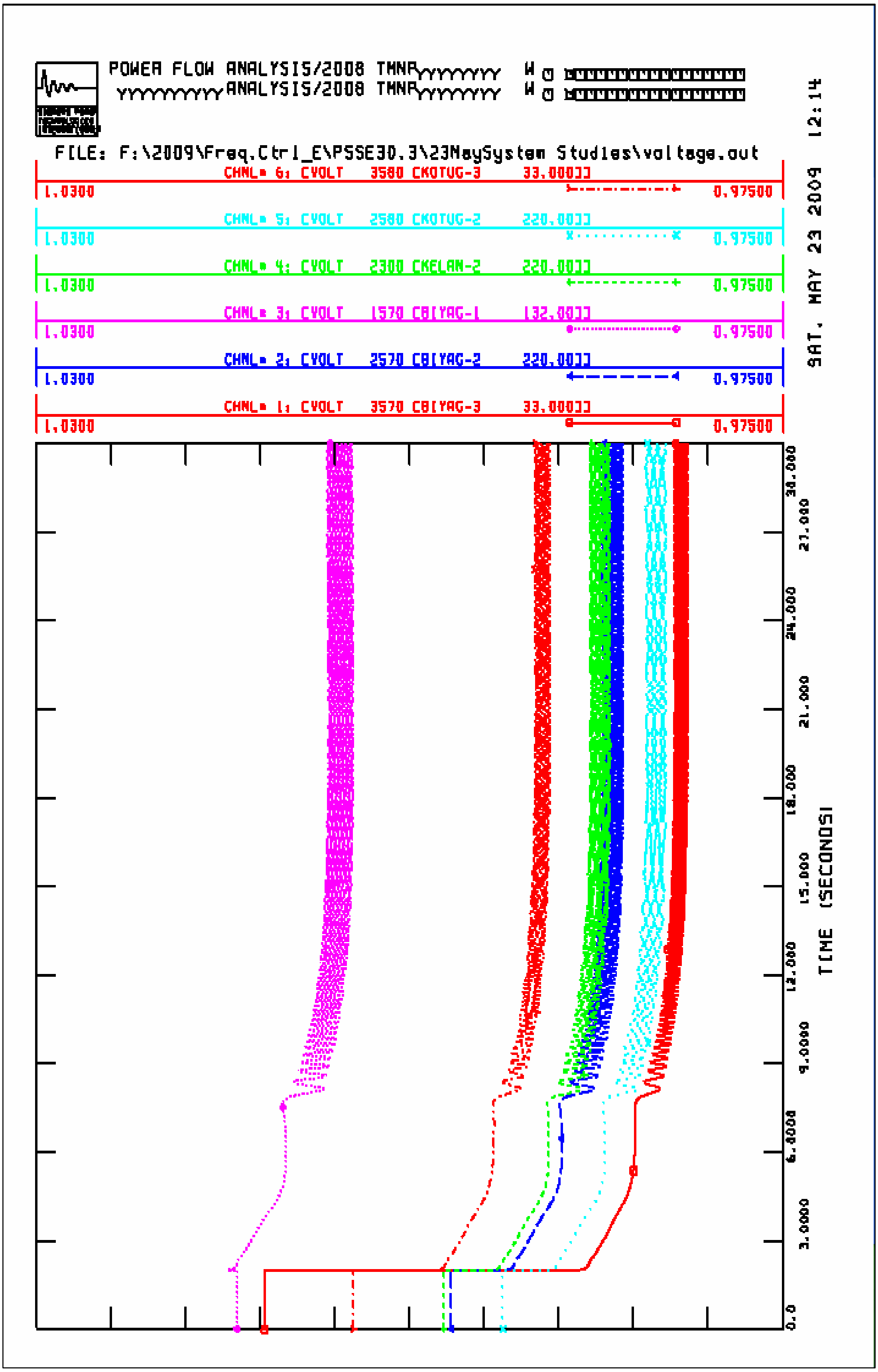


**Figure 8.3 : Voltage variation following an approximately 233% (up to full load) load variation at Biyalama 33kV winding**

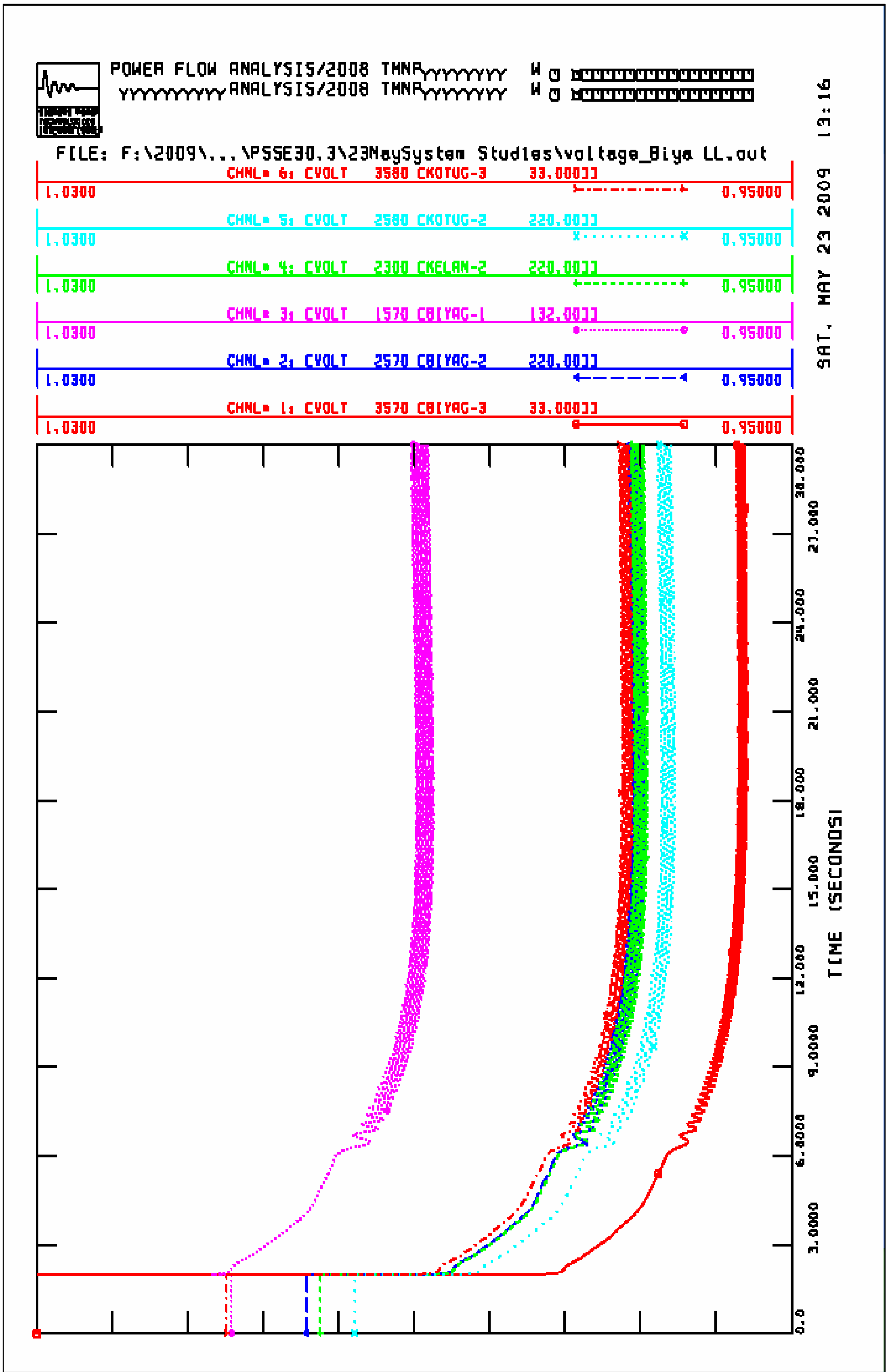


**Figure 8.4 : Voltage variation following an approximately 233% (up to full load) load variation at Biyalama 33kV winding, fixed capacitors, transformers at their nominal values**

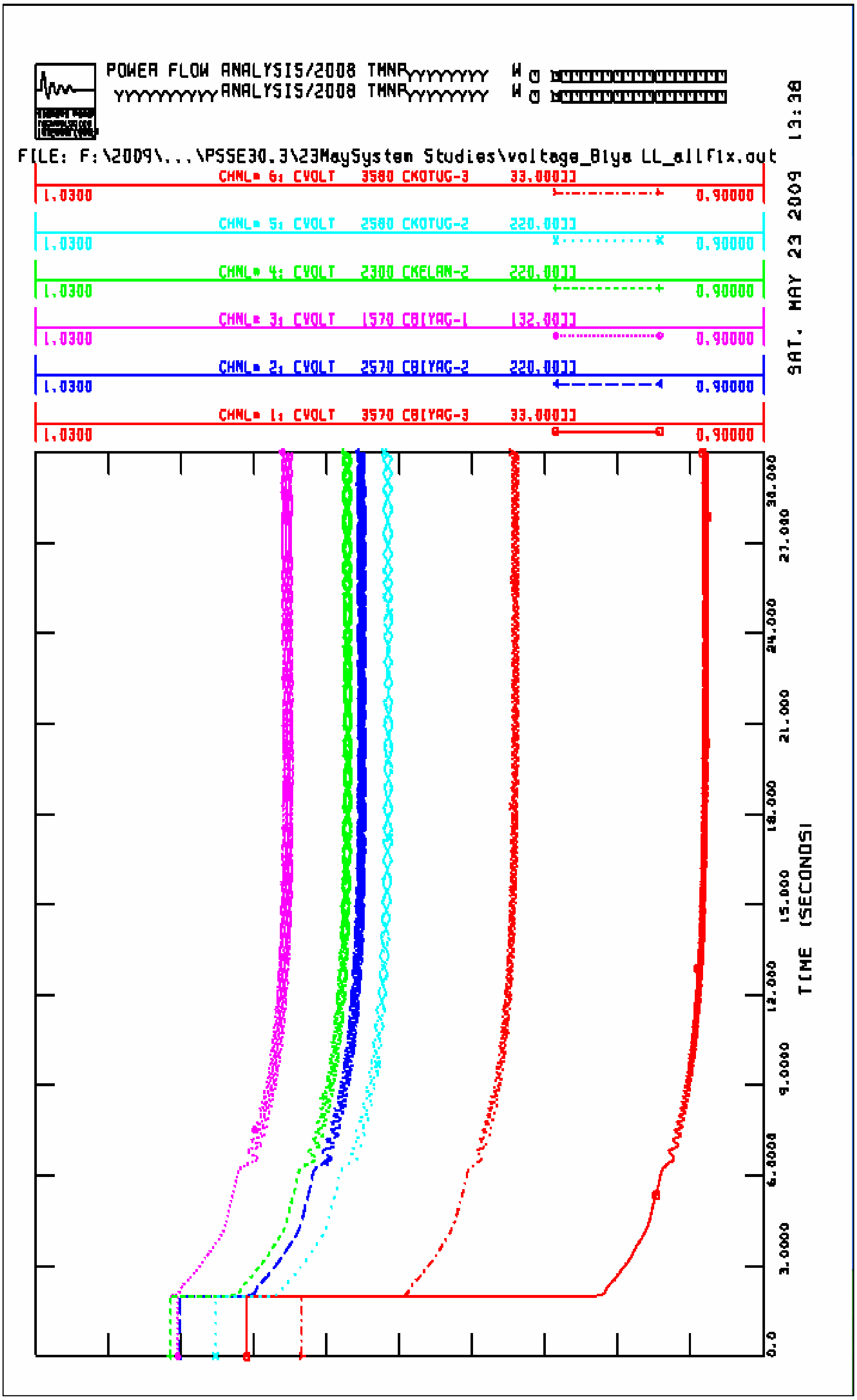


**Figure 8.5 : Effect of adding 50Mvar capacitors to Biyagama 33kV level at t=3sec.**

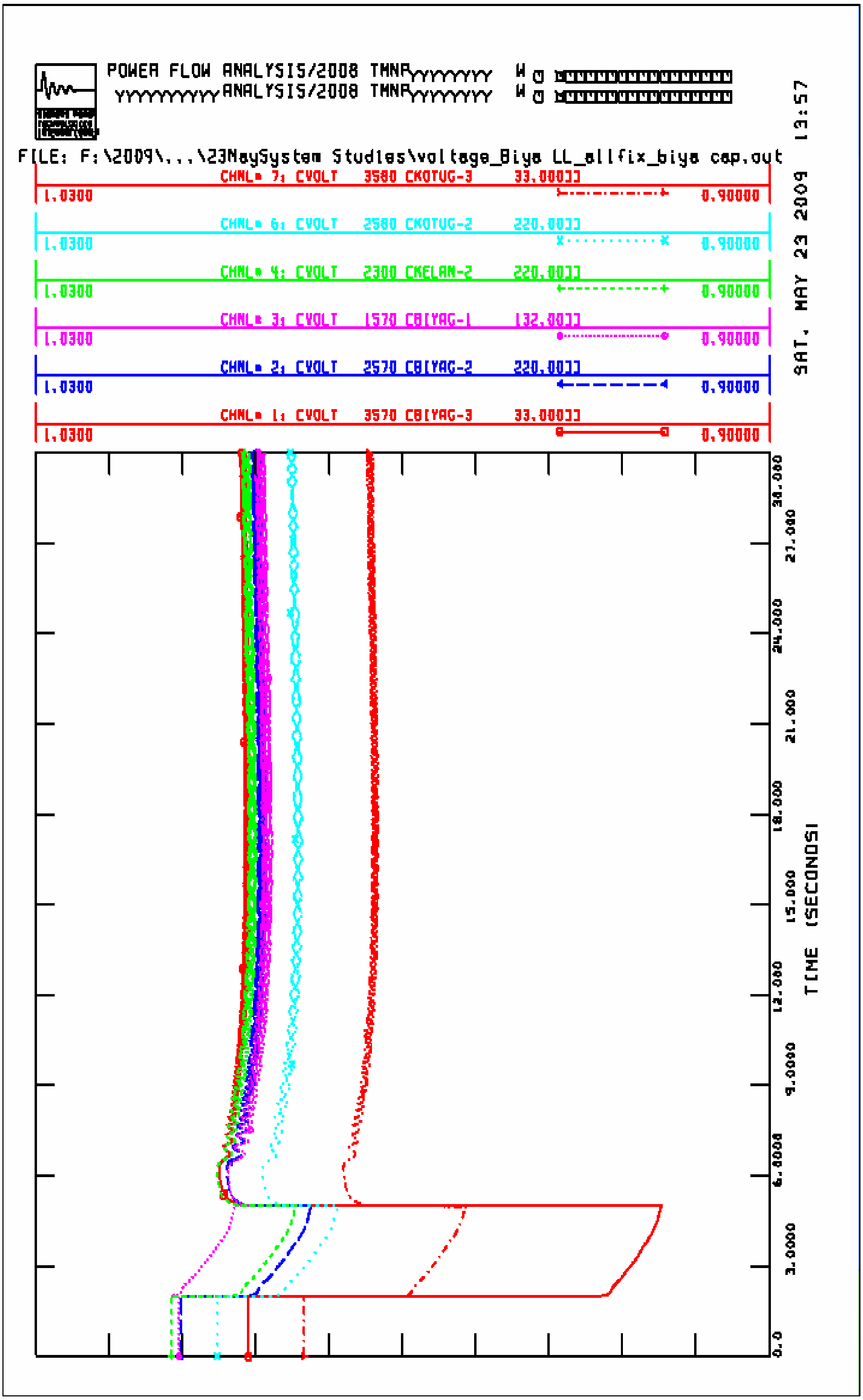


**Figure 8.6: Voltage variation following an approximately 21.6% (up to full load) load variation at Biyalama 33kV winding, with exciters in service**

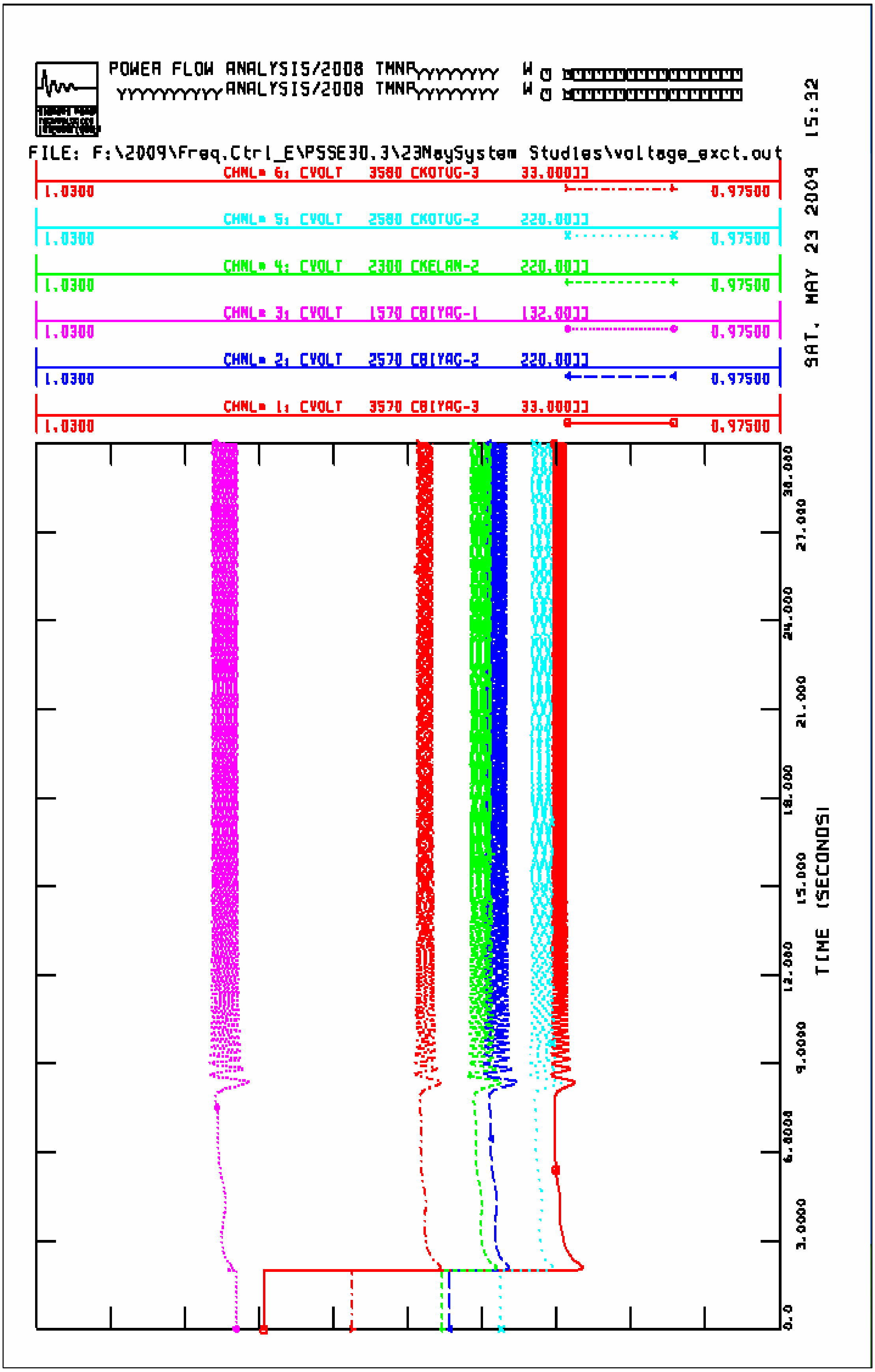


**Figure 8.7 : Voltage variation following an approximately 233% (up to full load) load variation at Biyalama 33kV winding – with exciters in service**

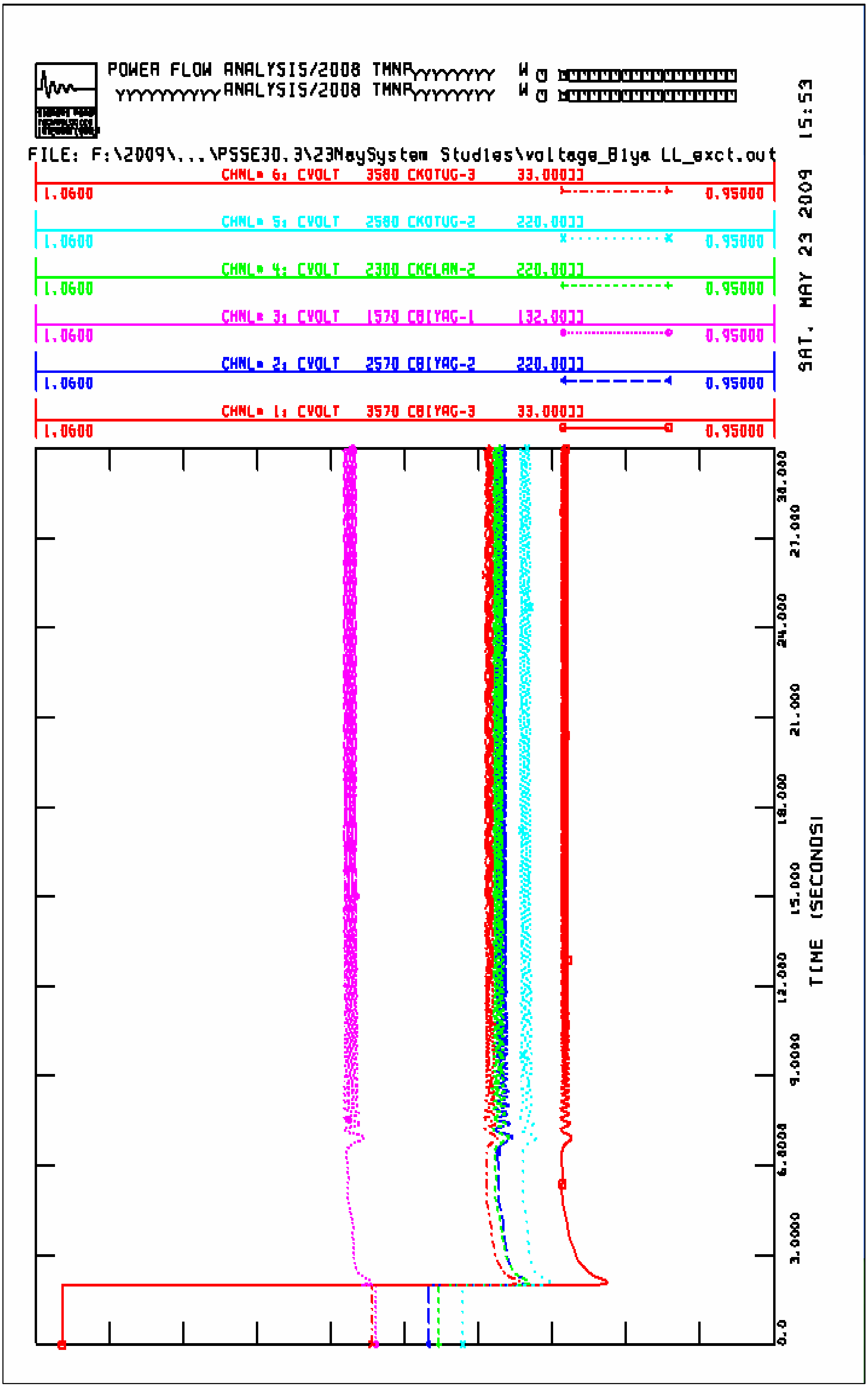
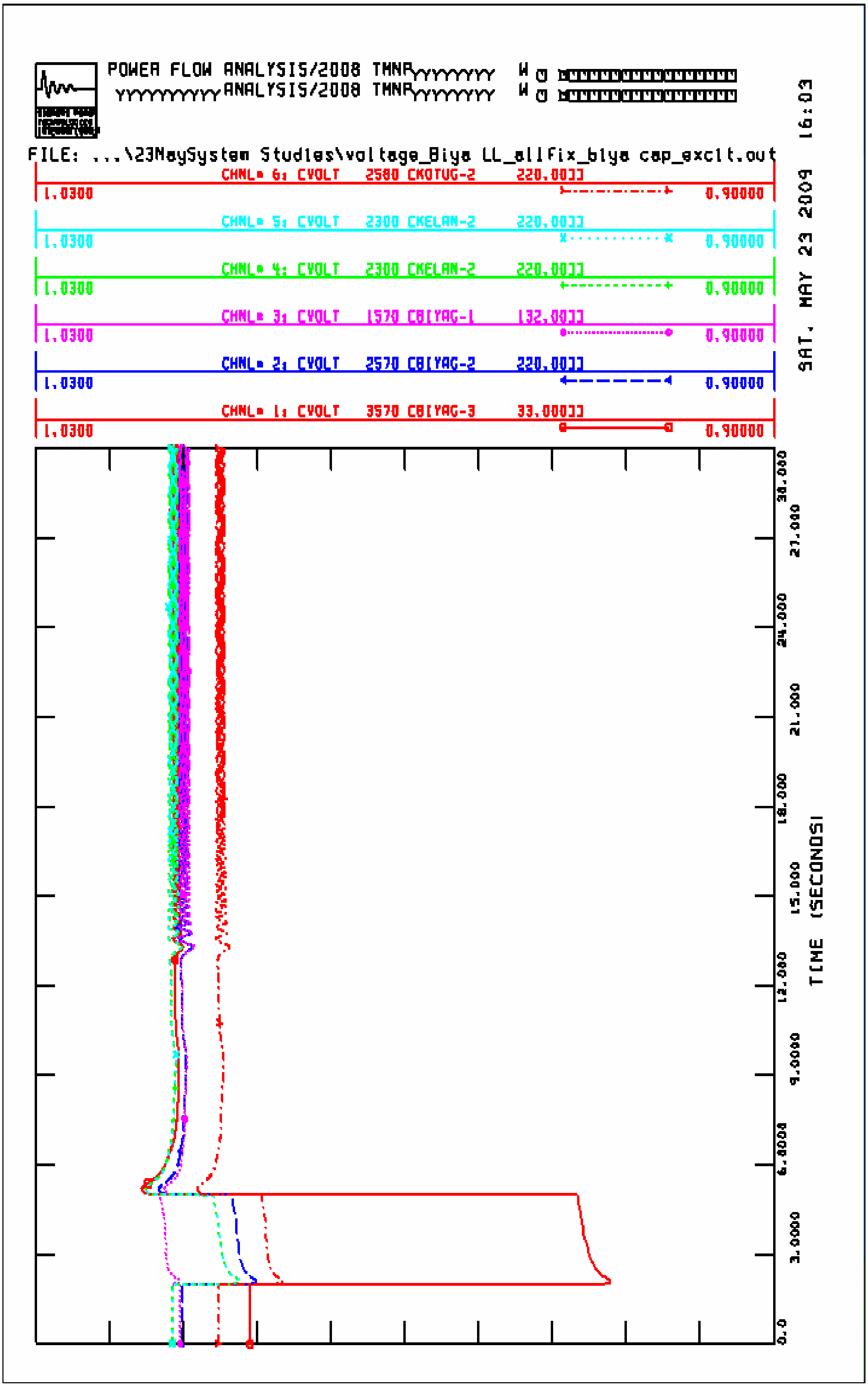


**Figure 8.8 : Effect of adding 50Mvar capacitors to Biyagama 33kV level at t=3sec. with exciters in service**



Observations and Recommendations:

(B) VAR Scheduling considered:

(Scenario: Thermal Maximum Night Peak)

Base Case Voltage Control Element Status:

- All Tap Changer Controls removed
- All AVR Controls removed
- Existing VAR compensator status are listed in Table 1

**Table 1 : Existing Capacitor Status**

| Bus No | Bus Name | MVAR Contribution | Control Mode |
|---|---|---|---|
| 3530 | THULH-3 33.000 | 10.00 | Discrete |
| 3565 | PANNI-T 33.000 | 100.00 | Discrete |
| 3580 | KOTUG-3 33.000 | 50.00 | Discrete |
| 3650 | GALLE-3 33.000 | 20.00 | Discrete |
| 3680 | KURUN-3 33.000 | 10.00 | Discrete |
| 3690 | HABAR-3 33.000 | 10.00 | Discrete |
| 3700 | ANURA-3A 33.000 | 15.00 | Discrete |
| 3770 | KIRIB-3 33.000 | 20.00 | Discrete |
| 3800 | MATUG-3 33.000 | 20.00 | Discrete |
| 3810 | PUTTA-3 33.000 | 20.00 | Discrete |
| 3820 | ATURU-3 33.000 | 15.00 | Discrete |
| 3850 | PANAD-3 33.000 | 20.00 | Discrete |
| 3880 | AMBALA 33.000 | 10.00 | Discrete |
| 3910 | ANIYA 33.000 | 10.00 | Discrete |
| 4650 | GALLE-SV 5.9000 | 20.00 | Continuous |

Base case voltage violations

Base case voltage violations observed are listed in Table 2. Busbars with planning criteria violations are highlighted on the same table. Annex 1 shows the load flow diagram for Thermal Maximum Night Peak Scenario – Base Case.

Switched Shunt Capacitor Compensation Requirement Identified

| Bus bar | MVAR |
|---|---|
| Galle 132kV | 80 |
| Ampara 33kV | 40 |
| Kurunegala 33kV | 25+10* |
| Valachchenai 33kV | 20 |

*Existing MVAR

Tap Changer Controller Requirement Identified

- Set Biyagama inter-bus to control 33kV/33kV voltage
- Set New Anuradhapura inter-bus transformer to control 132kV voltage
- Set Madampe transformer to control 33kV busbar
- Set Colombo E transformer to control 11kV busbar
- Set Colombo A transformer to control 11kV busbar
- Set Colombo F transformer to control 11kV busbar
- Set Trincomalee transformer to control 33kV busbar
- Set Veyangoda transformer to control 33kV busbar
- Set Bolawatta transformer to control 33kV busbar
- Set Kosgama transformer to control 33kV busbar
- Set J'Pura transformer to control 33kV busbar
- Set Nuwara-Eliya transformer to control 33kV busbar
- Set Badulla transformer to control 33kV busbar

AVR Set Points Considered

- Set Kotmale, Victoria and Randenigala 220kV busbars to 1.02 p.u using respective machine AVRs

- Set Kelanitissa 220 kV and 132 kV busbar voltages to 1.02 p.u using respective machine AVRs

**Table 2 : Base Case Voltage Violations**

| Bus No. | Bus Name | Voltage Level | Voltage (p.u) | Voltage (kV) |
|---|---|---|---|---|
| 1150 | AMPA-1 | 132 | 0.7867 | 103.8 |
| 1640 | DENIY-1 | 132 | 0.9246 | 122.0 |
| 1680 | KURUN-1 | 132 | 0.9349 | 123.4 |
| 1710 | TRINC-1 | 132 | 0.9289 | 122.6 |
| 1780 | VALACH_1 | 132 | 0.8613 | 113.7 |
| 3160 | INGIN-3 | 33 | 0.8227 | 27.1 |
| 3500 | KOSGA-3 | 33 | 0.9434 | 31.1 |
| 3570 | BIYAG-3 | 33 | 0.9376 | 30.9 |
| 3620 | BADUL-3 | 33 | 0.9345 | 30.8 |
| 3650 | GALLE-3 | 33 | 0.7973 | 26.3 |
| 3690 | HABAR-3 | 33 | 0.9231 | 30.5 |
| 3770 | KIRIB-3 | 33 | 0.9357 | 30.9 |
| 3830 | VEYAN-33 | 33 | 0.9499 | 31.3 |
| 3860 | MADAM-3 | 33 | 0.919 | 30.3 |
| 4750 | COL_E-11 | 11 | 0.9111 | 10.0 |
| 5160 | INGI-1T1 | 132 | 0.8227 | 108.6 |
| 1160 | INGIN-1 | 132 | 0.8227 | 108.6 |
| 1650 | GALLE-1 | 132 | 0.8808 | 116.3 |
| 1690 | HABAR-1 | 132 | 0.938 | 123.8 |
| 1770 | KIRIB-1 | 132 | 0.9481 | 125.2 |
| 3150 | AMPA-3 | 33 | 0.7544 | 24.9 |
| 3200 | UKUWE-3 | 33 | 0.9275 | 30.6 |
| 3520 | NUWAR-3 | 33 | 0.9447 | 31.2 |
| 3600 | BOLAW-3 | 33 | 0.9426 | 31.1 |
| 3640 | DENIY-3 | 33 | 0.9149 | 30.2 |
| 3680 | KURUN-3 | 33 | 0.9198 | 30.4 |
| 3710 | TRINC-3 | 33 | 0.9002 | 29.7 |
| 3780 | VALACH_3 | 33 | 0.7821 | 25.8 |
| 3840 | JPURA_3 | 33 | 0.9395 | 31.0 |
| 4435 | COL_A_11 | 11 | 0.9474 | 10.4 |
| 4760 | COL_F-11 | 11 | 0.9426 | 10.4 |

Option 01

- Changing AVR set points.

**Table 3 : Voltage violations with AVR set points**

| Bus No. | Bus Name | Voltage Level | Voltage (p.u) | Voltage (kV) |
|---|---|---|---|---|
| 1150 | AMPA-1 | 132 | 0.8036 | 106.1 |
| 1640 | DENIY-1 | 132 | 0.9296 | 122.7 |
| 1680 | KURUN-1 | 132 | 0.9439 | 124.6 |
| 1710 | TRINC-1 | 132 | 0.9377 | 123.8 |
| 3150 | AMPA-3 | 33 | 0.7725 | 25.5 |
| 3200 | UKUWE-3 | 33 | 0.9365 | 30.9 |
| 3640 | DENIY-3 | 33 | 0.9200 | 30.4 |
| 3680 | KURUN-3 | 33 | 0.9293 | 30.7 |
| 3710 | TRINC-3 | 33 | 0.9093 | 30.0 |
| 3780 | VALACH_3 | 33 | 0.7947 | 26.2 |
| 4750 | COL_E-11 | 11 | 0.9277 | 10.2 |
| 1160 | INGIN-1 | 132 | 0.8384 | 110.7 |
| 1650 | GALLE-1 | 132 | 0.8867 | 117.1 |
| 1690 | HABAR-1 | 132 | 0.9469 | 125.0 |
| 1780 | VALACH_1 | 132 | 0.8720 | 115.1 |
| 3160 | INGIN-3 | 33 | 0.8384 | 27.7 |
| 3620 | BADUL-3 | 33 | 0.9459 | 31.2 |
| 3650 | GALLE-3 | 33 | 0.8047 | 26.6 |
| 3690 | HABAR-3 | 33 | 0.9325 | 30.8 |
| 3770 | KIRIB-3 | 33 | 0.9451 | 31.2 |
| 3860 | MADAM-3 | 33 | 0.9267 | 30.6 |
| 5160 | INGI-1T1 | 132 | 0.8384 | 110.7 |

Voltage violations observed with AVR set points are listed in Table 3. Busbars with planning criteria violations are highlighted on Table 3. Annex 2 shows the load flow diagram for Thermal Maximum Night Peak Scenario – AVR set points.

Option 02

- Tap change control

Voltage violations observed with Tap change controls are listed in Table 4. Busbars with planning criteria violations are highlighted on the same table. Annex 3 shows the load flow diagram for Thermal Maximum Night Peak Scenario – Tap Change Control.

**Table 4 : Voltage violations with tap change control**

| Bus No. | Bus Name | Voltage Level | Voltage (p.u) | Voltage (kV) |
|---|---|---|---|---|
| 1150 | AMPA-1 | 132 | 0.7885 | 104.1 |
| 1640 | DENIY-1 | 132 | 0.9257 | 122.2 |
| 1680 | KURUN-1 | 132 | 0.9405 | 124.1 |
| 1780 | VALACH_1 | 132 | 0.8762 | 115.7 |
| 3150 | AMPA-3 | 33 | 0.7564 | 25.0 |
| 3200 | UKUWE-3 | 33 | 0.9350 | 30.9 |
| 3650 | GALLE-3 | 33 | 0.7990 | 26.4 |
| 3690 | HABAR-3 | 33 | 0.9363 | 30.9 |
| 3780 | VALACH_3 | 33 | 0.7997 | 26.4 |
| 1160 | INGIN-1 | 132 | 0.8244 | 108.8 |
| 1650 | GALLE-1 | 132 | 0.8821 | 116.4 |
| 1710 | TRINC-1 | 132 | 0.9451 | 124.8 |
| 2705 | NEWANU-2 | 220 | 0.9384 | 206.4 |
| 3160 | INGIN-3 | 33 | 0.8244 | 27.2 |
| 3640 | DENIY-3 | 33 | 0.9160 | 30.2 |
| 3680 | KURUN-3 | 33 | 0.9257 | 30.5 |
| 3770 | KIRIB-3 | 33 | 0.9415 | 31.1 |
| 5160 | INGI-1T1 | 132 | 0.8244 | 108.8 |

Option 03

- Switched Shunt Controls

Voltage violations observed with tap change controls are listed in Table 5. Busbars with planning criteria violations are highlighted on the same table. Annex 4 shows the load flow diagram for Thermal Maximum Night Peak Scenario – Switched Shunt Controls.

**Table 5: Voltage violations with Switched Shunt Controls**

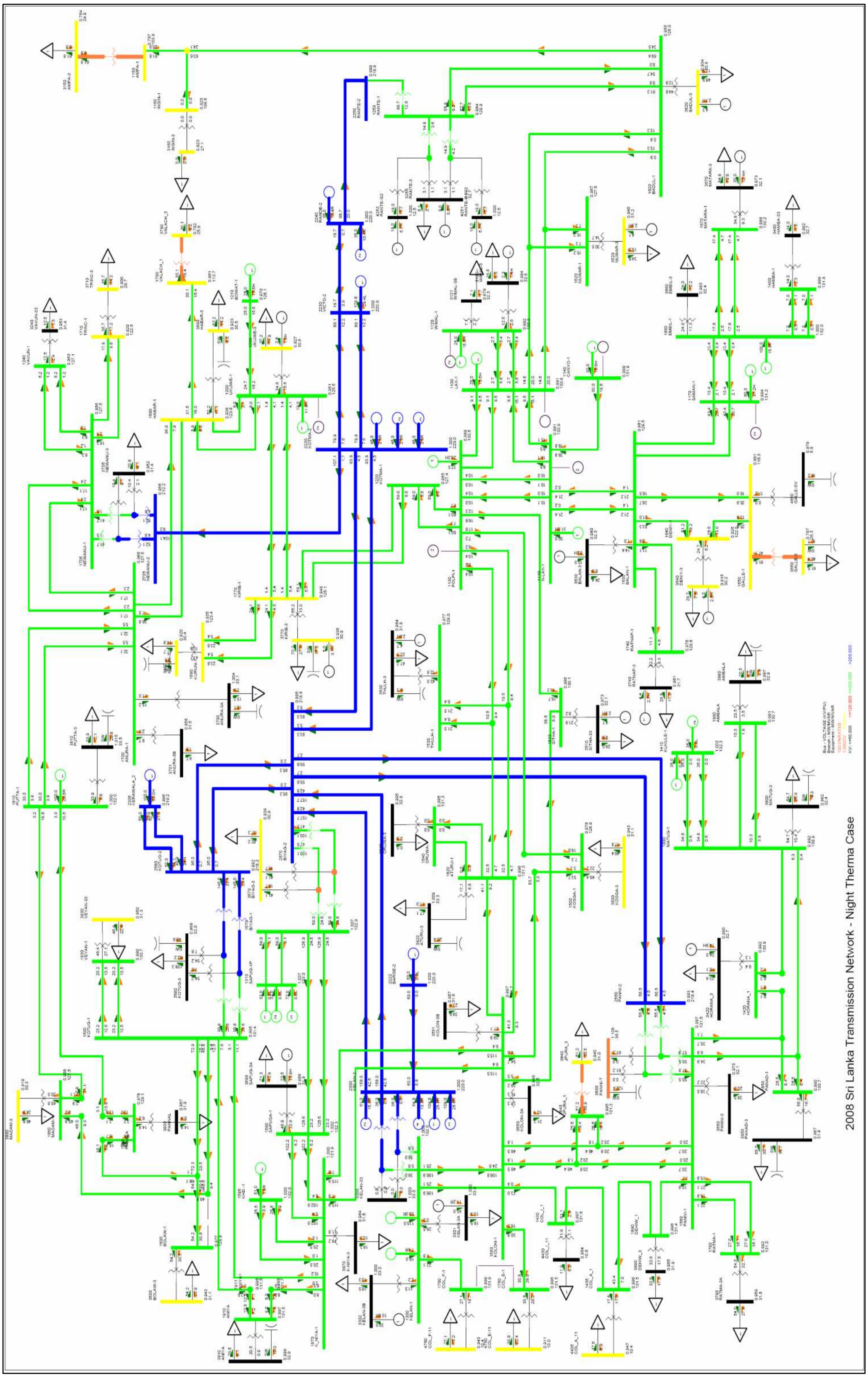
| Bus No. | Bus Name | Voltage Level | Voltage (p.u) | Voltage (kV) |
|---|---|---|---|---|
| 1710 | TRINC-1 | 132 | 0.9431 | 124.5 |
| 3570 | BIYAG-3 | 33 | 0.9374 | 30.9 |
| 3710 | TRINC-3 | 33 | 0.9149 | 30.2 |
| 3860 | MADAM-3 | 33 | 0.9191 | 30.3 |
| 4750 | COL_E-11 | 11 | 0.9116 | 10.0 |
| 3500 | KOSGA-3 | 33 | 0.9483 | 31.3 |
| 3600 | BOLAW-3 | 33 | 0.9427 | 31.1 |
| 3840 | JPURA_3 | 33 | 0.9400 | 31.0 |
| 4435 | COL_A_11 | 11 | 0.9479 | 10.4 |
| 4760 | COL_F-11 | 11 | 0.9426 | 10.4 |

<u>Option 04</u>

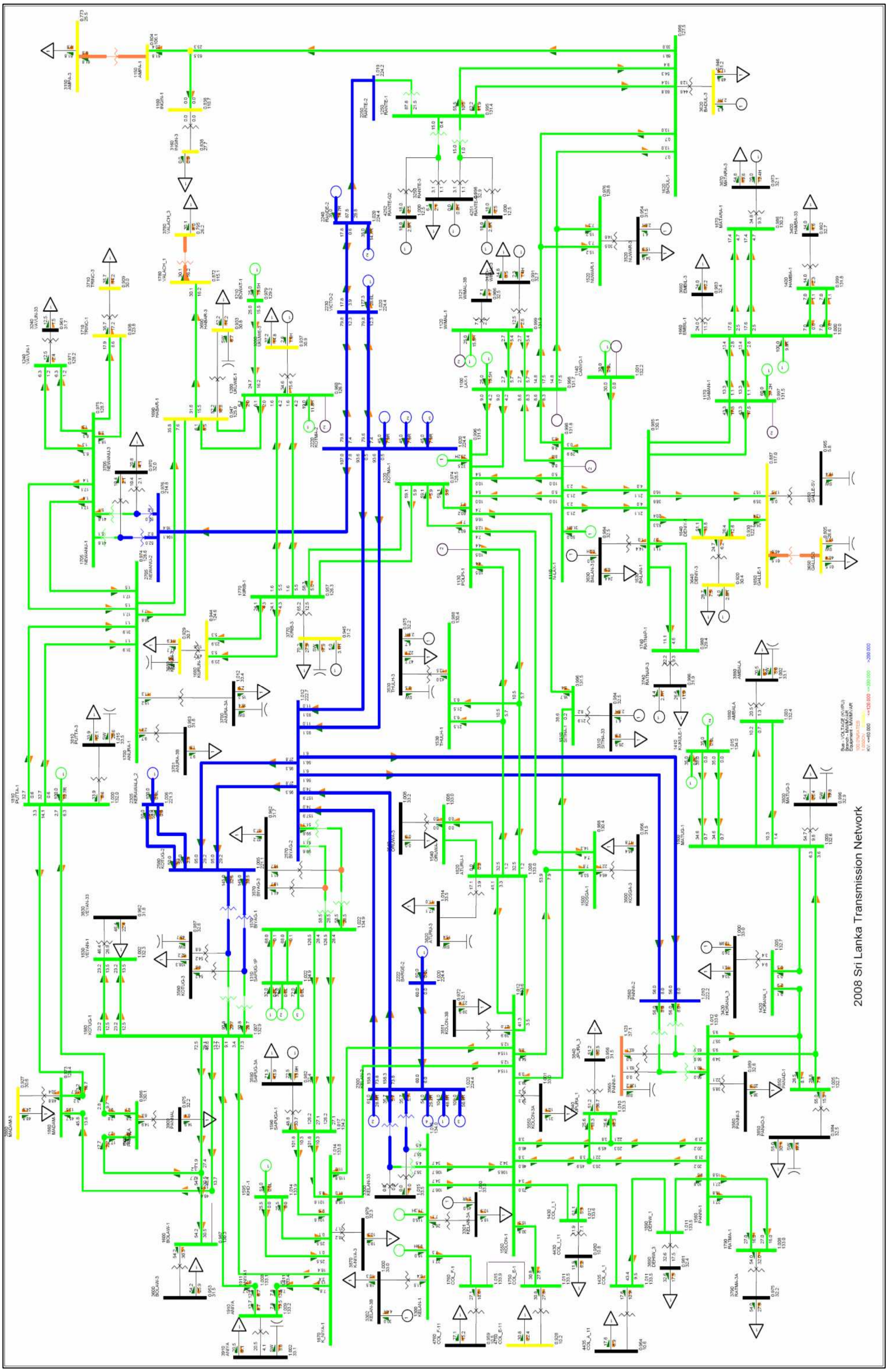
- With all three controls

No voltage above or below 5% has been observed.

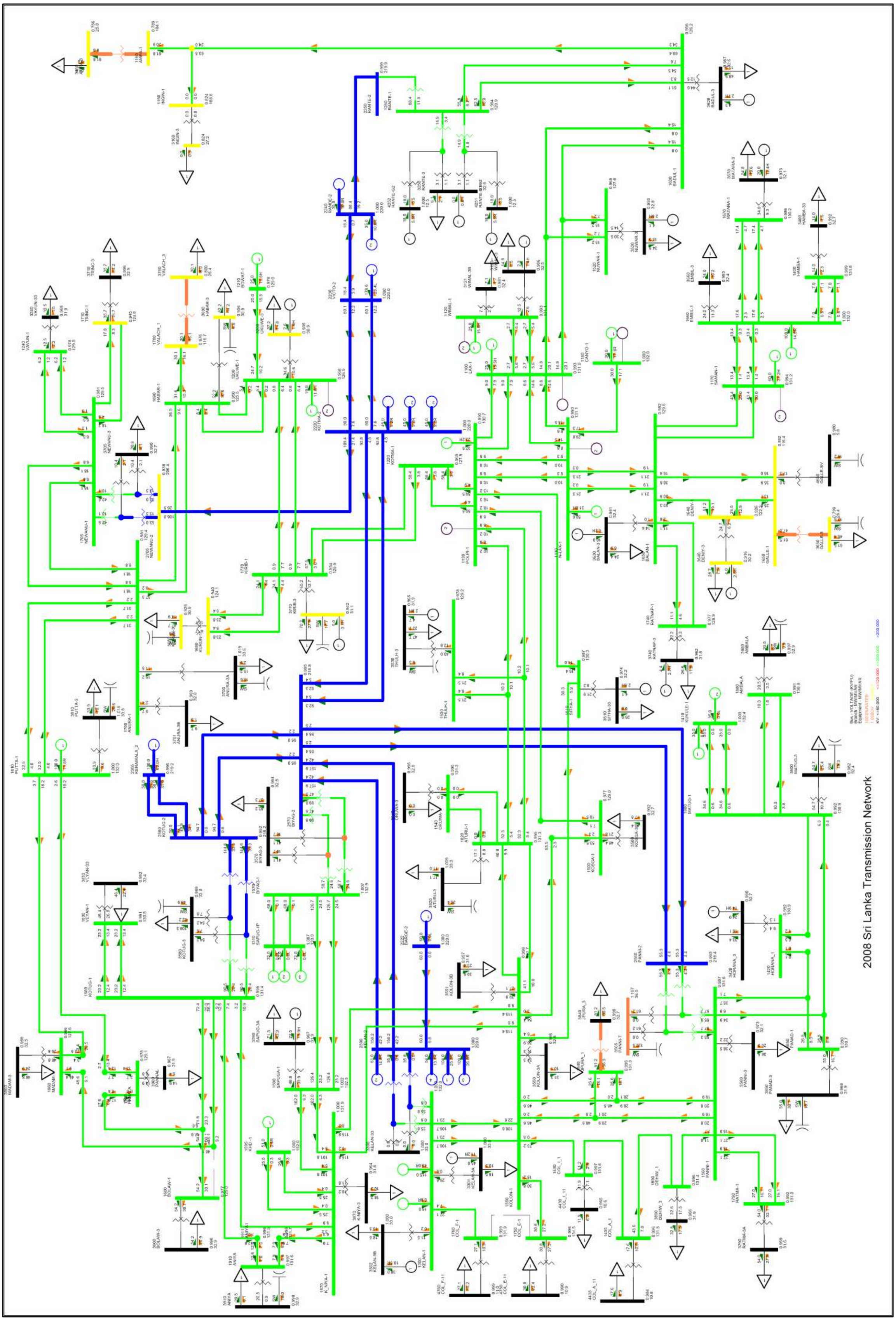
# Annex 1 : Load Flow Diagram Night Thermal Scenario - Base Case



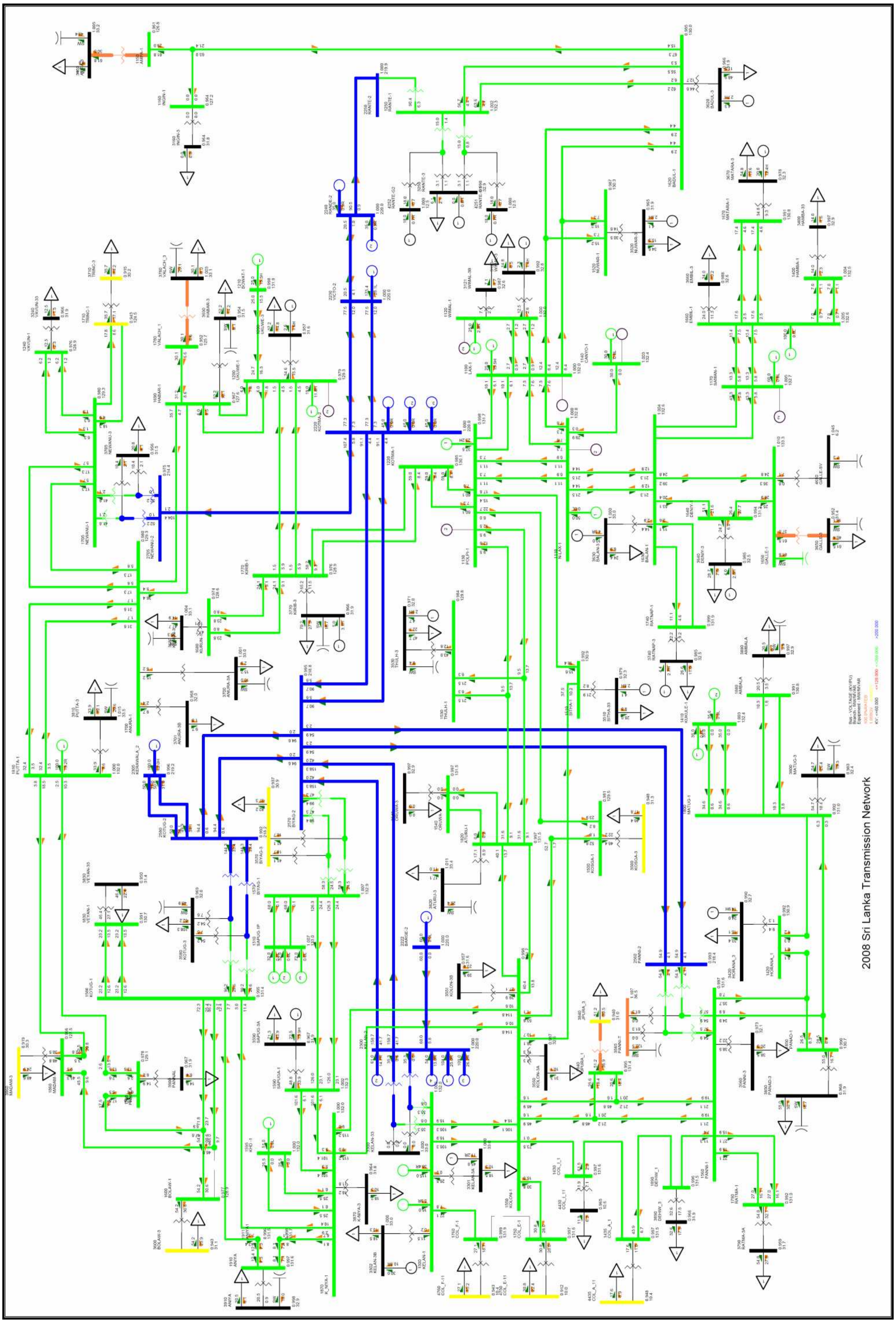
## Annex 2: Load Flow Diagram Night Thermal Scenario –AVR Set Points



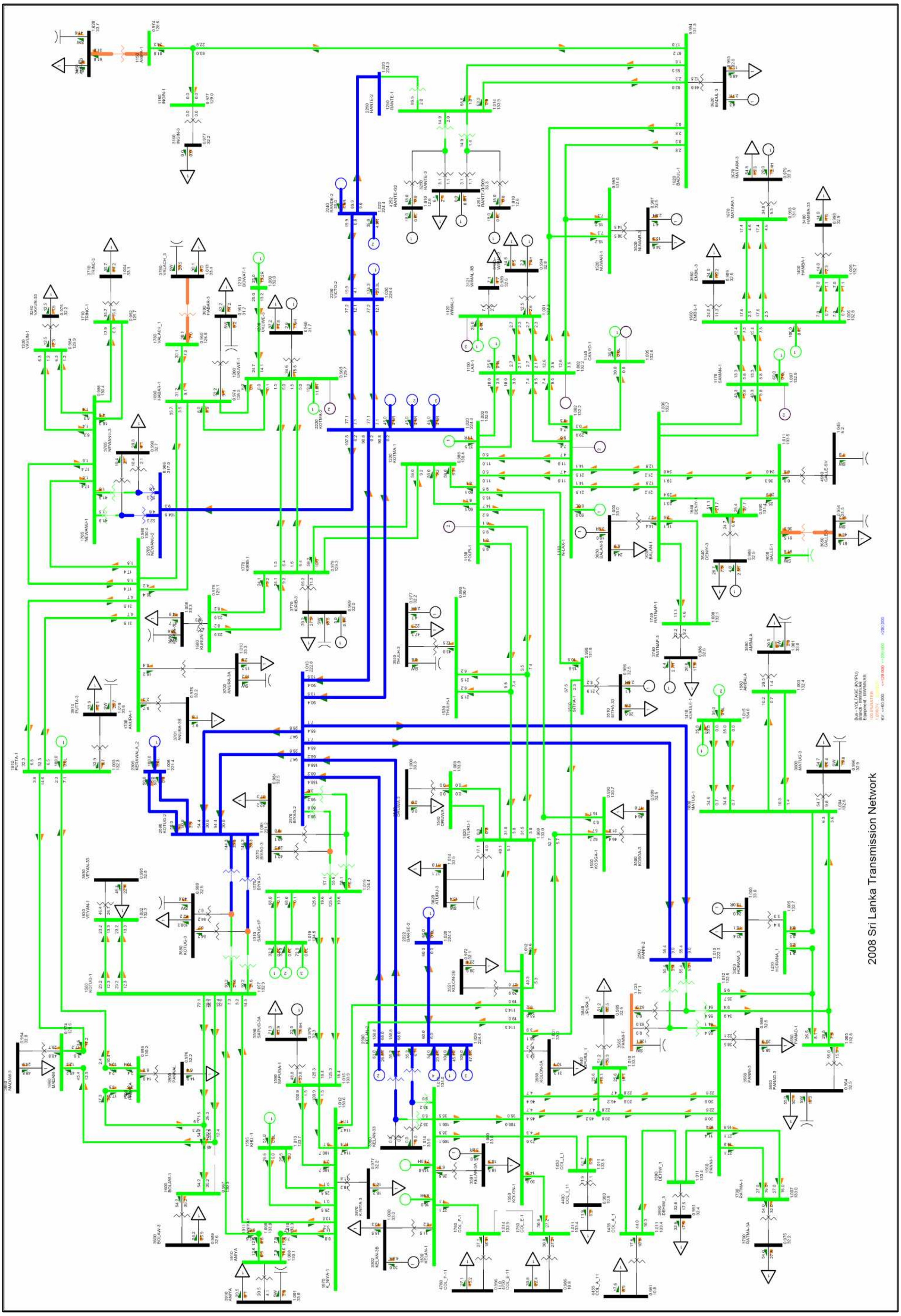
# Annex 3 : Load Flow Diagram Night Thermal Scenario – Tap Change Control



# Annex 4: Load Flow Diagram Night Thermal Scenario – Switched Shunt Control

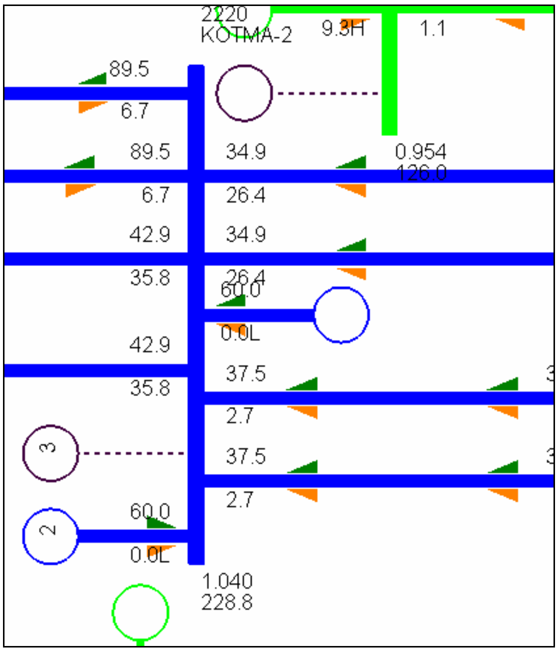


# Annex 5: Load Flow Diagram Night Thermal Scenario – With All Controls

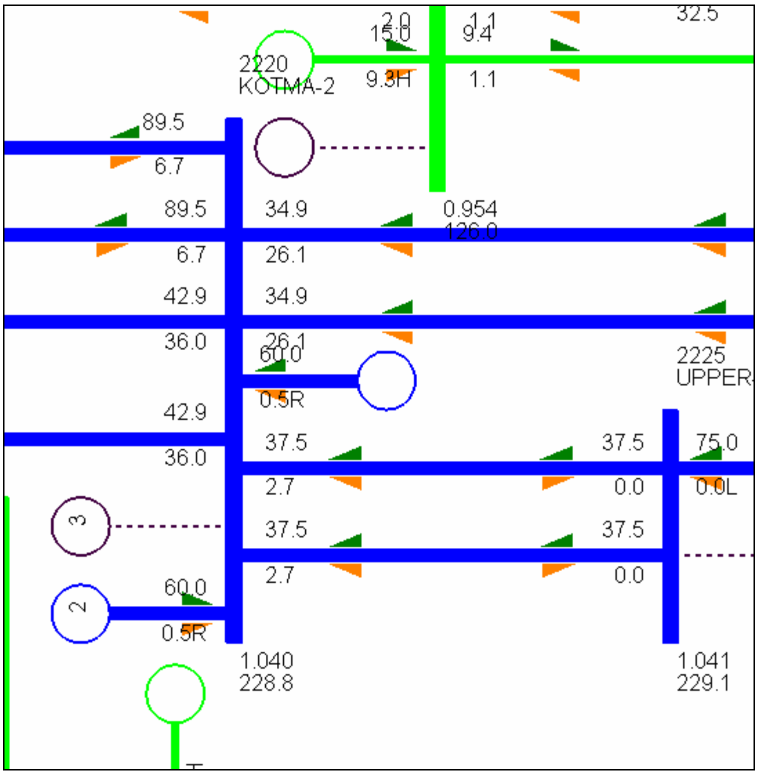


## (C) AVR Setpoint Variation:

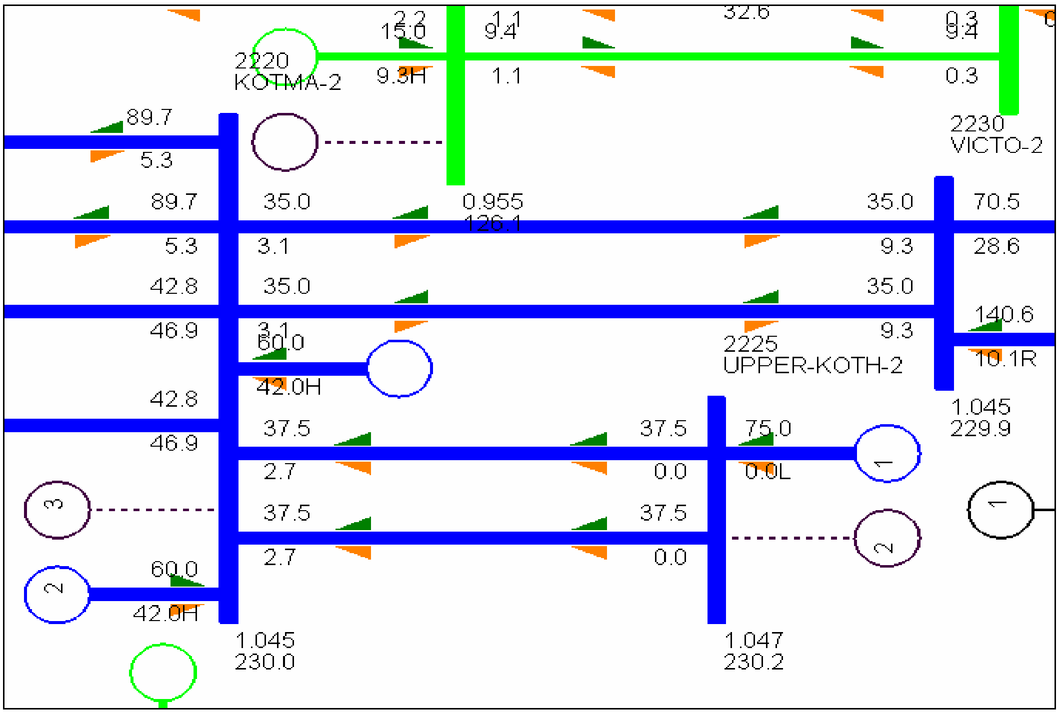
Kotmale Vshedu=<1.03



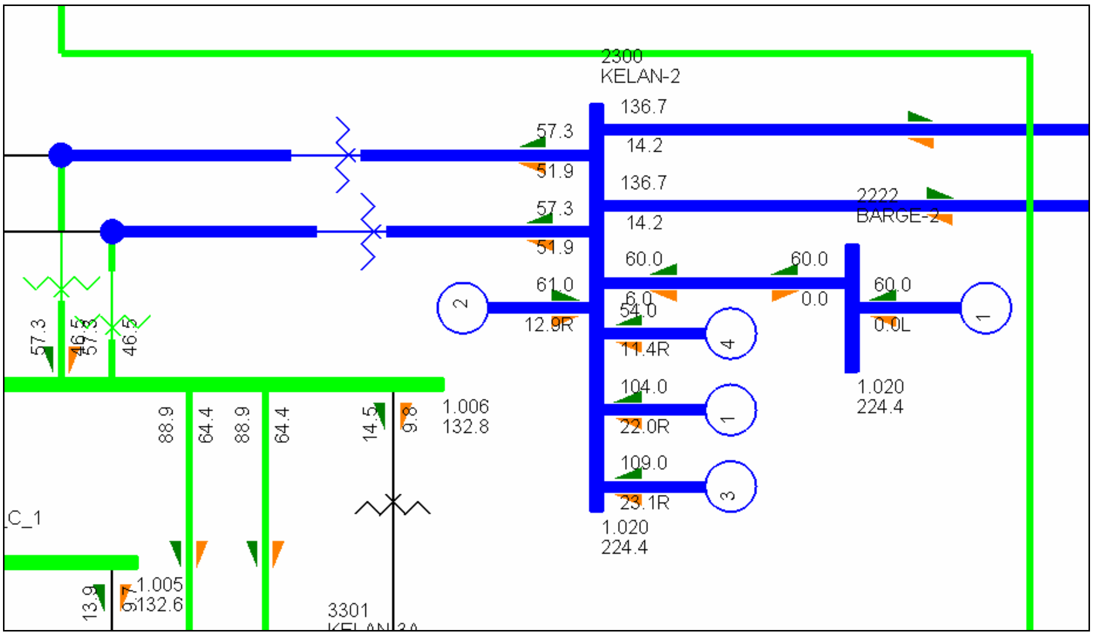

Kotmale Vshedu=1.04



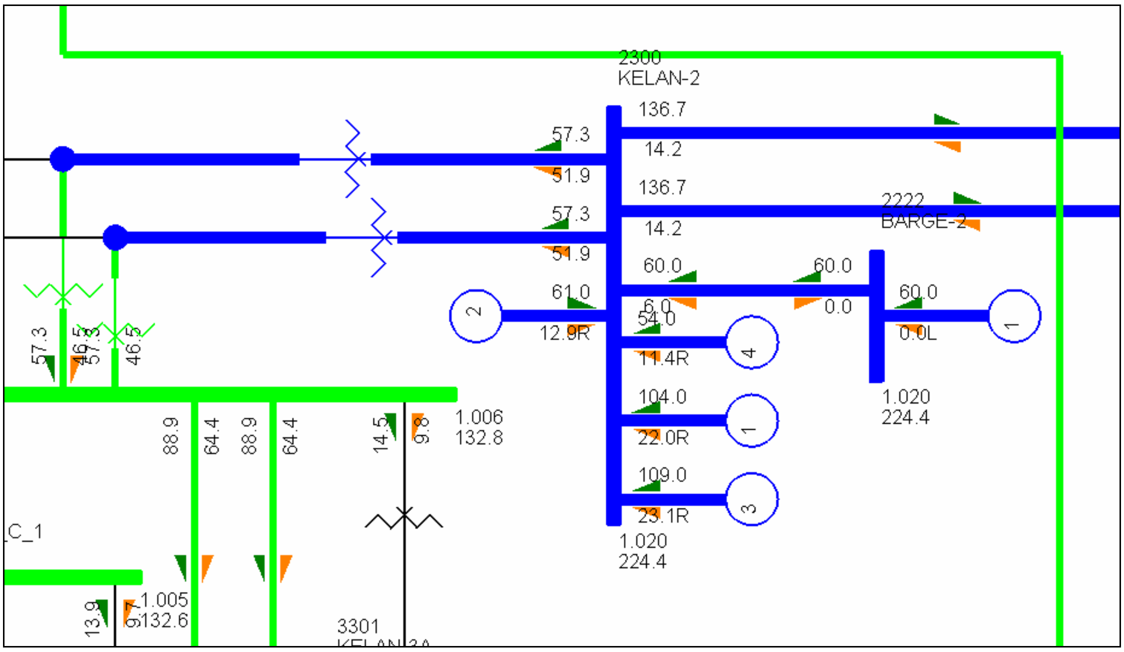
Kotmale Vshedu=1.05pu



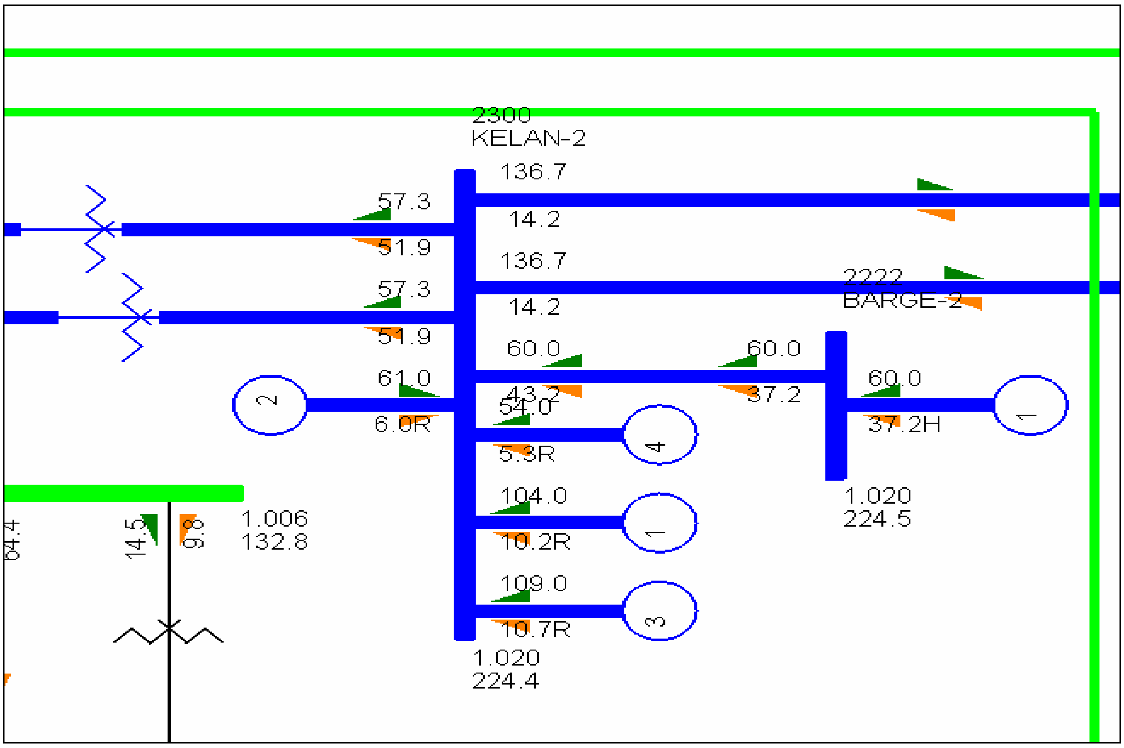

Barge Vshedu=1.02pu



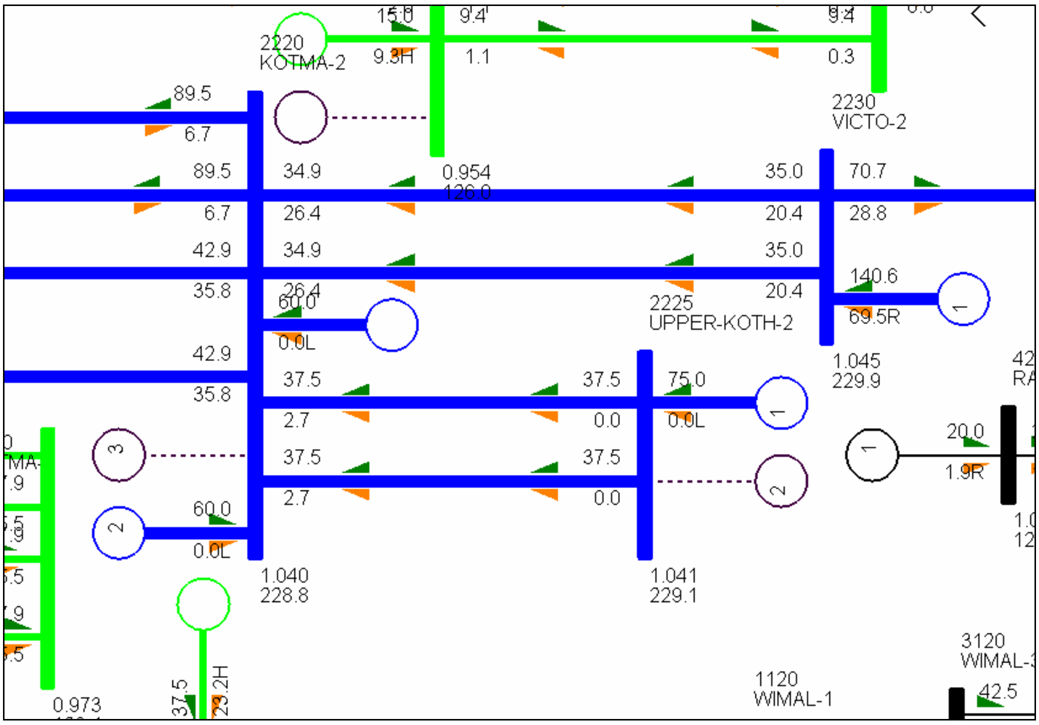
Barge Vshedu=1.025pu



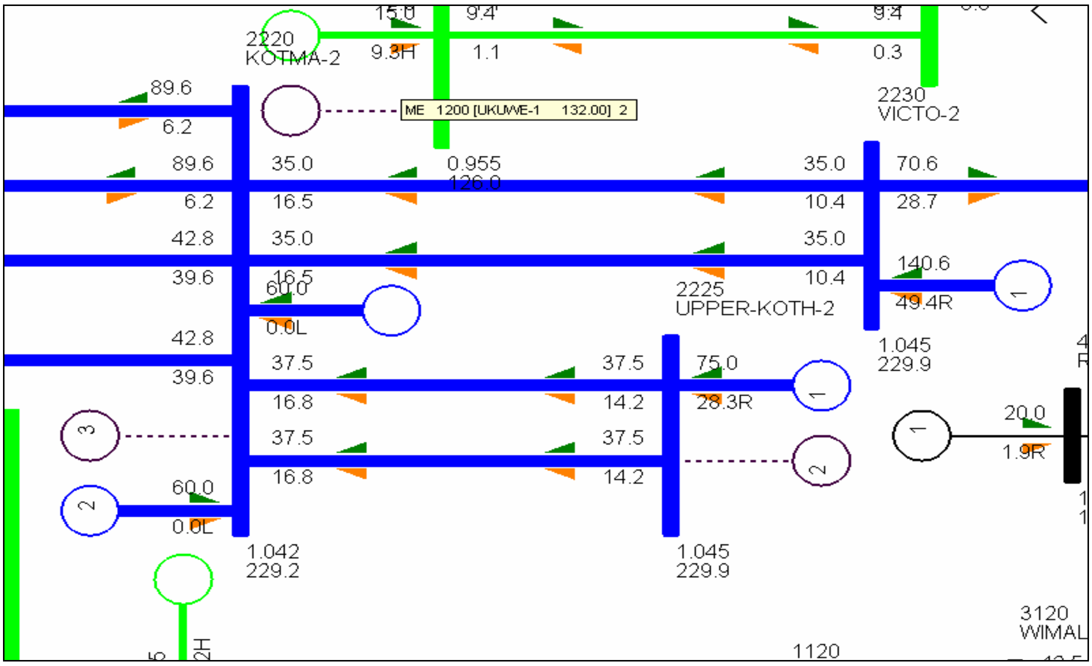

Barge Vshedu=1.03pu



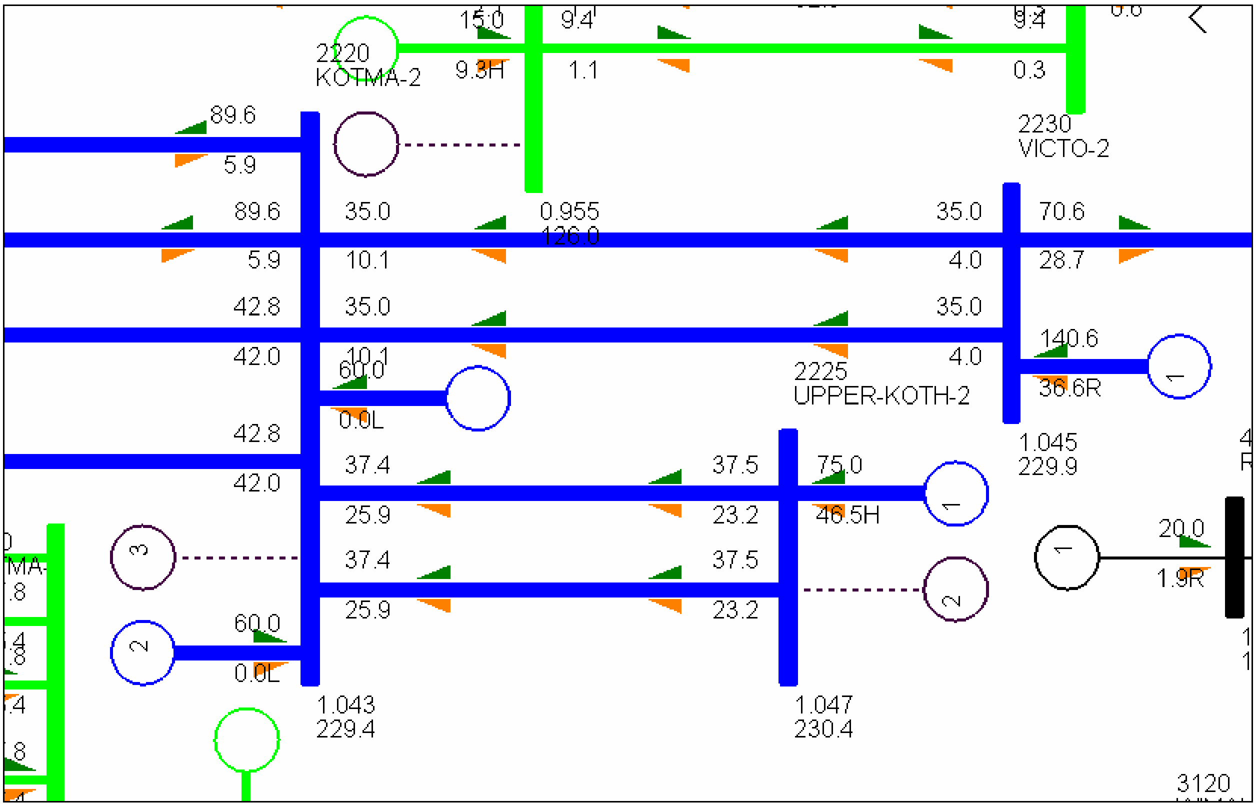
Upper Kotmale Vshedu=1.04pu



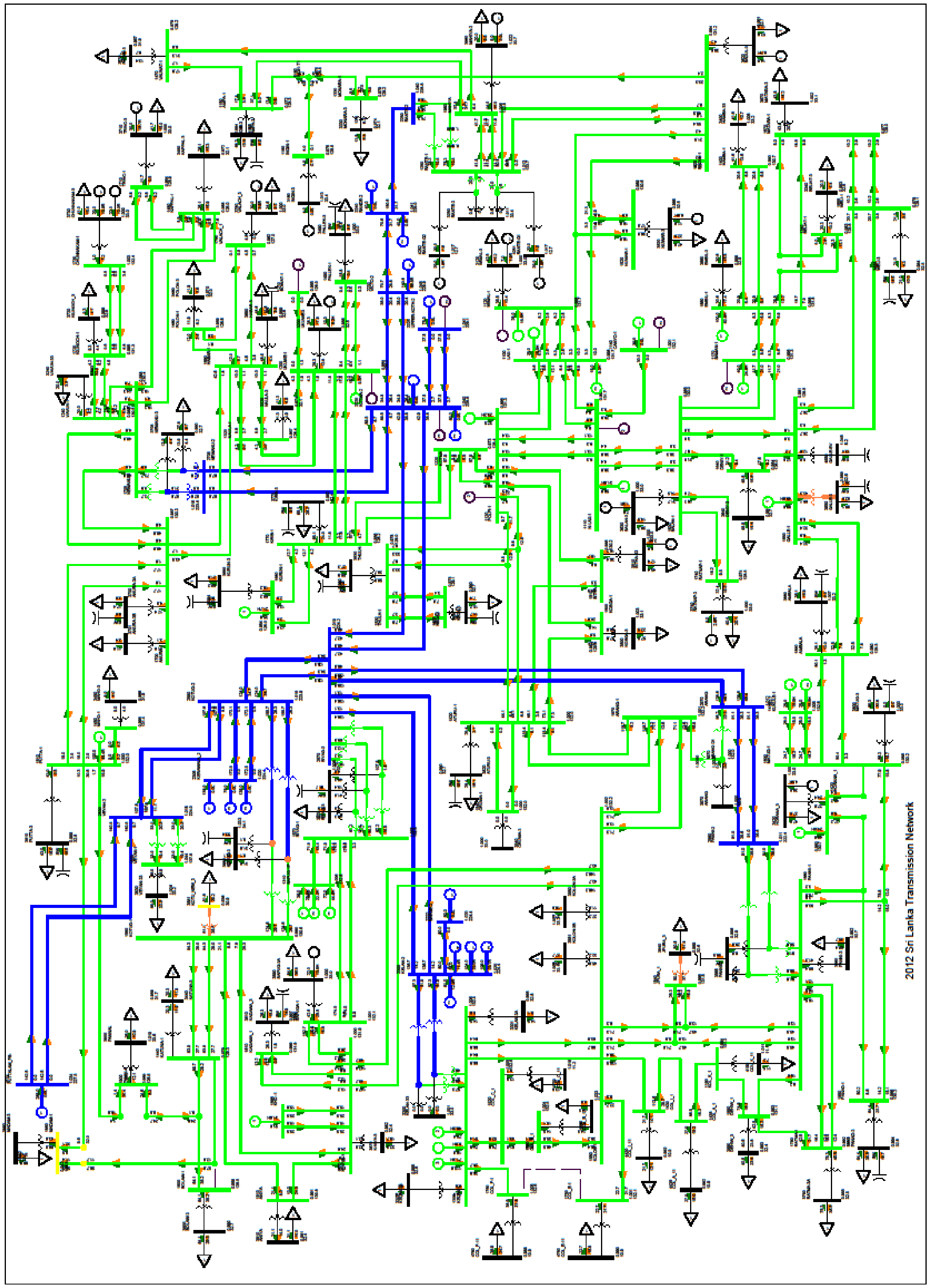

Upper Kotmale Vshedu=1.045pu



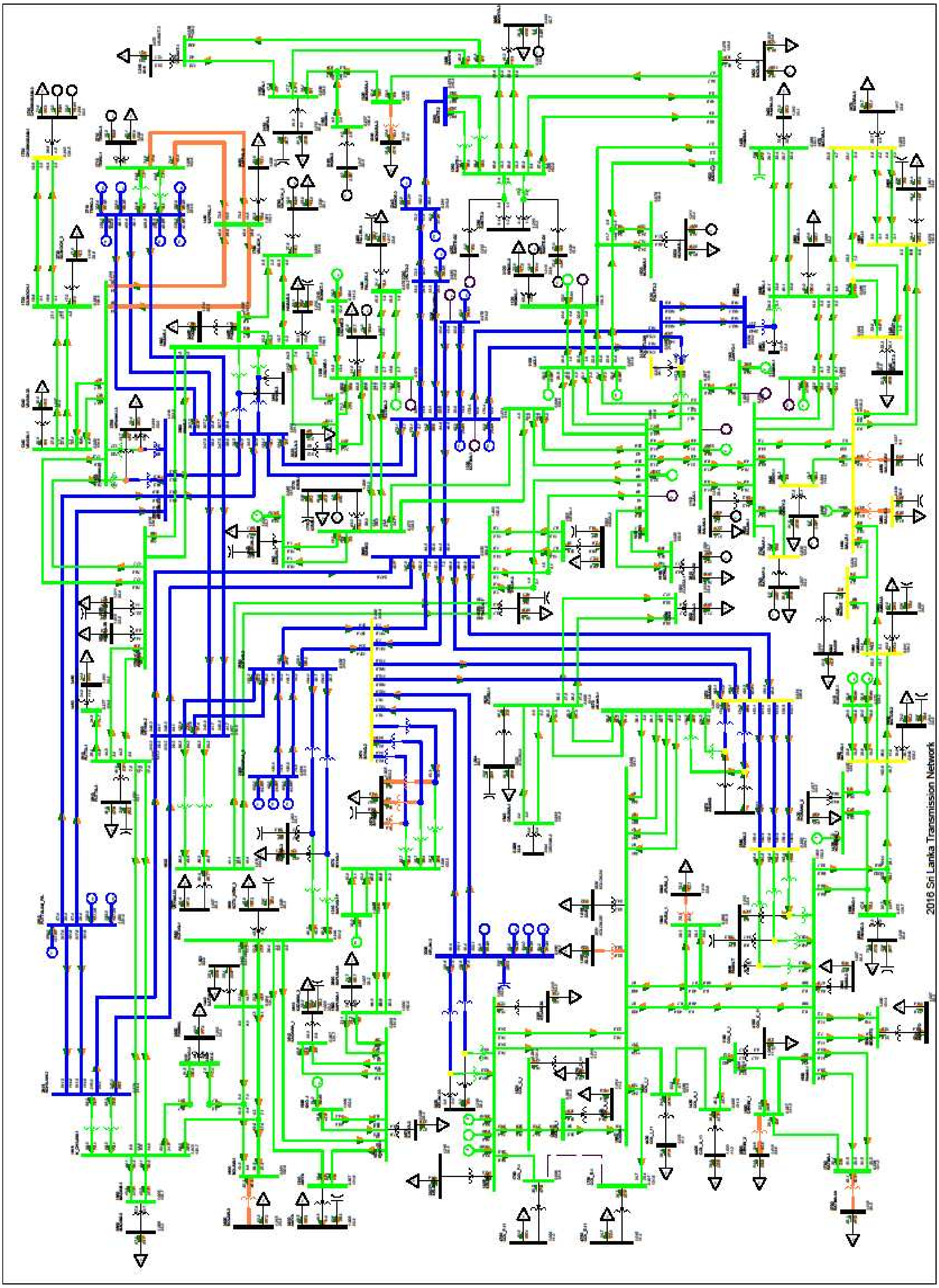
Upper Kotmale Vshedu=1.05pu



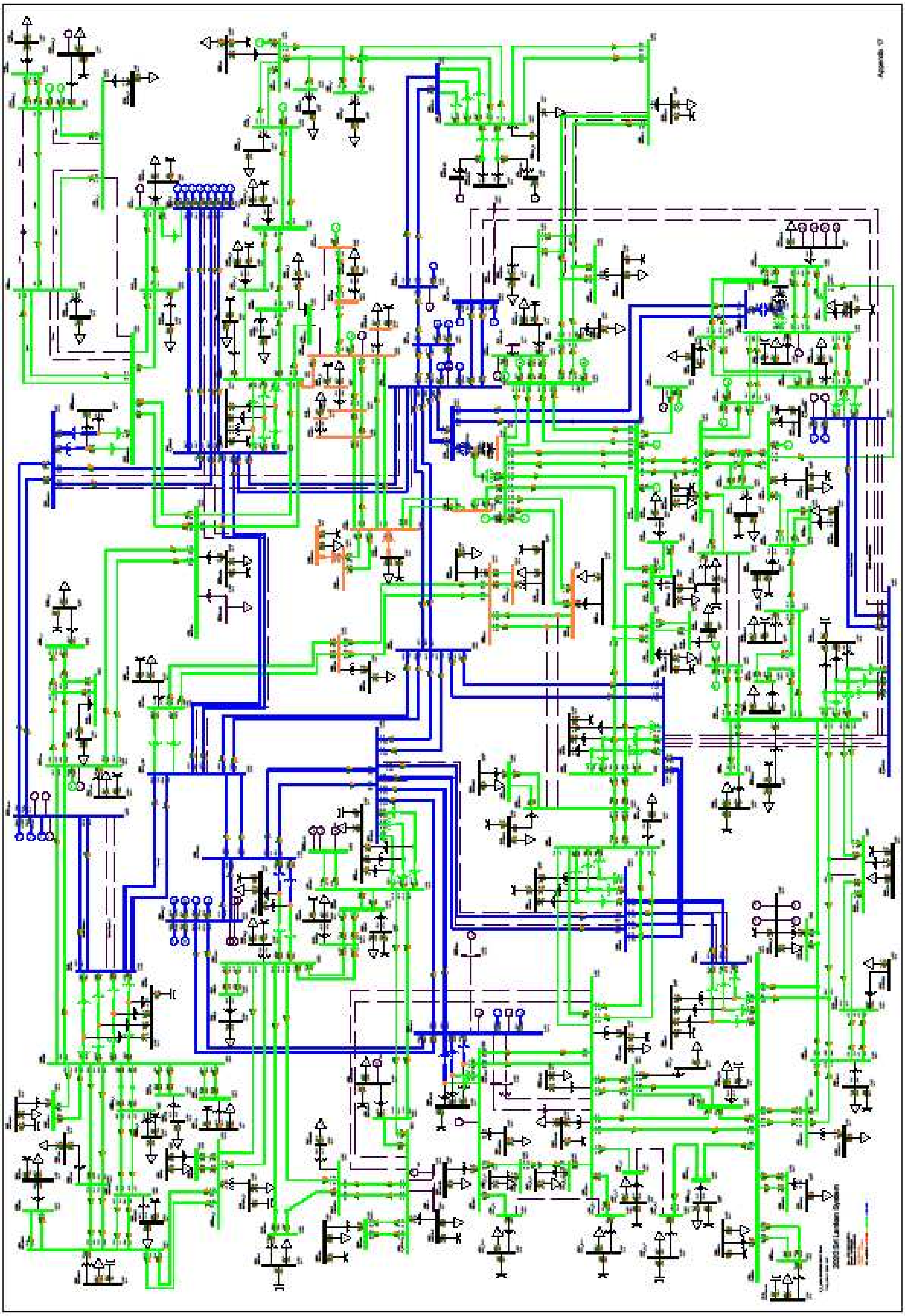
2012 Sri Lanka Transmission Network



2016 Sri Lanka Transmission Network



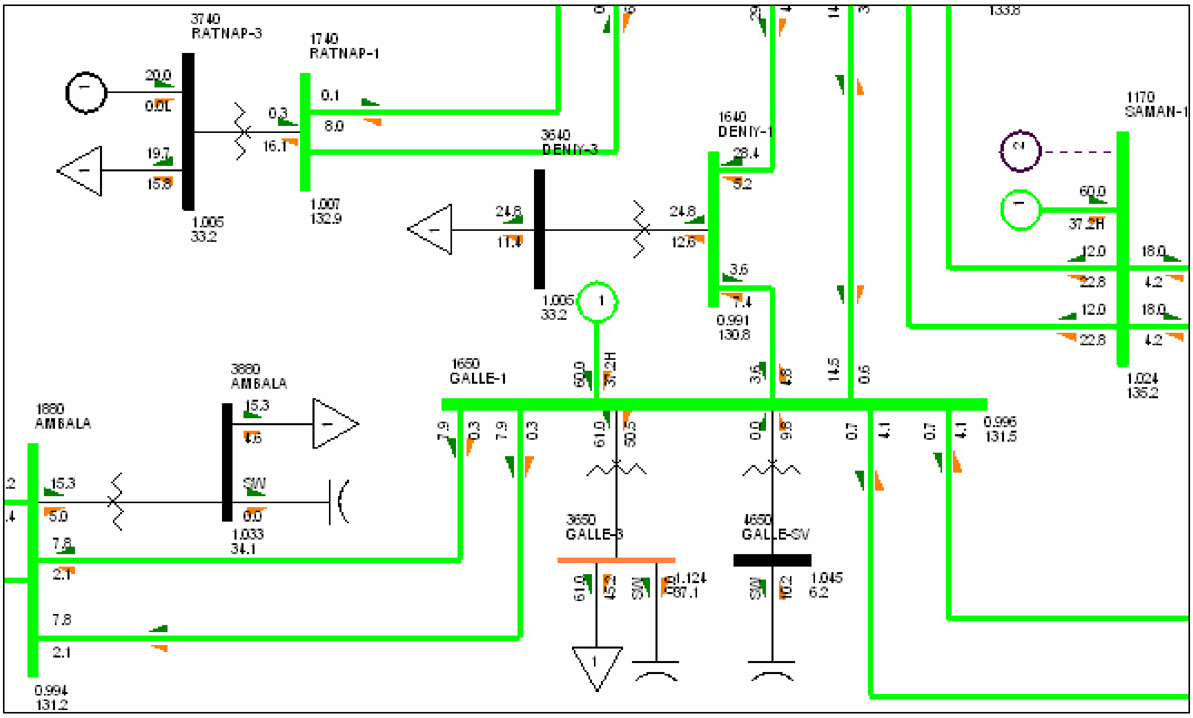
2016 Sri Lanka Transmission Network



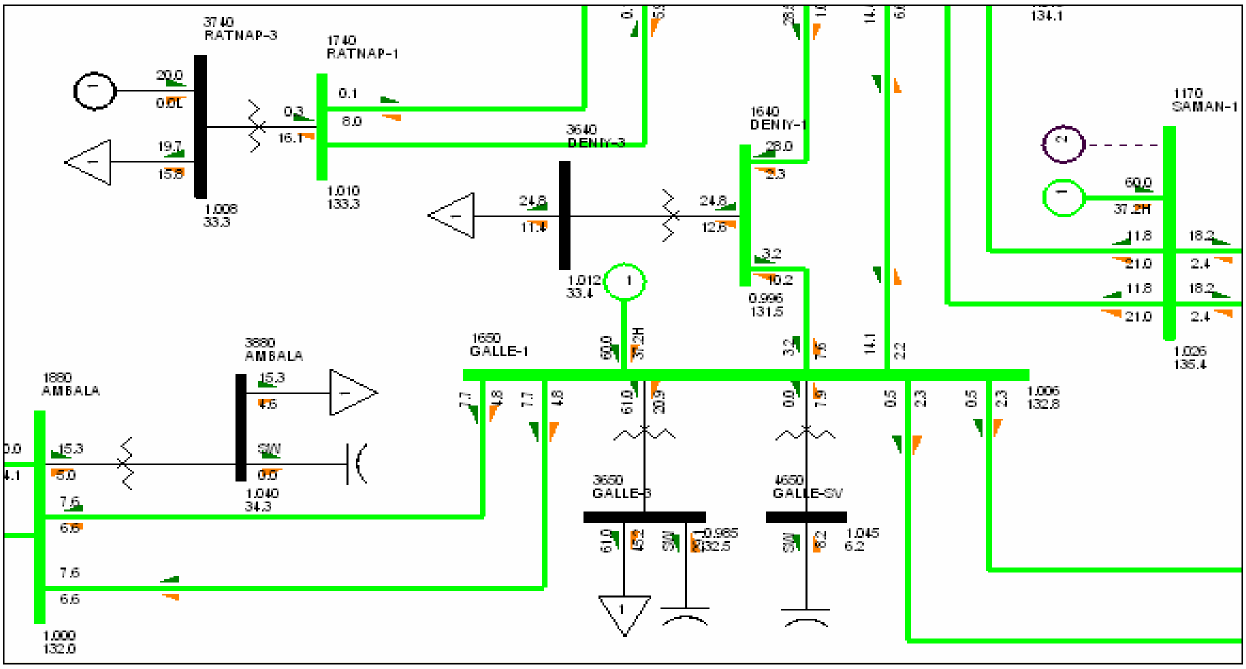
## (D) TAP Positions

### (i) (2012 – Galle GSS):

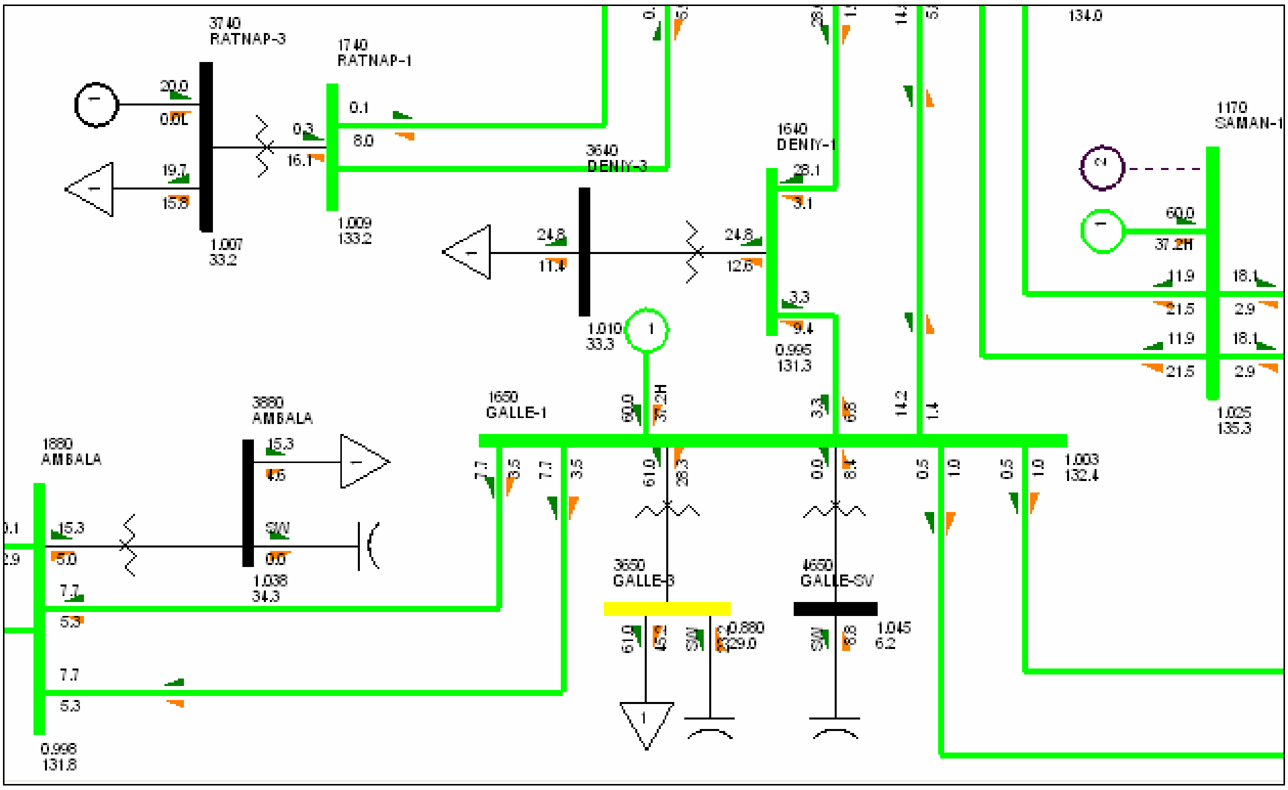
Matara GSS – 15% load increase at minimum tap position



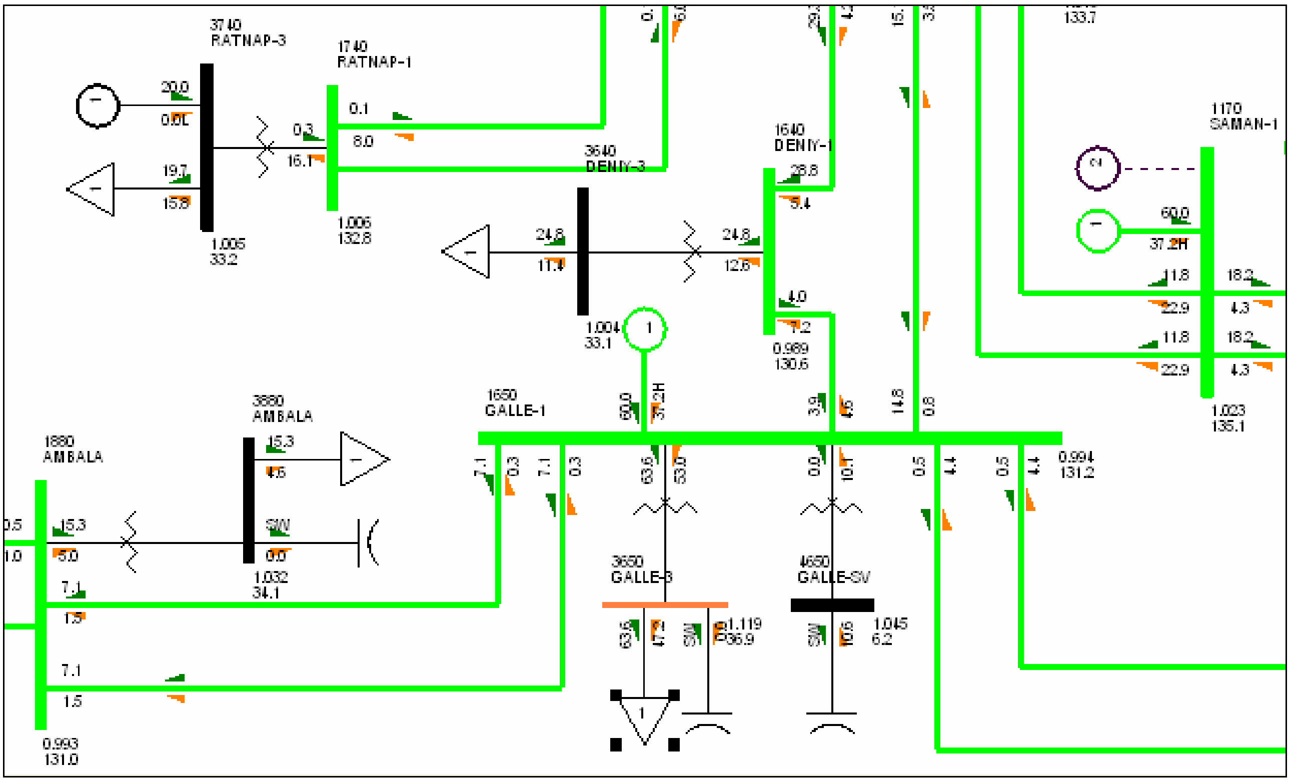

Galle GSS – 15% load increase at nominal tap position



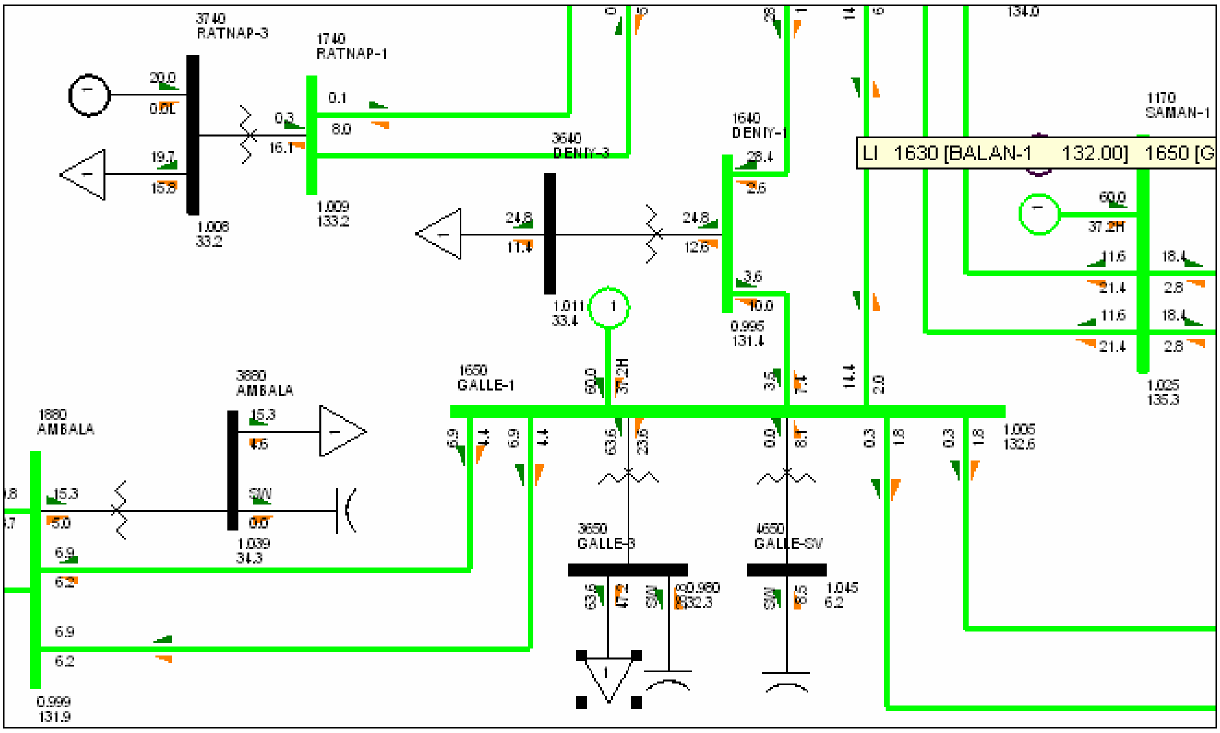
Galle GSS – 15% load increase at maximum tap position



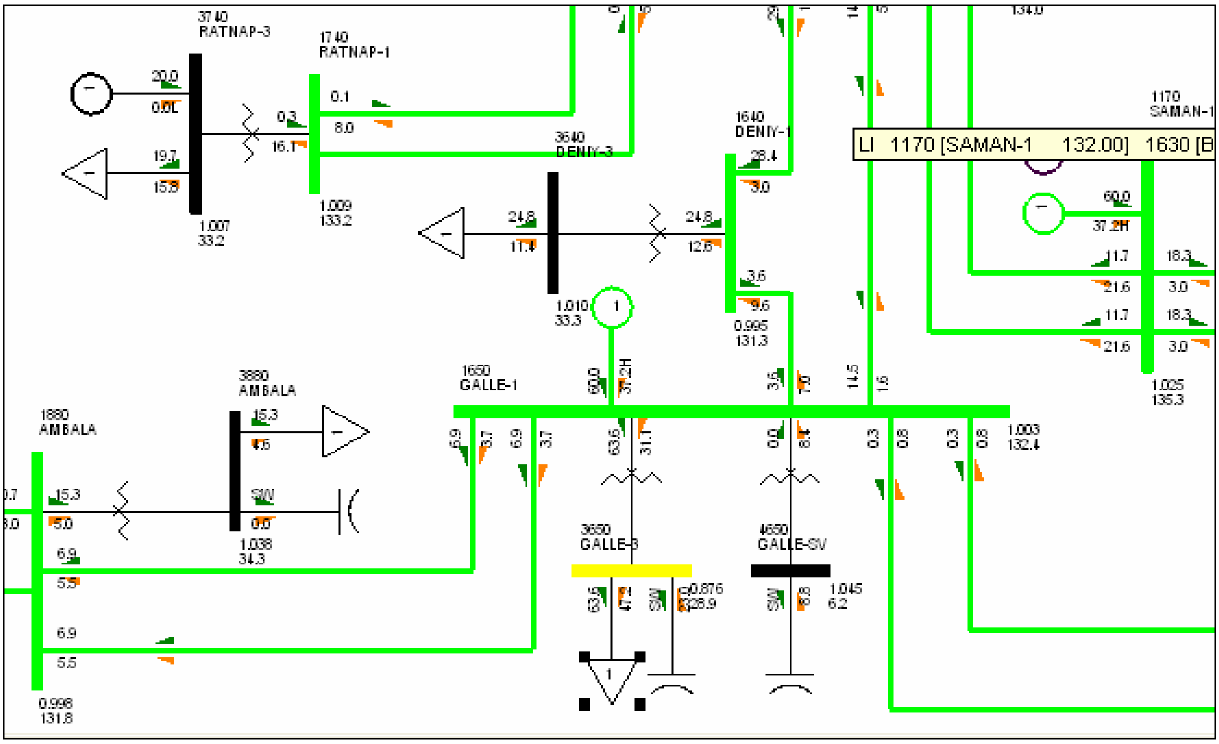

Galle GSS – 20% load increase at minimum tap position



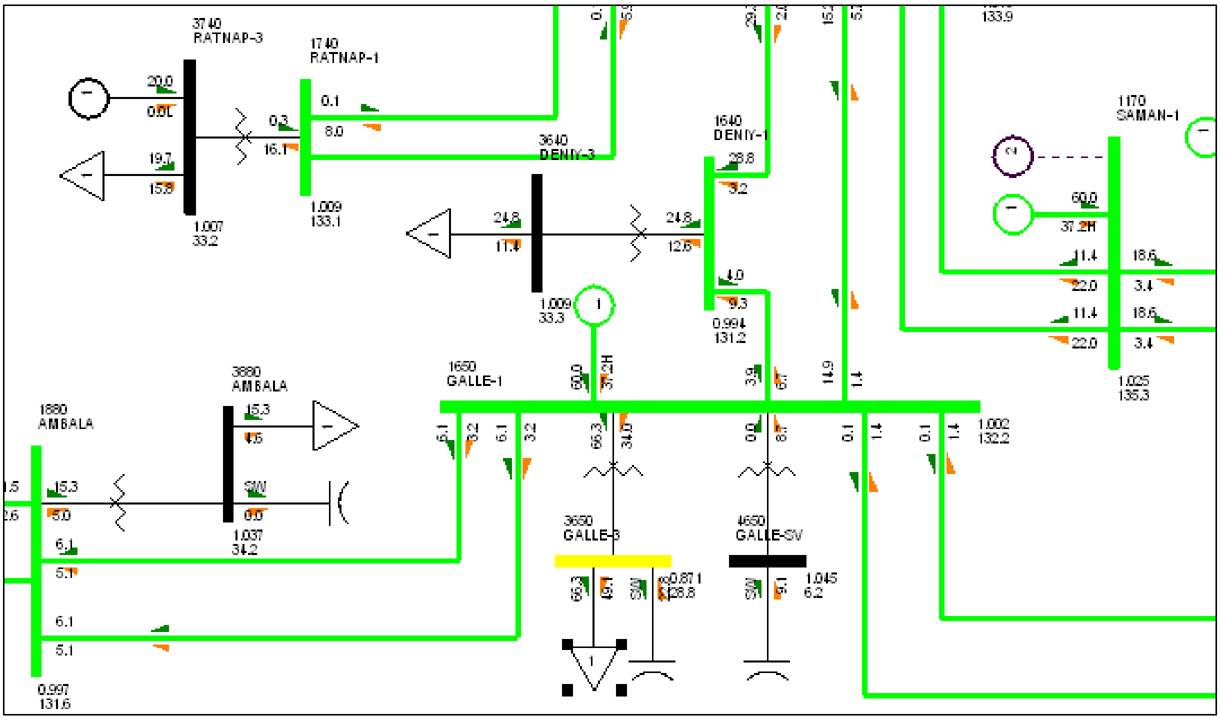
Galle GSS – 20% load increase at nominal tap position



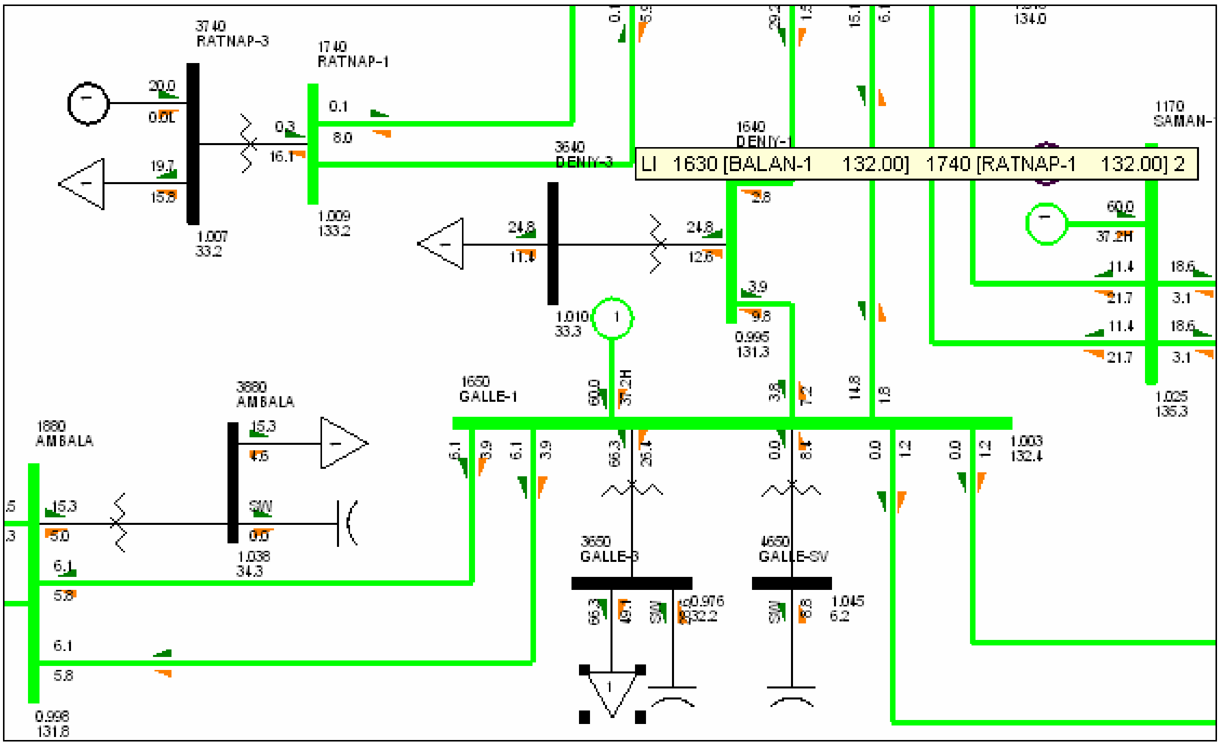

Galle GSS – 20% load increase at maximum tap position



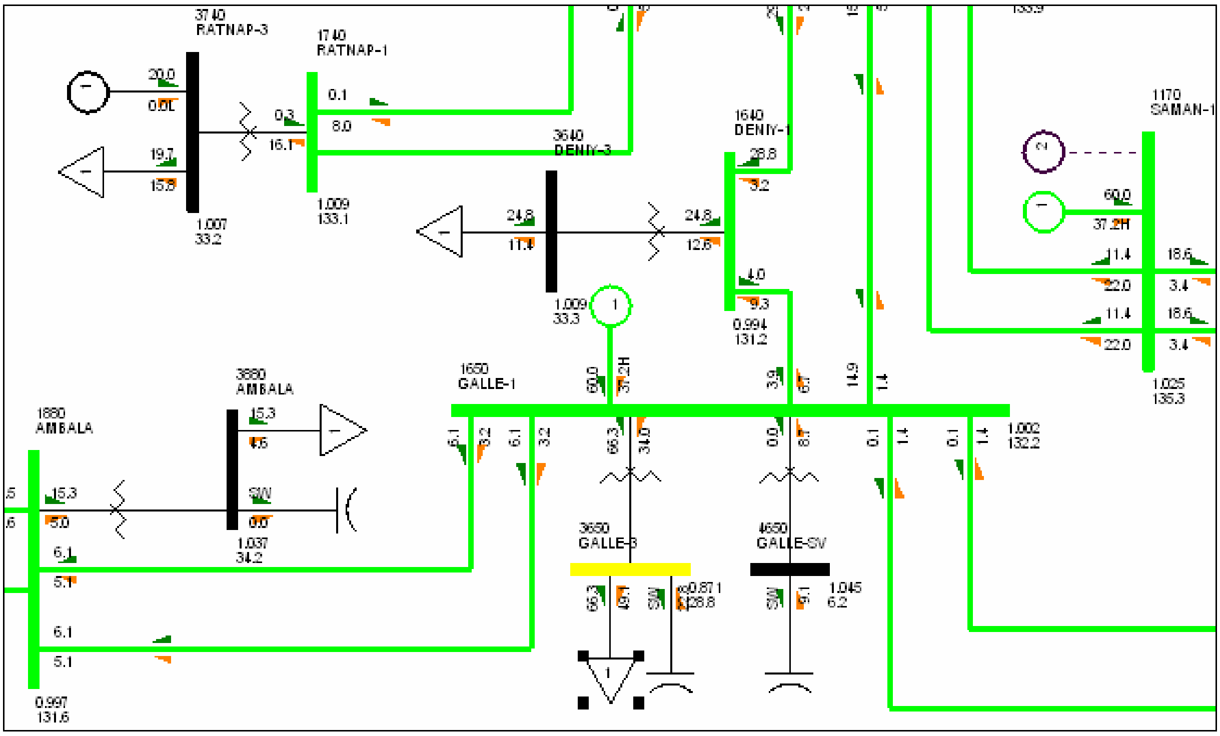
Galle GSS – 25% load increase at minimum tap position



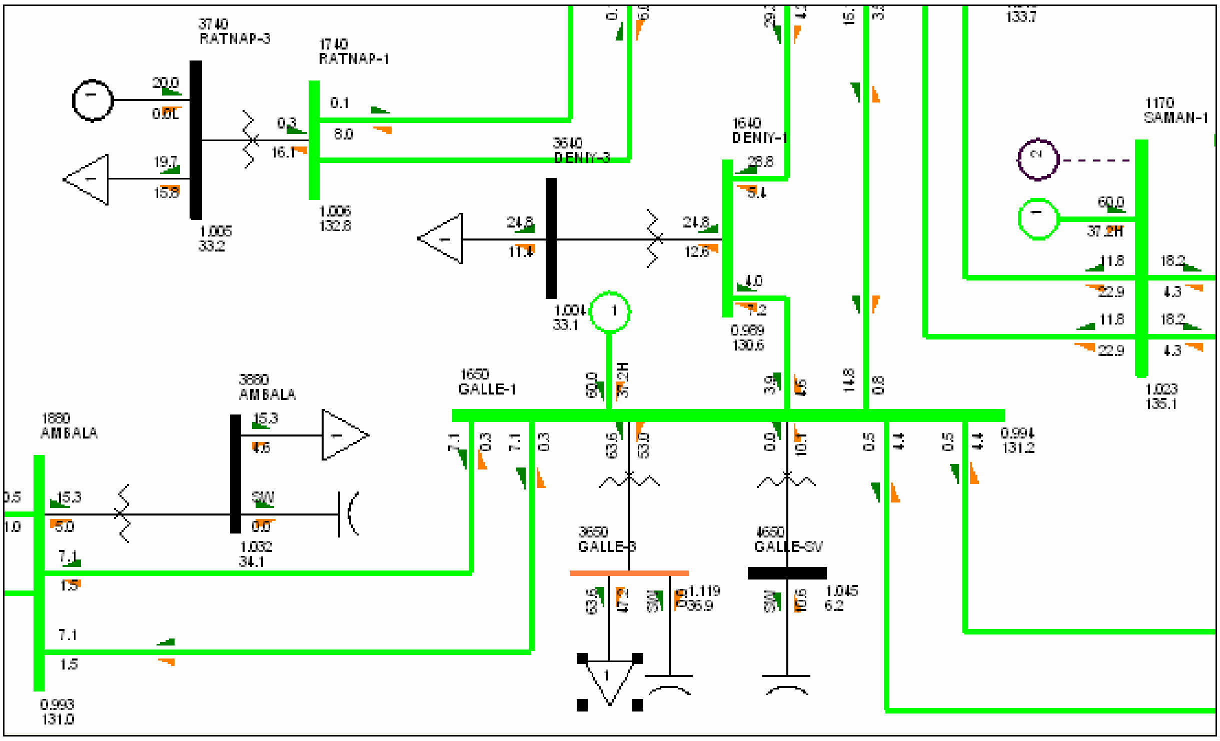

Galle GSS – 25% load increase at nominal tap position



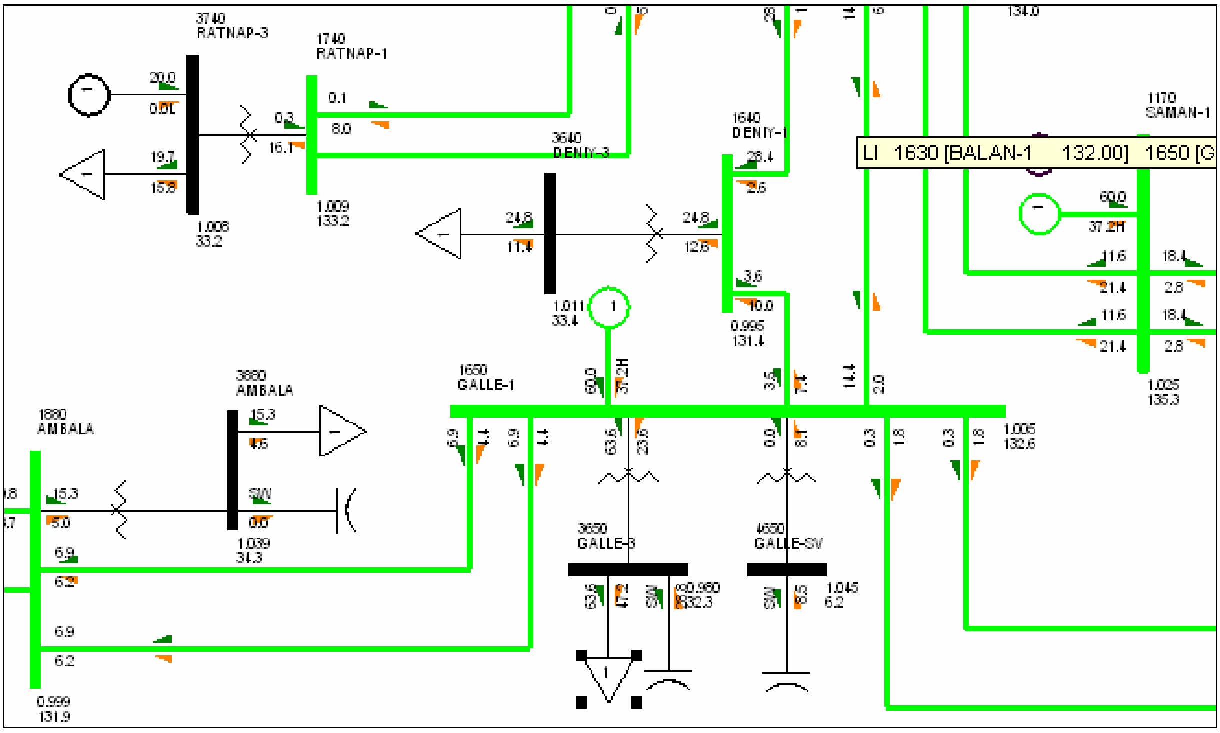
Galle GSS – 25% load increase at maximum tap position



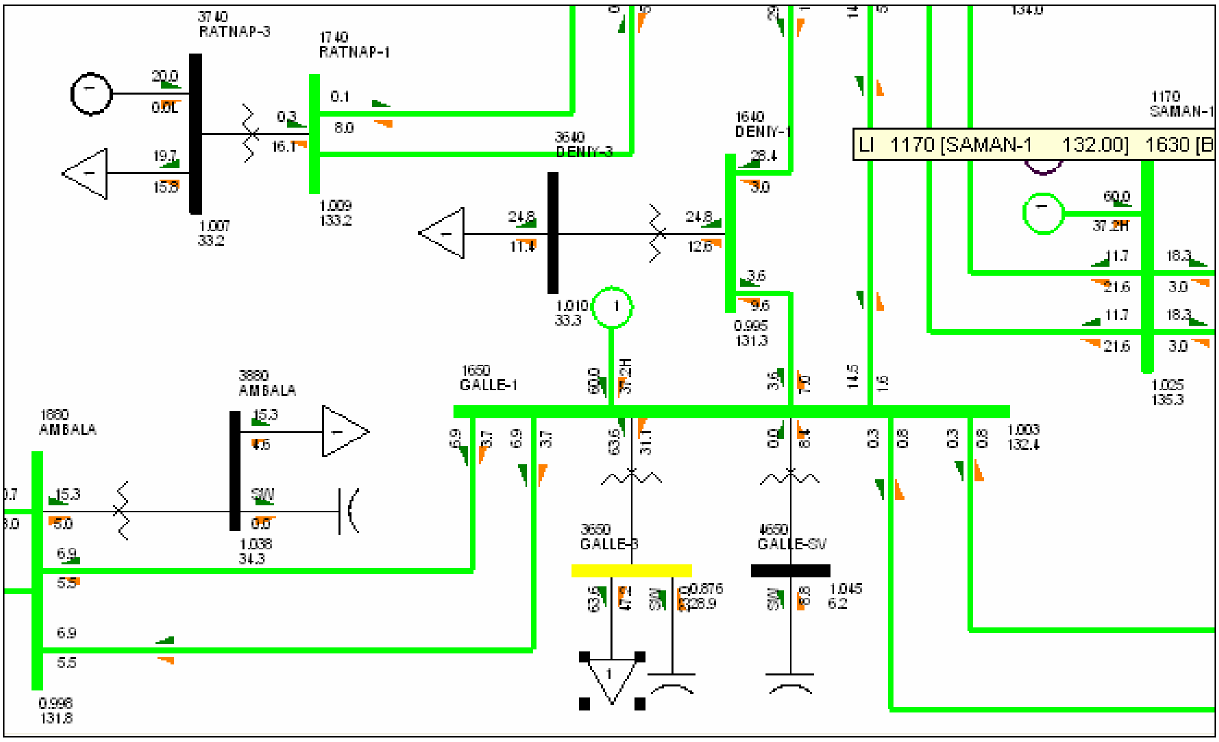

Galle GSS –5% load decrease from 1.25% Load at minimum tap position



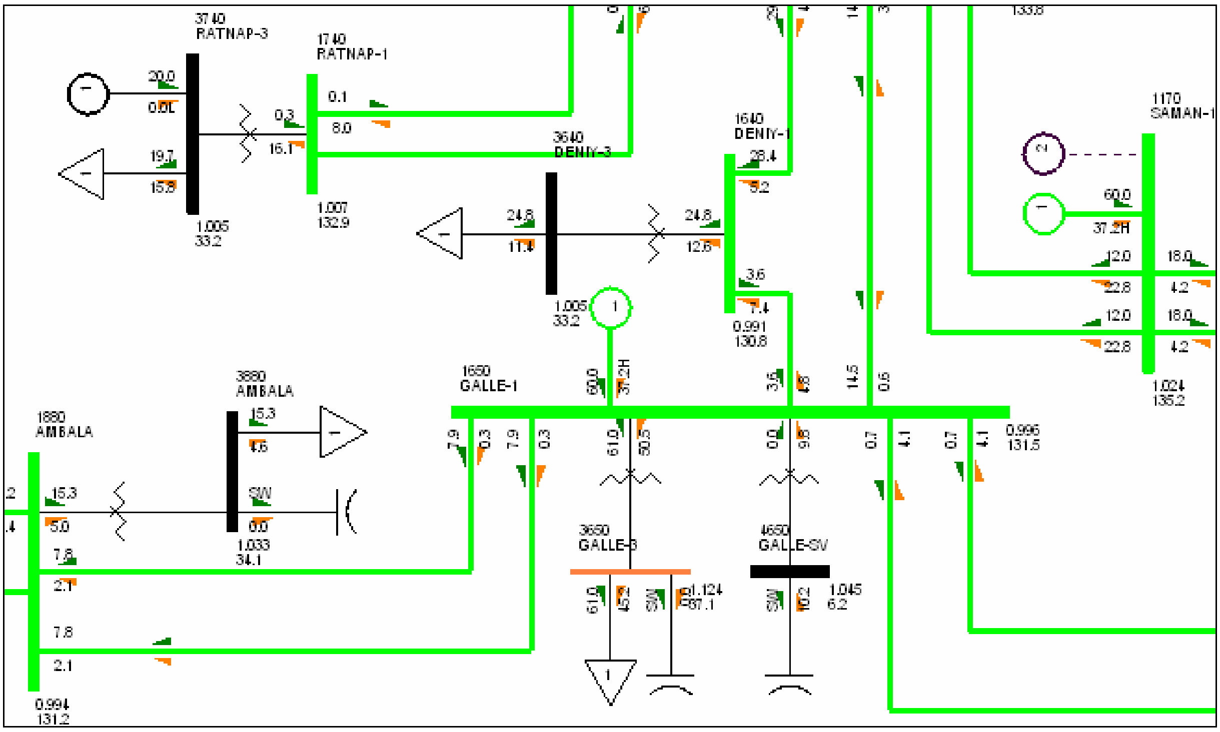
Galle GSS –5% load decrease from 1.25% Load at nominal tap position



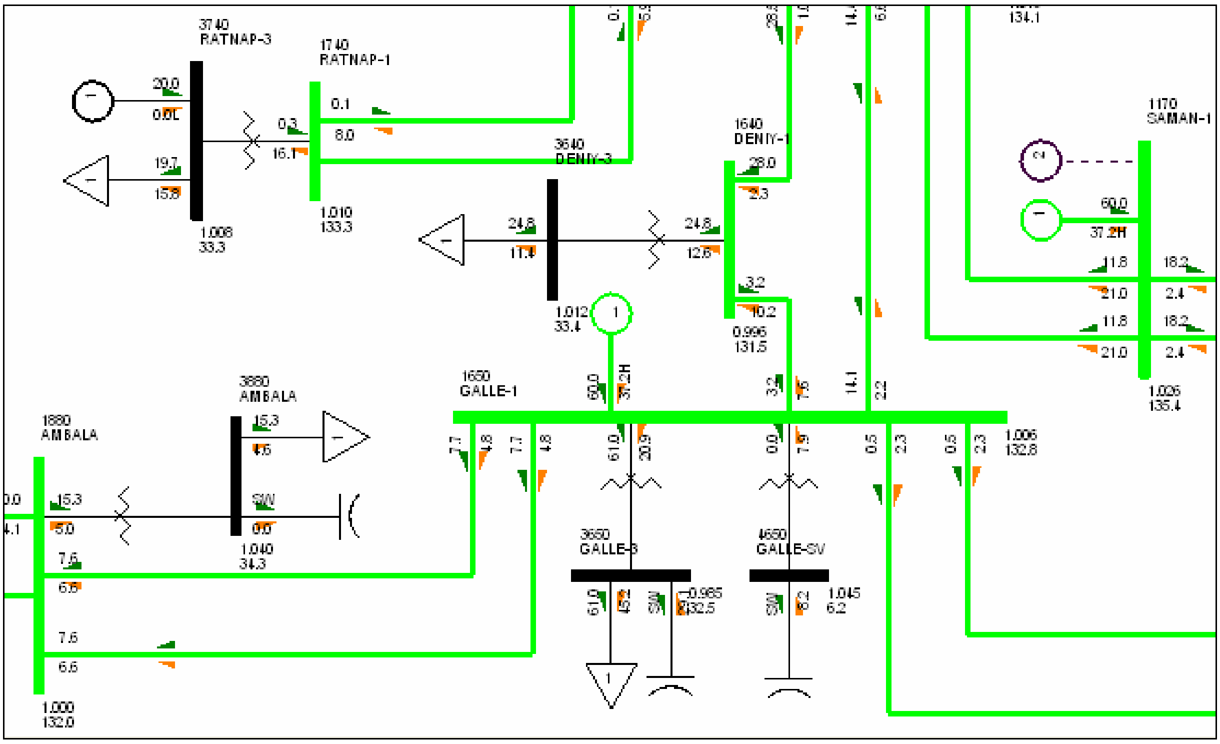

Galle GSS –5% load decrease from 1.25% Load at maximum tap position



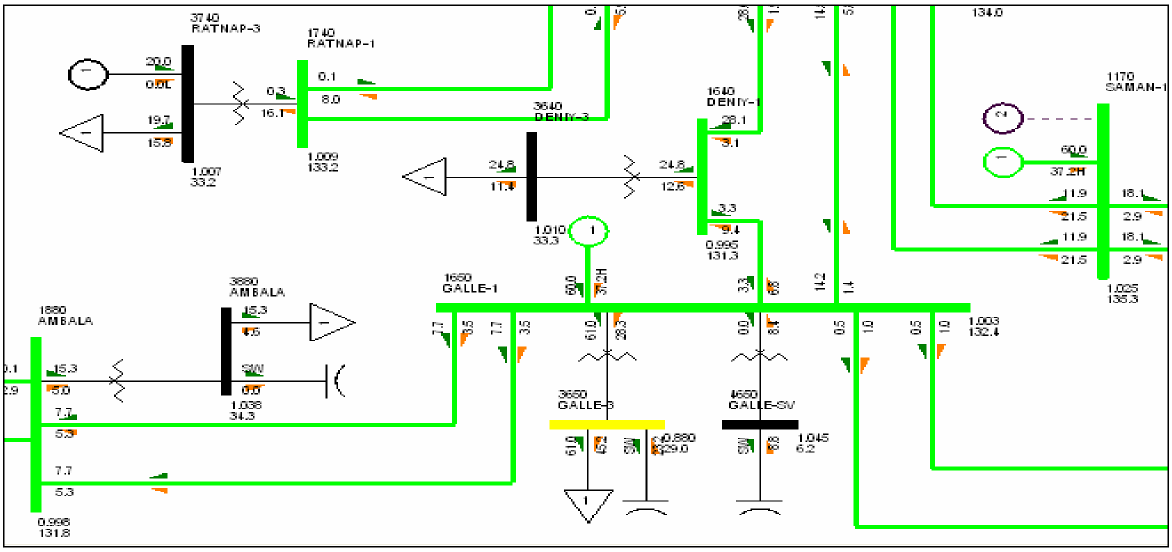
Galle GSS –10% load decrease from 1.25% Load at minimum tap position




Galle GSS –10% load decrease from 1.25% Load at nominal tap position

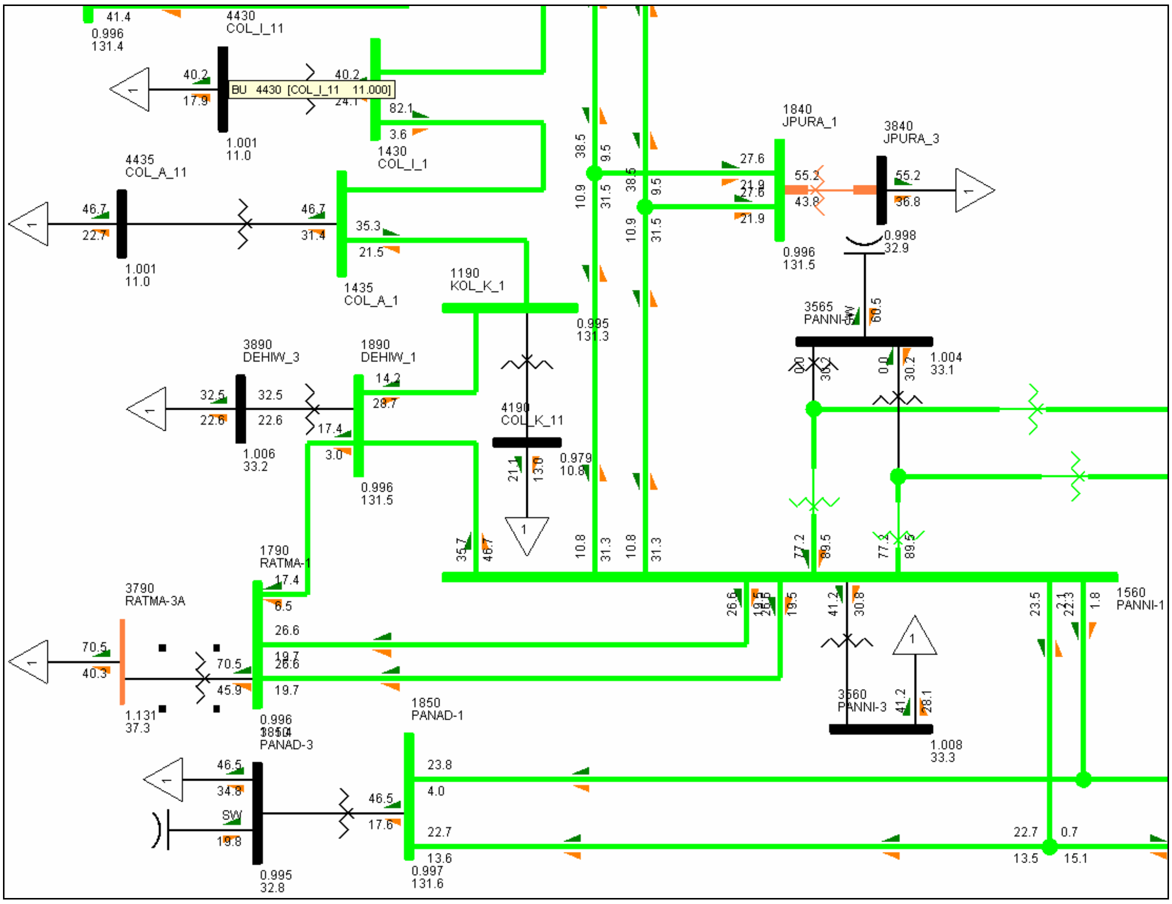


Galle GSS –10% load decrease from 1.25% Load at maximum tap position

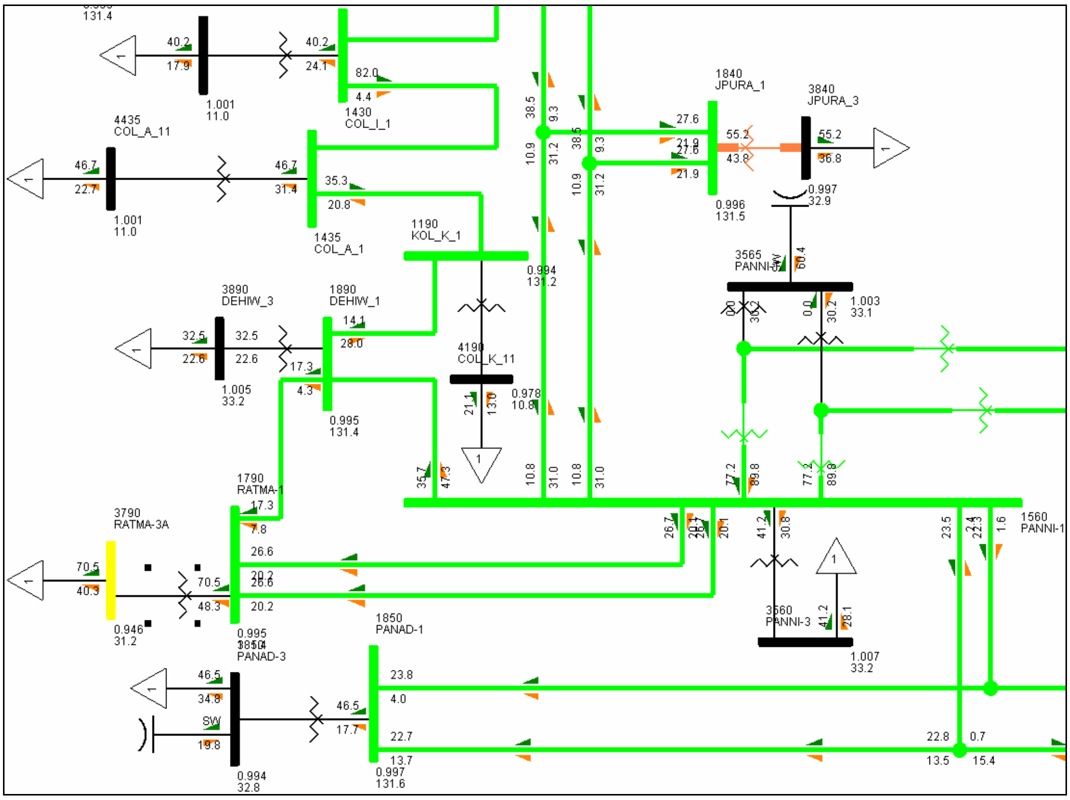



## (ii) 2012 - Ratmalana GSS :

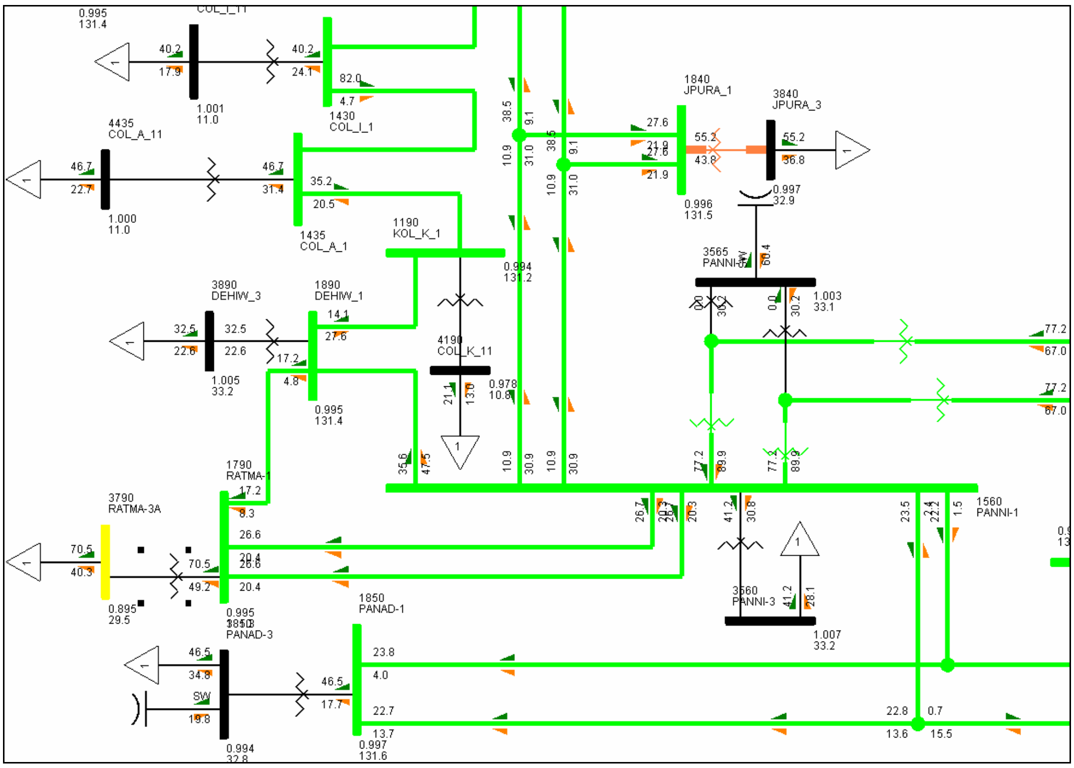
Ratmalana GSS – 15% load increase at minimum tap position



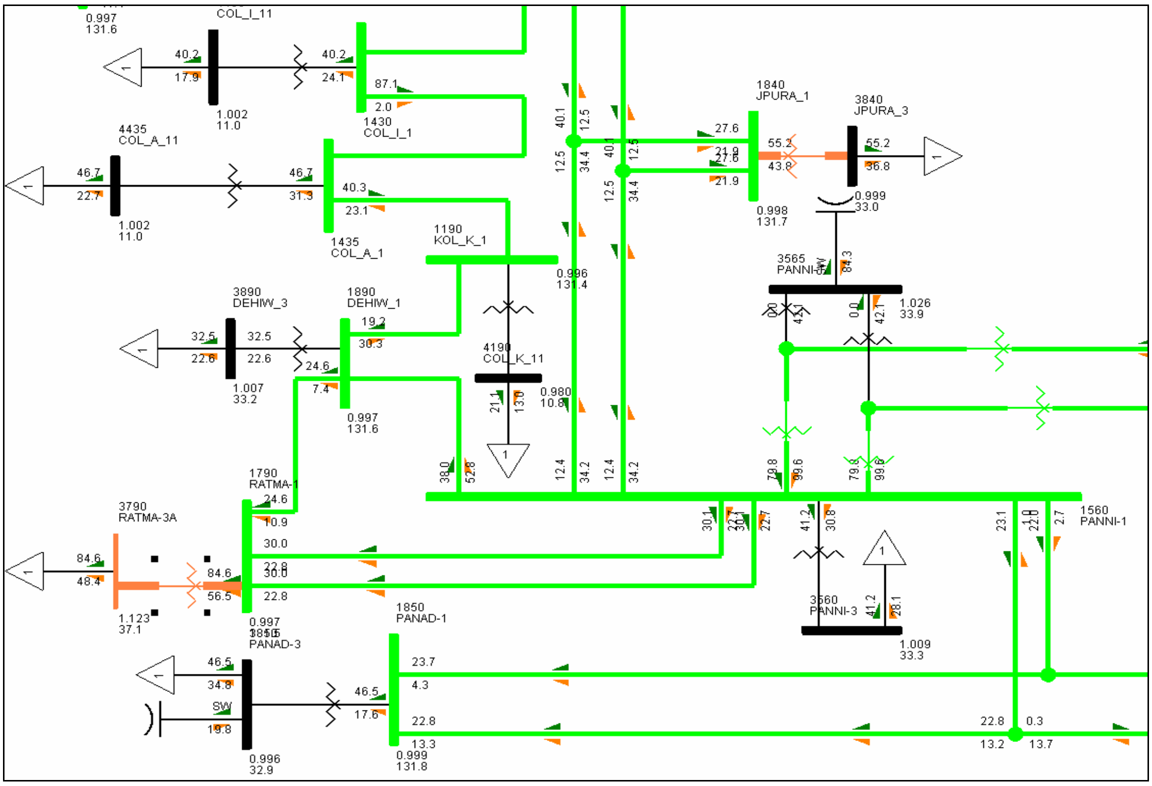
Ratmalana GSS – 15% load increase at nominal tap position



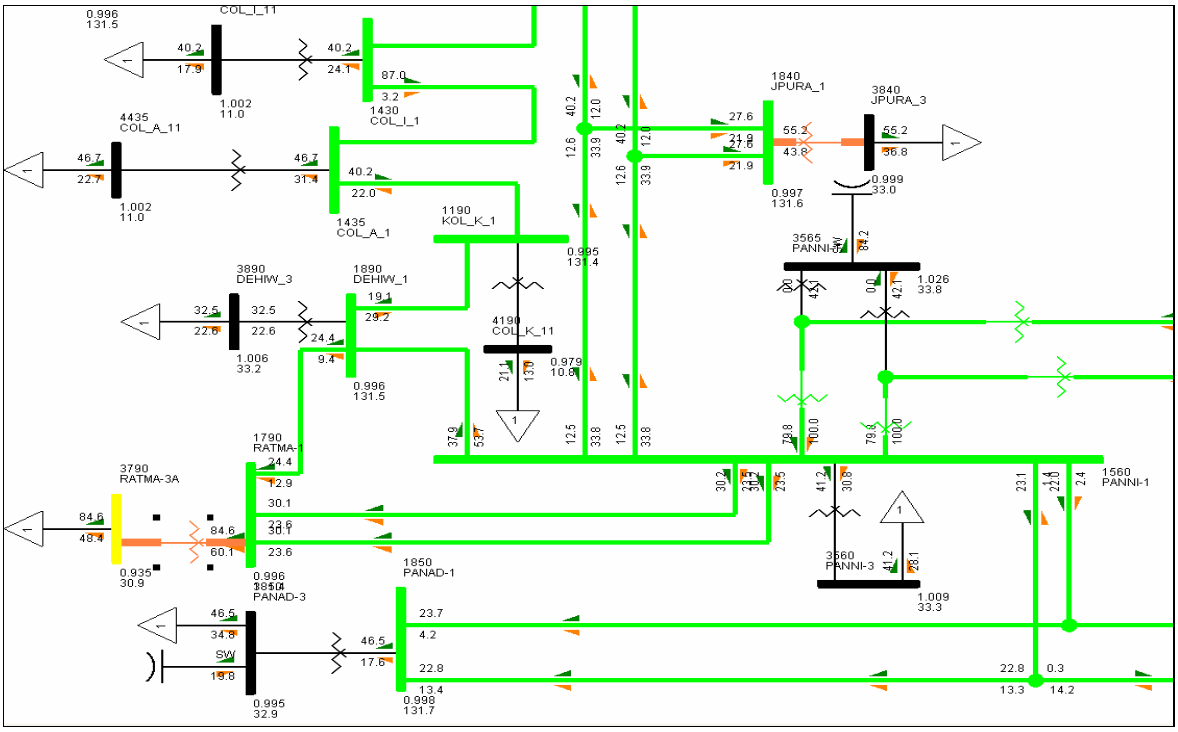

Ratmalana GSS – 15% load increase at maximum tap position



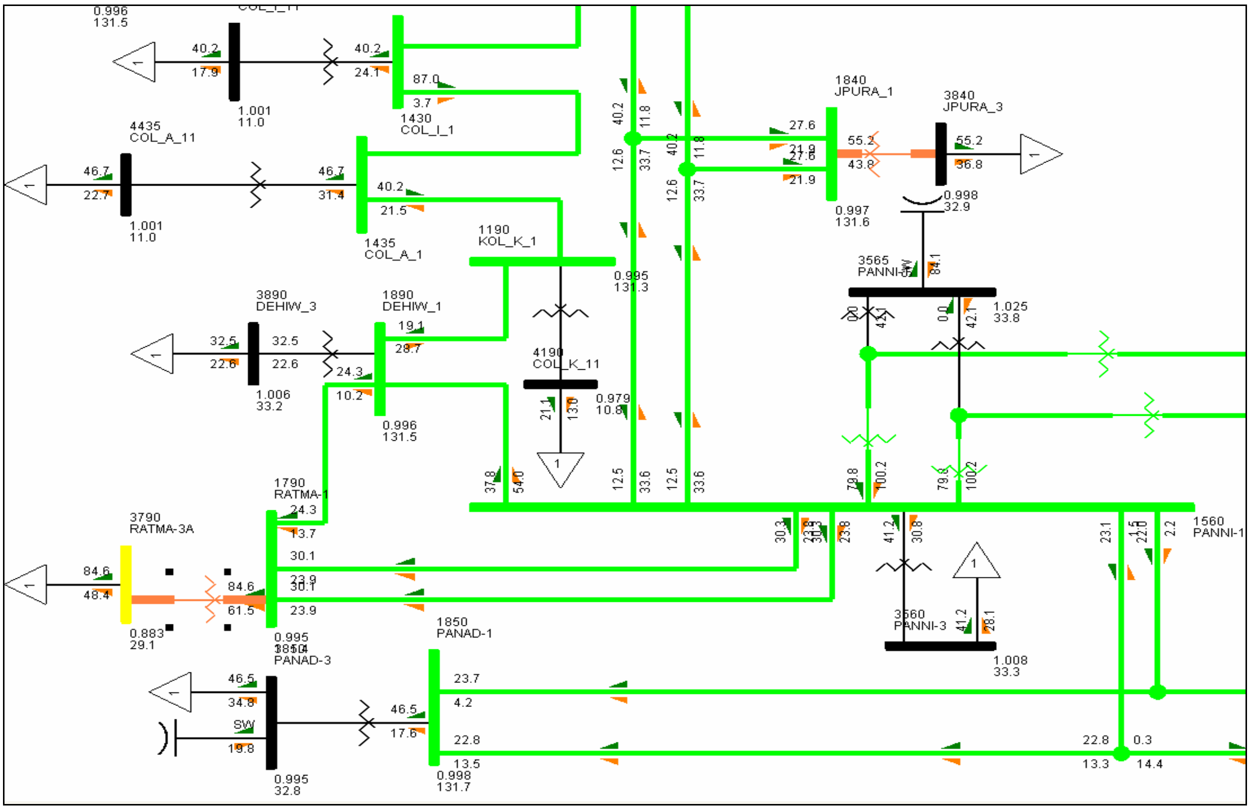
Ratmalana GSS – 20% load increase at minimum tap position



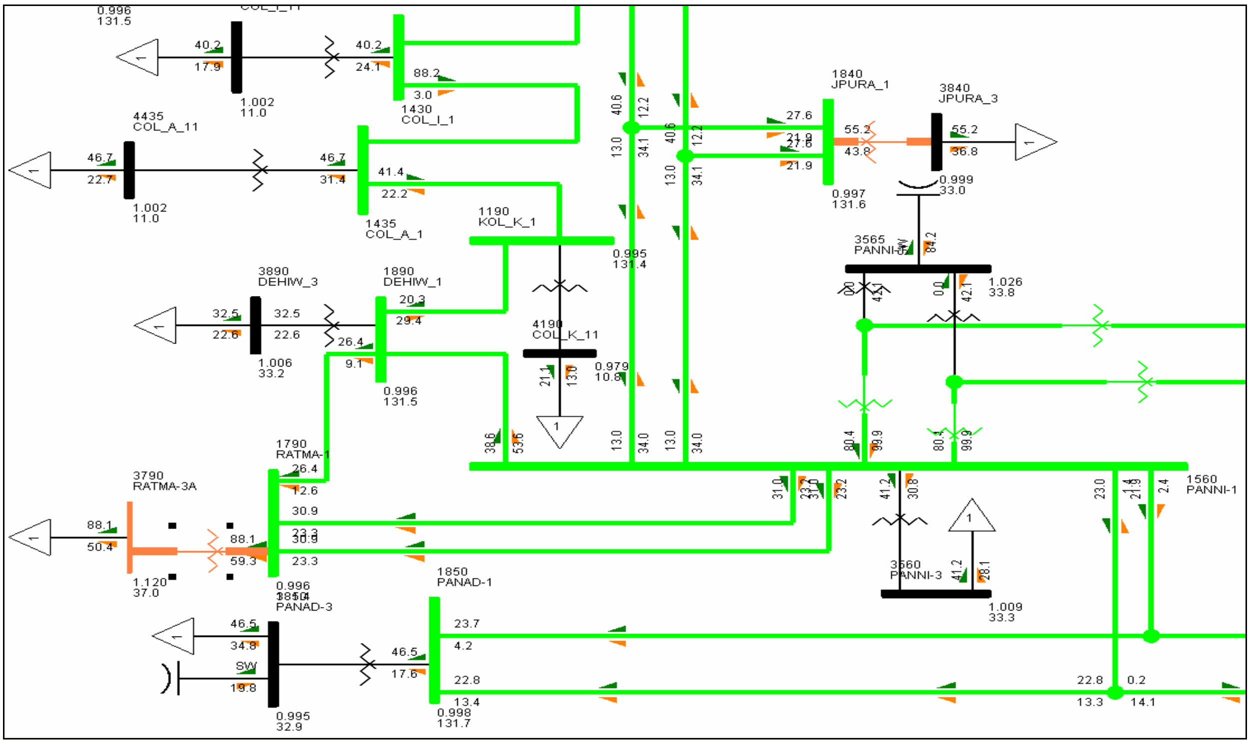
Ratmalana GSS – 20% load increase at nominal tap position



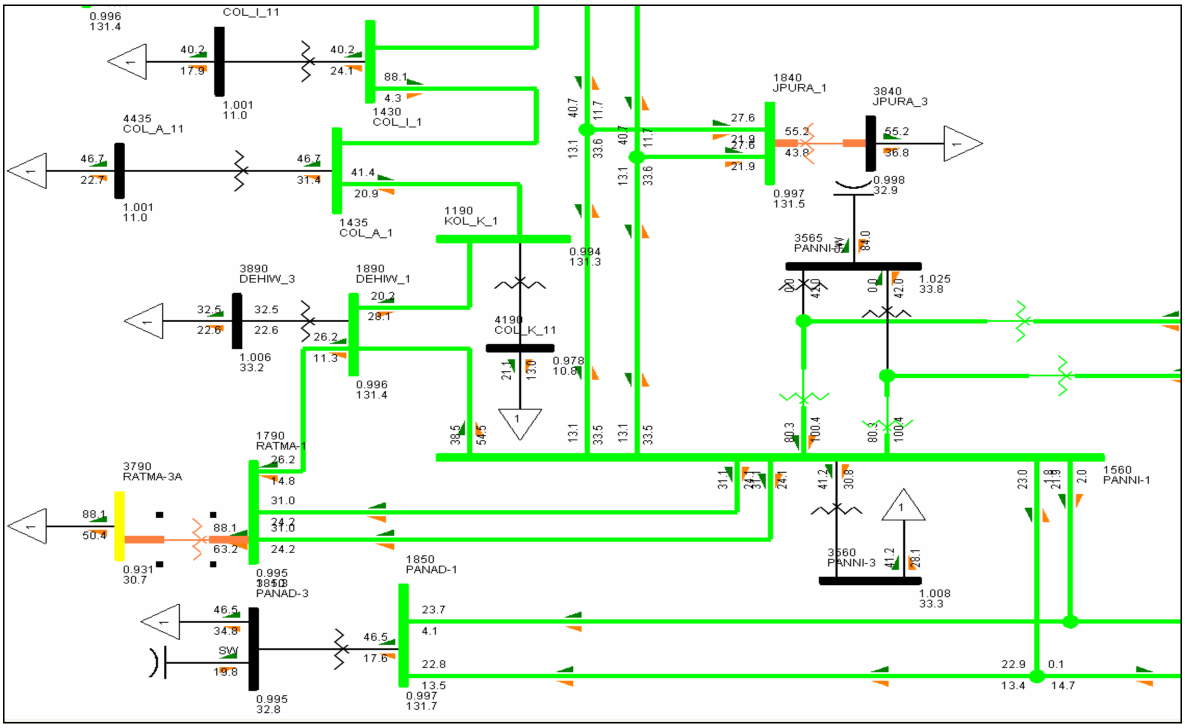
Ratmalana GSS – 20% load increase at maximum tap position



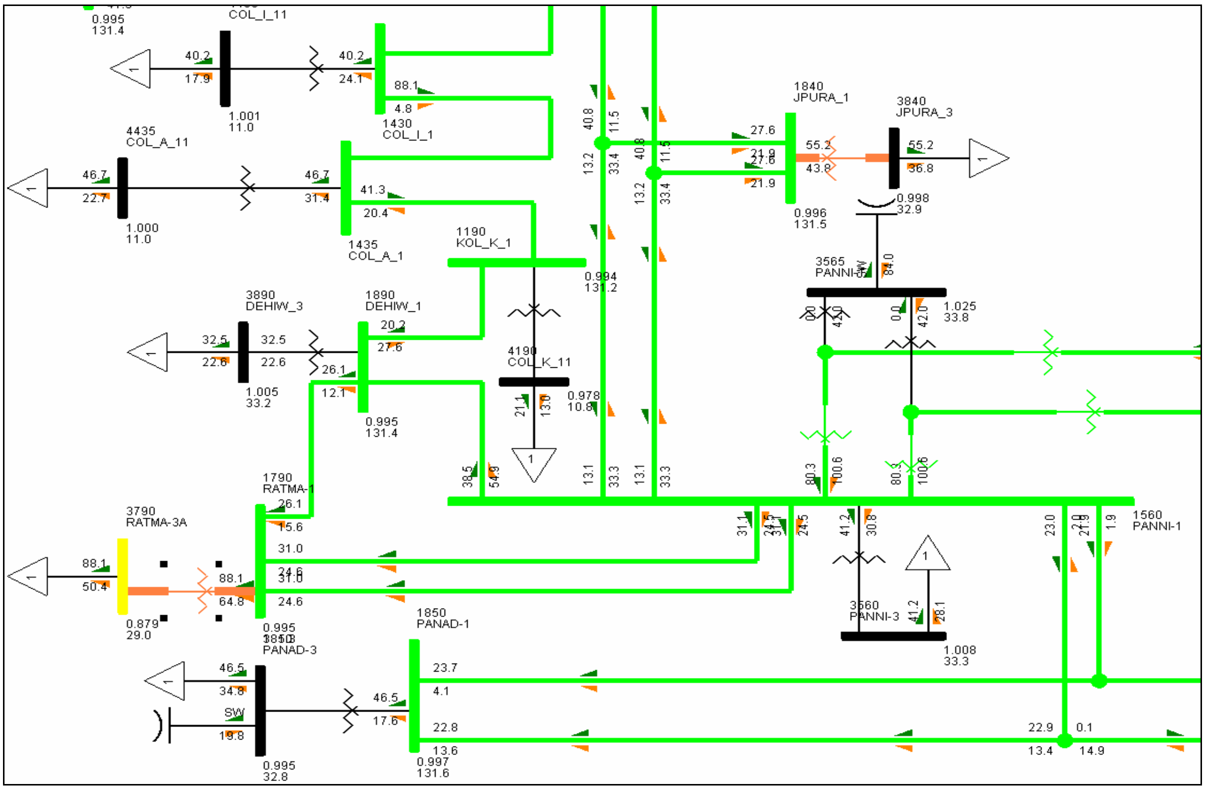
Ratmalana GSS – 25% load increase at minimum tap position



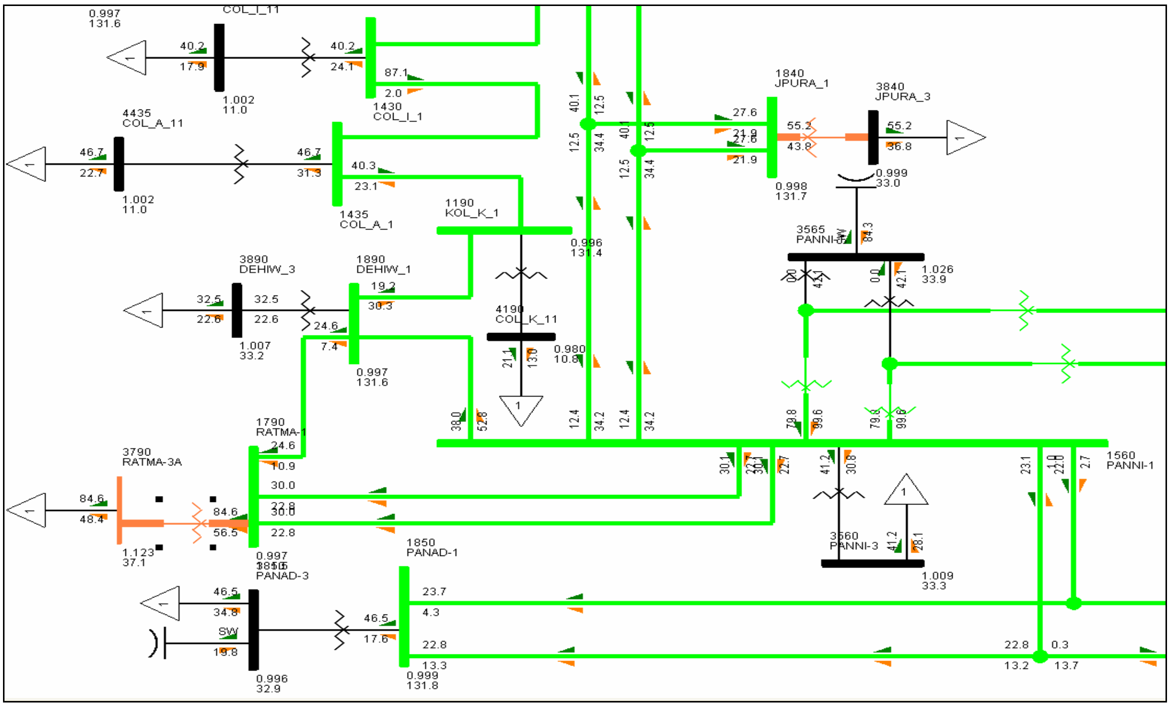
Ratmalana GSS – 25% load increase at nominal tap position



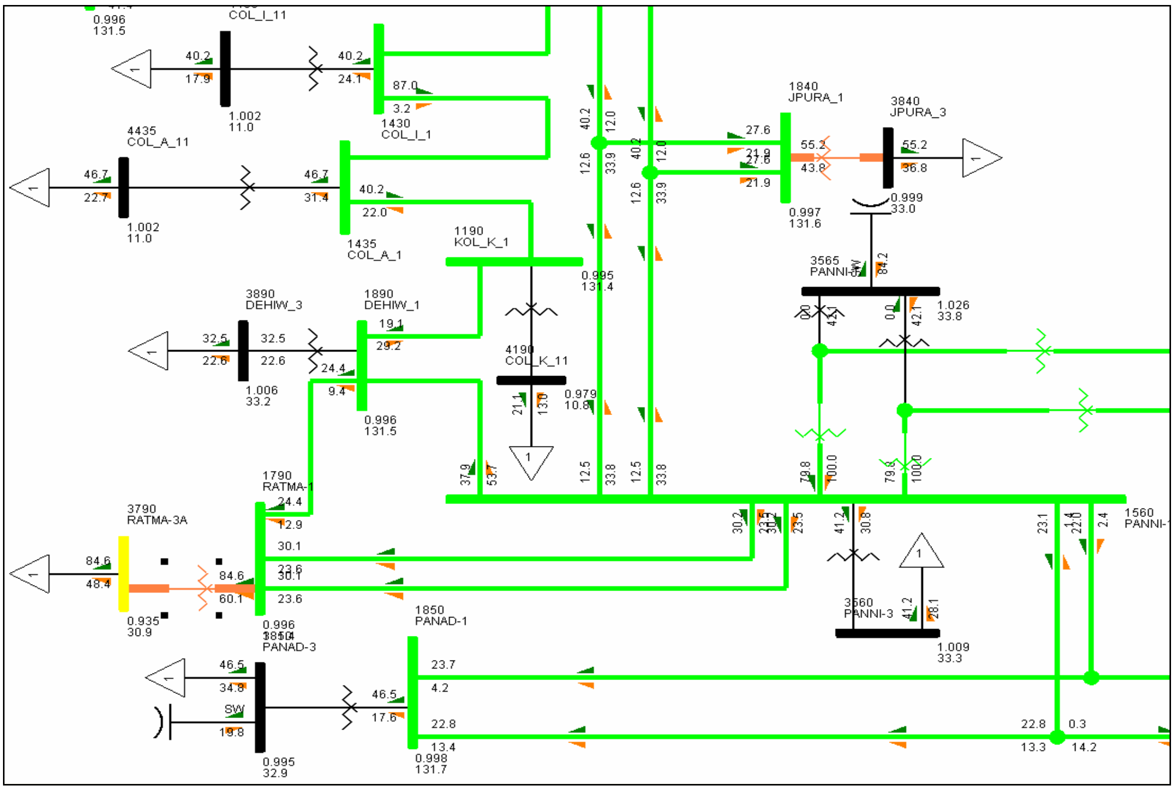

Ratmalana GSS – 25% load increase at maximum tap position



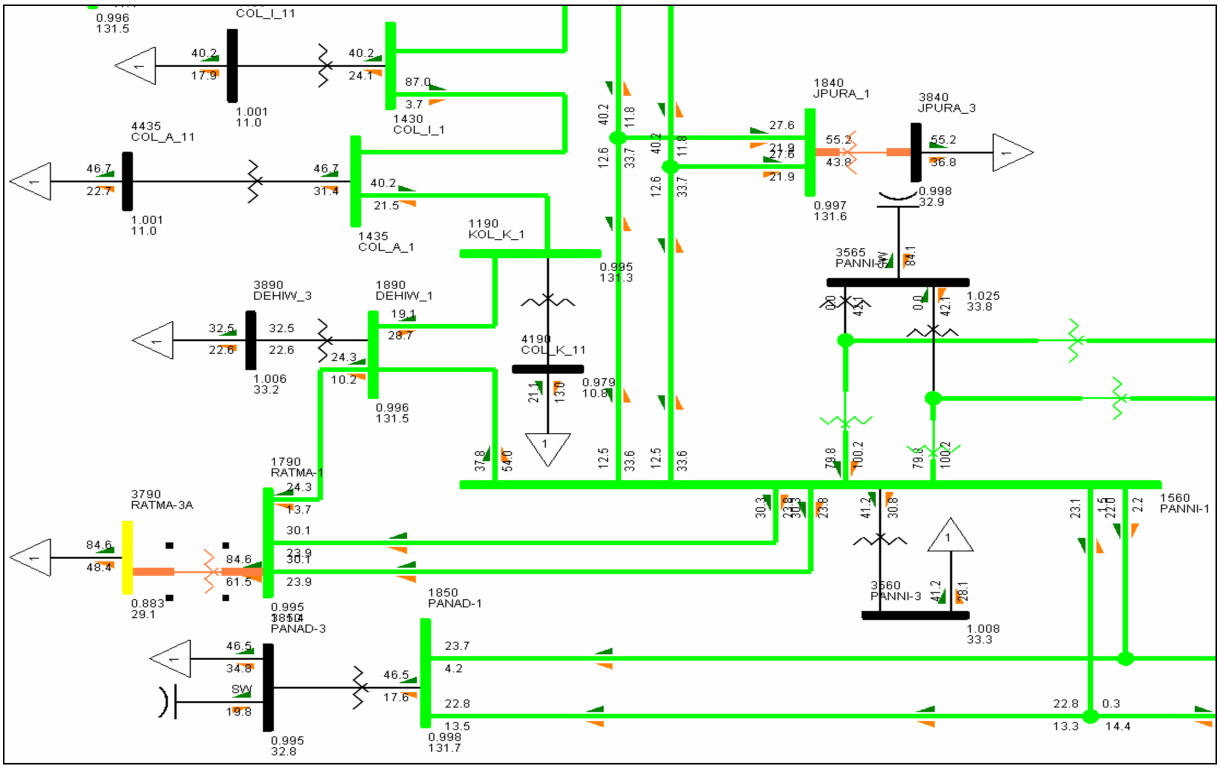
Ratmalana GSS –5% load decrease from 1.25% Load at minimum tap position



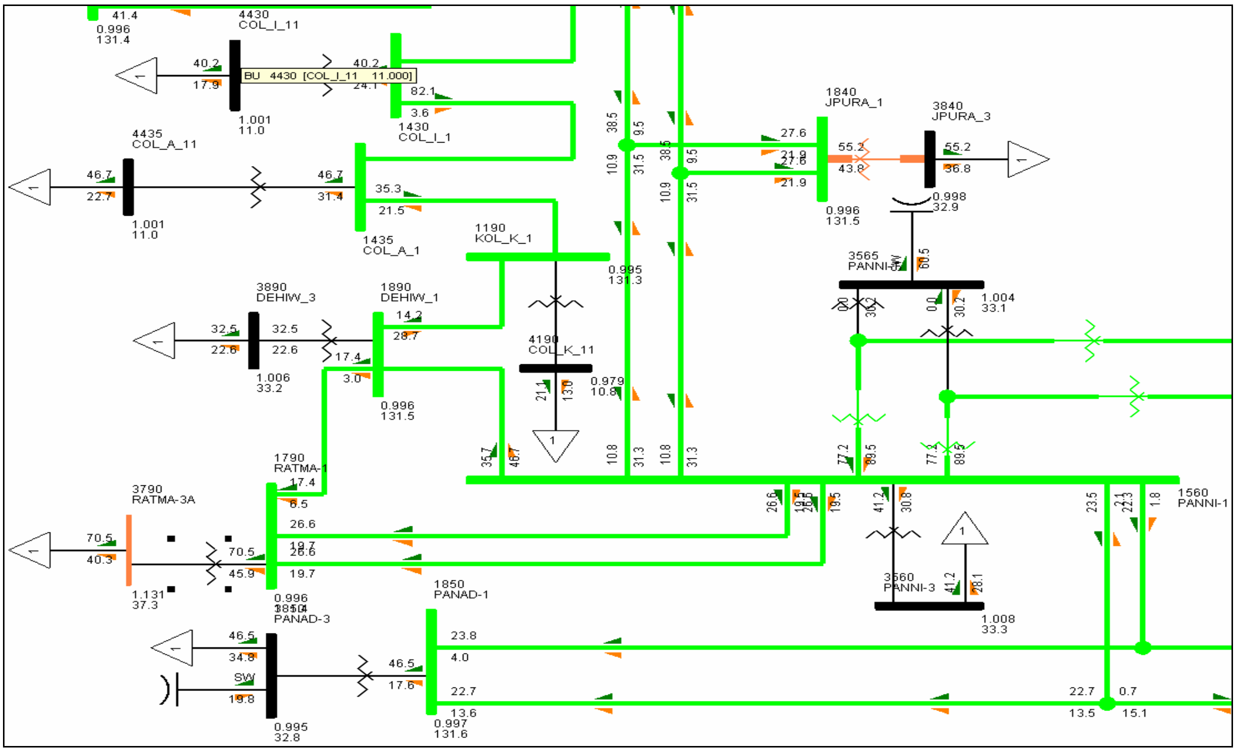

Ratmalana GSS –5% load decrease from 1.25% Load at nominal tap position



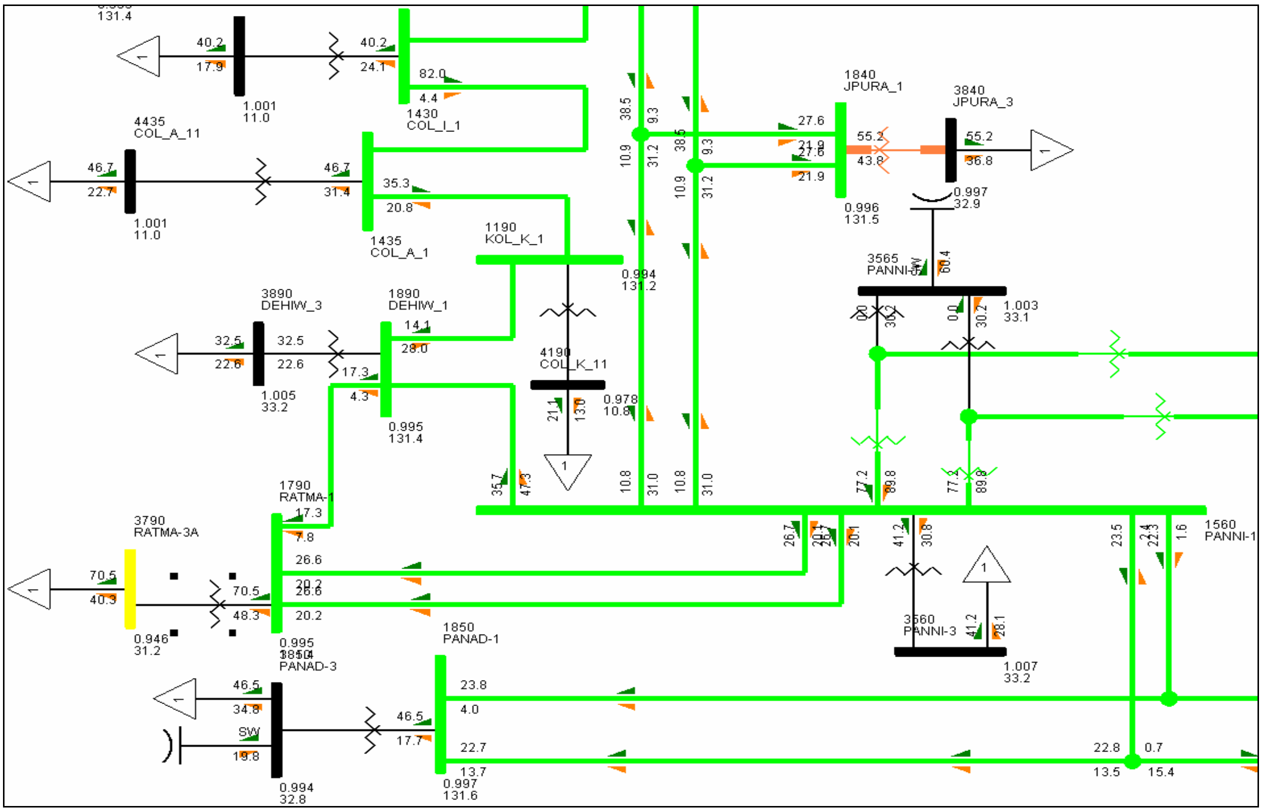
Ratmalana GSS –5% load decrease from 1.25% Load at maximum tap position



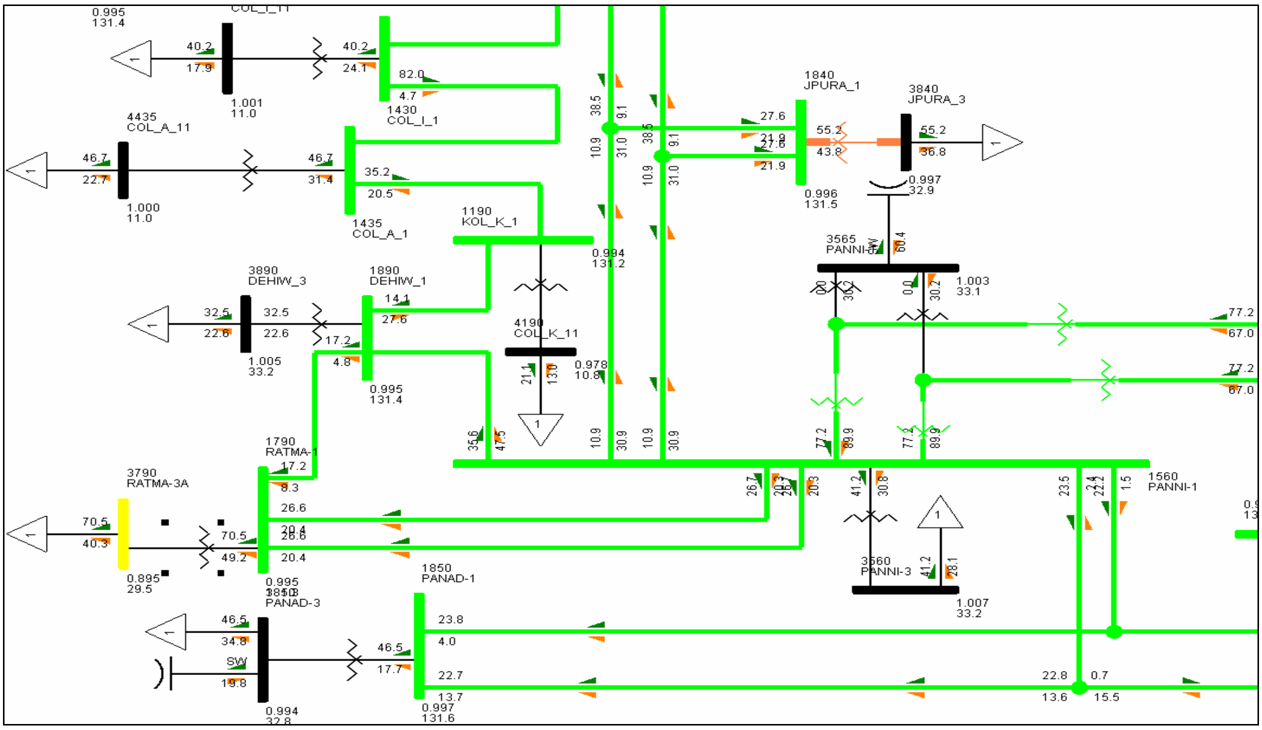
Ratmalana GSS –10% load decrease from 1.25% Load at minimum tap position



Ratmalana GSS –10% load decrease from 1.25% Load at nominal tap position

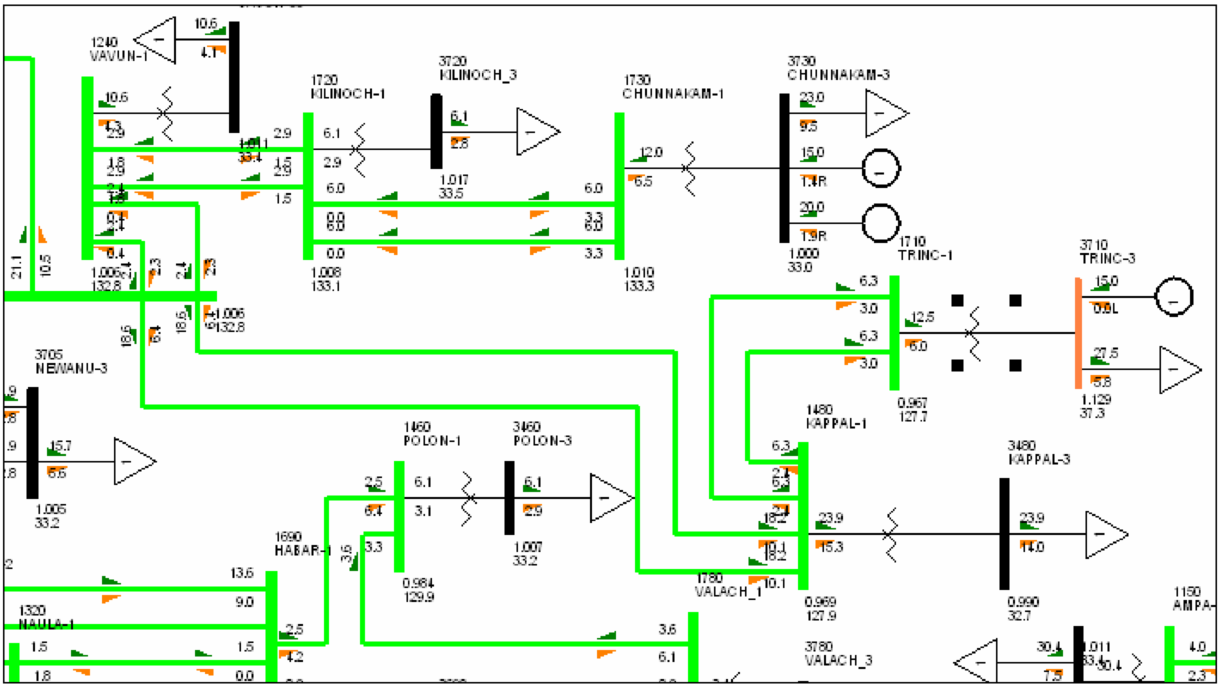



Ratmalana GSS –10% load decrease from 1.25% Load at maximum tap position

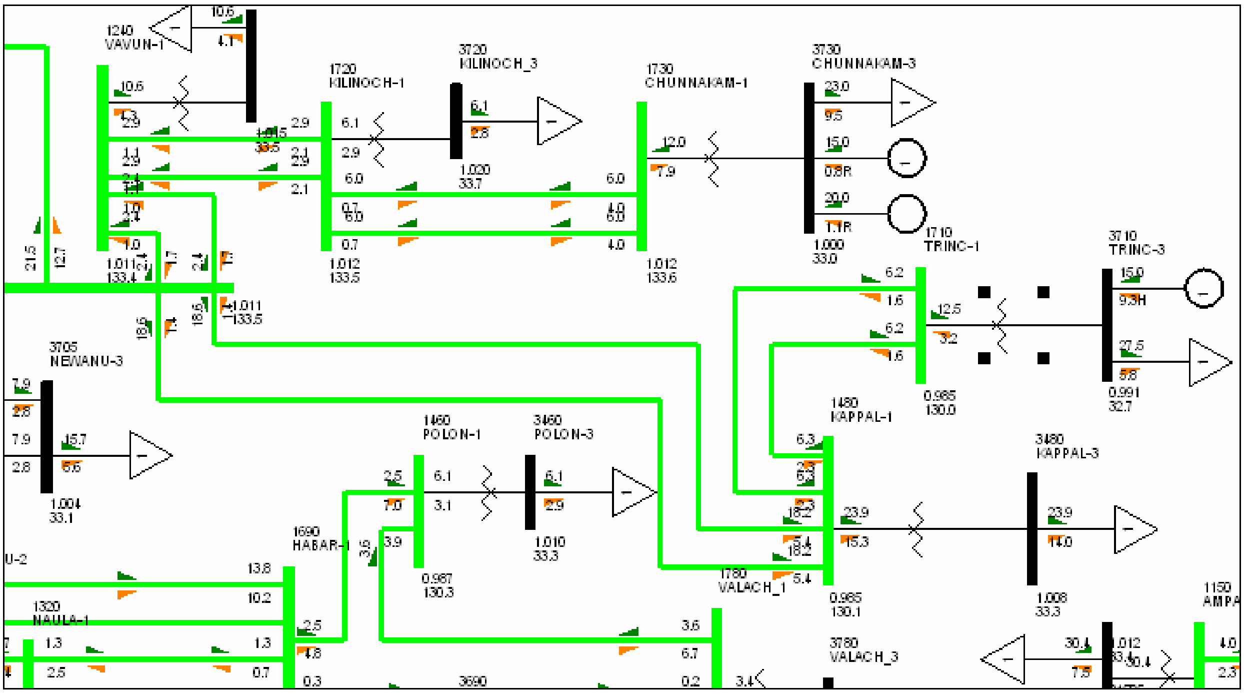


### (iii) 2012 - Trincomalee GSS

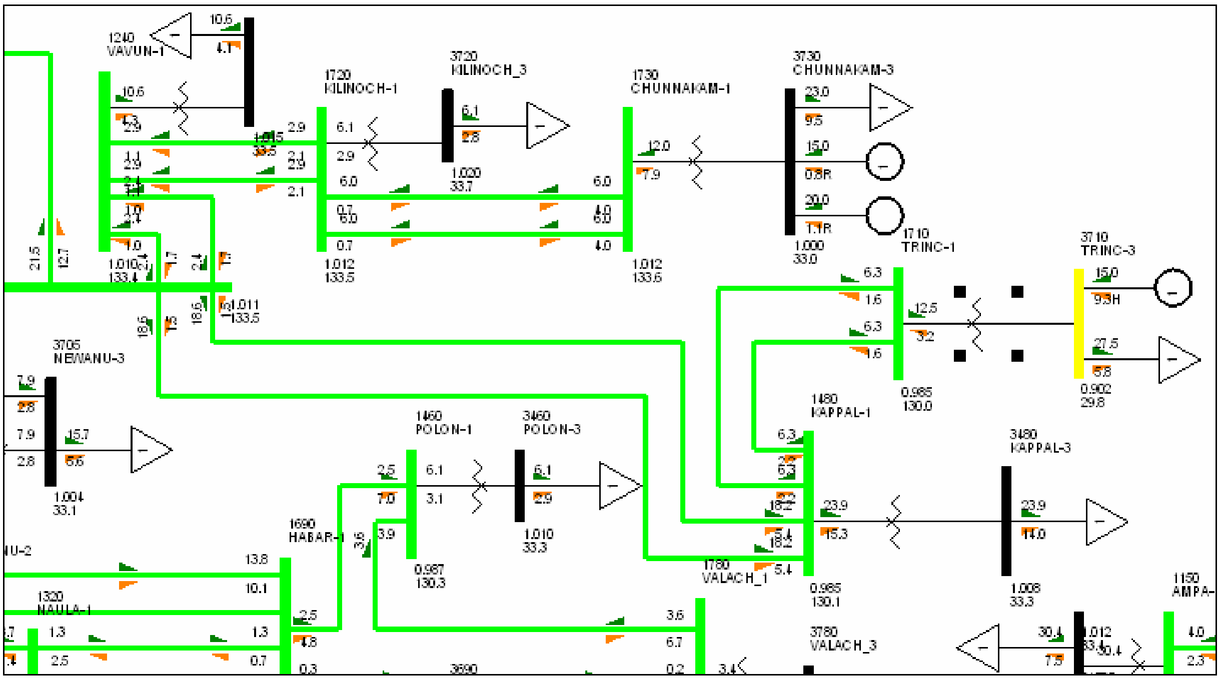
Trincomalee GSS – 15% load increase at minimum tap position



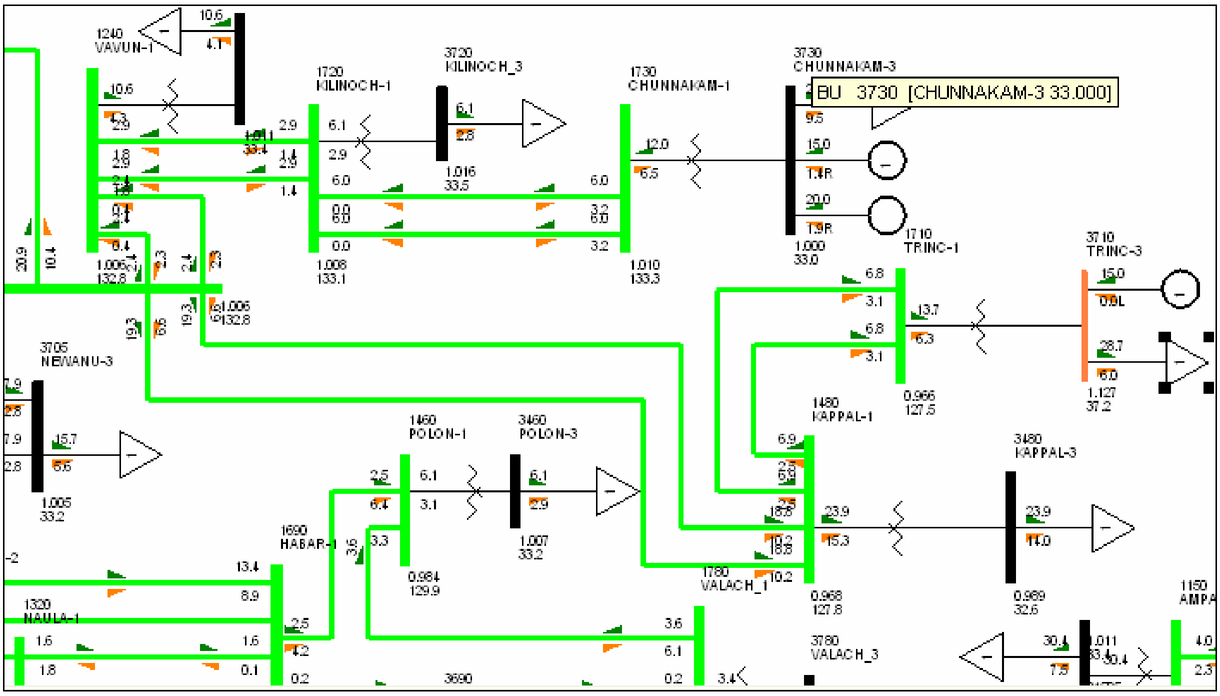

Trincomalee GSS – 15% load increase at nominal tap position



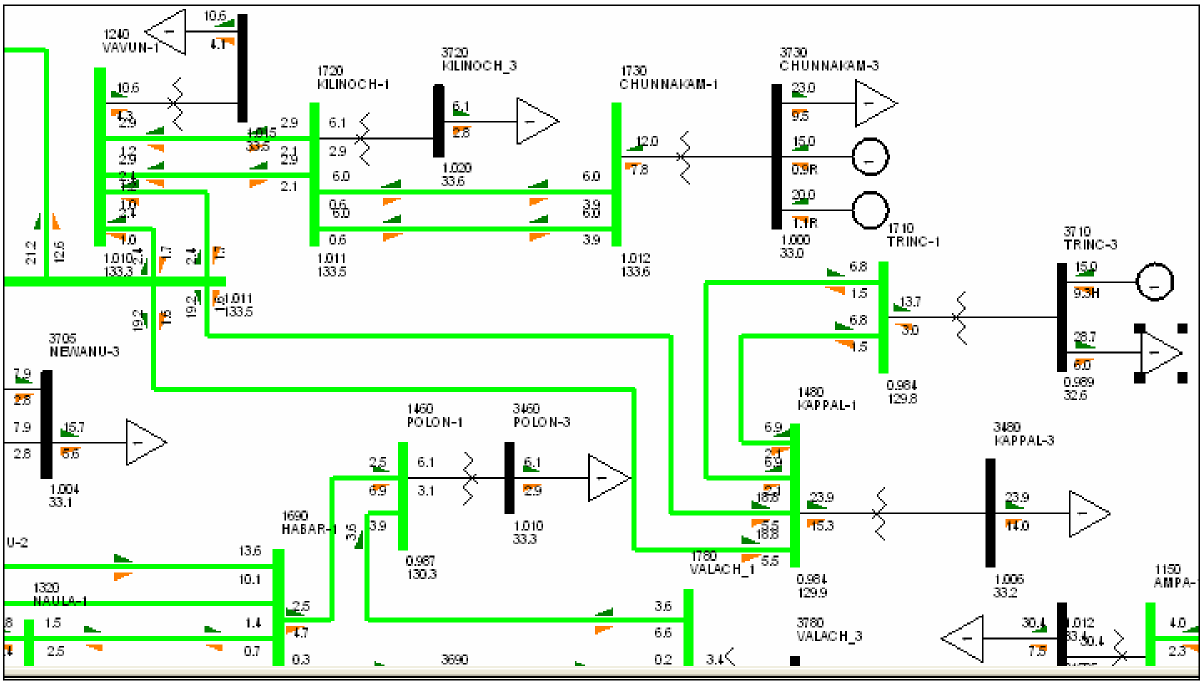
Trincomalee GSS – 15% load increase at maximum tap position



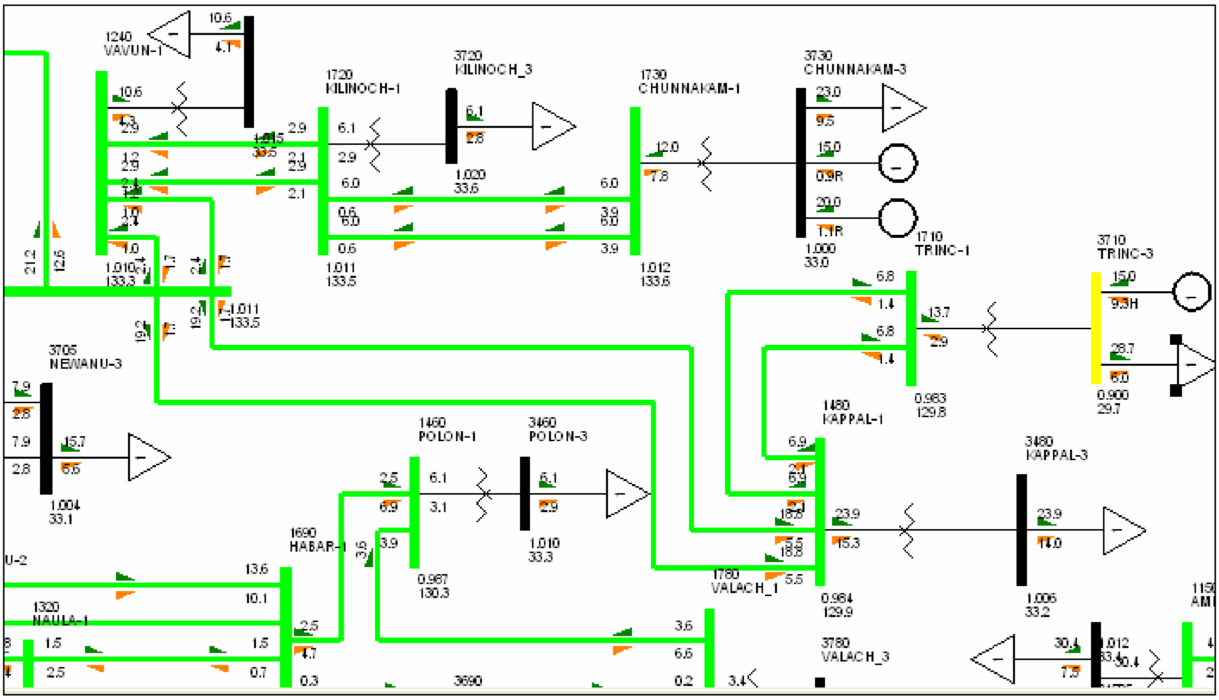
Trincomalee GSS – 20% load increase at minimum tap position



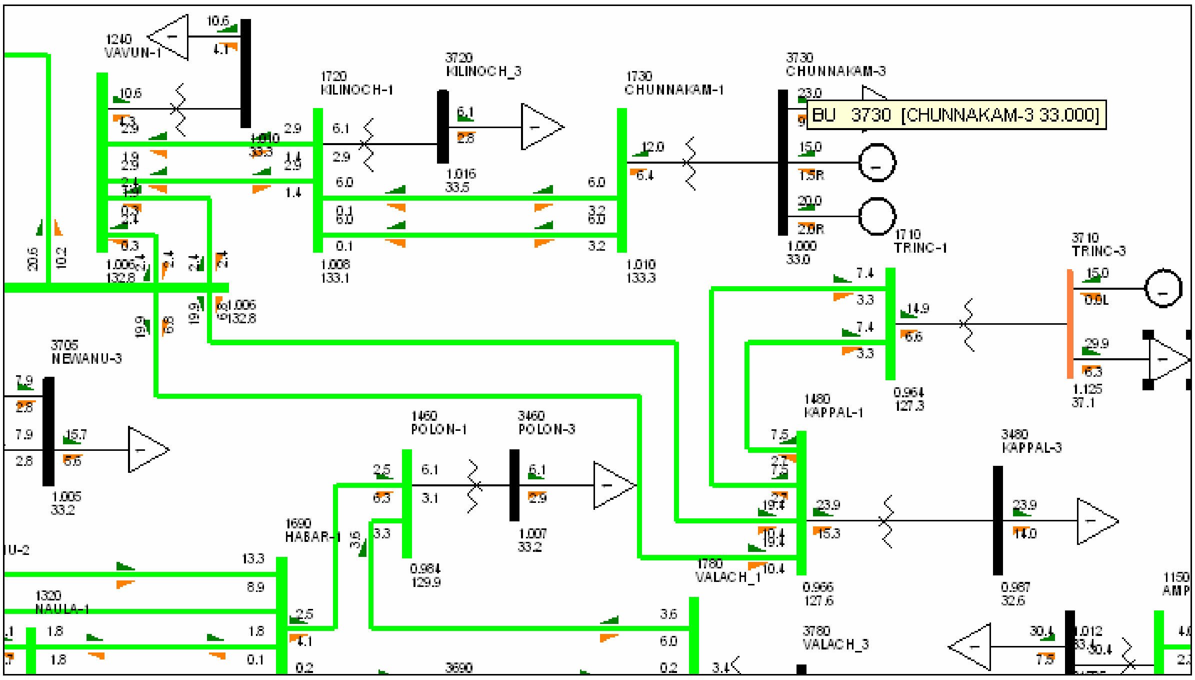
Trincomalee GSS – 20% load increase at nominal tap position



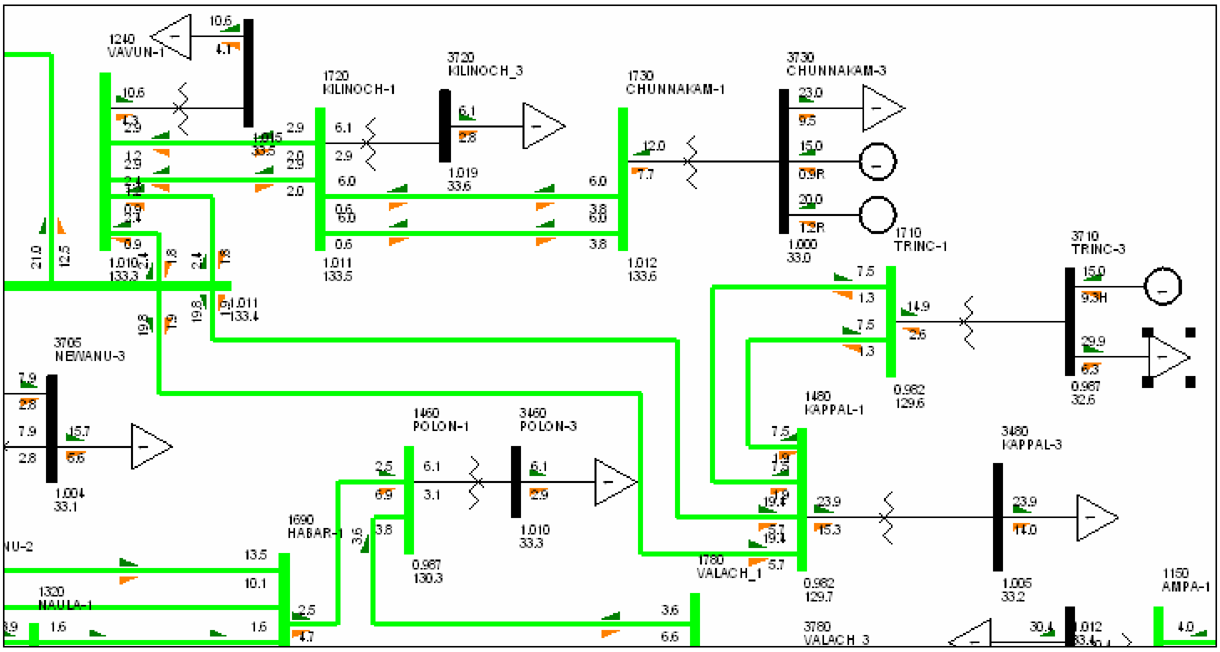
Trincomalee GSS – 20% load increase at maximum tap position



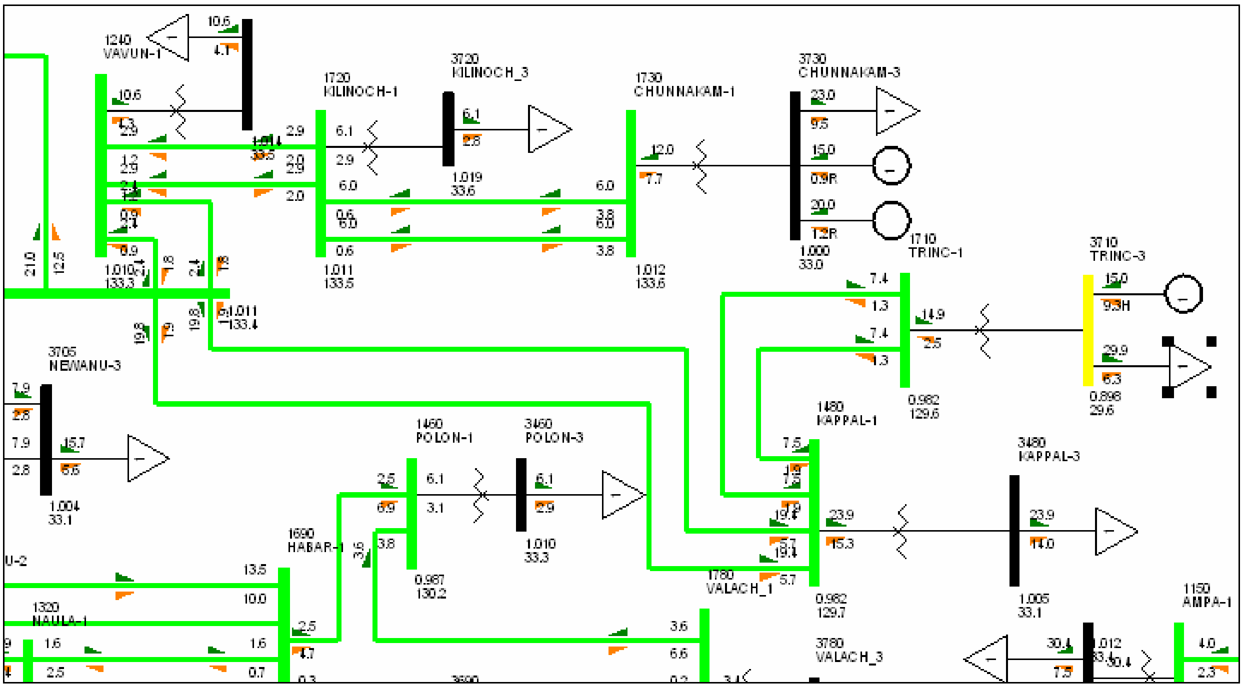
Trincomalee GSS – 25% load increase at minimum tap position



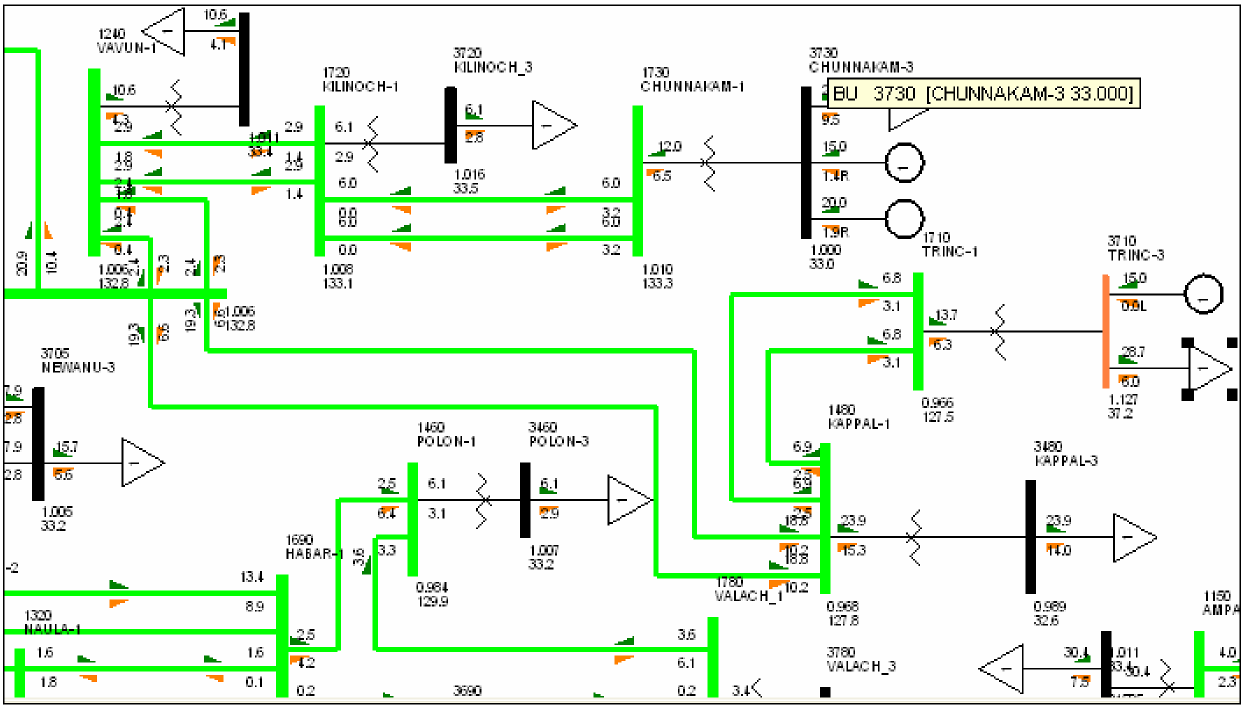

Trincomalee GSS – 25% load increase at nominal tap position



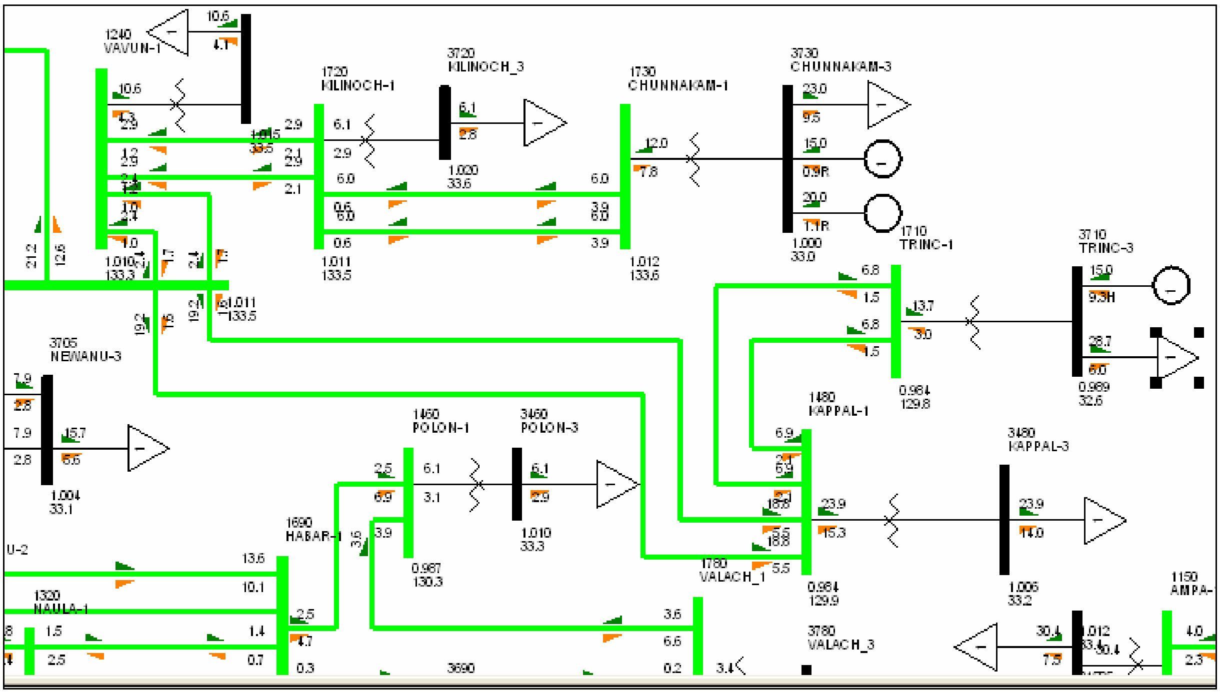
Trincomalee GSS – 25% load increase at maximum tap position



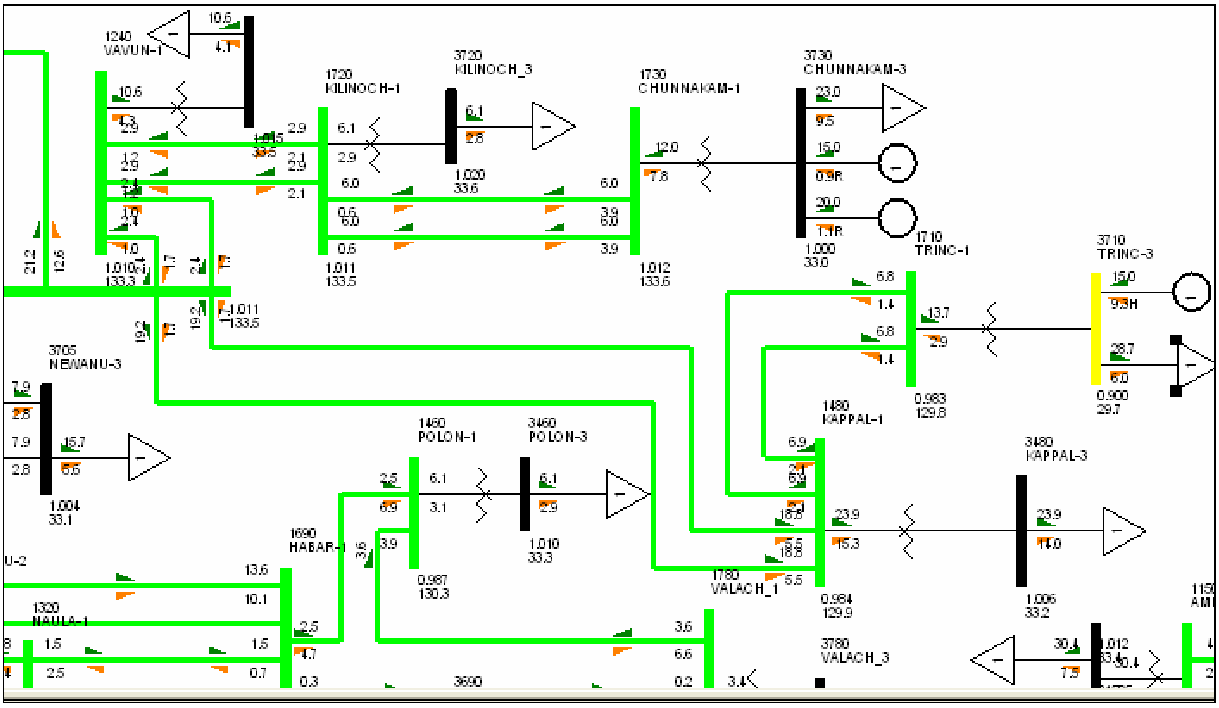

Trincomalee GSS –5% load decrease from 1.25%Load at minimum tap position



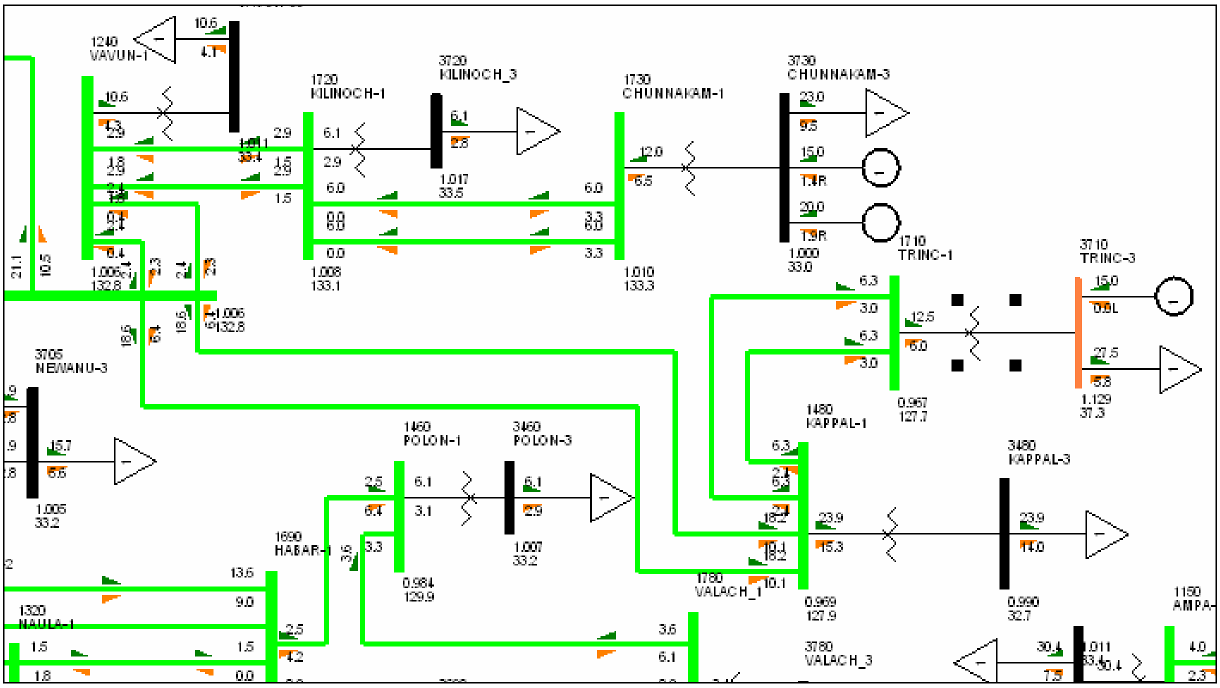
Trincomalee GSS –5% load decrease from 1.25% Load at nominal tap position



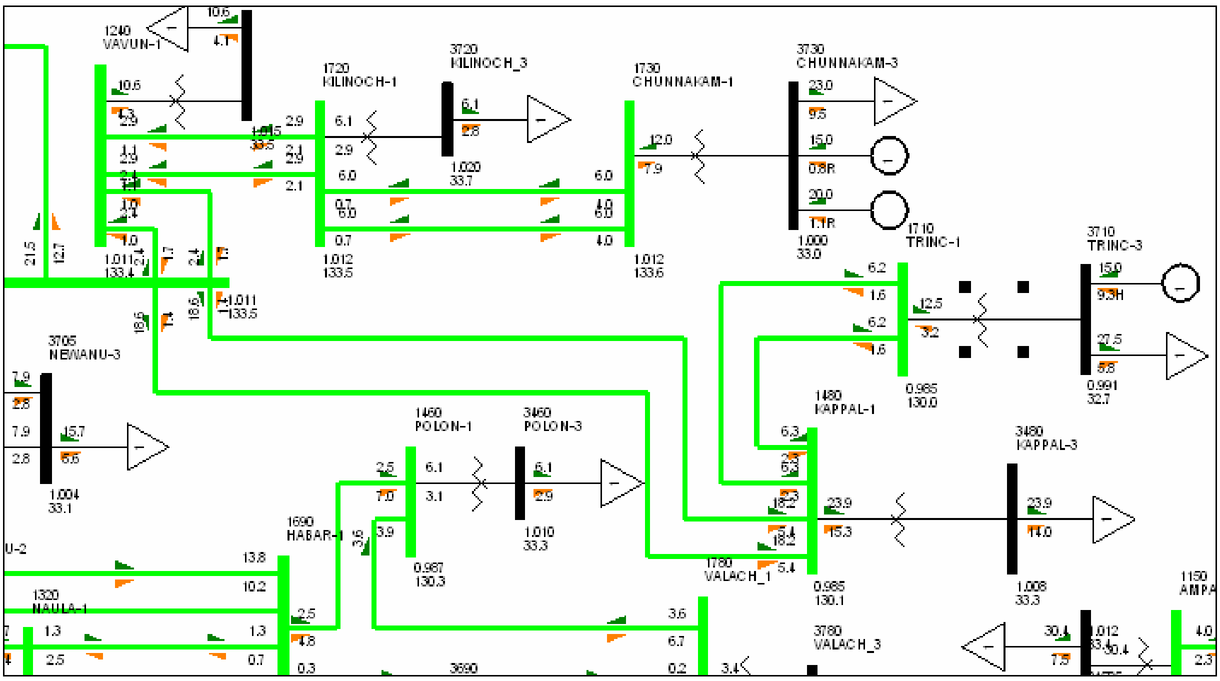

Trincomalee GSS –5% load decrease from 1.25% Load at maximum tap position



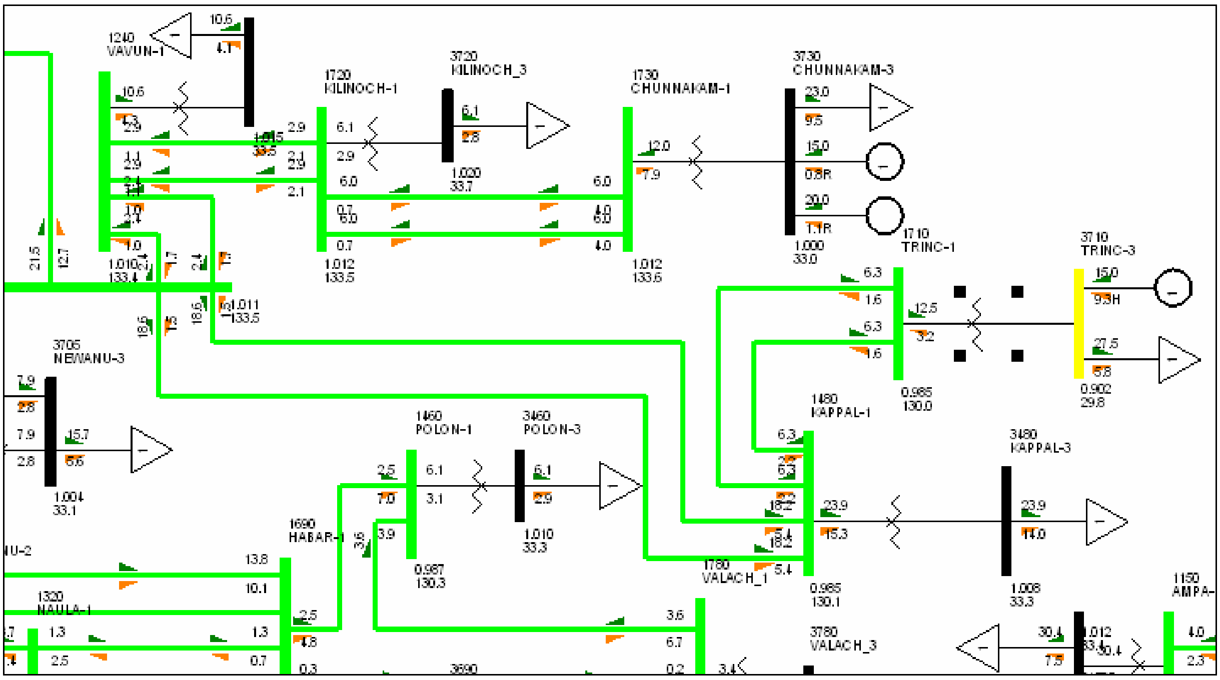
Trincomalee GSS –10% load decrease from 1.25% Load at minimum tap position




Trincomalee GSS –10% load decrease from 1.25% Load at nominal tap position

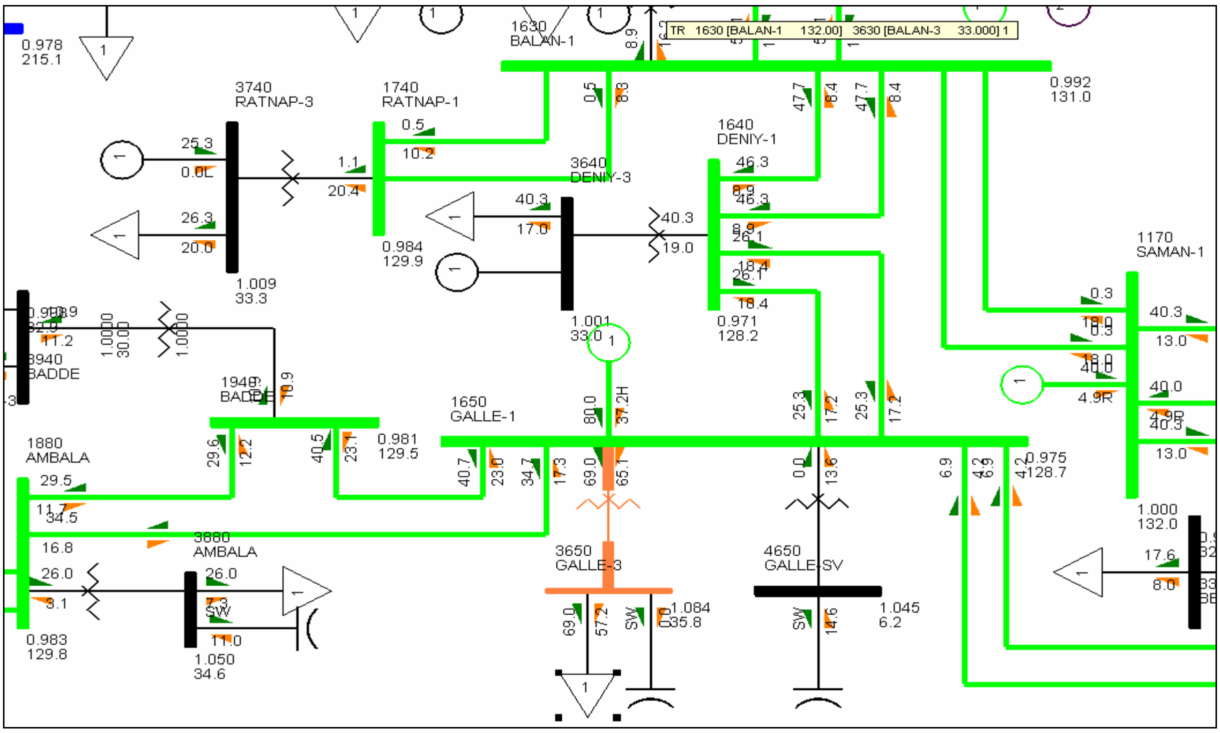


Trincomalee GSS –10% load decrease from 1.25% Load at maximum tap position

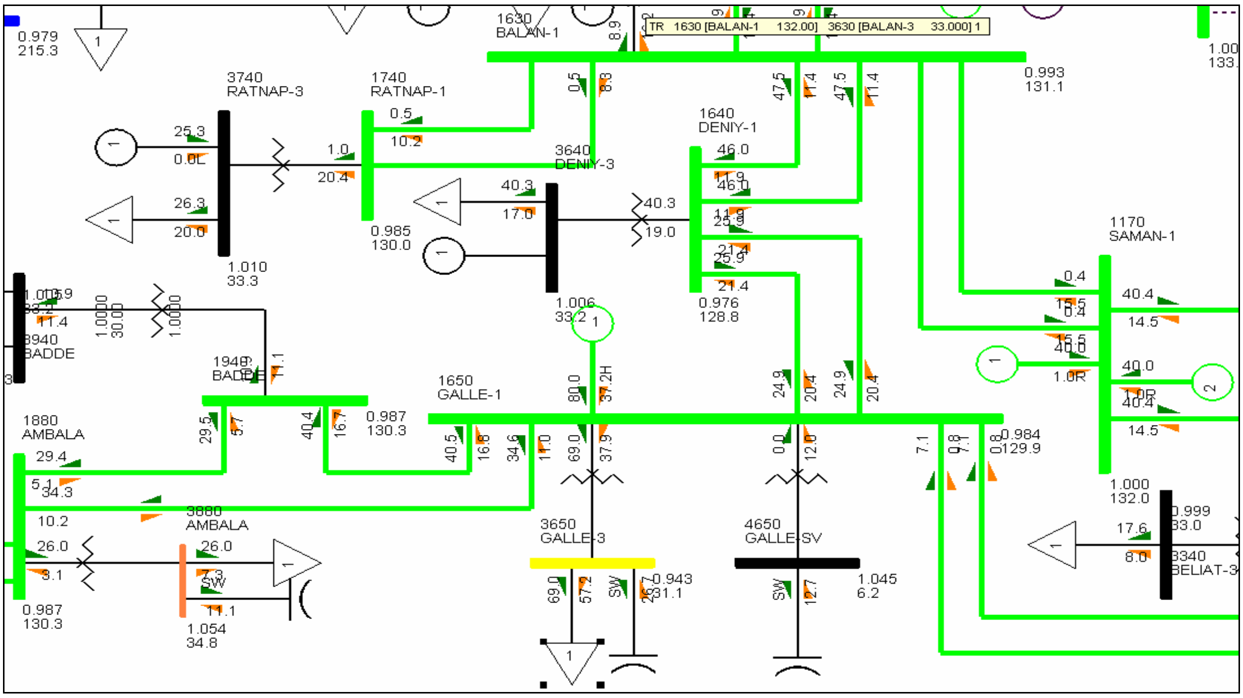



## (iv) 2016 – Galle GSS:

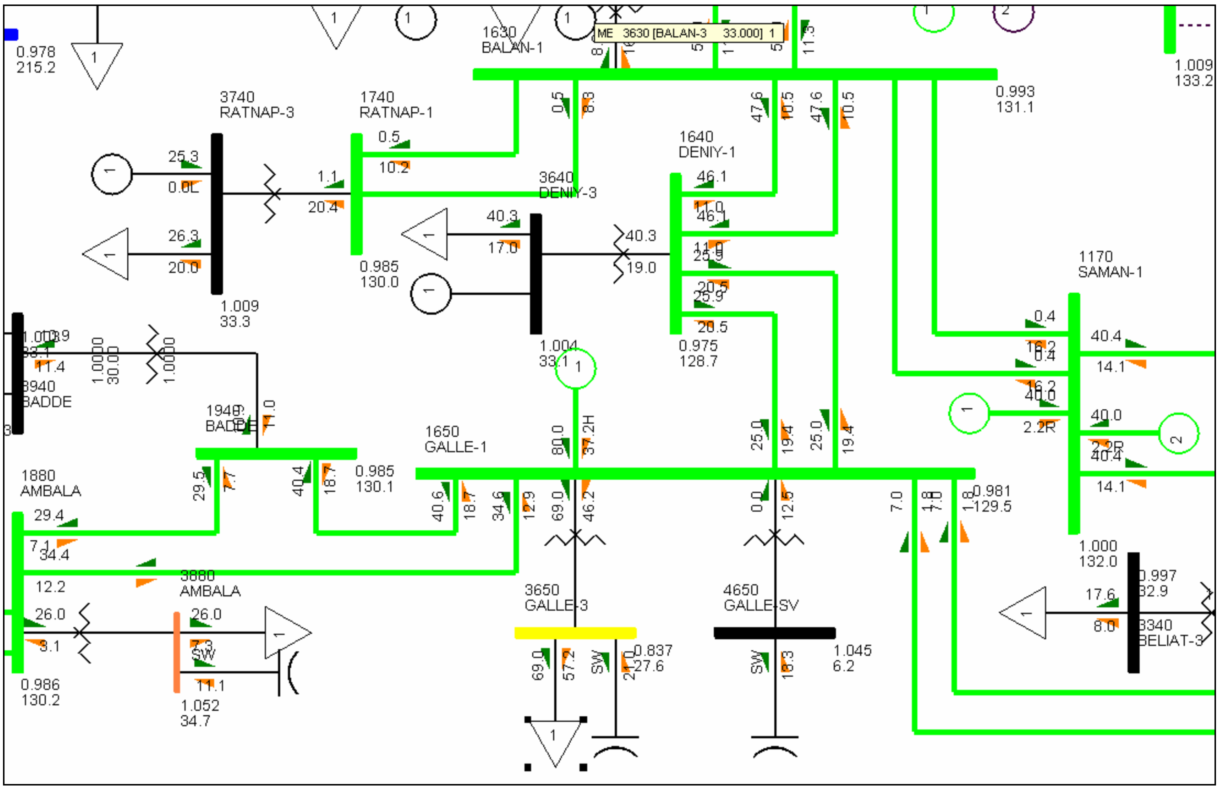
Galle GSS – 15% load increase at minimum tap position



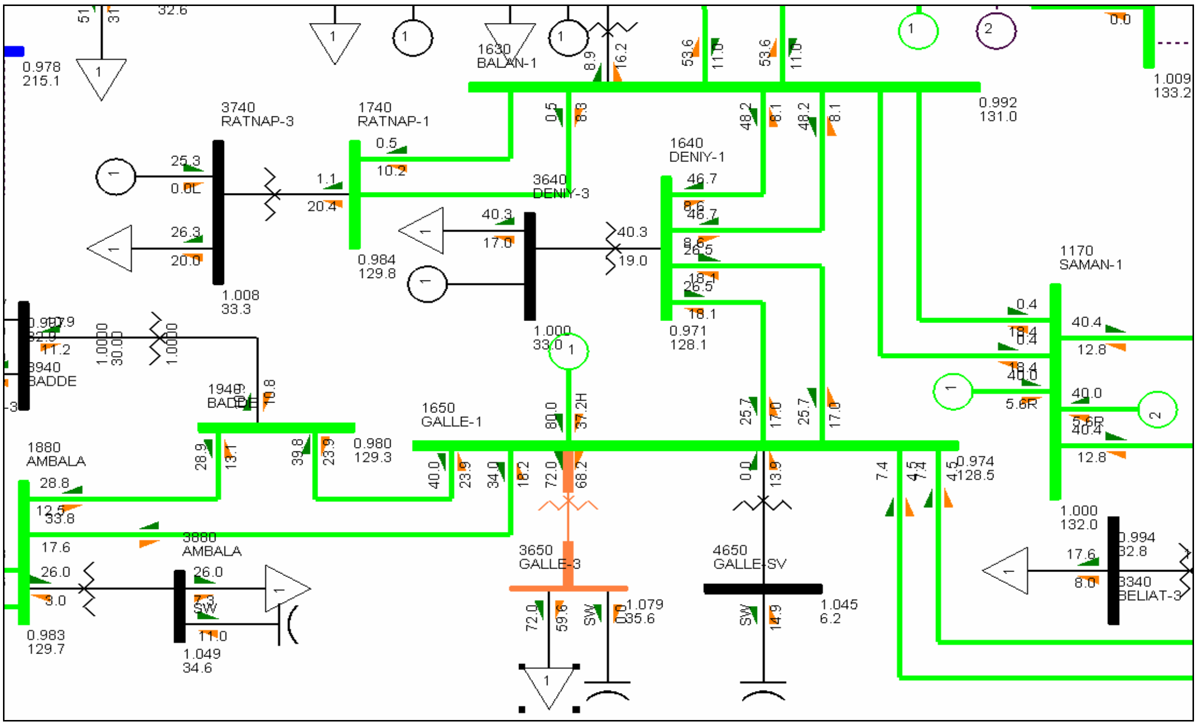
Galle GSS – 15% load increase at nominal tap position



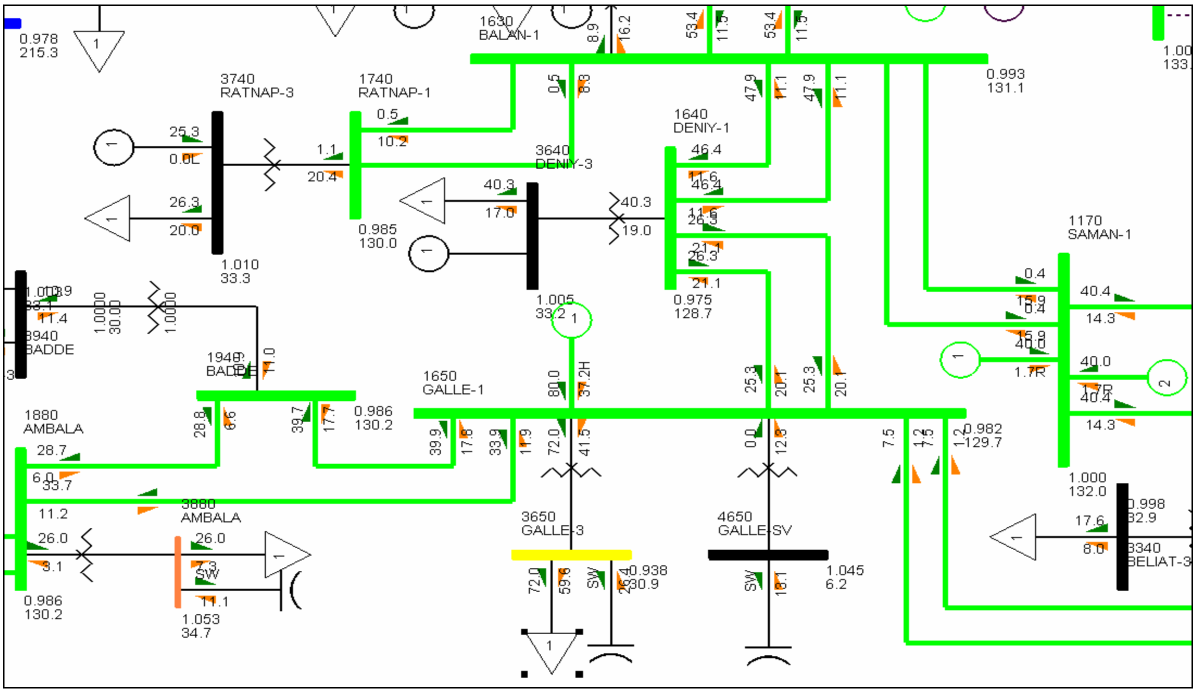
Galle GSS – 15% load increase at maximum tap position



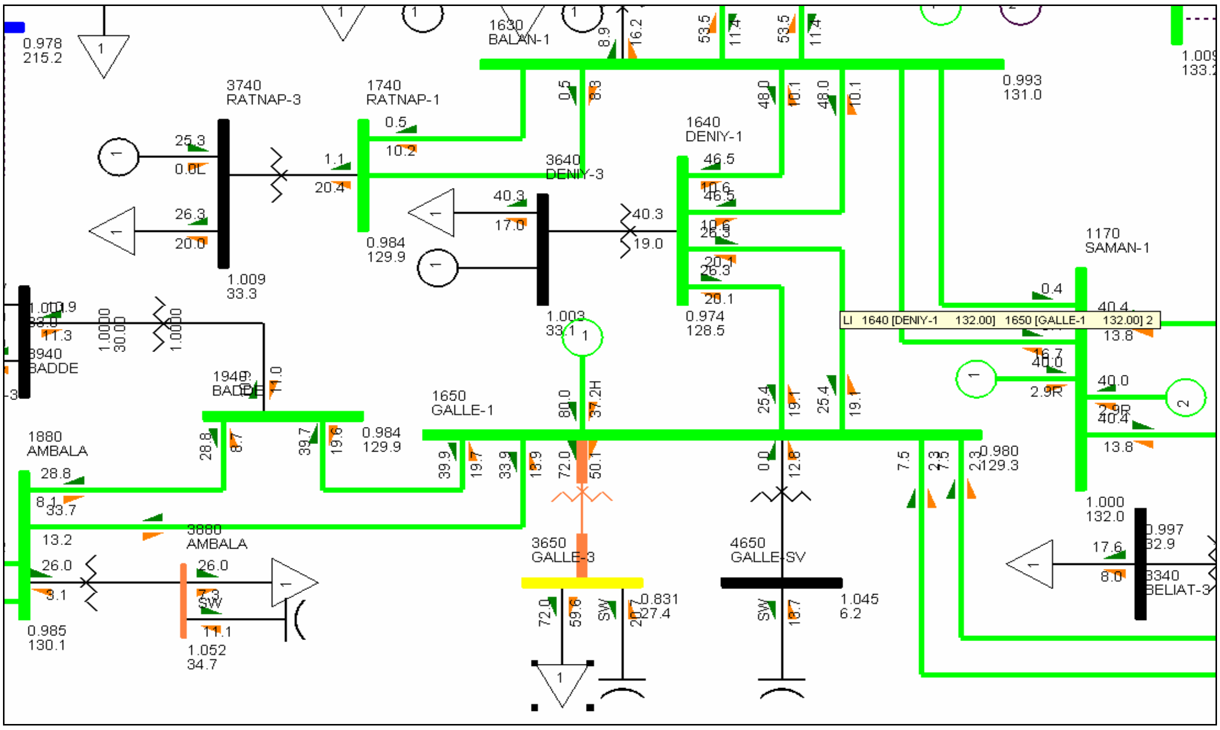
Galle GSS – 20% load increase at minimum tap position



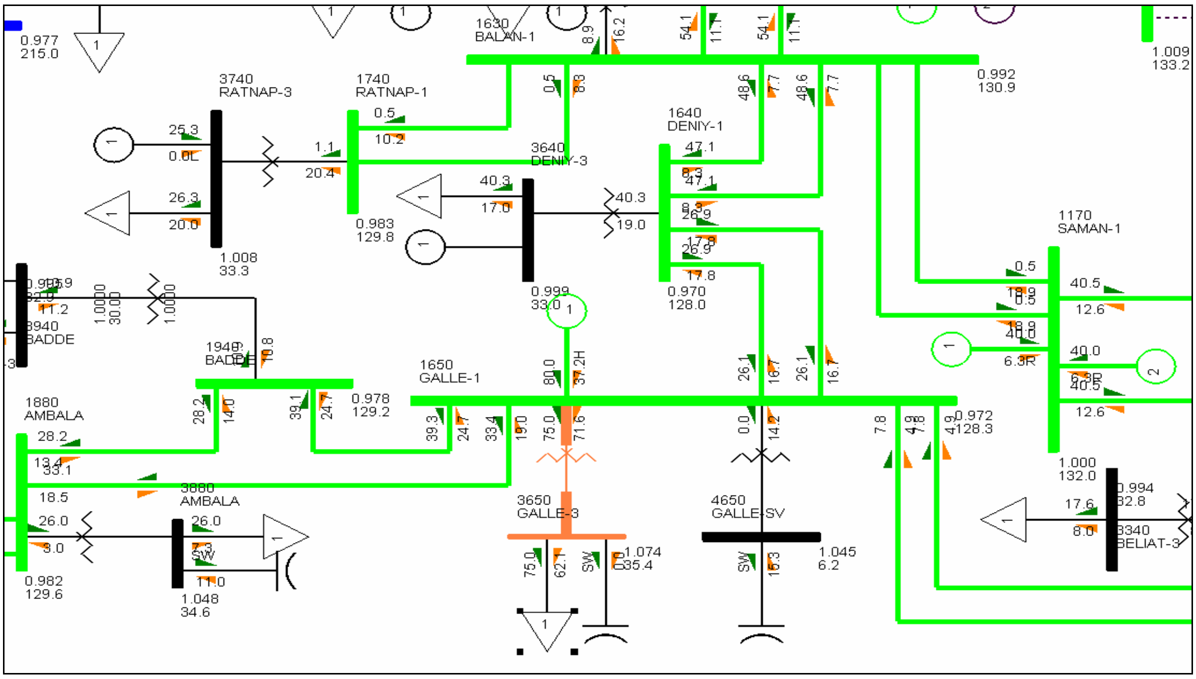

Galle GSS – 20% load increase at nominal tap position



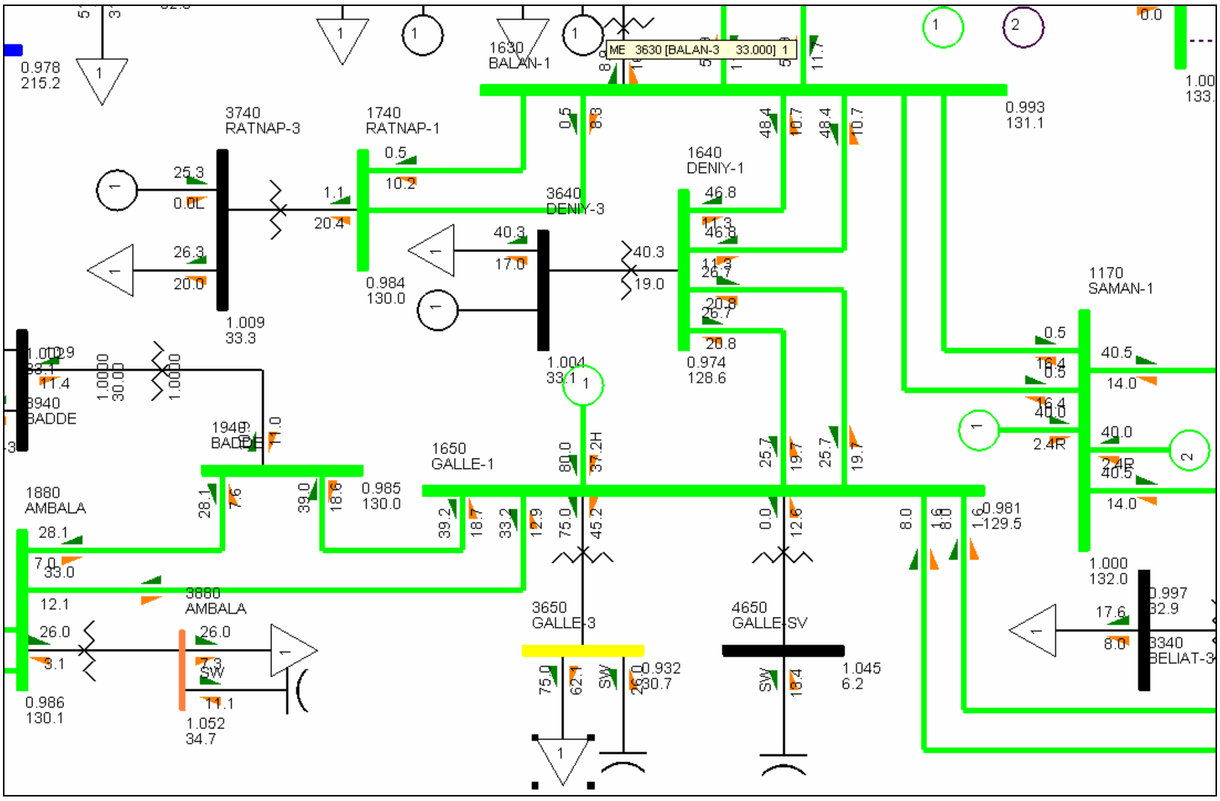
Galle GSS – 20% load increase at maximum tap position



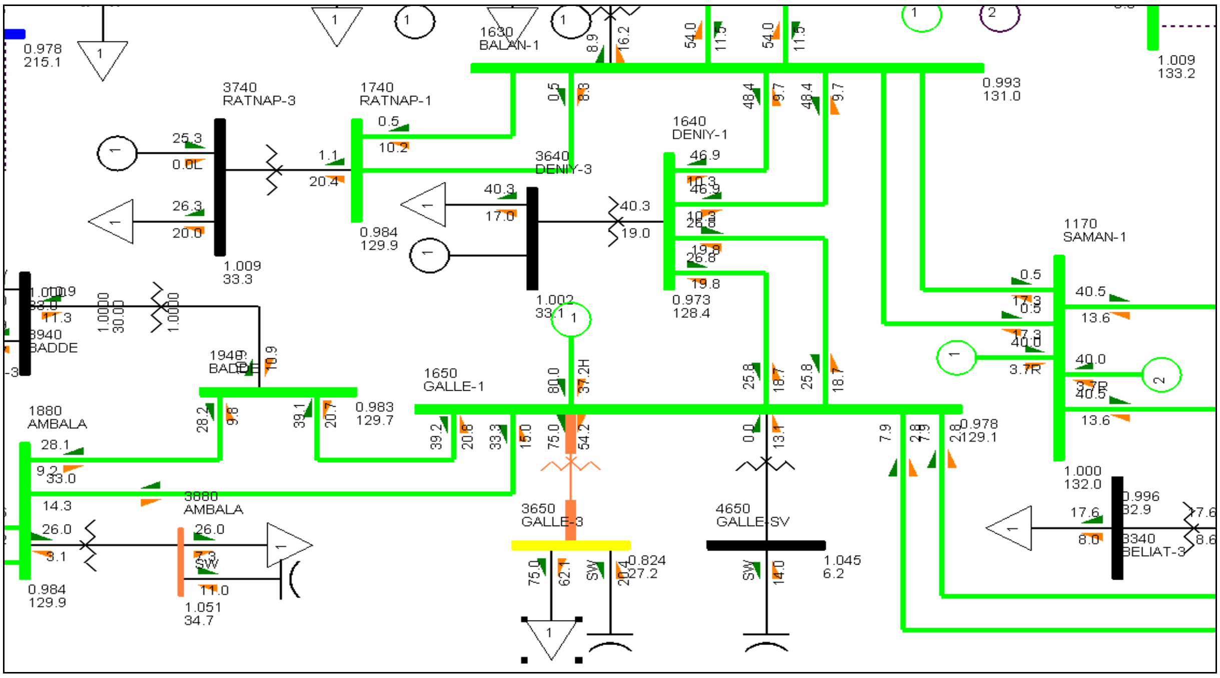
Galle GSS – 25% load increase at minimum tap position



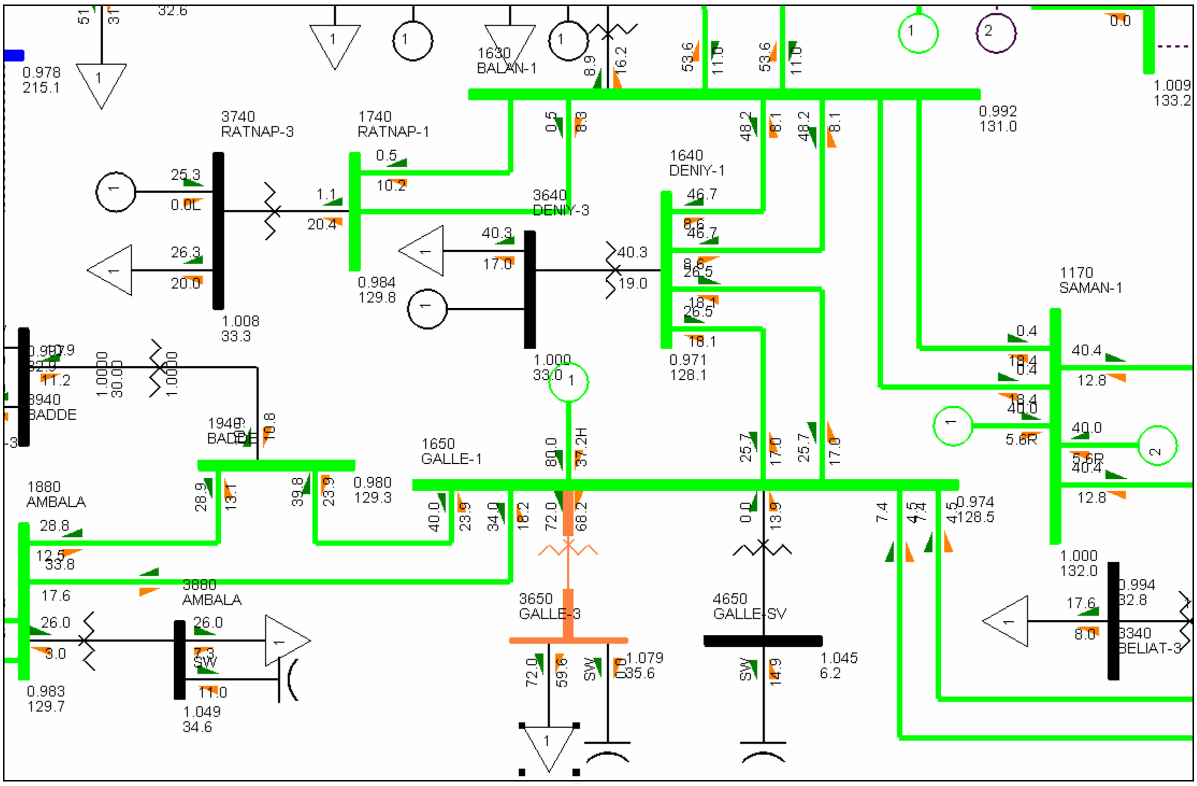
Galle GSS – 25% load increase at nominal tap position



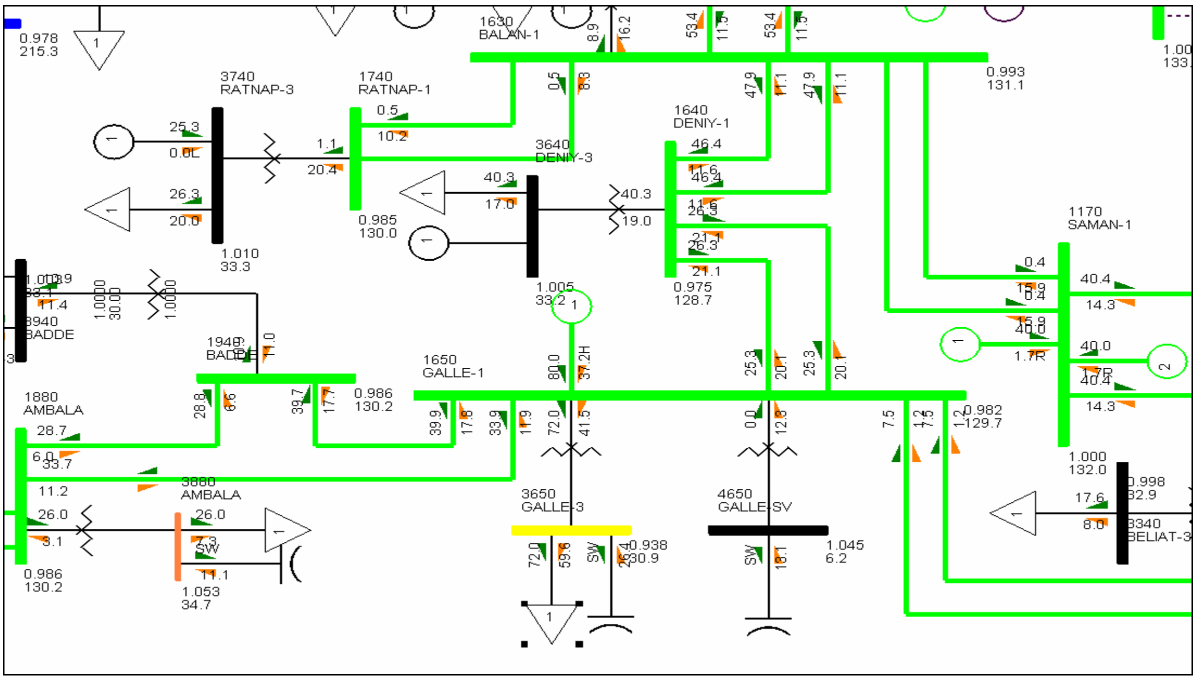
Galle GSS – 25% load increase at maximum tap position



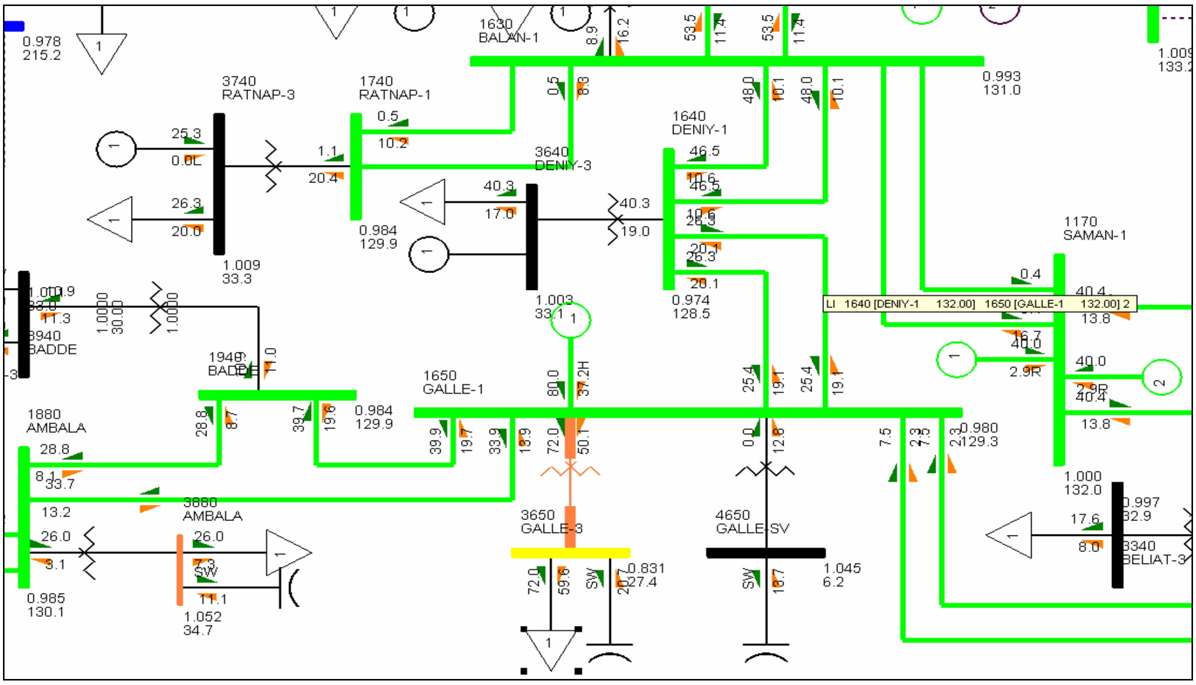
Galle GSS –5% load decrease from 1.25% Load at minimum tap position



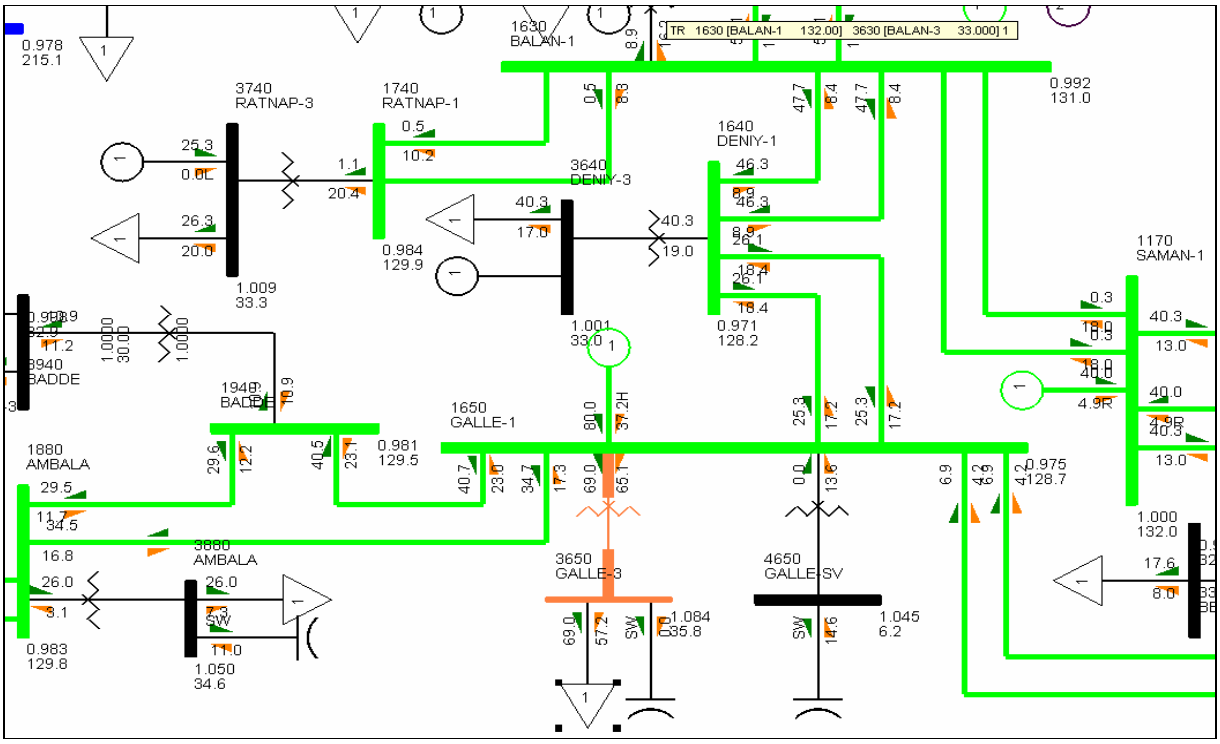

Galle GSS –5% load decrease from 1.25% Load at nominal tap position



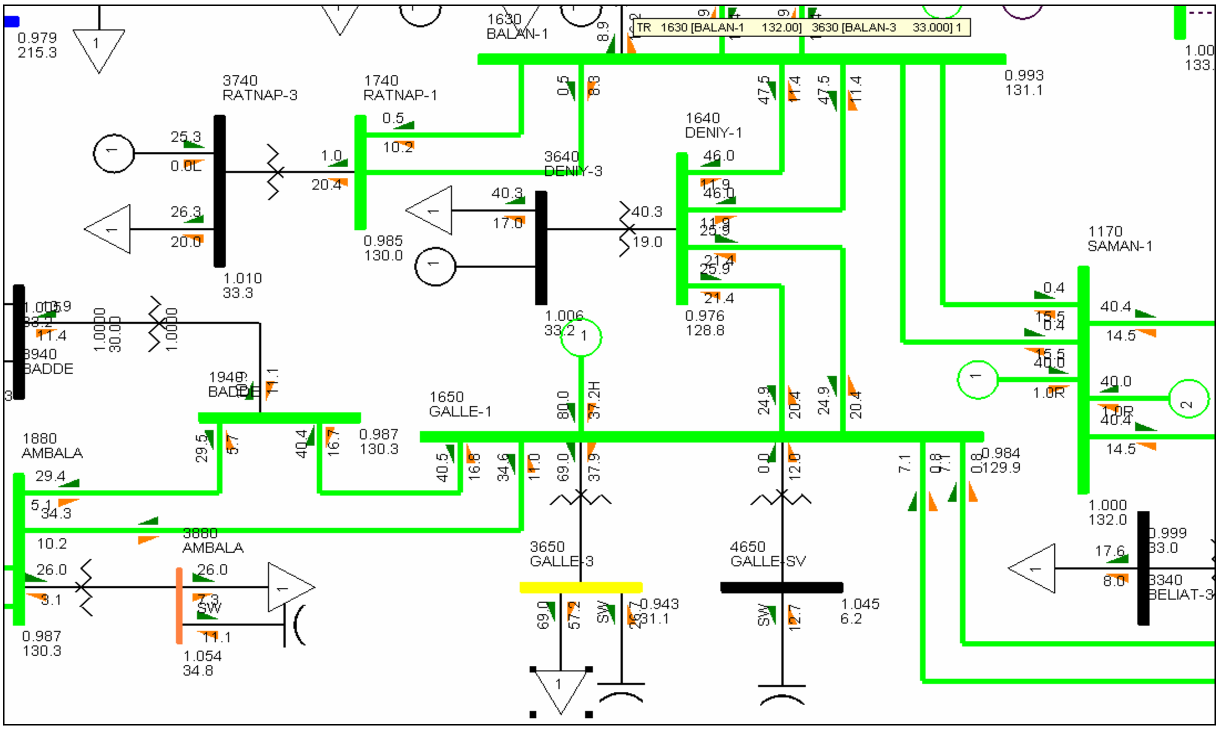
Galle GSS –5% load decrease from 1.25% Load at maximum tap position



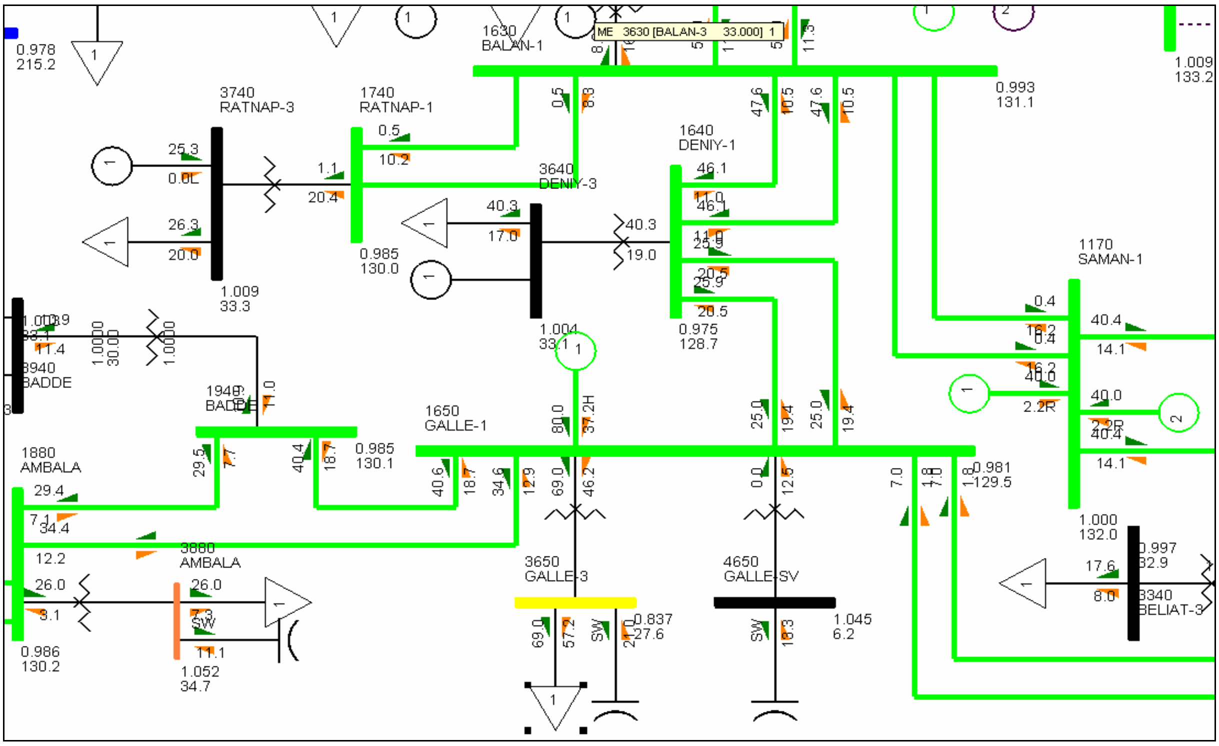

Galle GSS –10% load decrease from 1.25% Load at minimum tap position



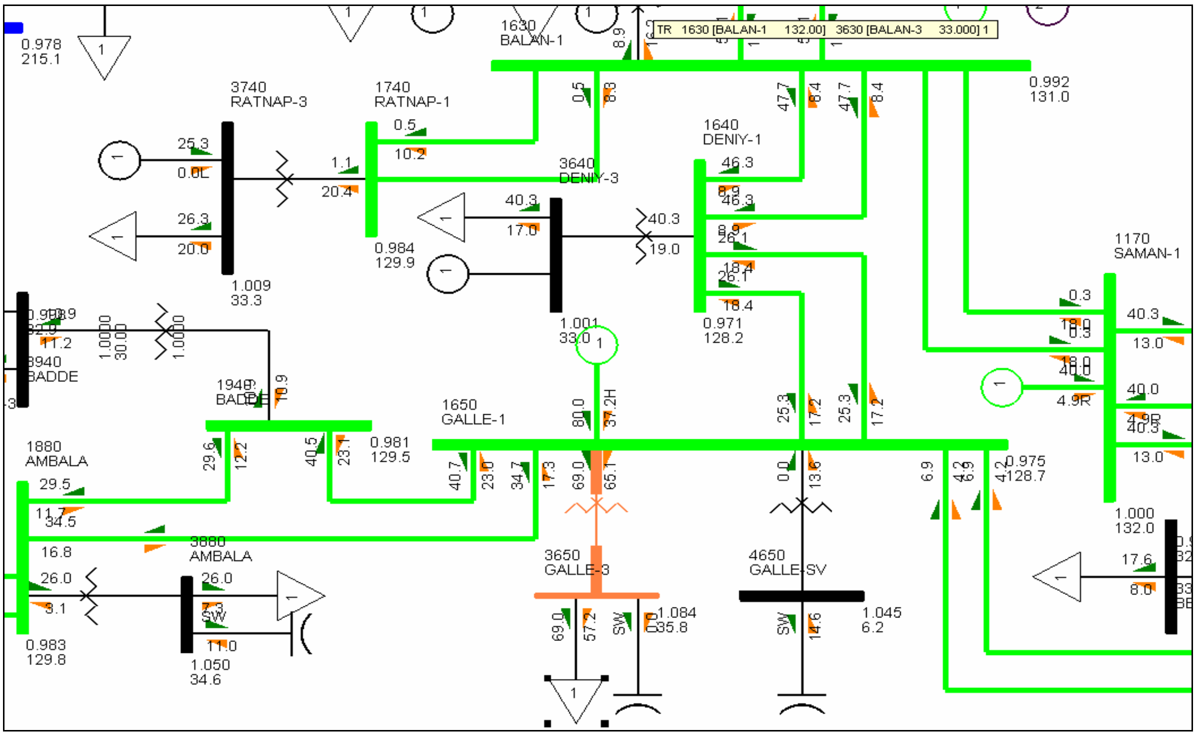
Galle GSS –10% load decrease from 1.25% Load at nominal tap position



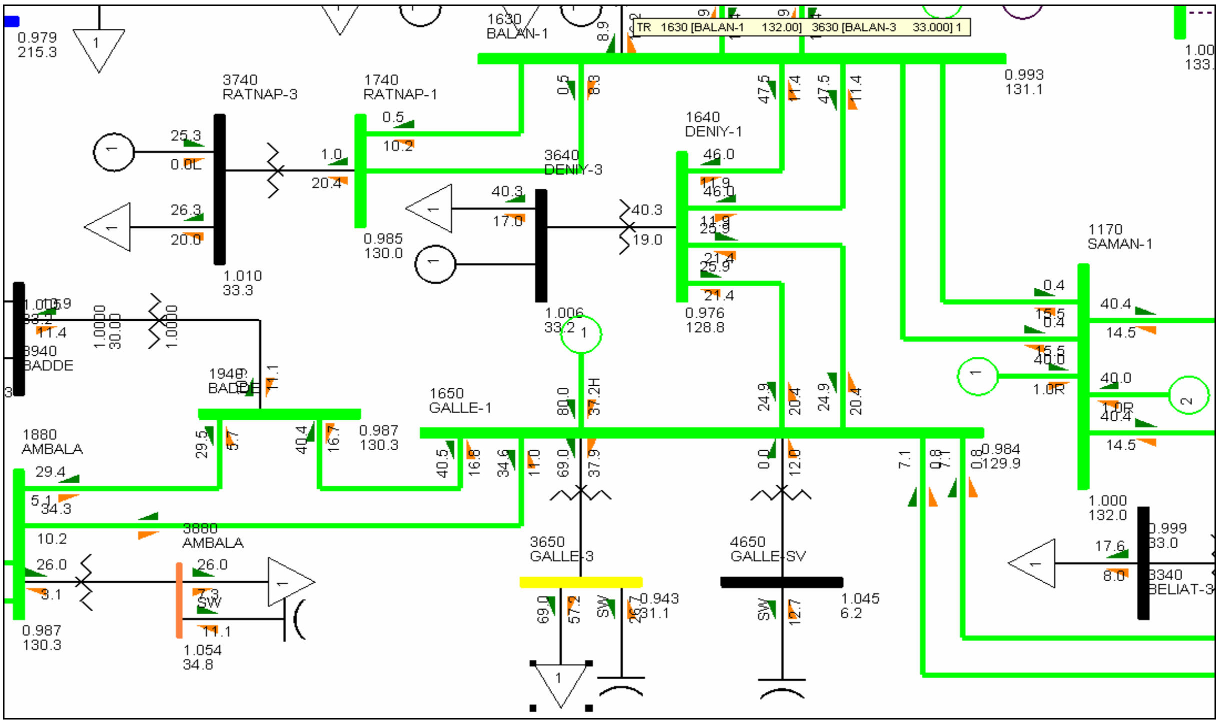

Galle GSS –10% load decrease from 1.25% Load at maximum tap position



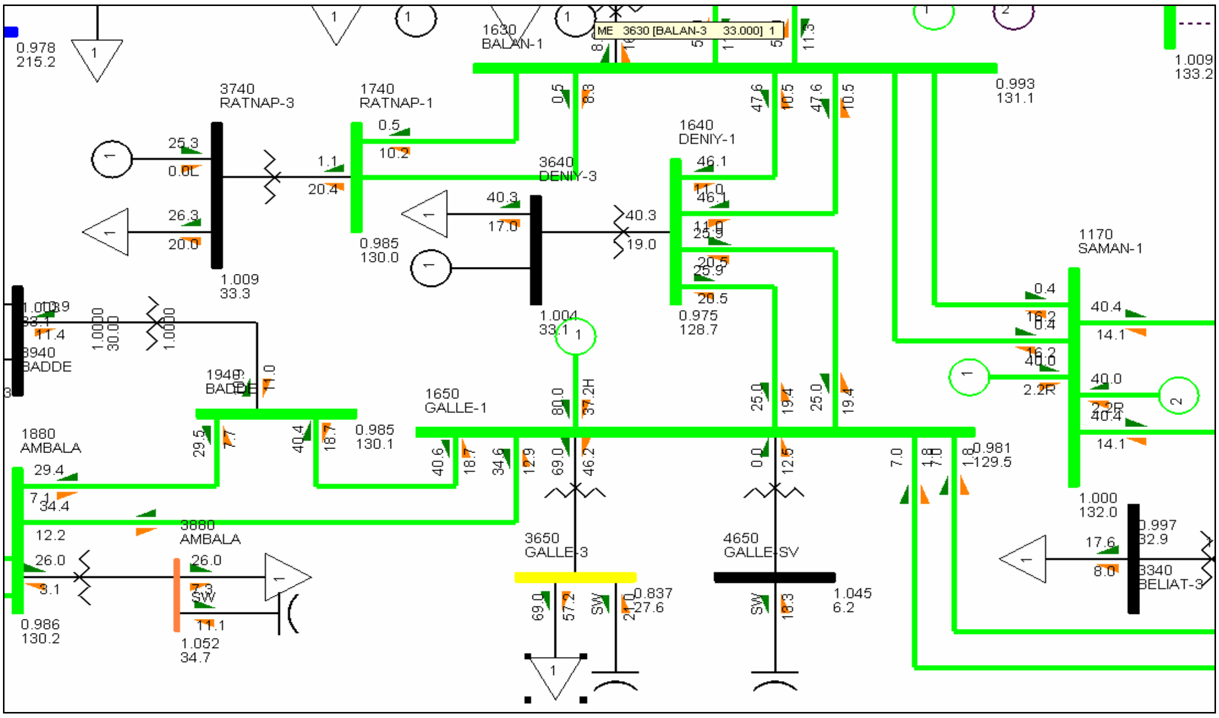
Galle GSS – 15% load increase at minimum tap position



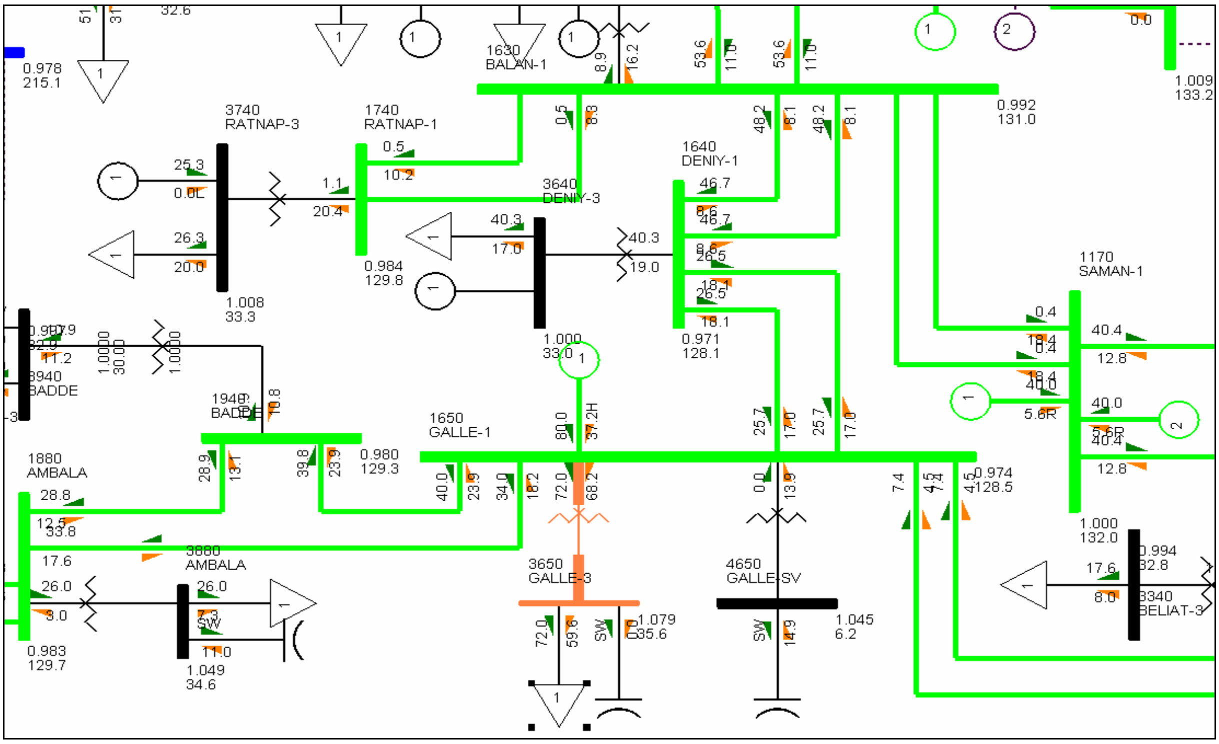

Galle GSS – 15% load increase at nominal tap position



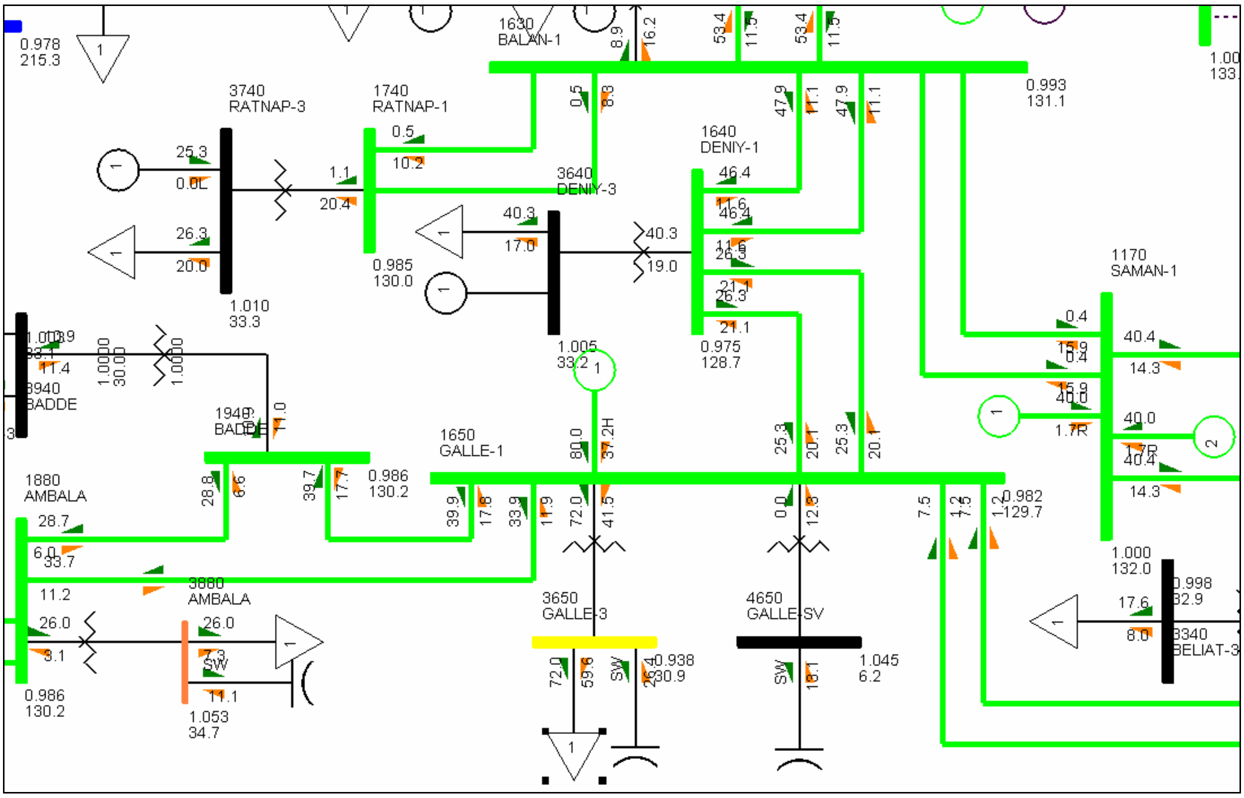
Galle GSS – 15% load increase at maximum tap position



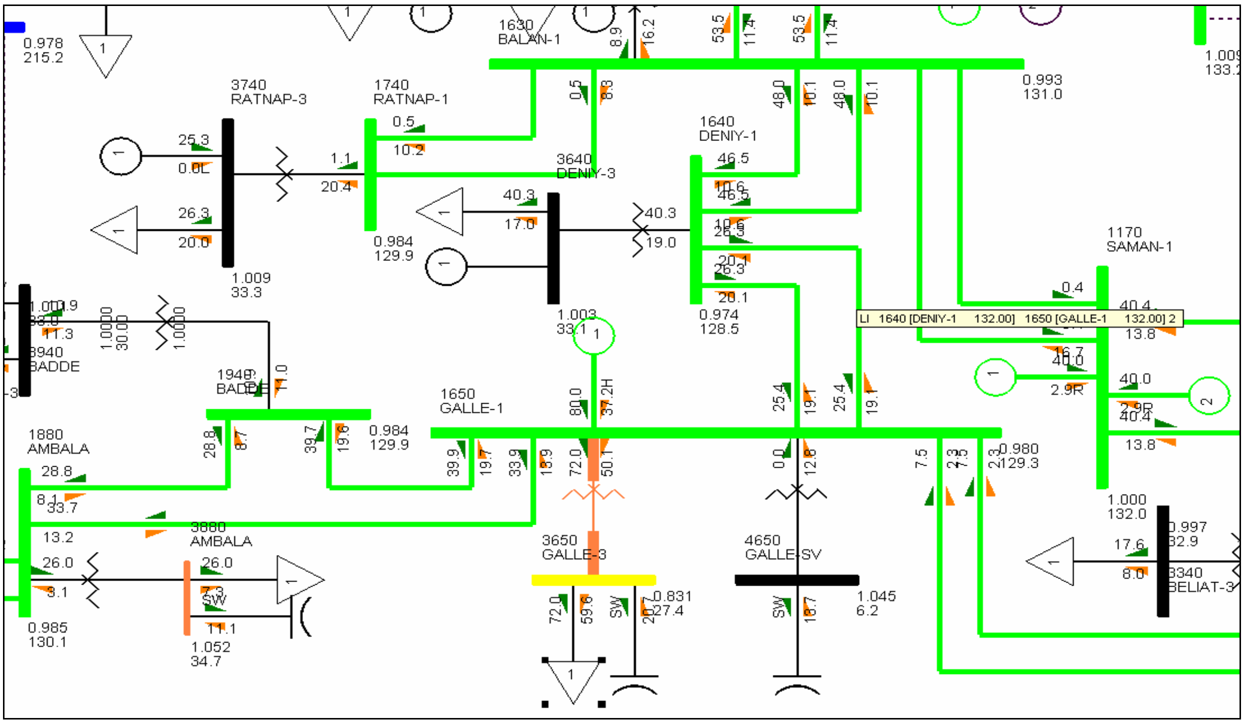

Galle GSS – 20% load increase at minimum tap position



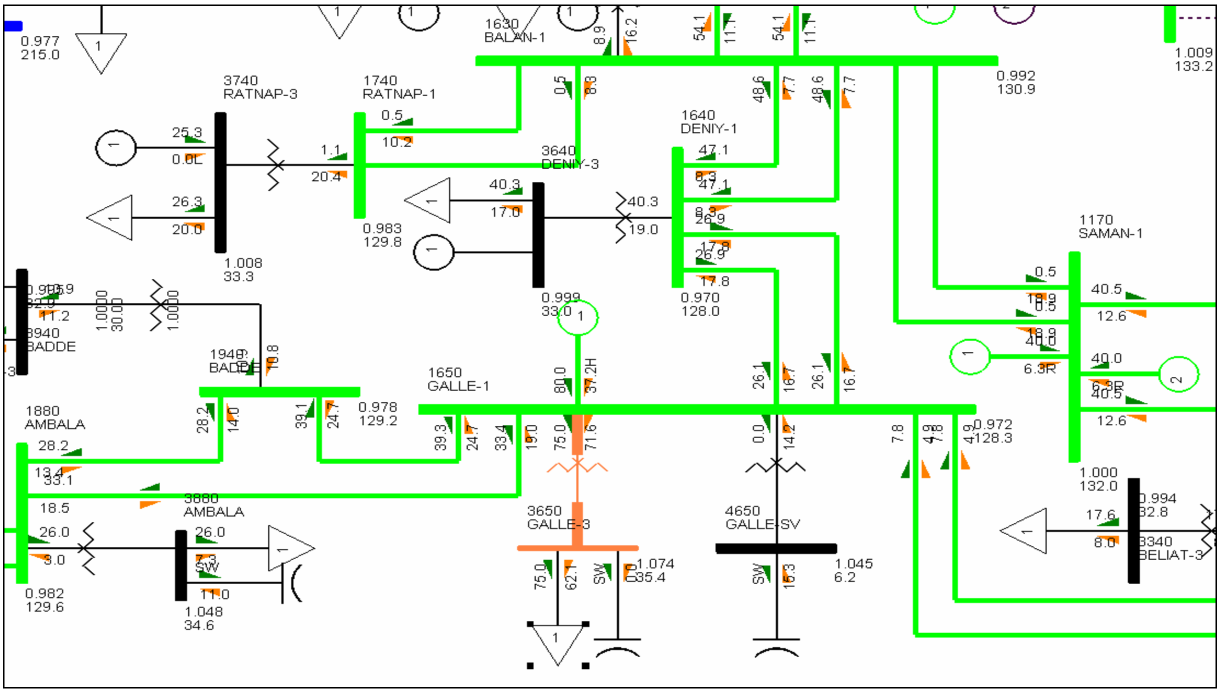
Galle GSS – 20% load increase at nominal tap position



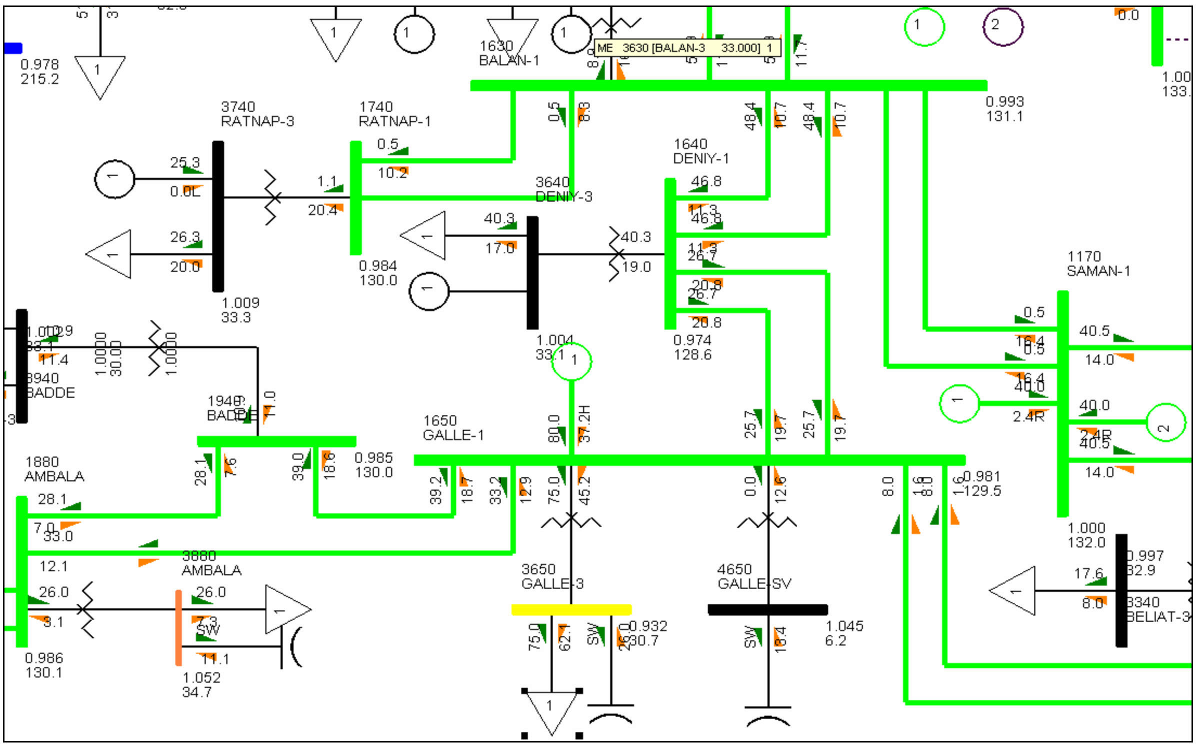

Galle GSS – 20% load increase at maximum tap position



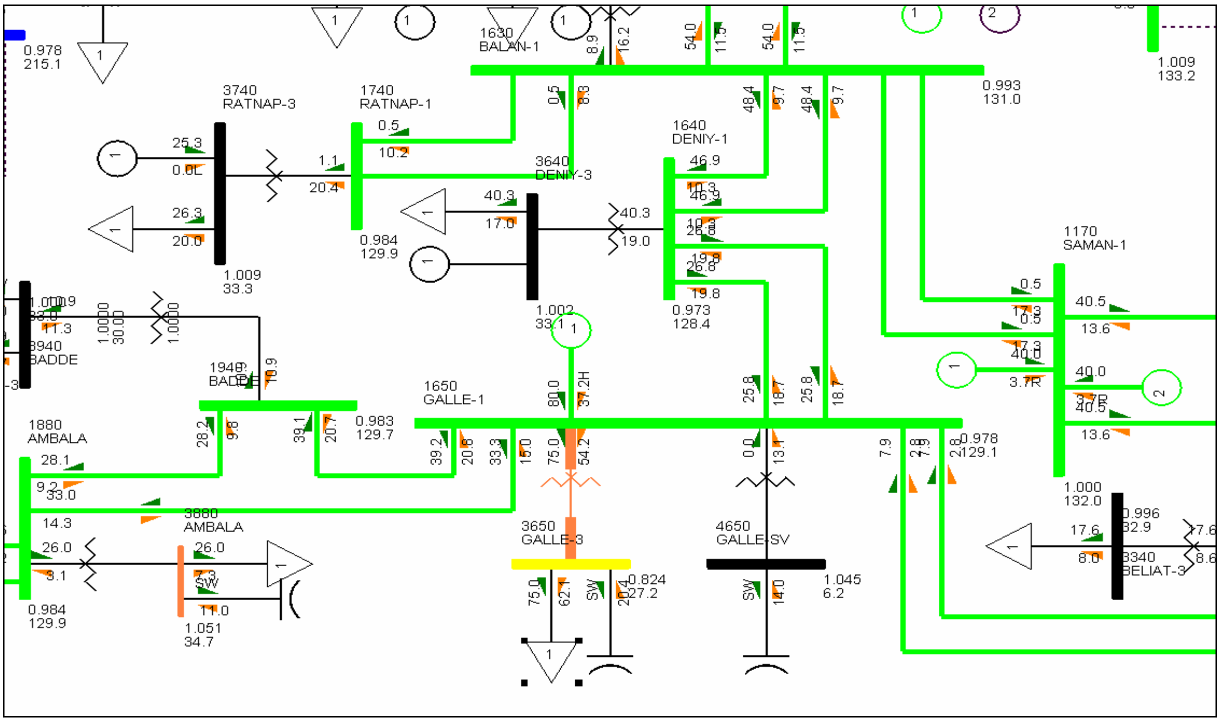
Galle GSS – 25% load increase at minimum tap position



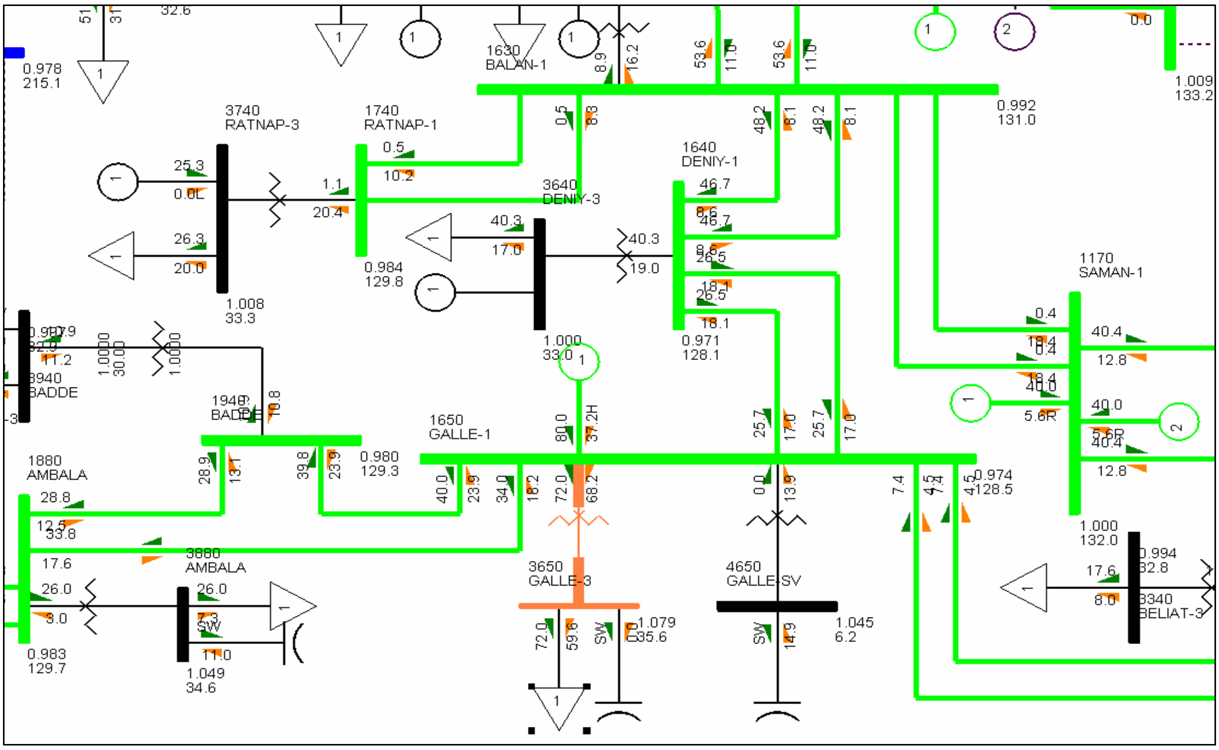

Galle GSS – 25% load increase at nominal tap position



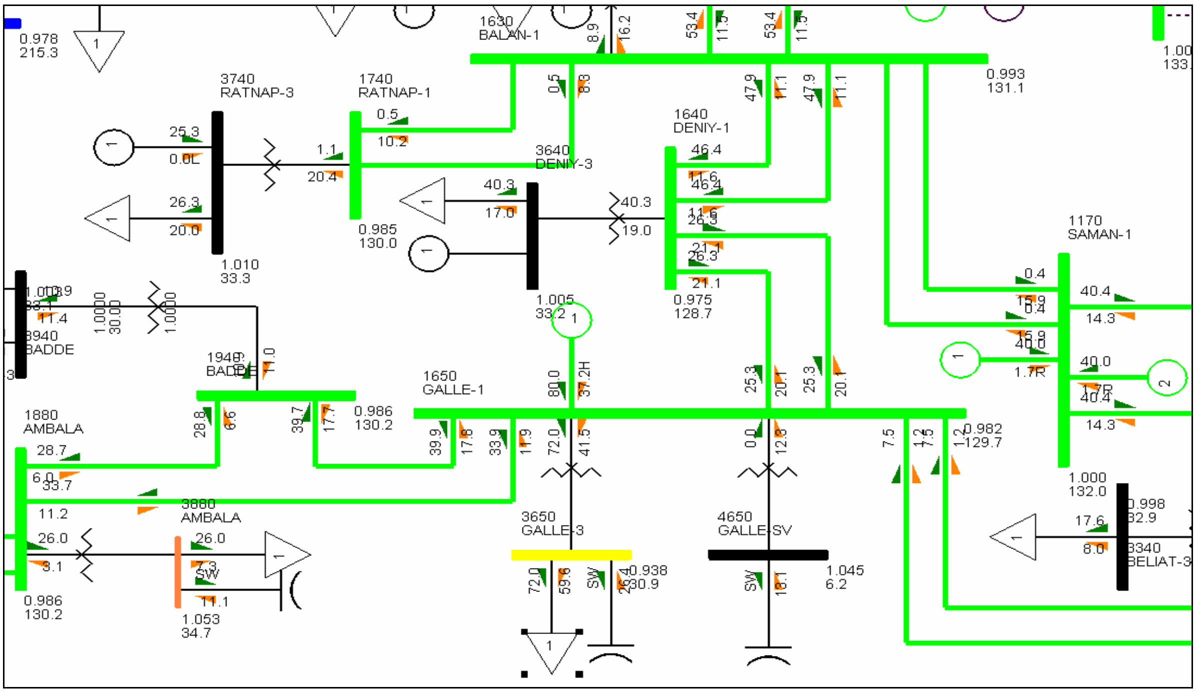
Galle GSS – 25% load increase at maximum tap position



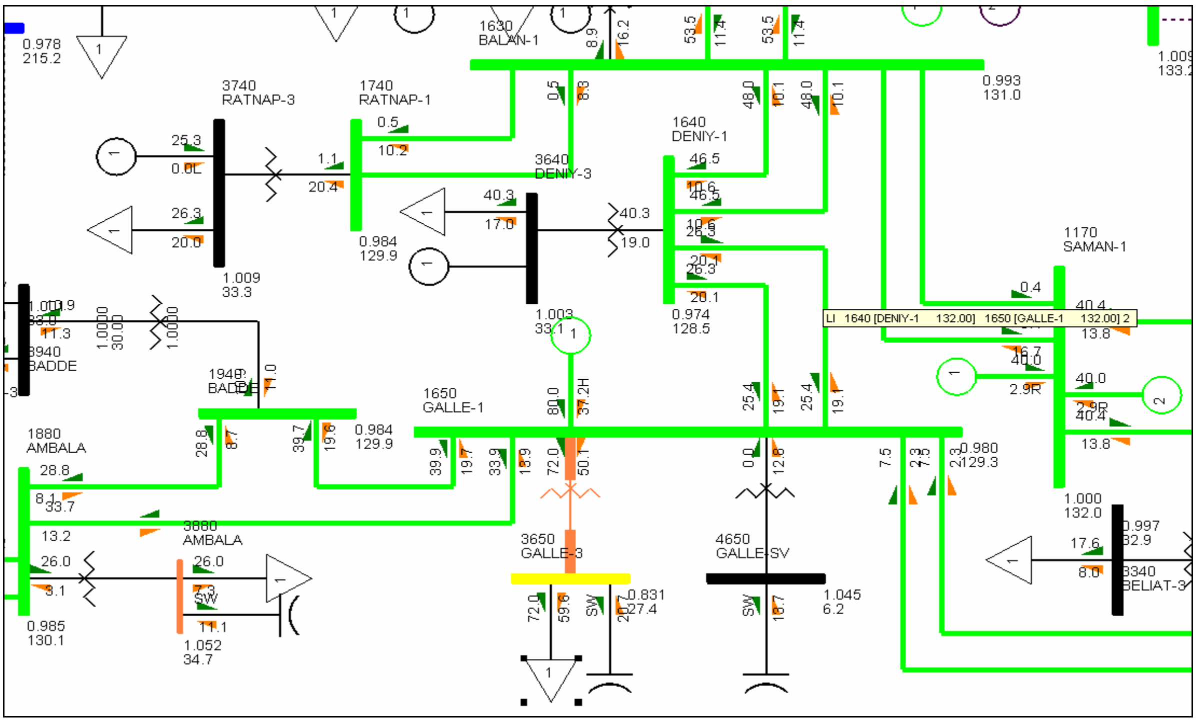

Galle GSS –5% load decrease from 1.25% Load at minimum tap position



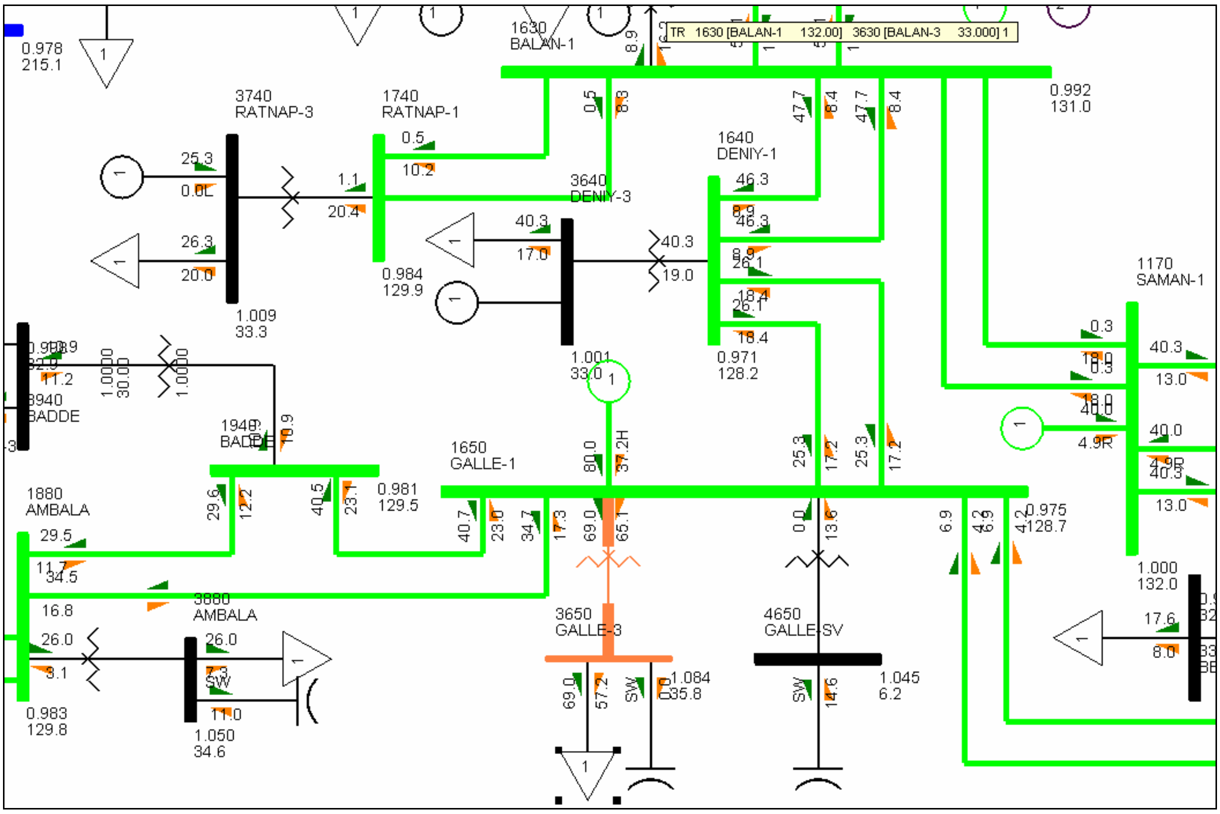
Galle GSS –5% load decrease from 1.25% Load at nominal tap position



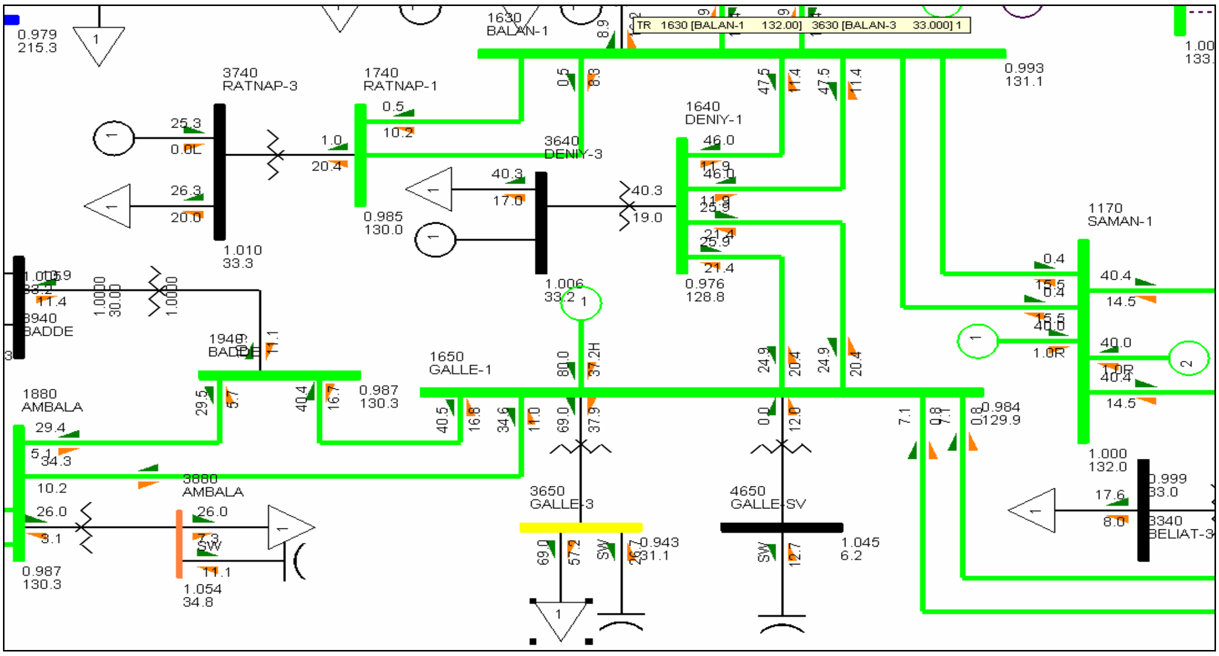

Galle GSS –5% load decrease from 1.25% Load at maximum tap position



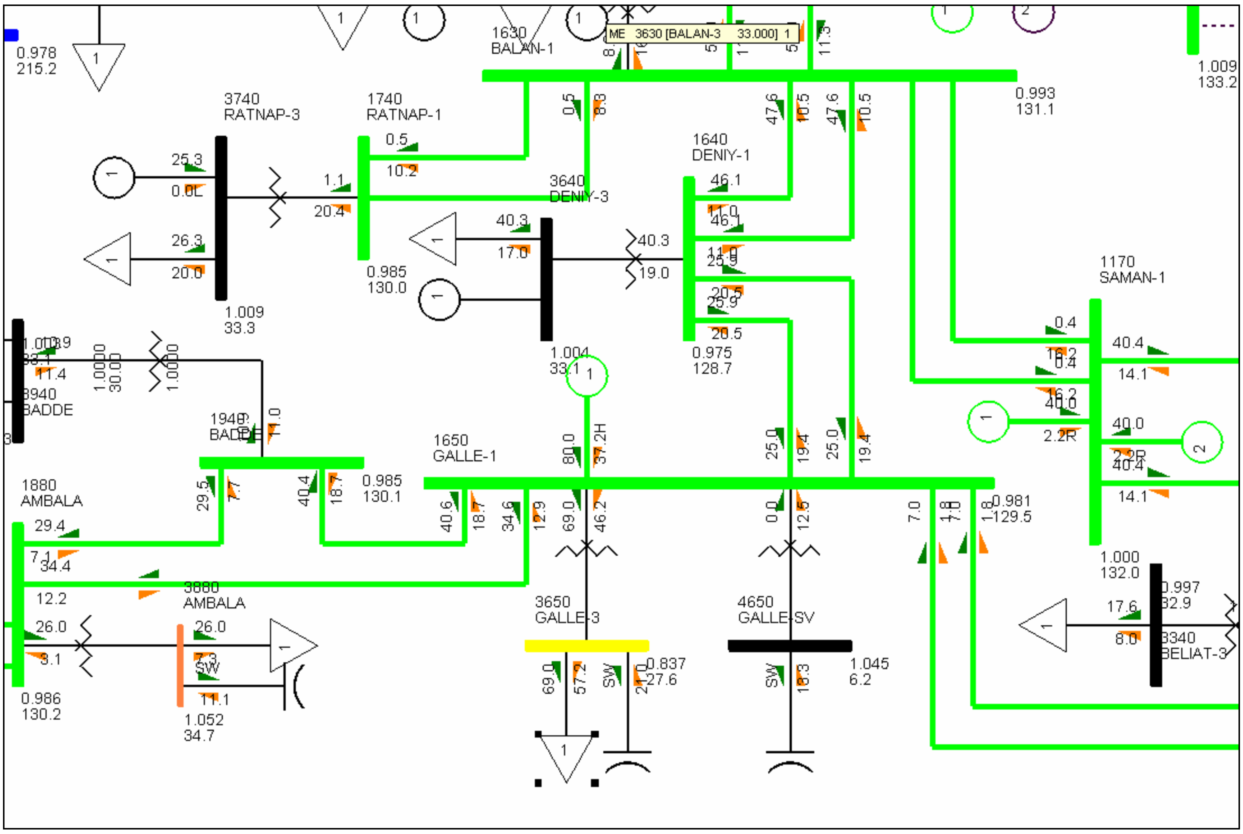
Galle GSS –10% load decrease from 1.25% Load at minimum tap position




Galle GSS –10% load decrease from 1.25% Load at nominal tap position

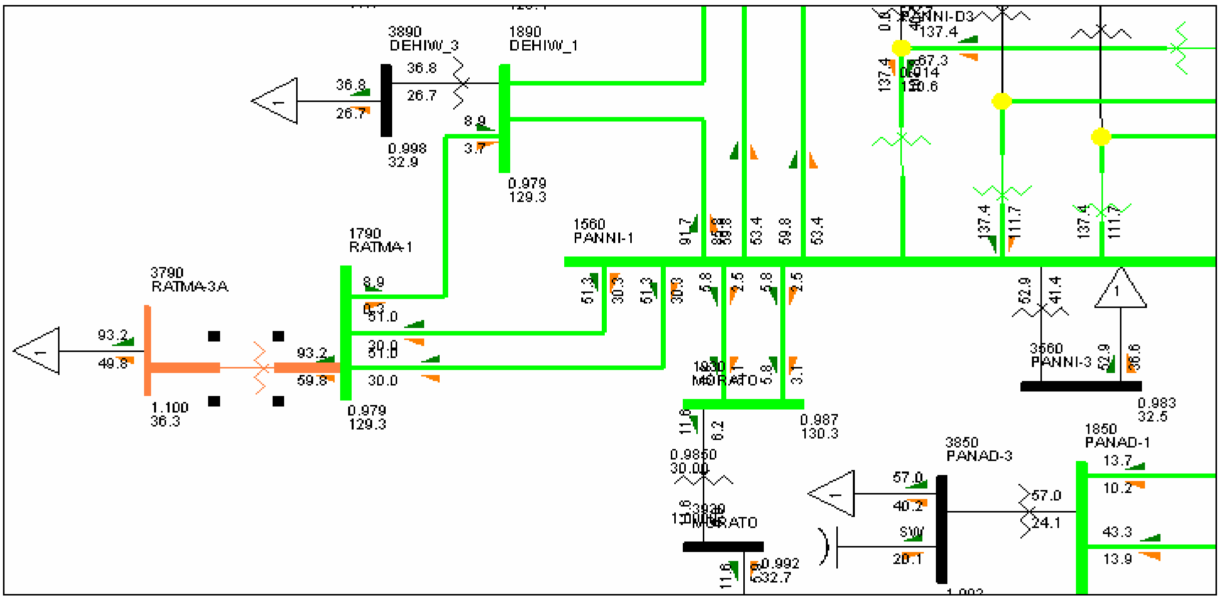


Galle GSS –10% load decrease from 1.25% Load at maximum tap position

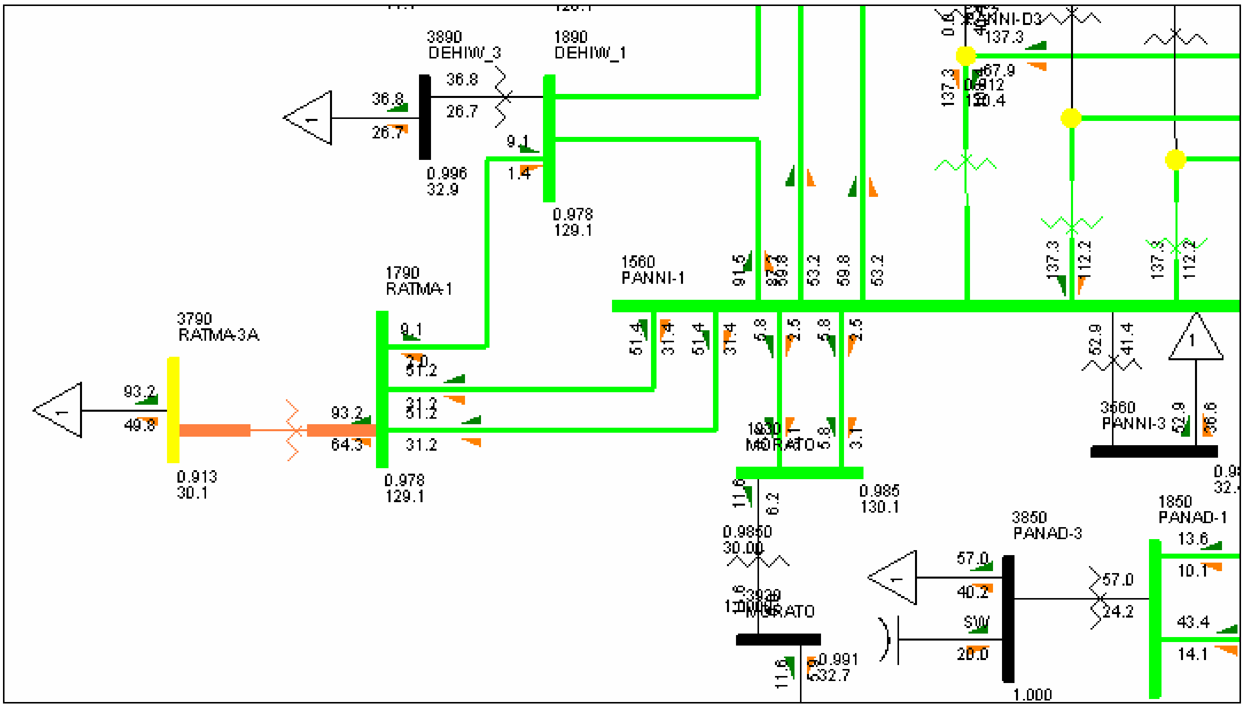


## (v) 2016 - Ratmalana GSS :

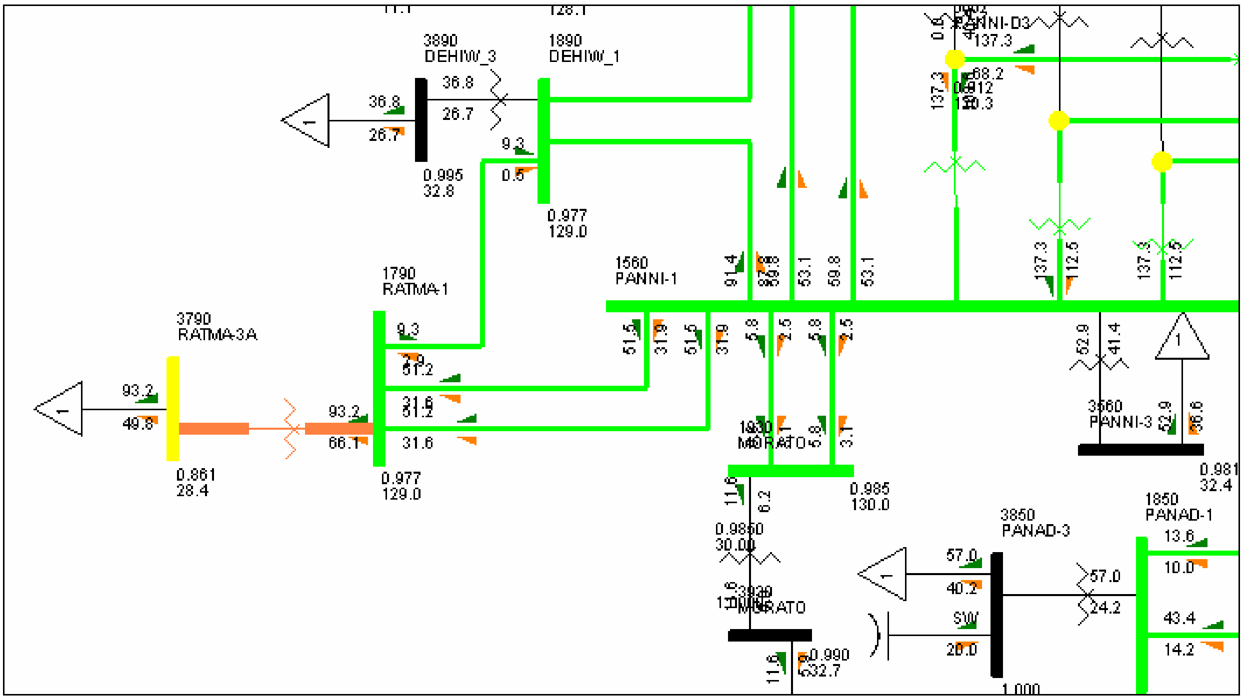
Ratmalana GSS – 15% load increase at minimum tap position



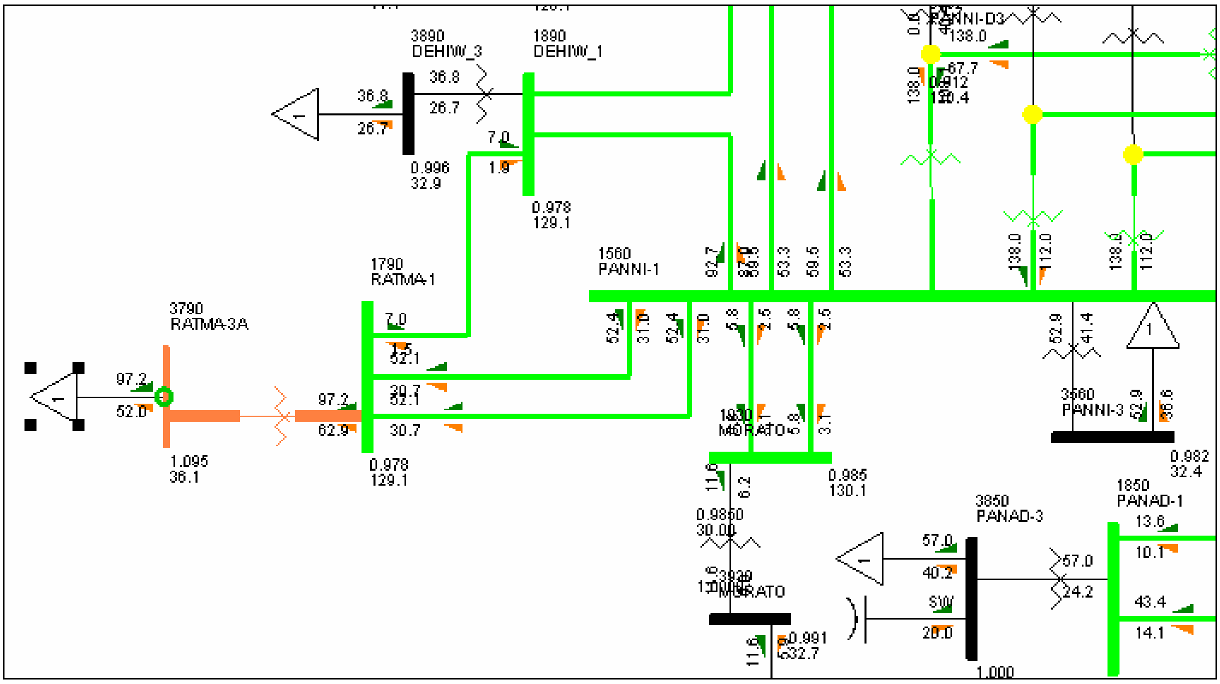
Ratmalana GSS – 15% load increase at nominal tap position



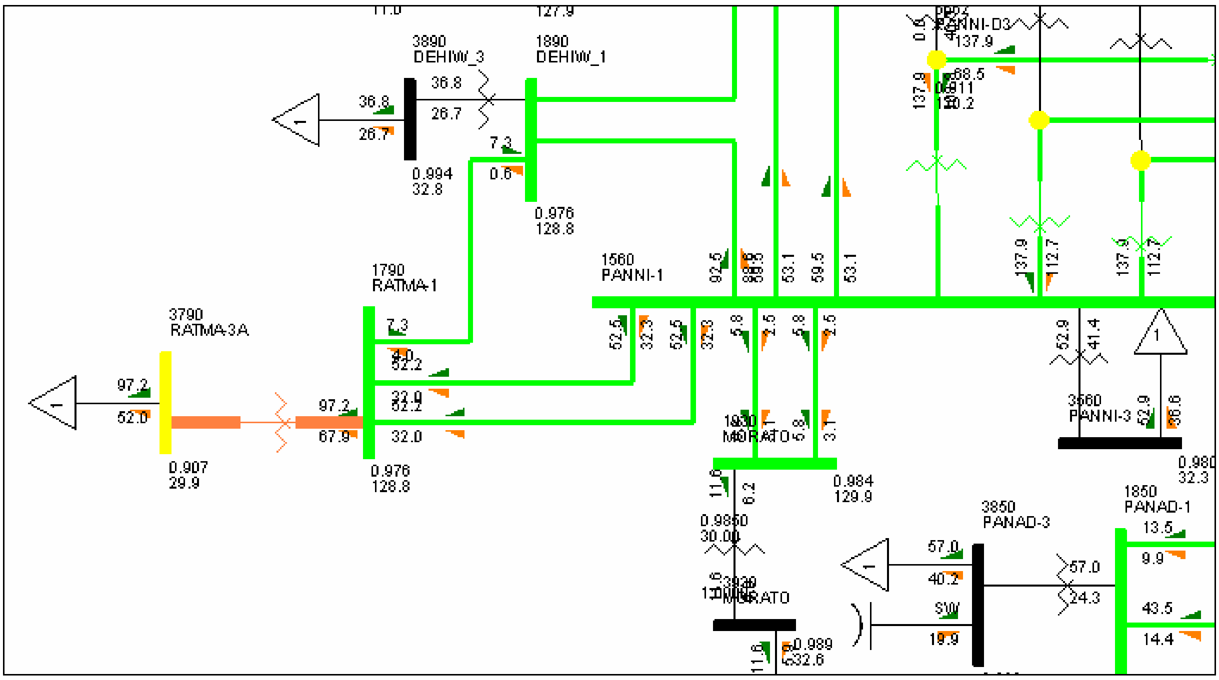

Ratmalana GSS – 15% load increase at maximum tap position



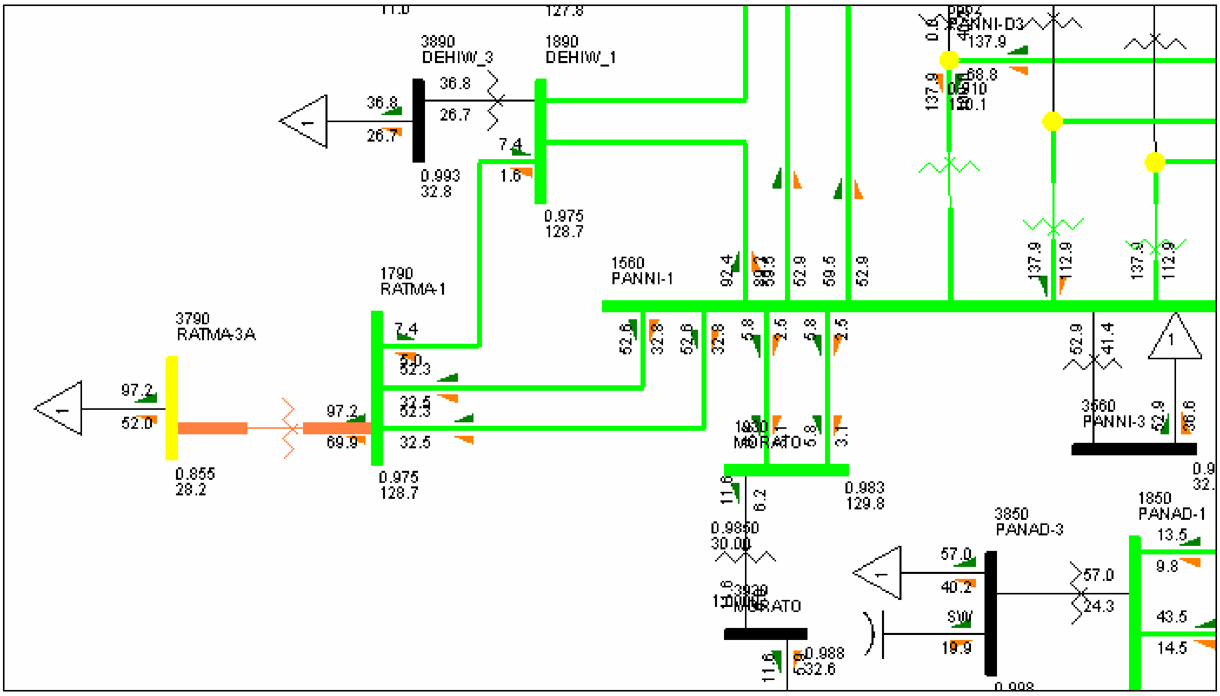
Ratmalana GSS – 20% load increase at minimum tap position



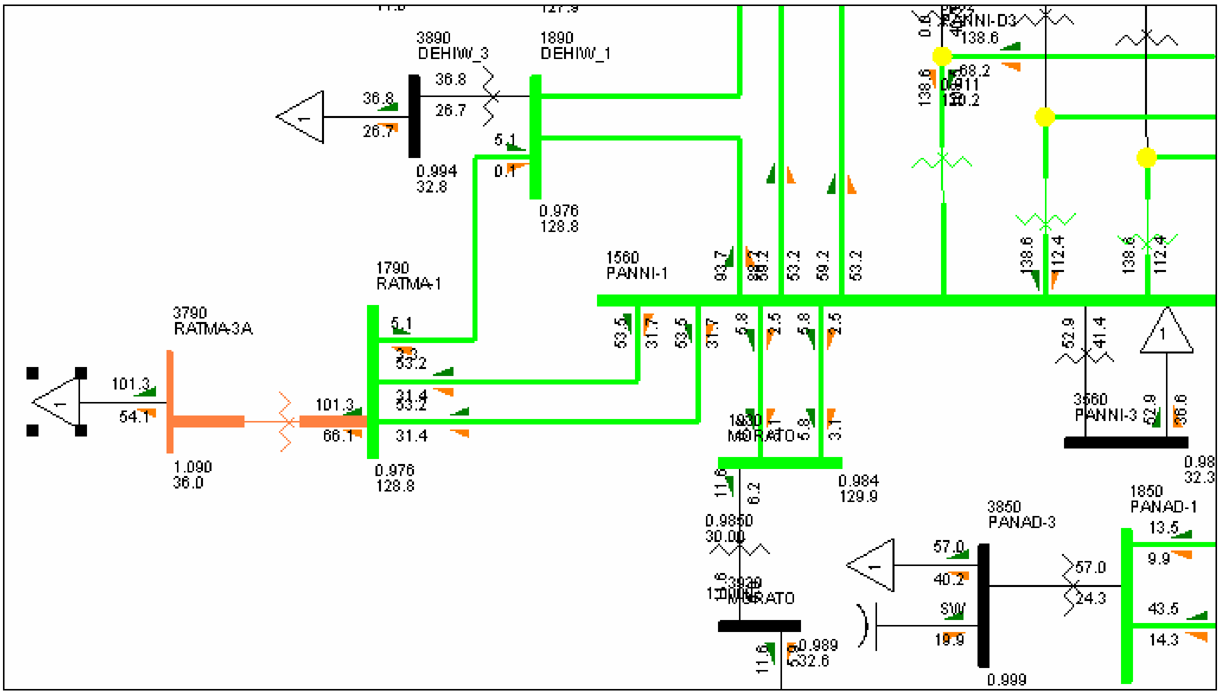

Ratmalana GSS – 20% load increase at nominal tap position



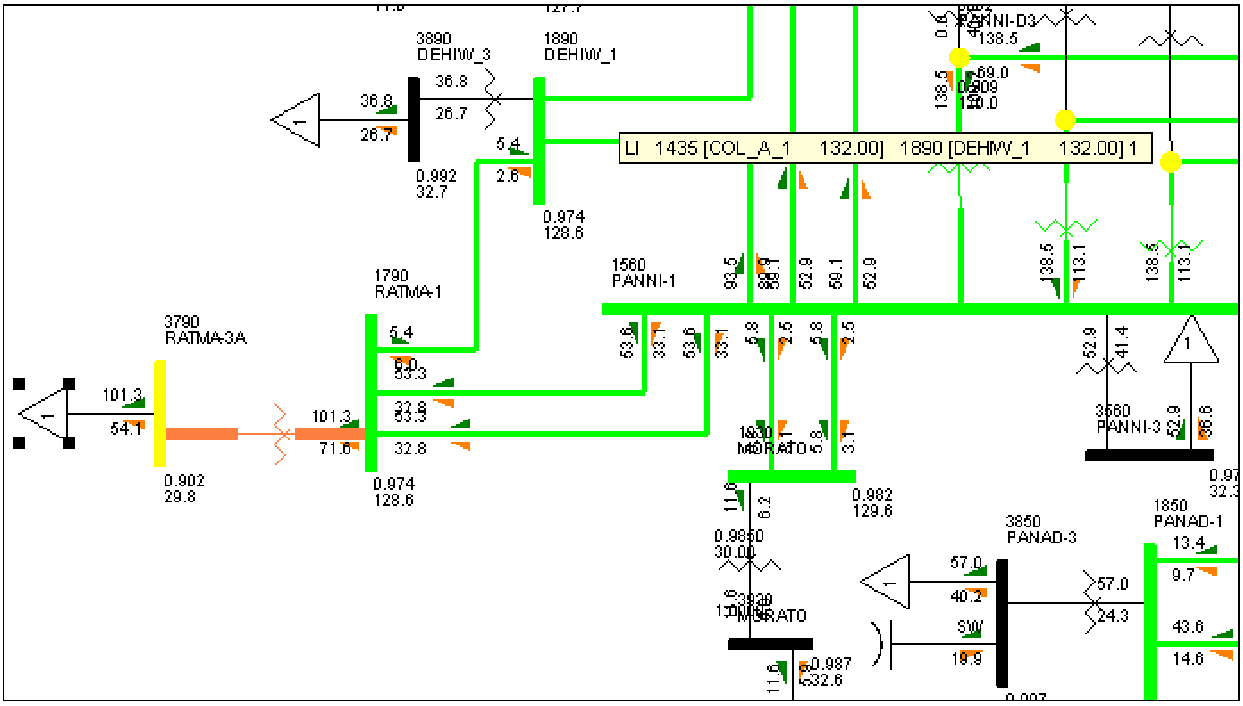
Ratmalana GSS – 20% load increase at maximum tap position



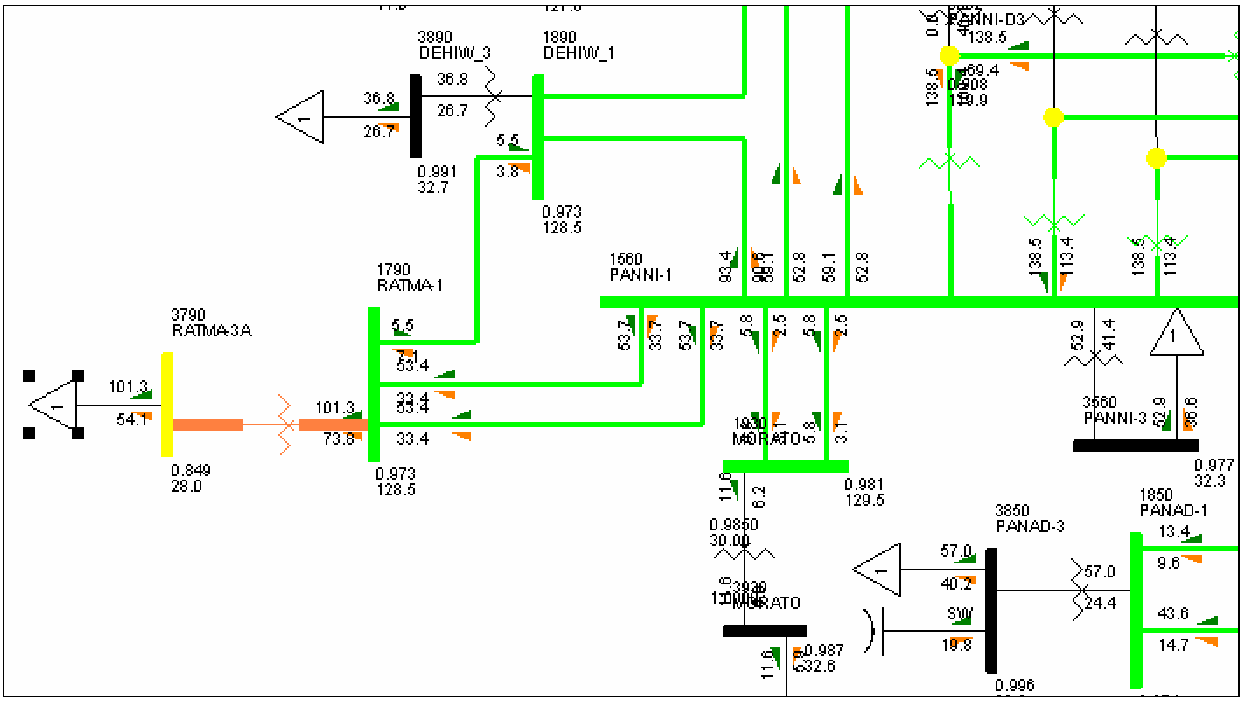
Ratmalana GSS – 25% load increase at minimum tap position



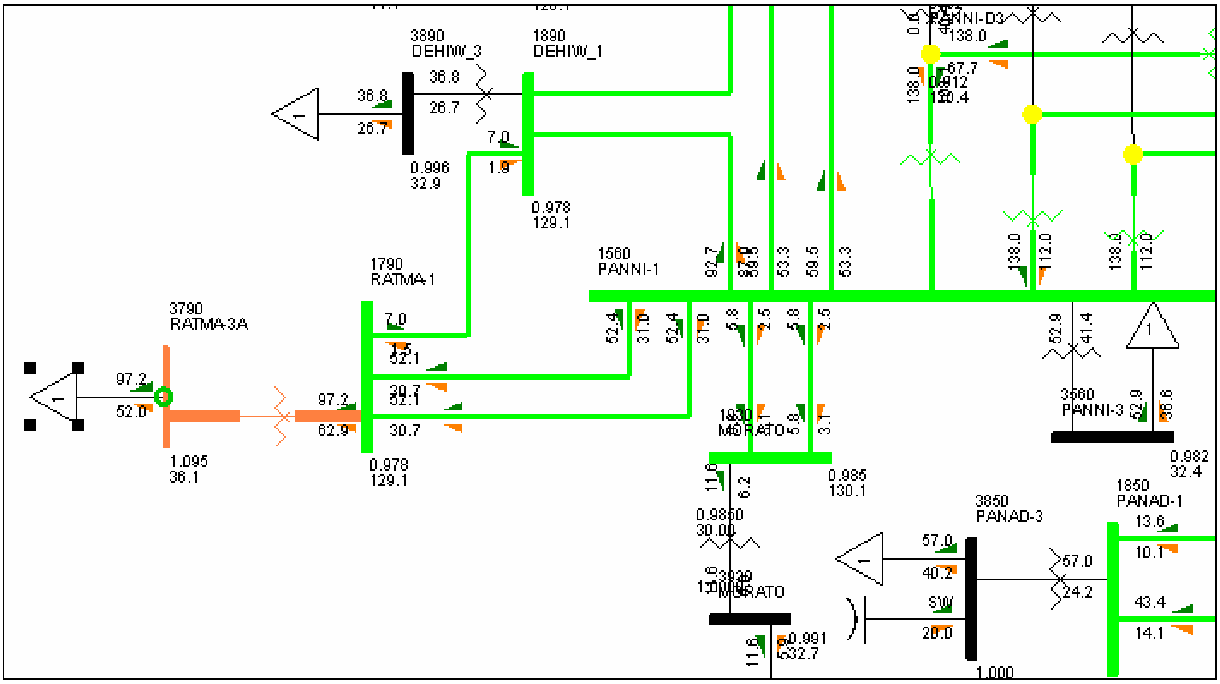
Ratmalana GSS – 25% load increase at nominal tap position



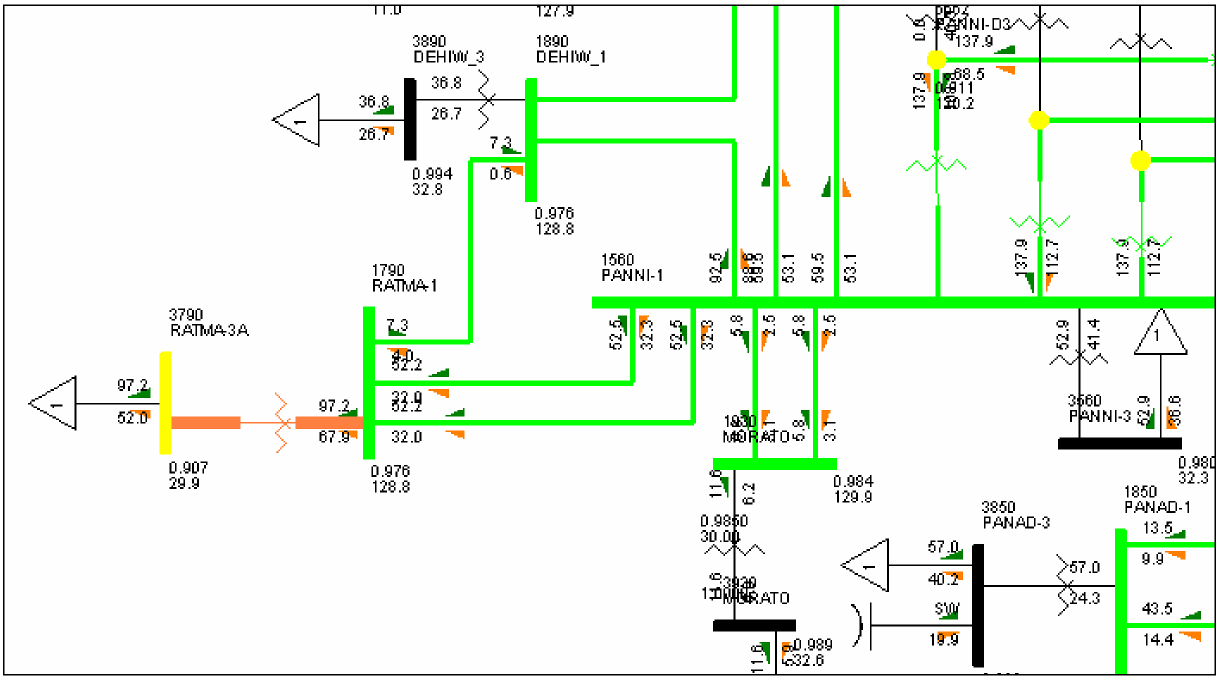

Ratmalana GSS – 25% load increase at maximum tap position



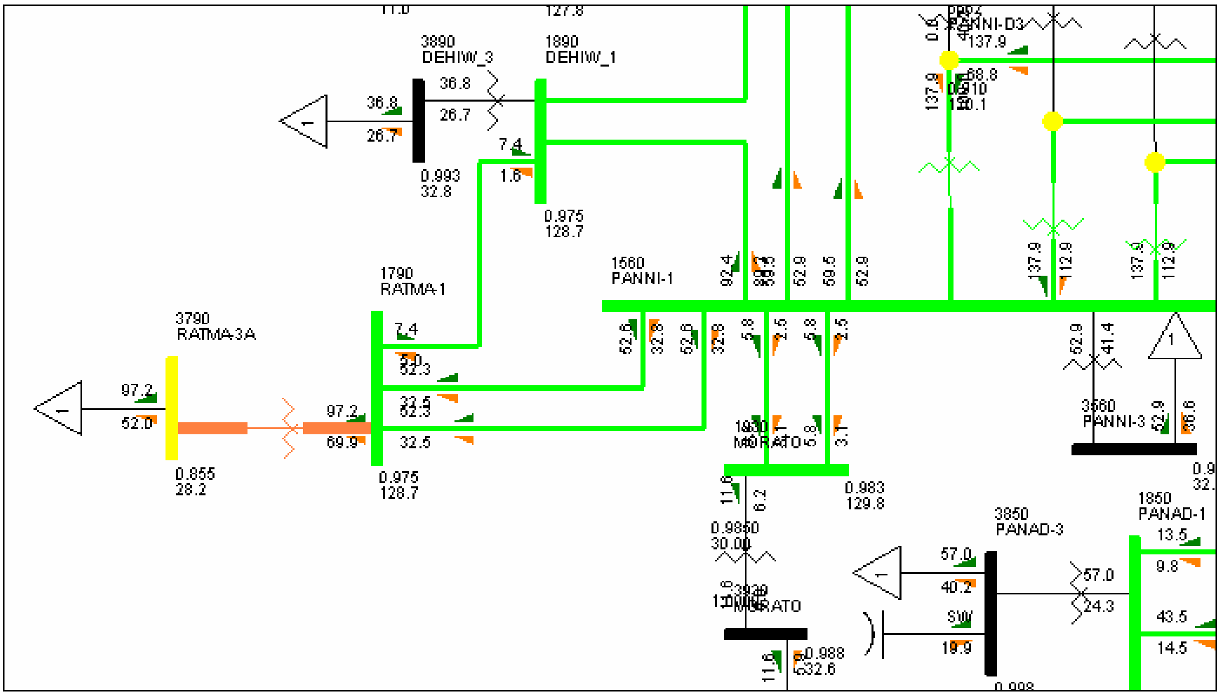
Ratmalana GSS –5% load decrease from 1.25% Load at minimum tap position



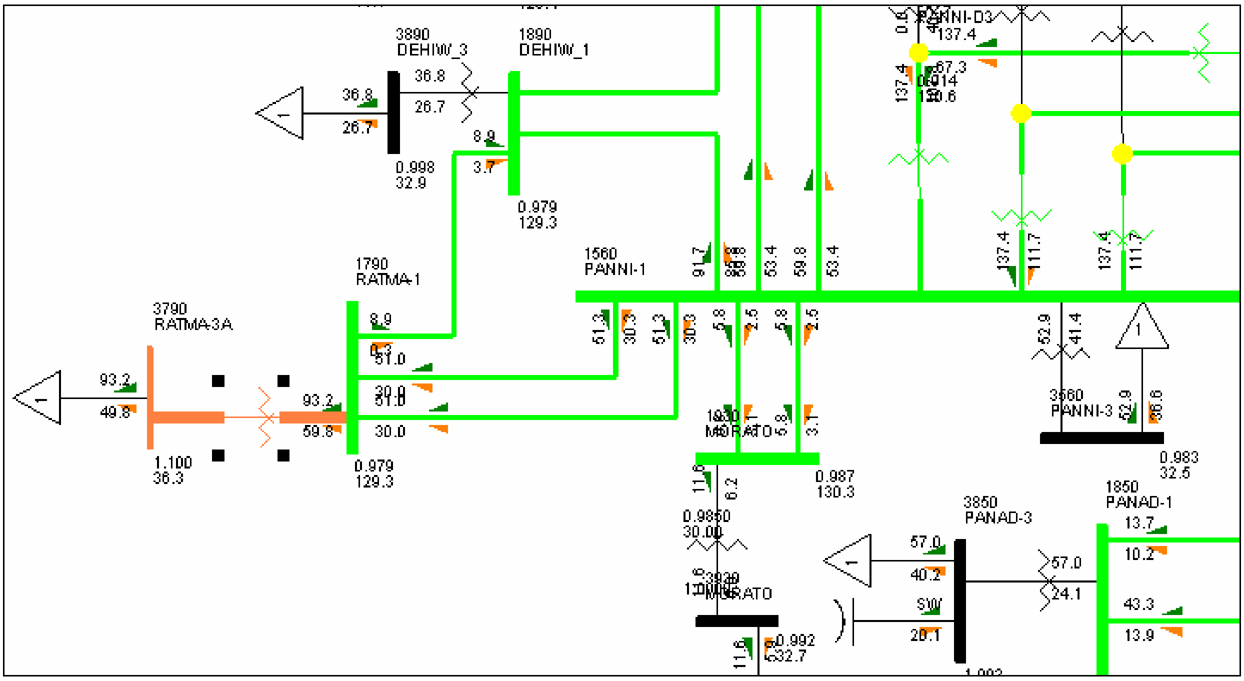
Ratmalana GSS –5% load decrease from 1.25% Load at nominal tap position



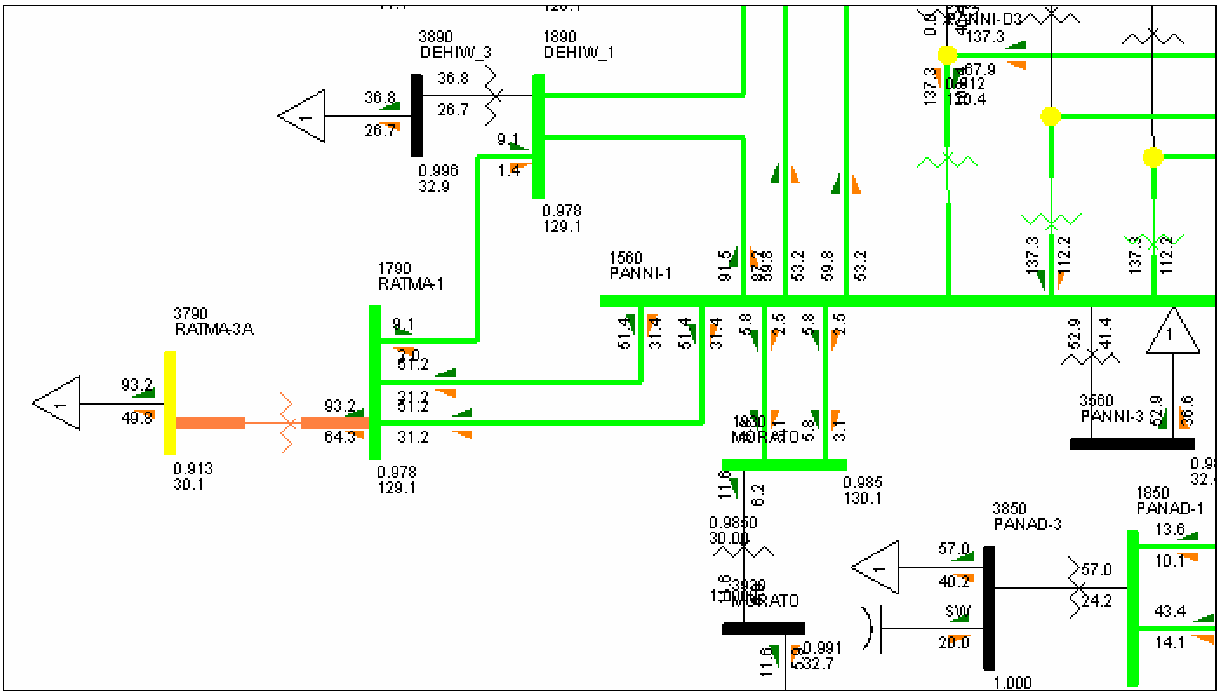
Ratmalana GSS –5% load decrease from 1.25% Load at maximum tap position



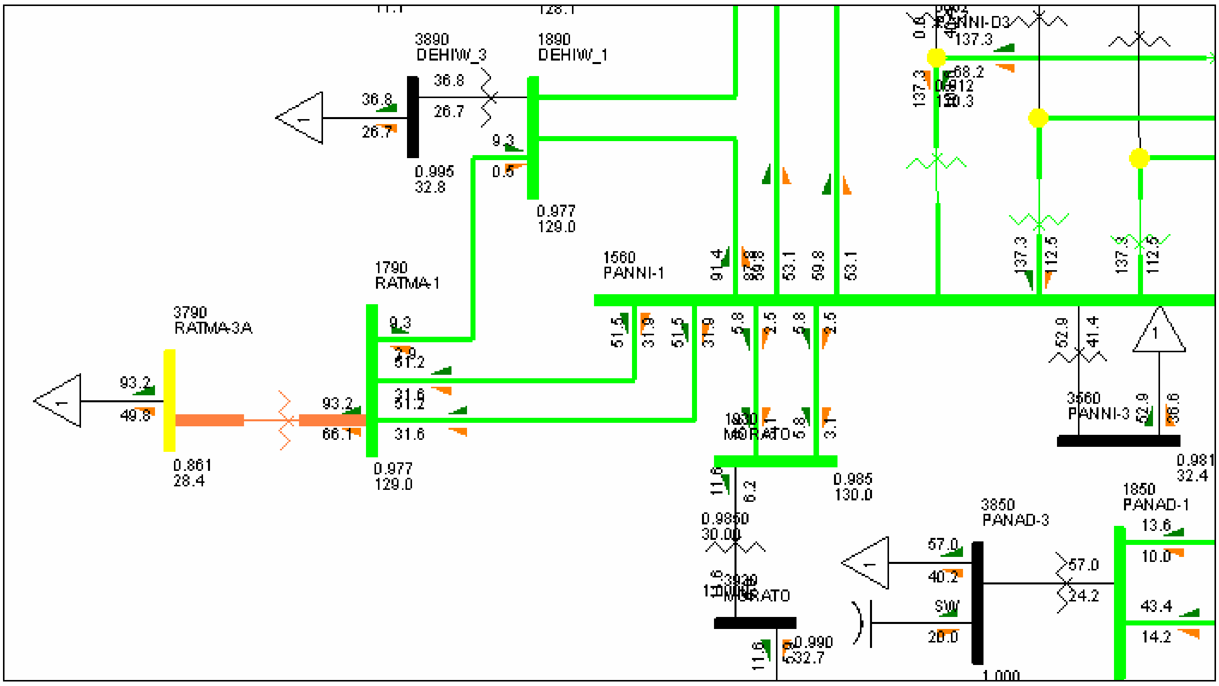

Ratmalana GSS –10% load decrease from 1.25% Load at minimum tap position



Ratmalana GSS –10% load decrease from 1.25% Load at nominal tap position

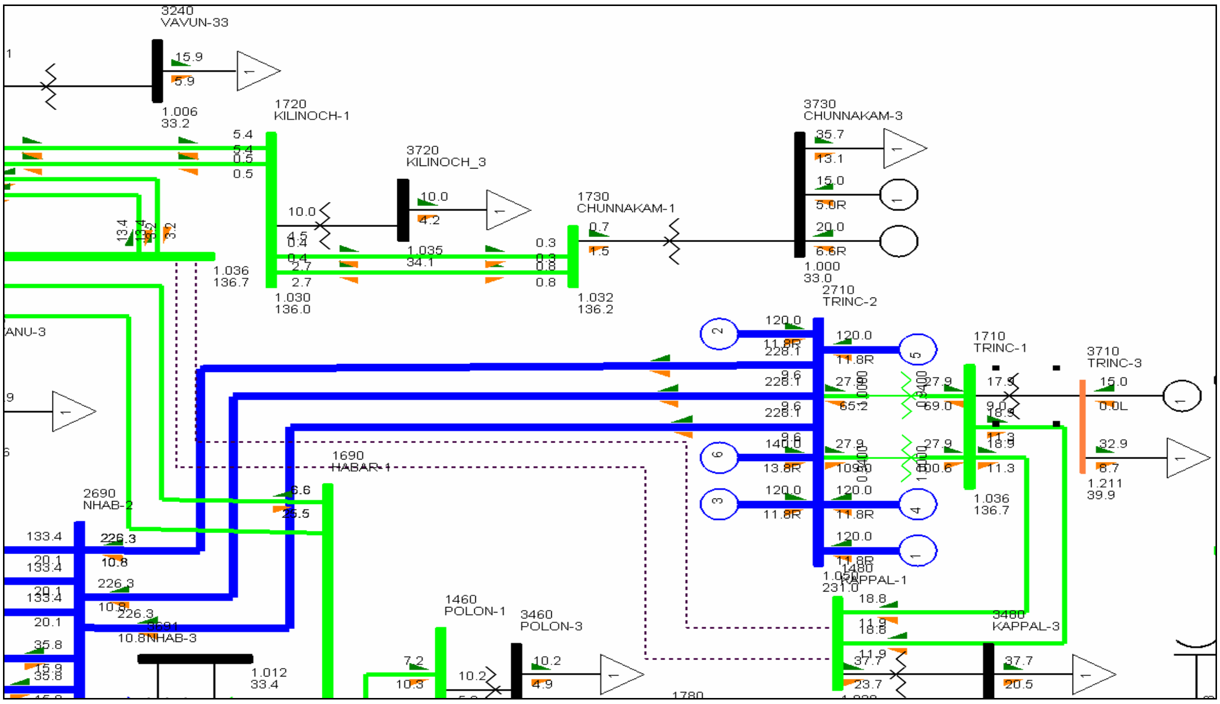



Ratmalana GSS –10% load decrease from 1.25% Load at maximum tap position

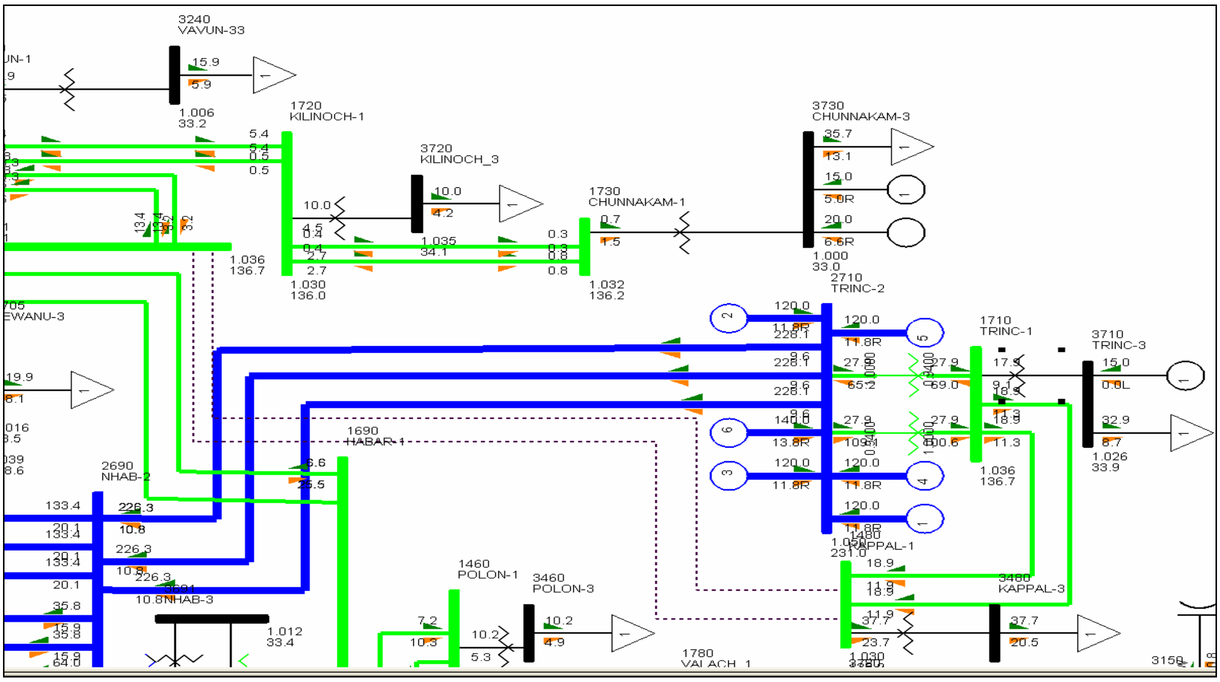


## (vi) 2016 - Trincomalee GSS :

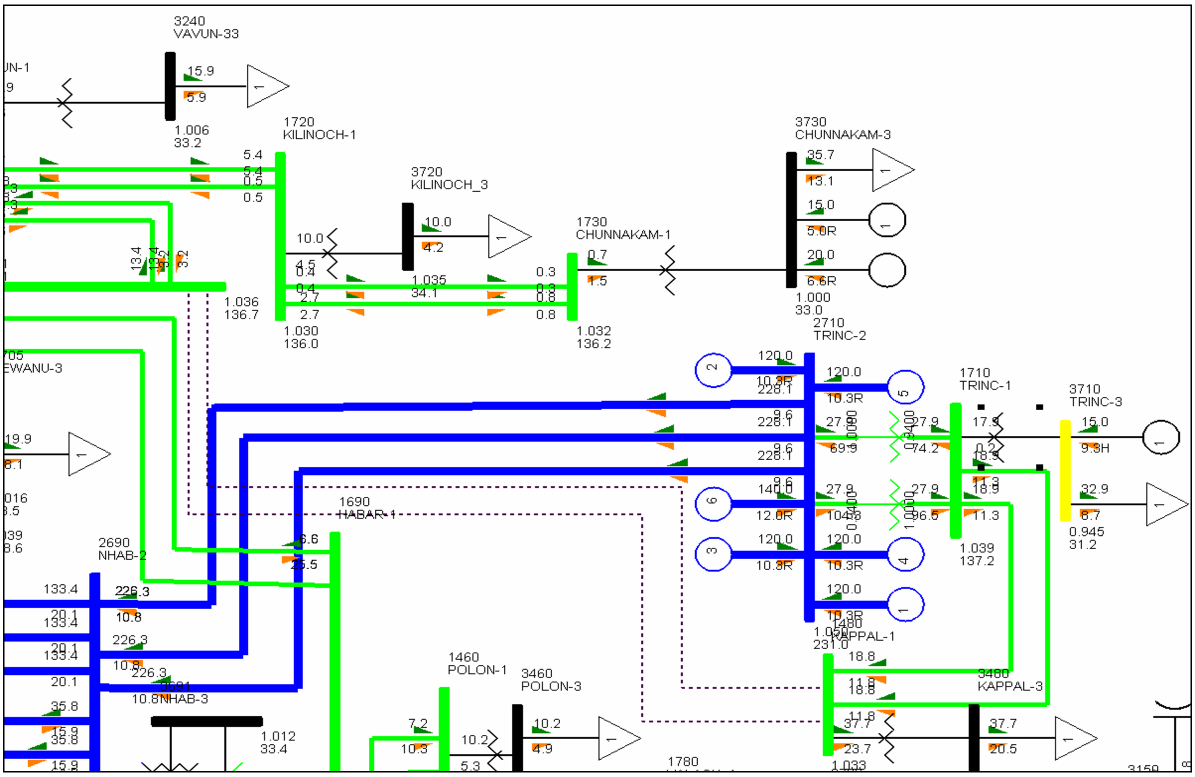
Trincomalee GSS – 15% load increase at minimum tap position



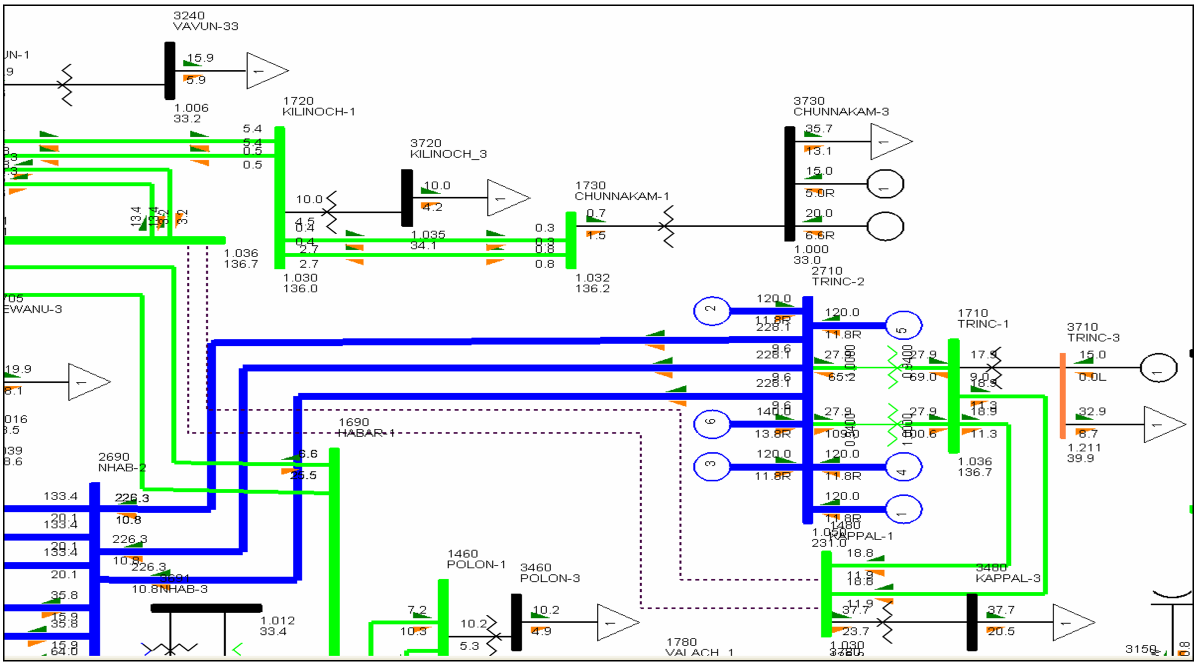

Trincomalee GSS – 15% load increase at nominal tap position



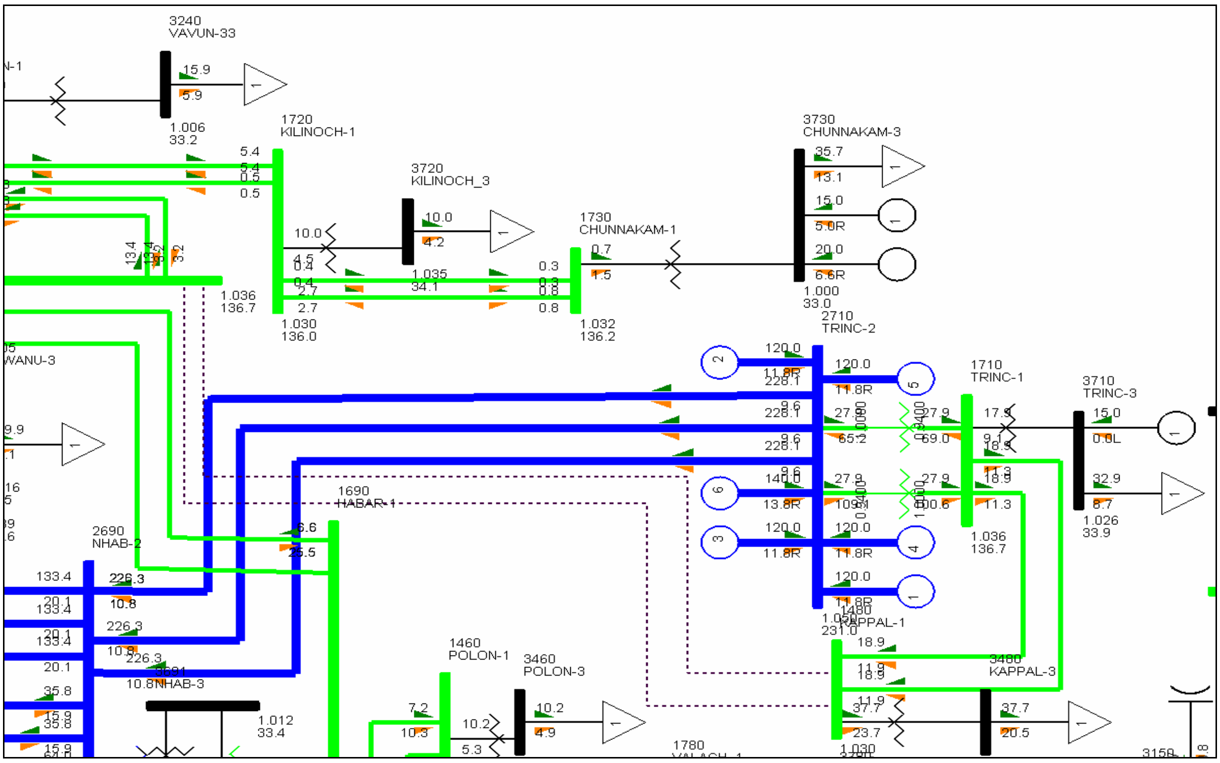
Trincomalee GSS – 15% load increase at maximum tap position



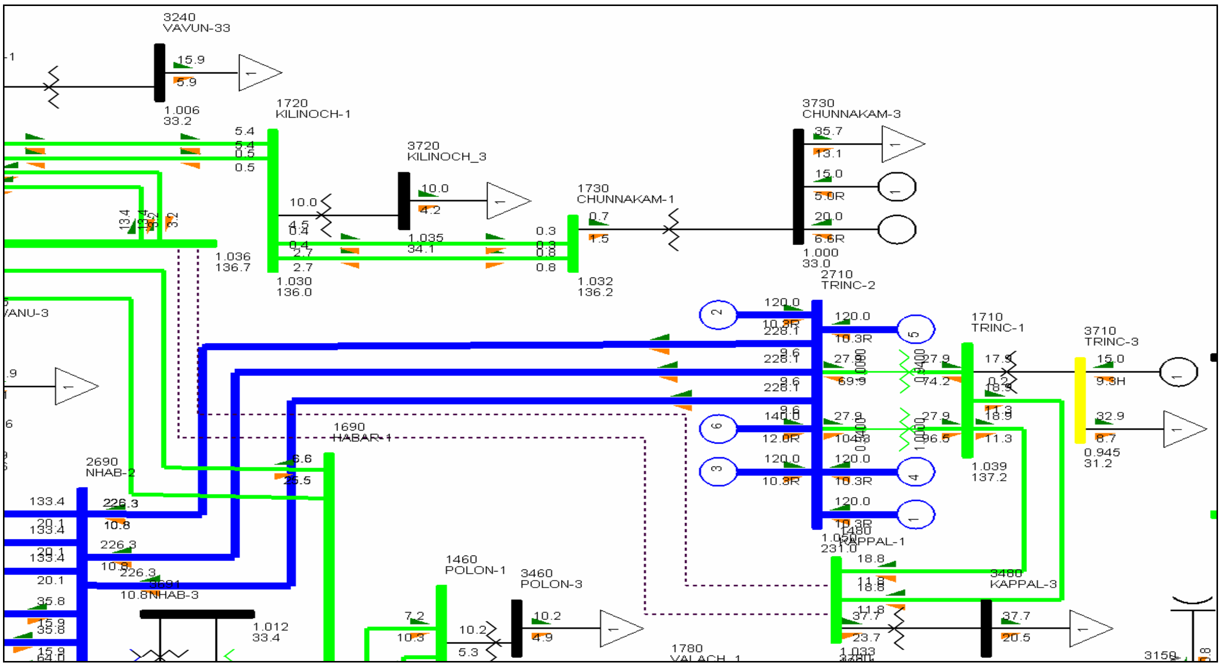
Trincomalee GSS – 20% load increase at minimum tap position



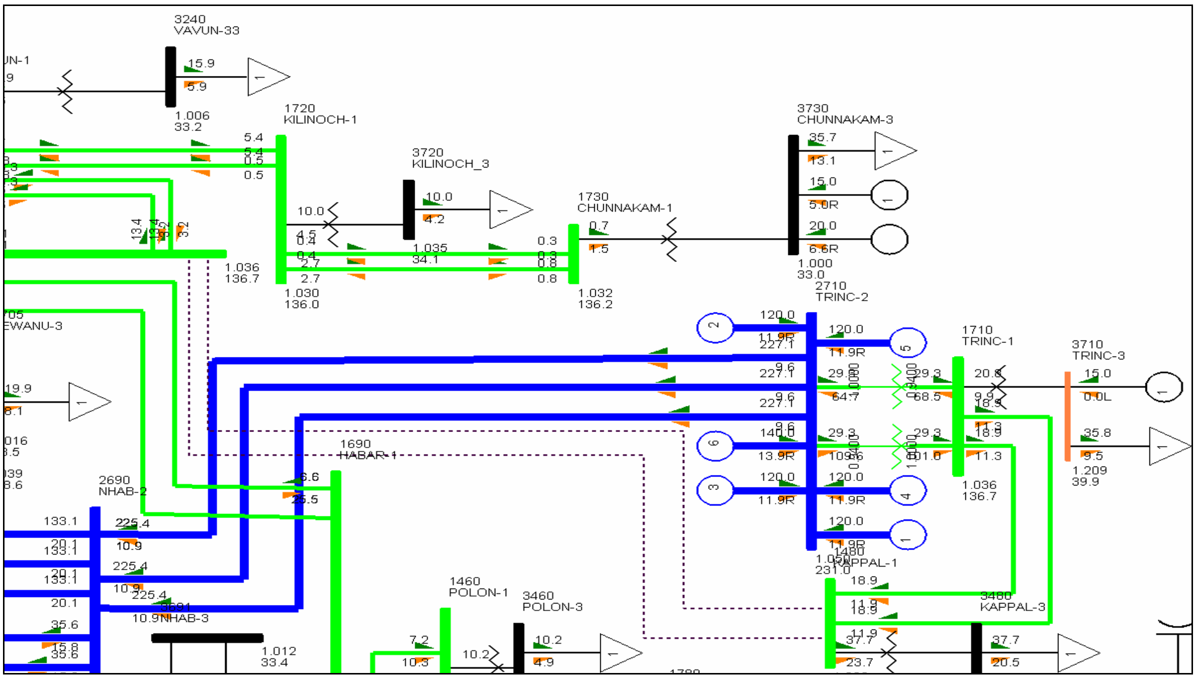
Trincomalee GSS – 20% load increase at nominal tap position



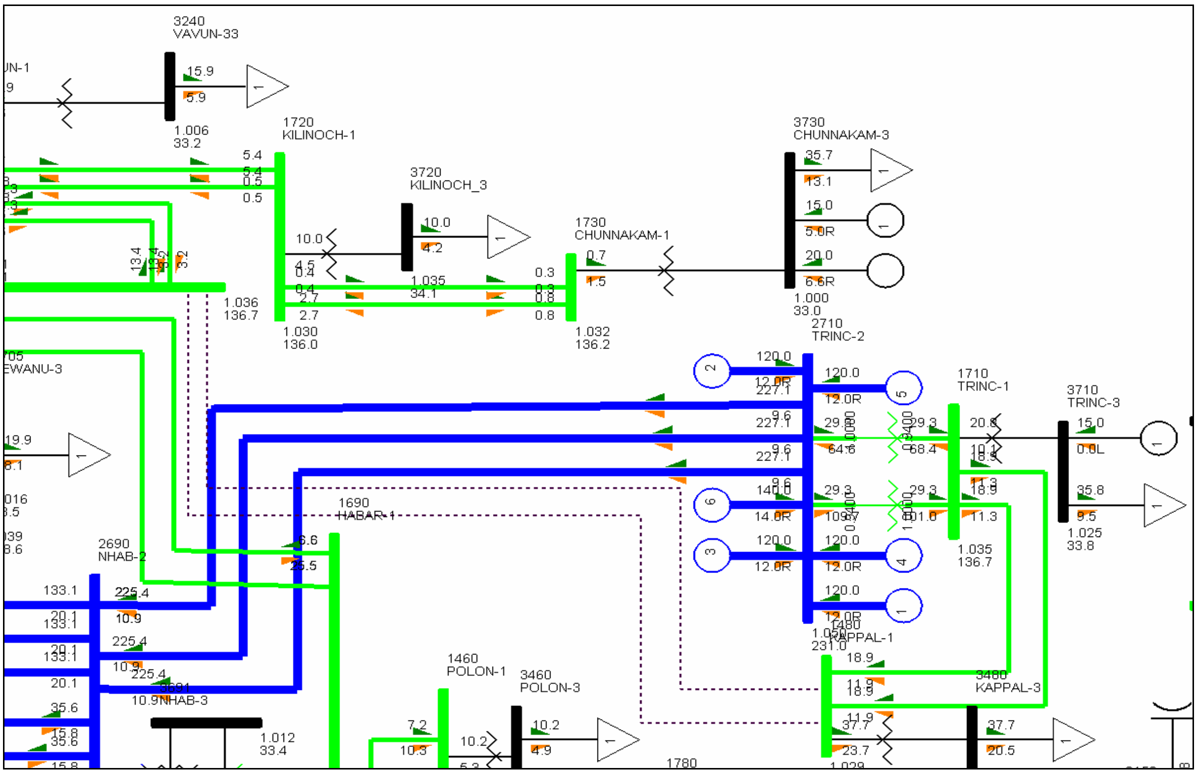

Trincomalee GSS – 20% load increase at maximum tap position



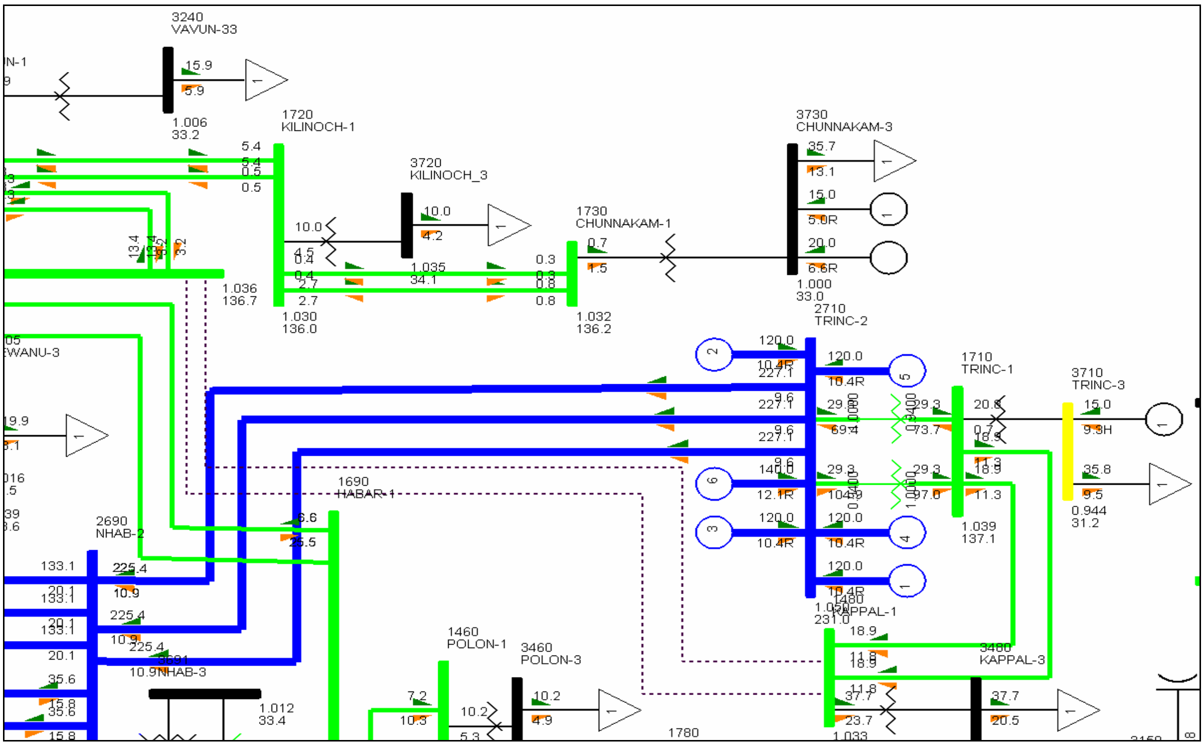
Trincomalee GSS – 25% load increase at minimum tap position



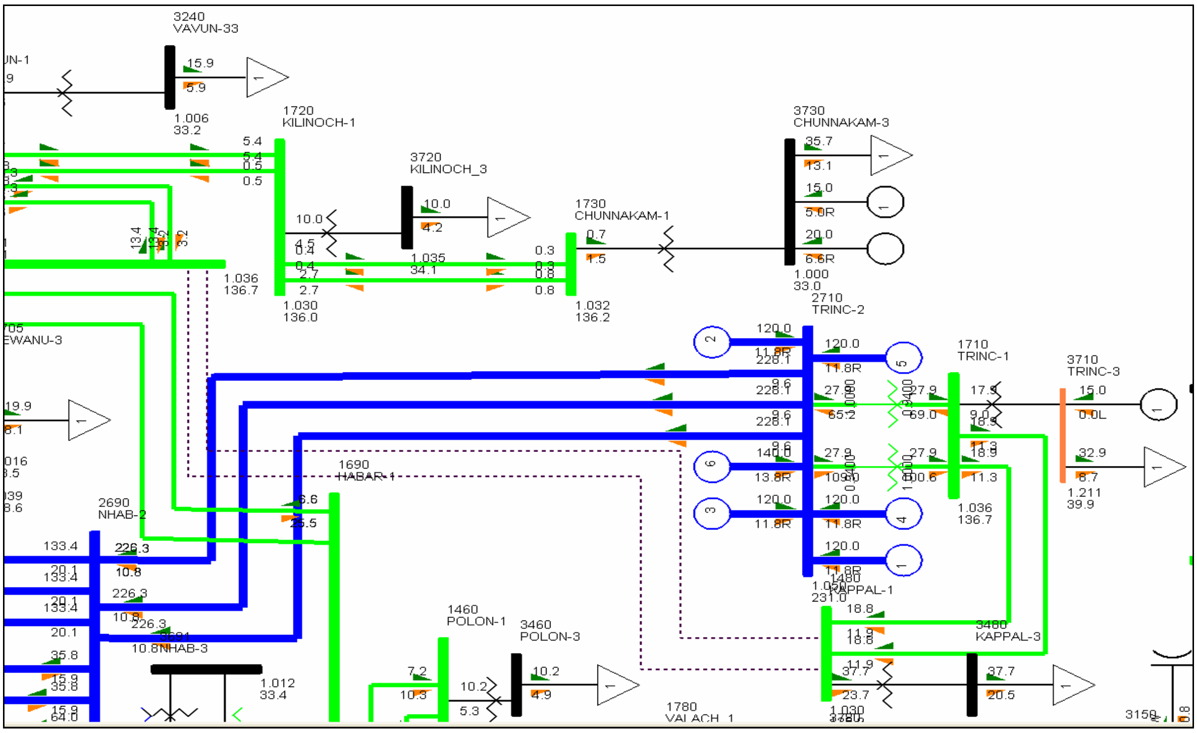

Trincomalee GSS – 25% load increase at nominal tap position



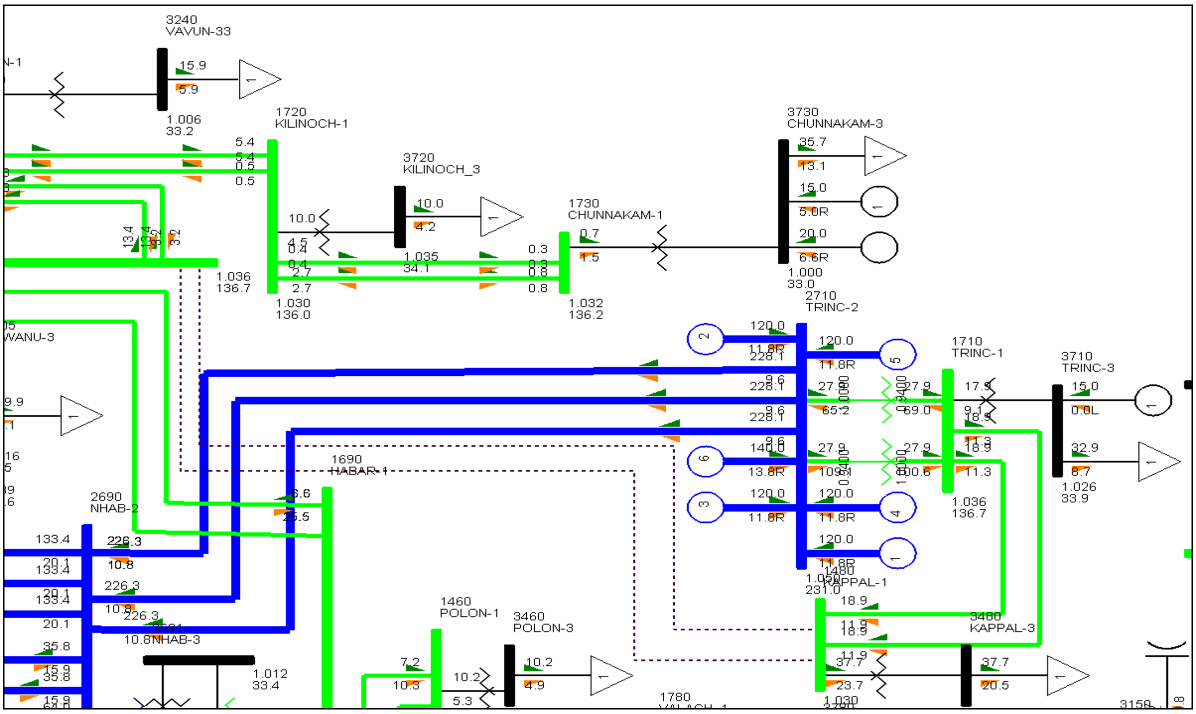
Trincomalee GSS – 25% load increase at maximum tap position



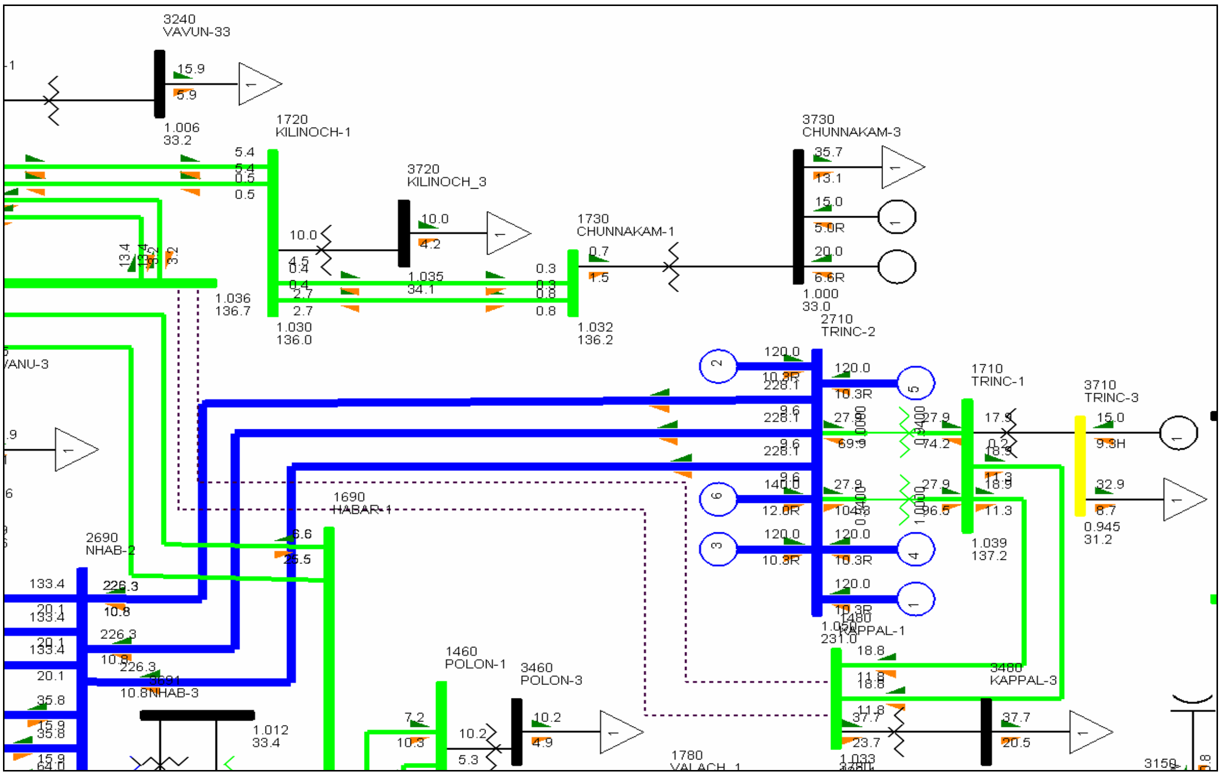

Trincomalee GSS –5% load decrease from 1.25% Load at minimum tap position



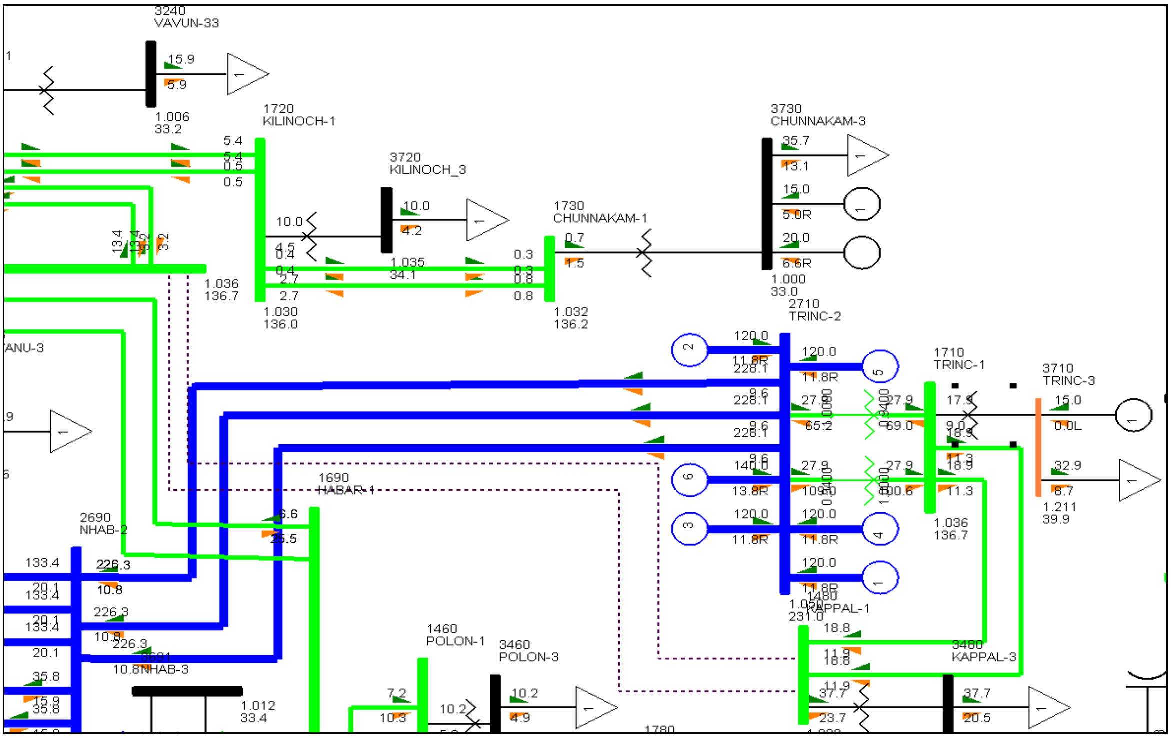
Trincomalee GSS –5% load decrease from 1.25% Load at nominal tap position



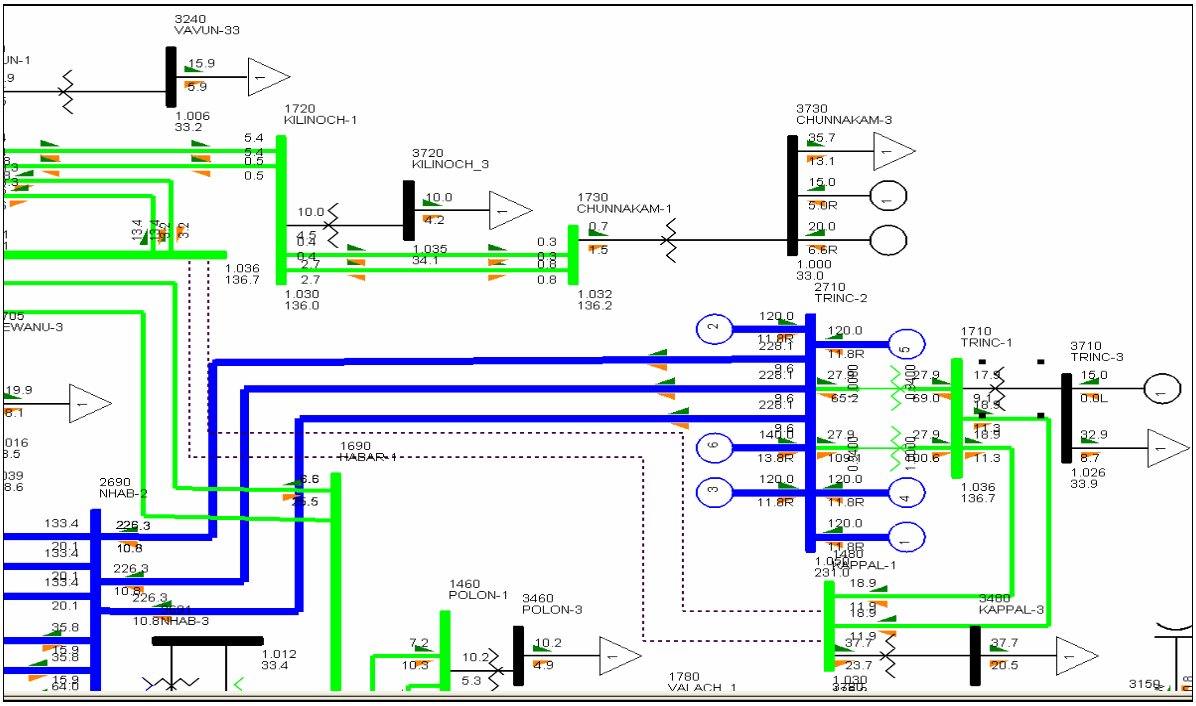

Trincomalee GSS –5% load decrease from 1.25% Load at maximum tap position



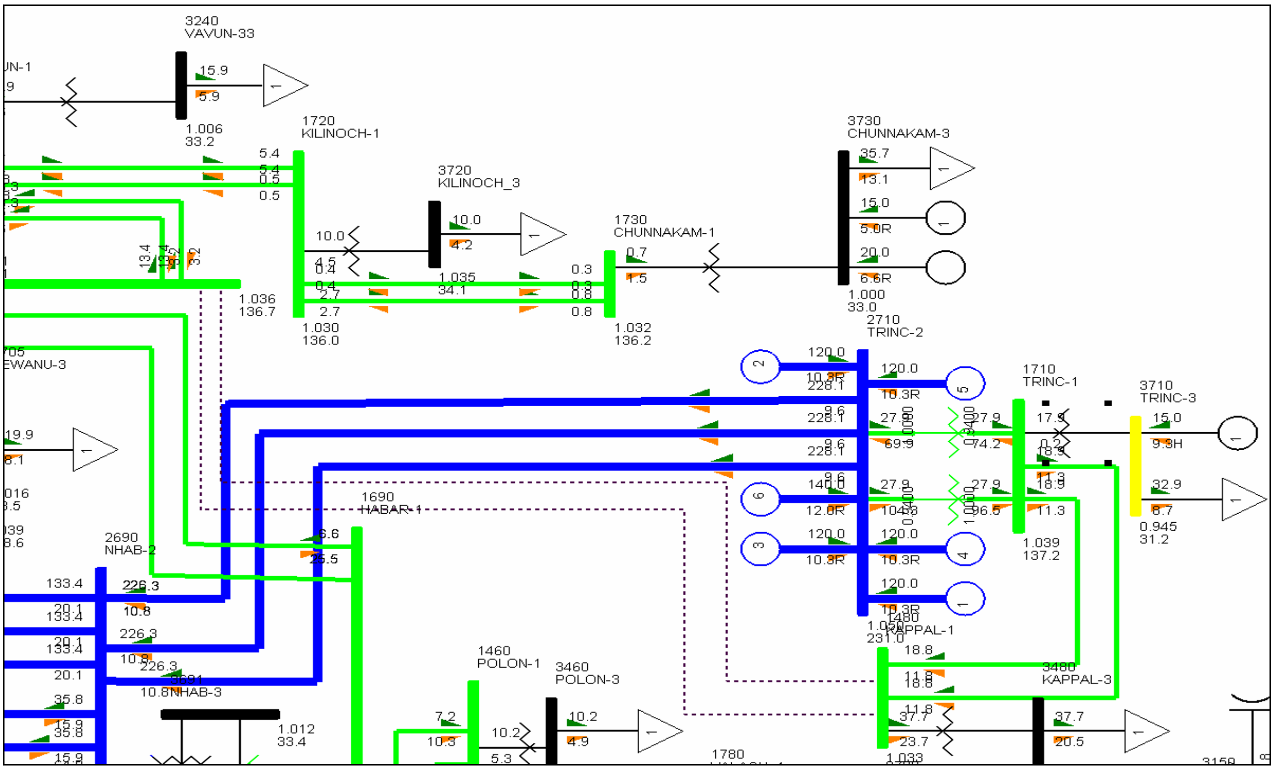
Trincomalee GSS –10% load decrease from 1.25% Load at minimum tap position




Trincomalee GSS –10% load decrease from 1.25% Load at nominal tap position



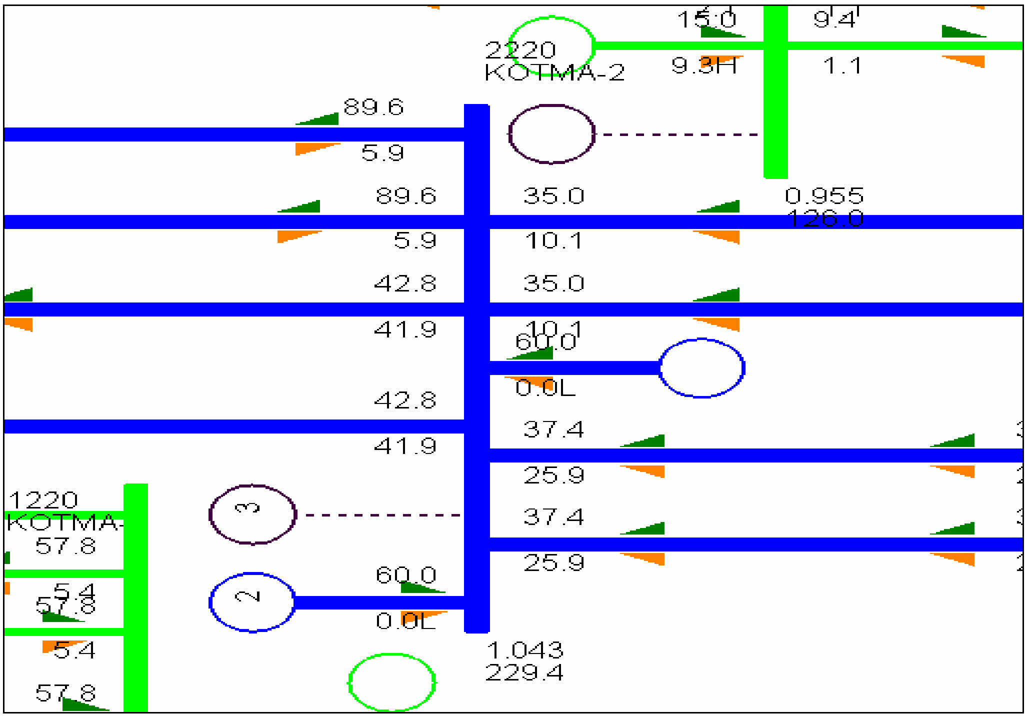
Trincomalee GSS –10% load decrease from 1.25% Load at maximum tap position

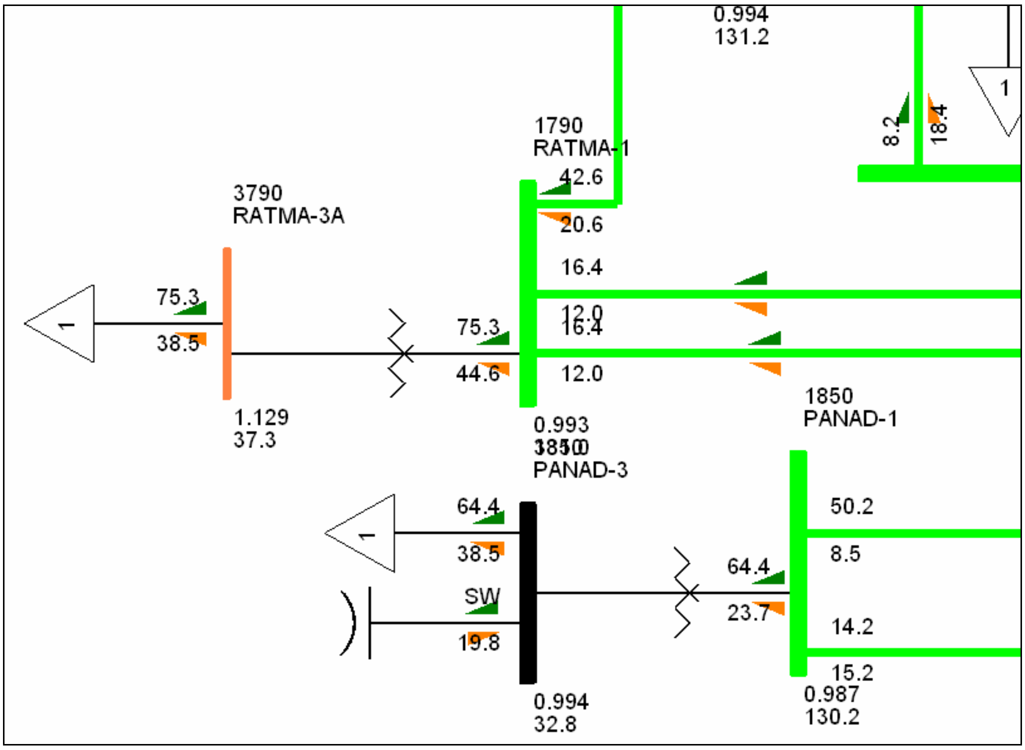


## (E) AVR Setpoints and Tap Positions:

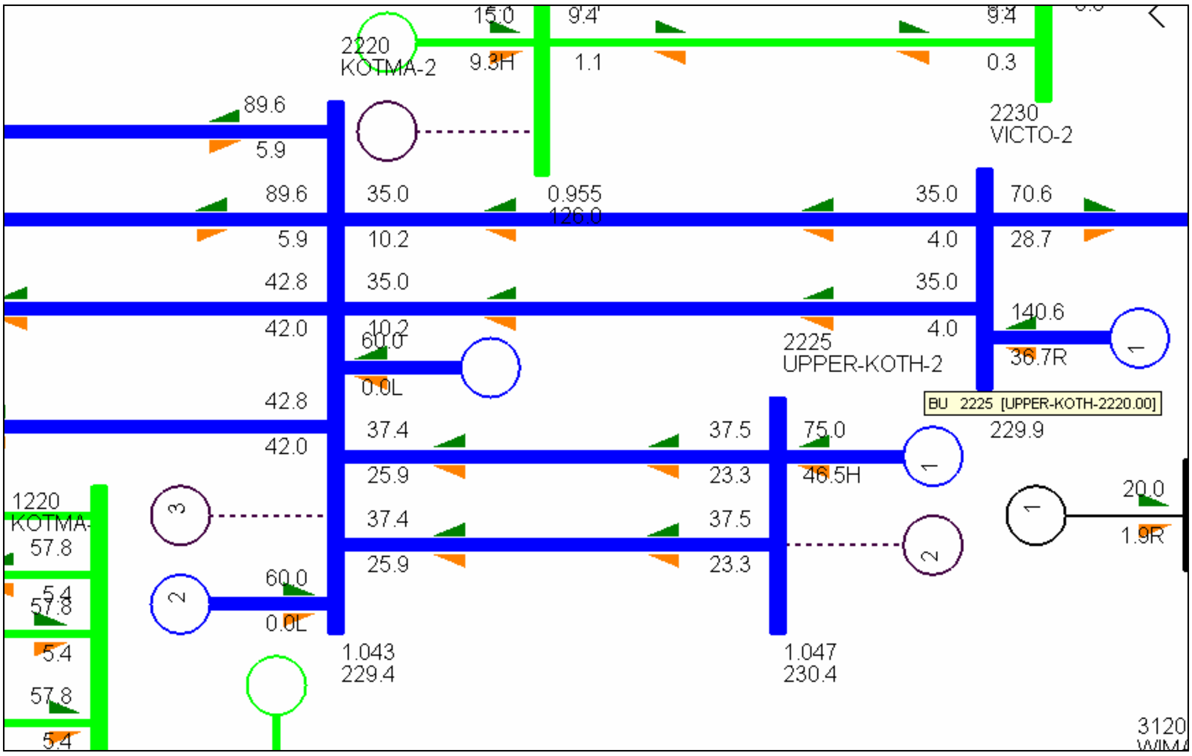
### *Kotmale PP and Ratmalana GSS:*

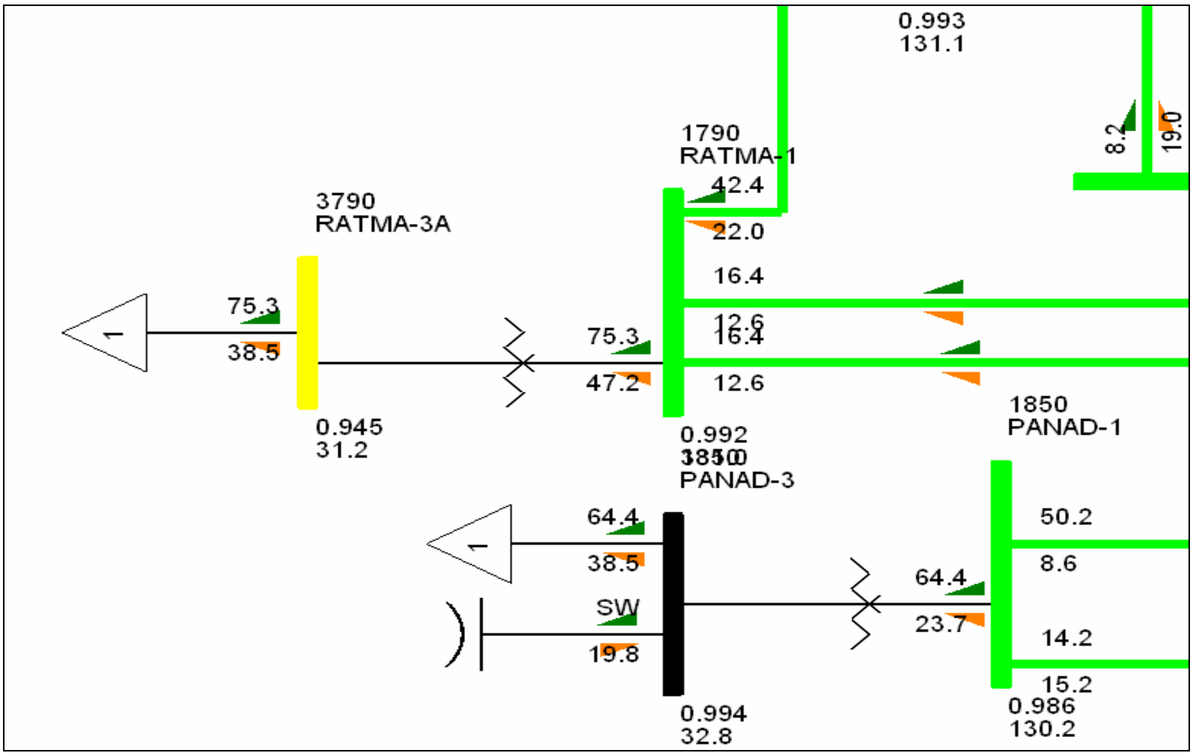
Kotmale Vshedu=<1.03 and Ratmalana GSS at minimum tap position



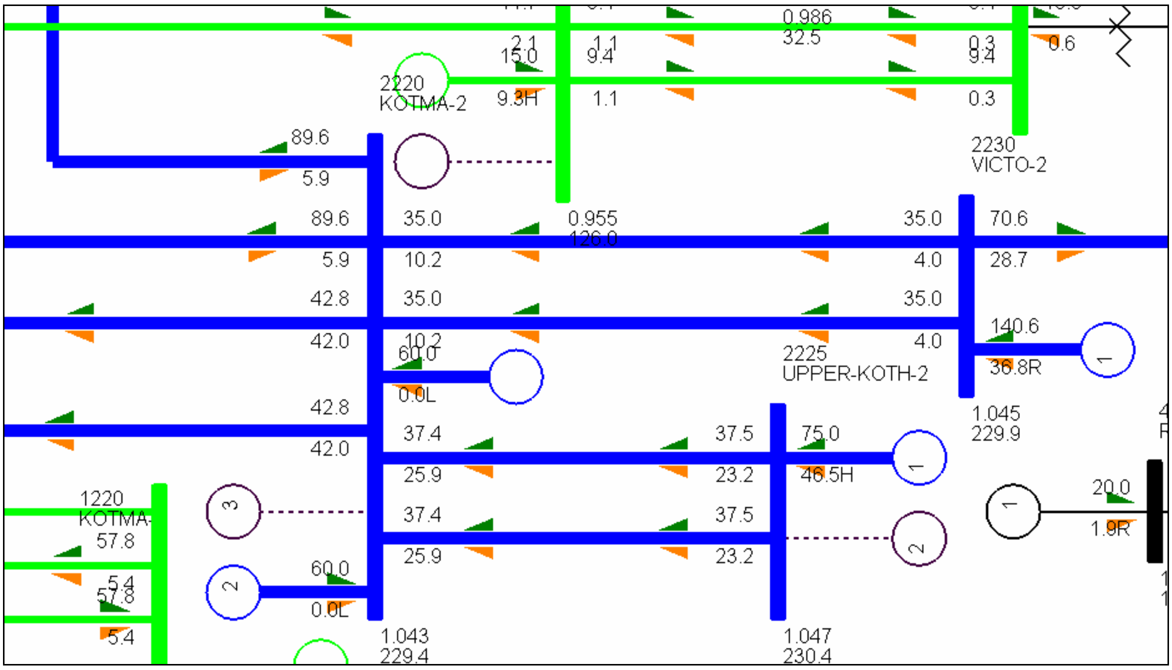



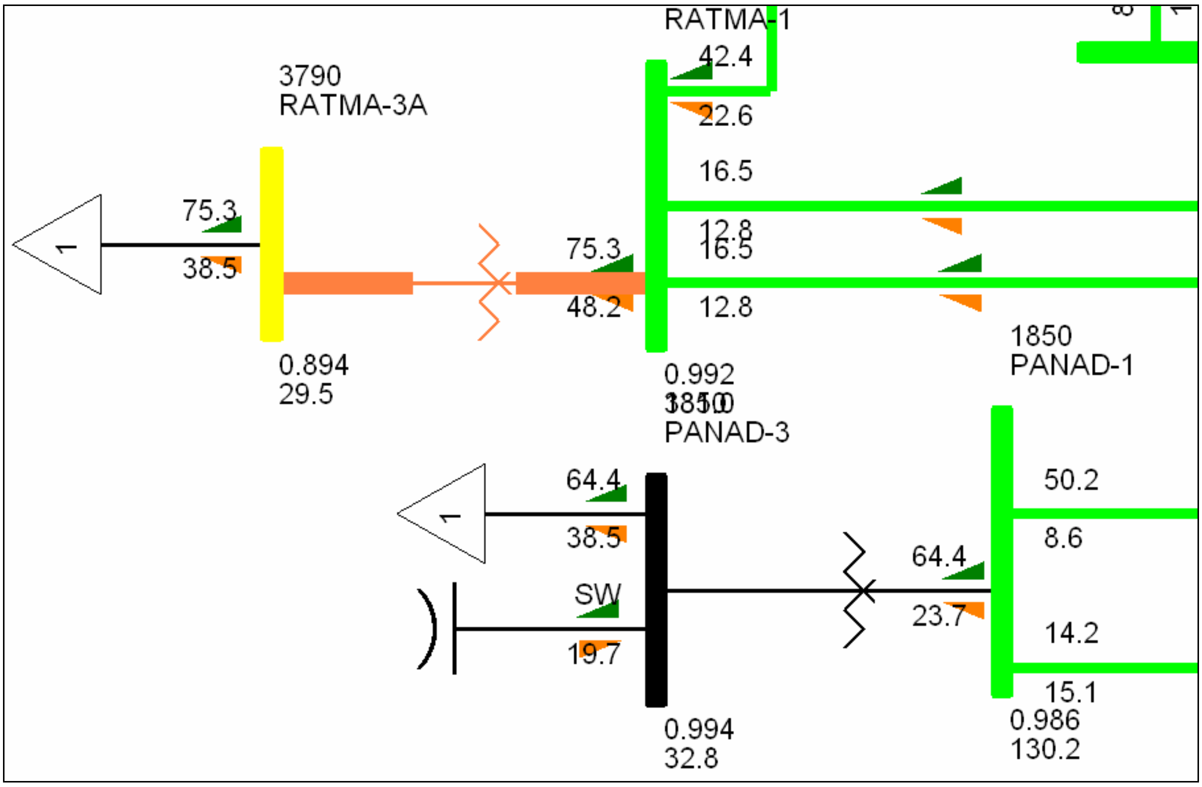
Kotmale Vshedu=<1.03 and Ratmalana GSS at nominal tap position



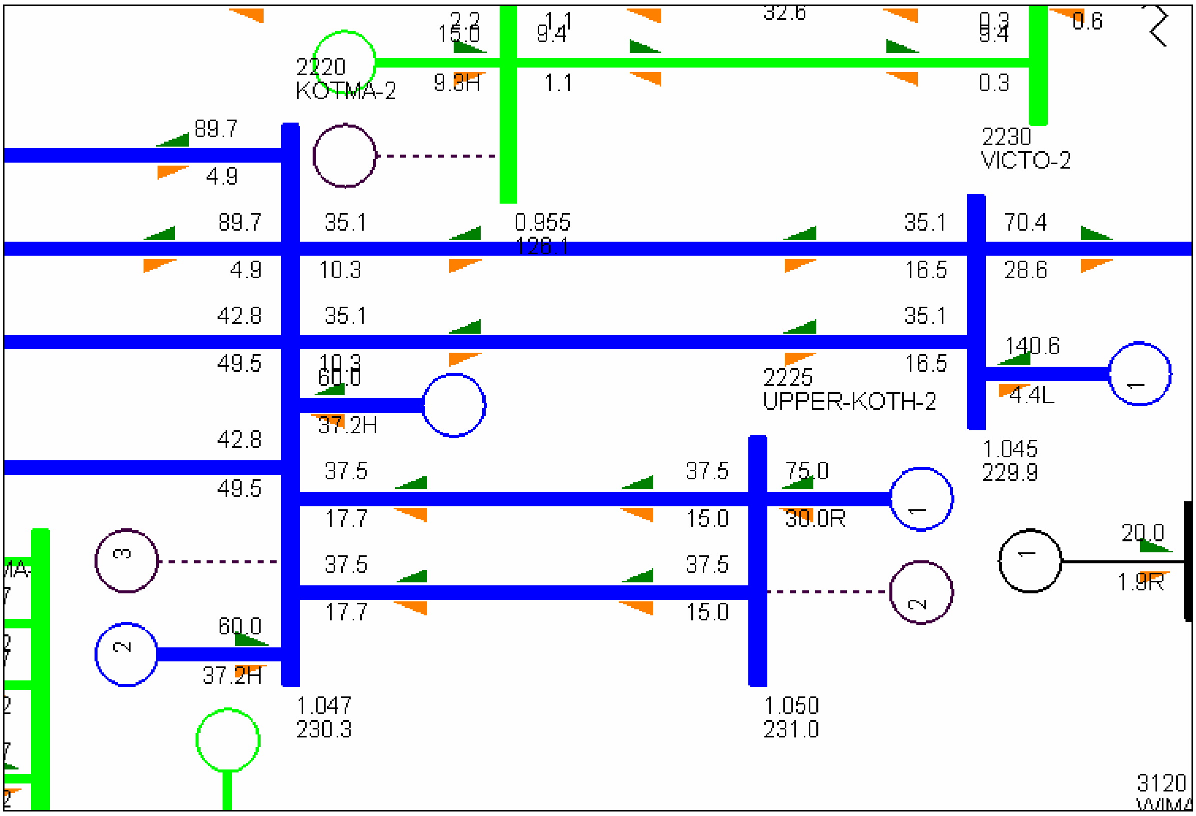



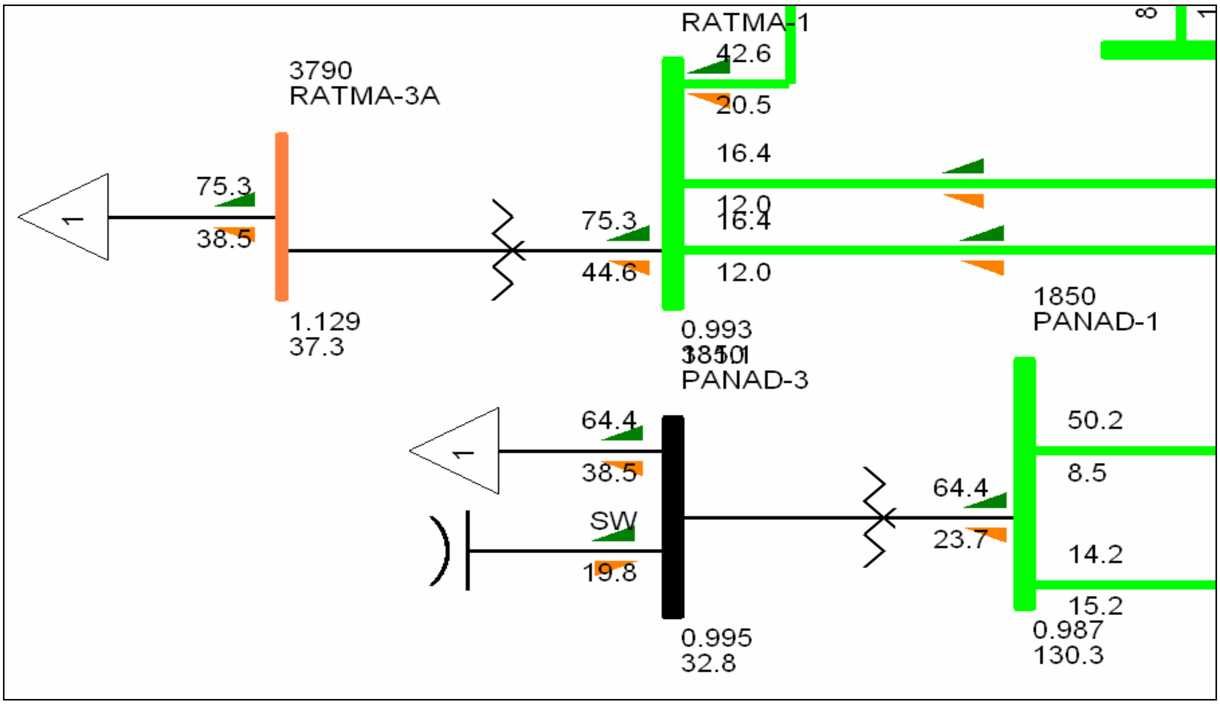
Kotmale Vshedu=<1.03 and Ratmalana GSS at maximum tap position



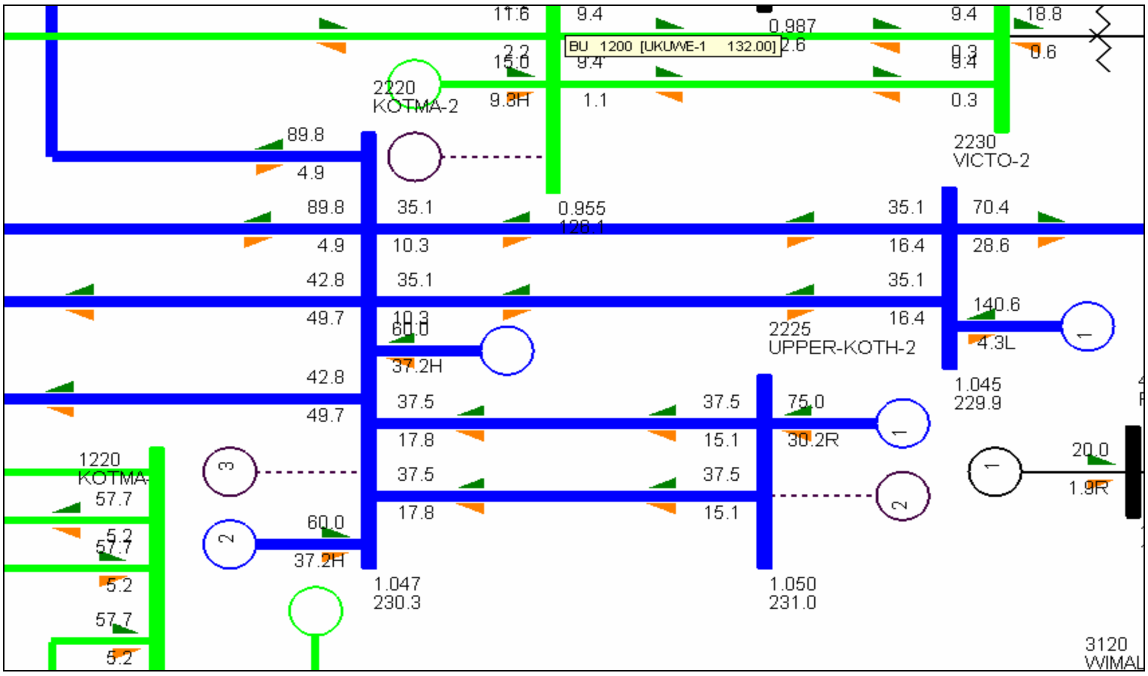



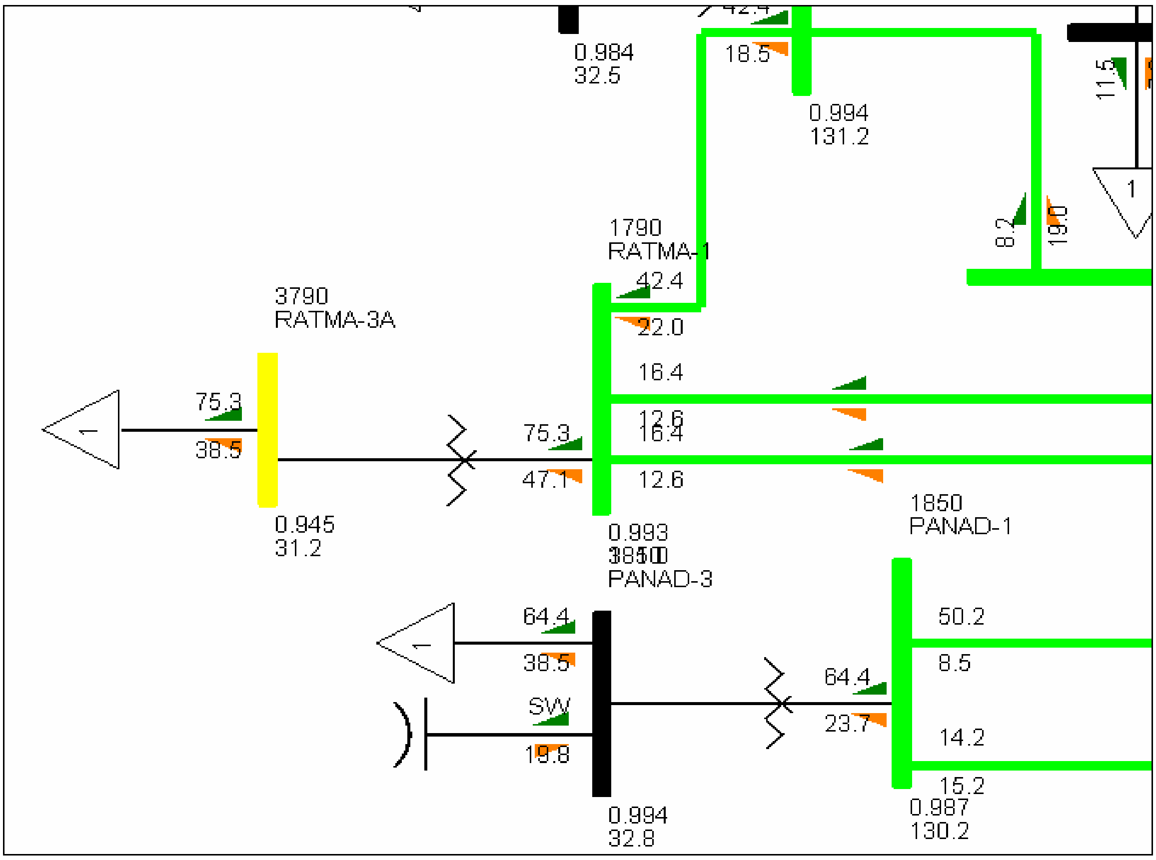
Kotmale Vshedu=1.05 and Ratmalana GSS at minimum tap position



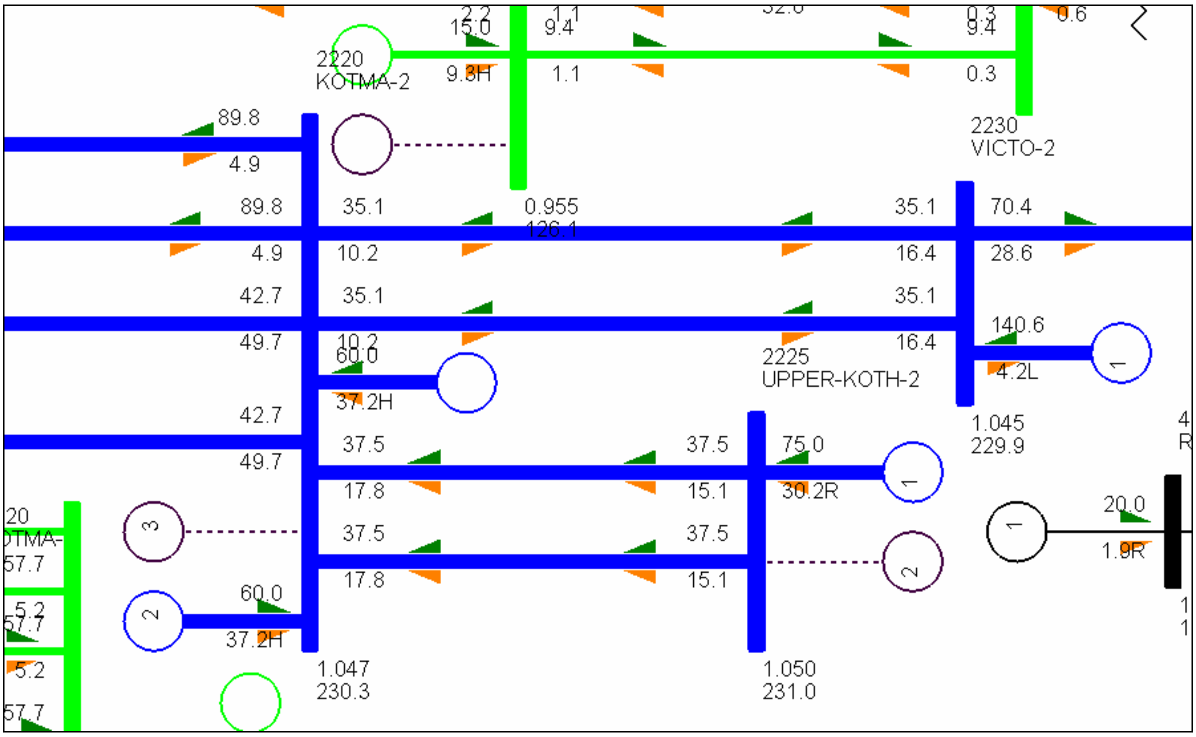



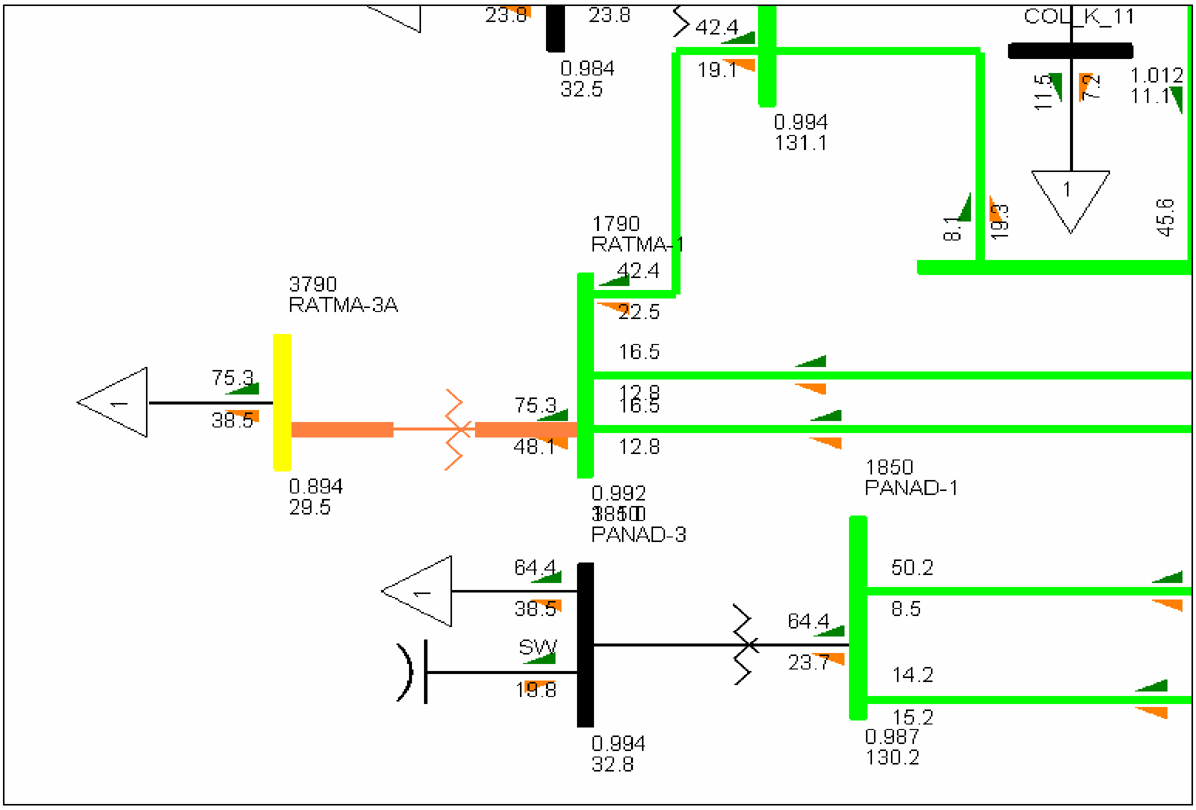
Kotmale Vshedu=1.05 and Ratmalana GSS at nominal tap position



Kotmale Vshedu=1.05 and Ratmalana GSS at maximum tap position

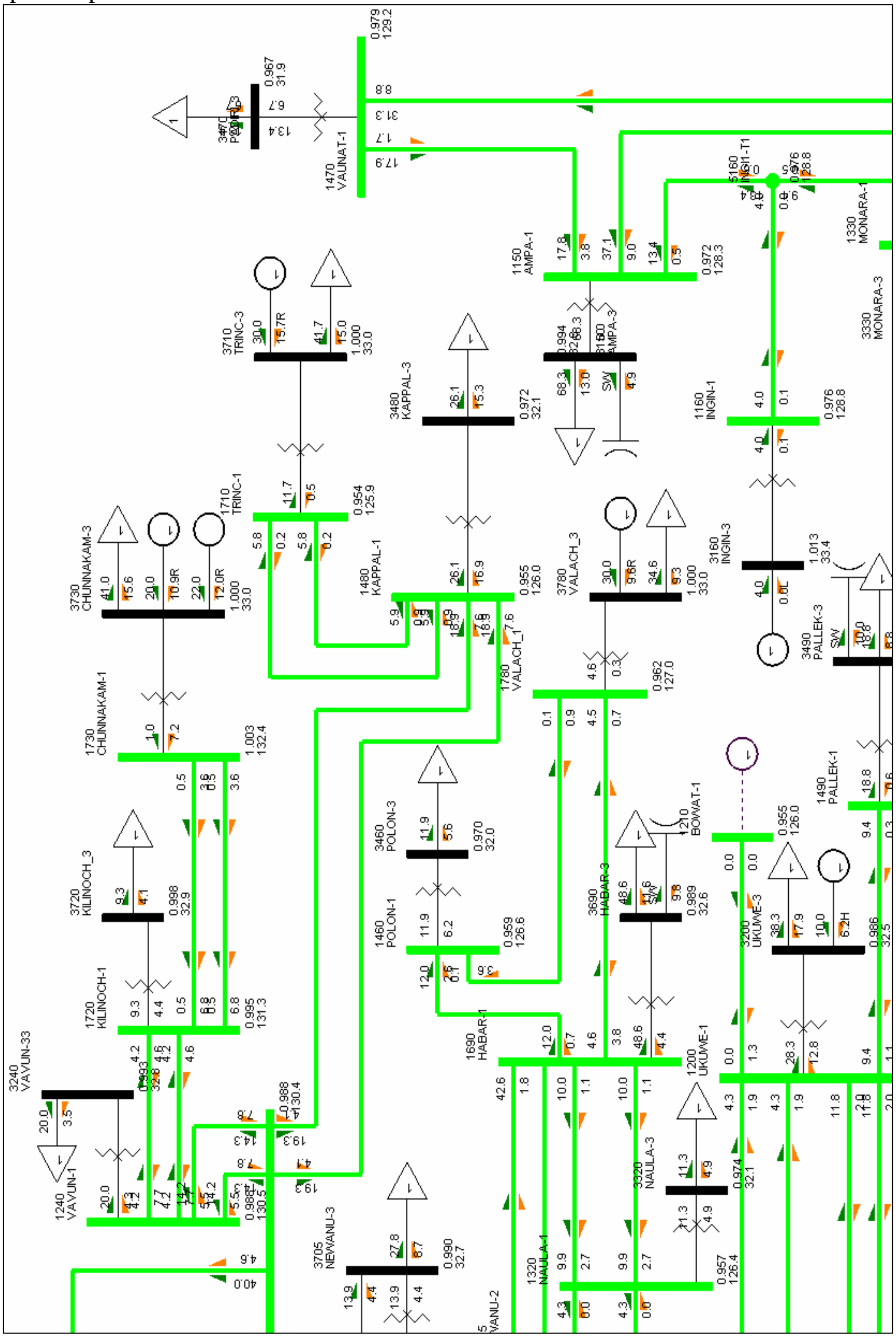


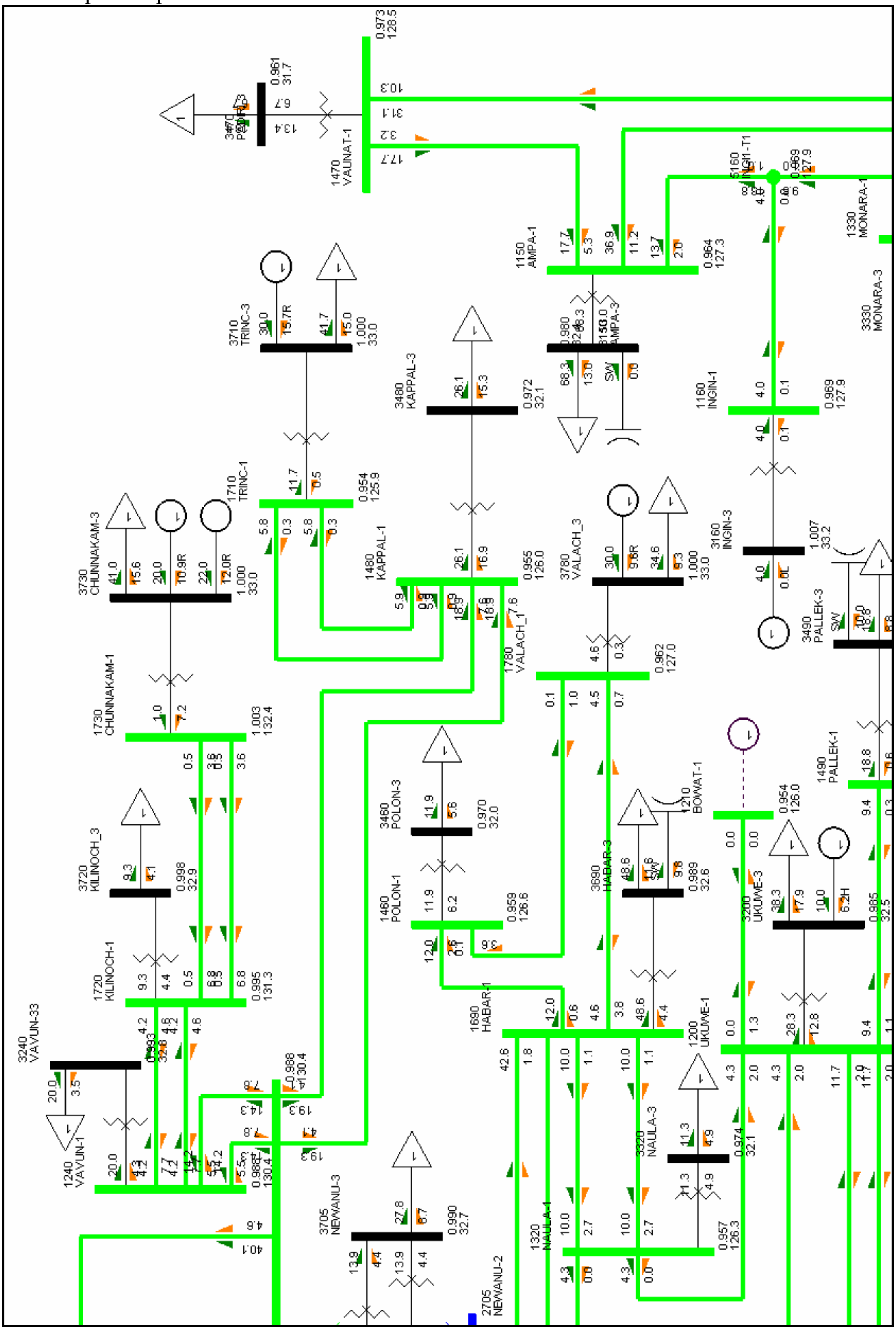
## **(F) Shunt Capacitors:**

### *( i ) CEB System – 2012:*

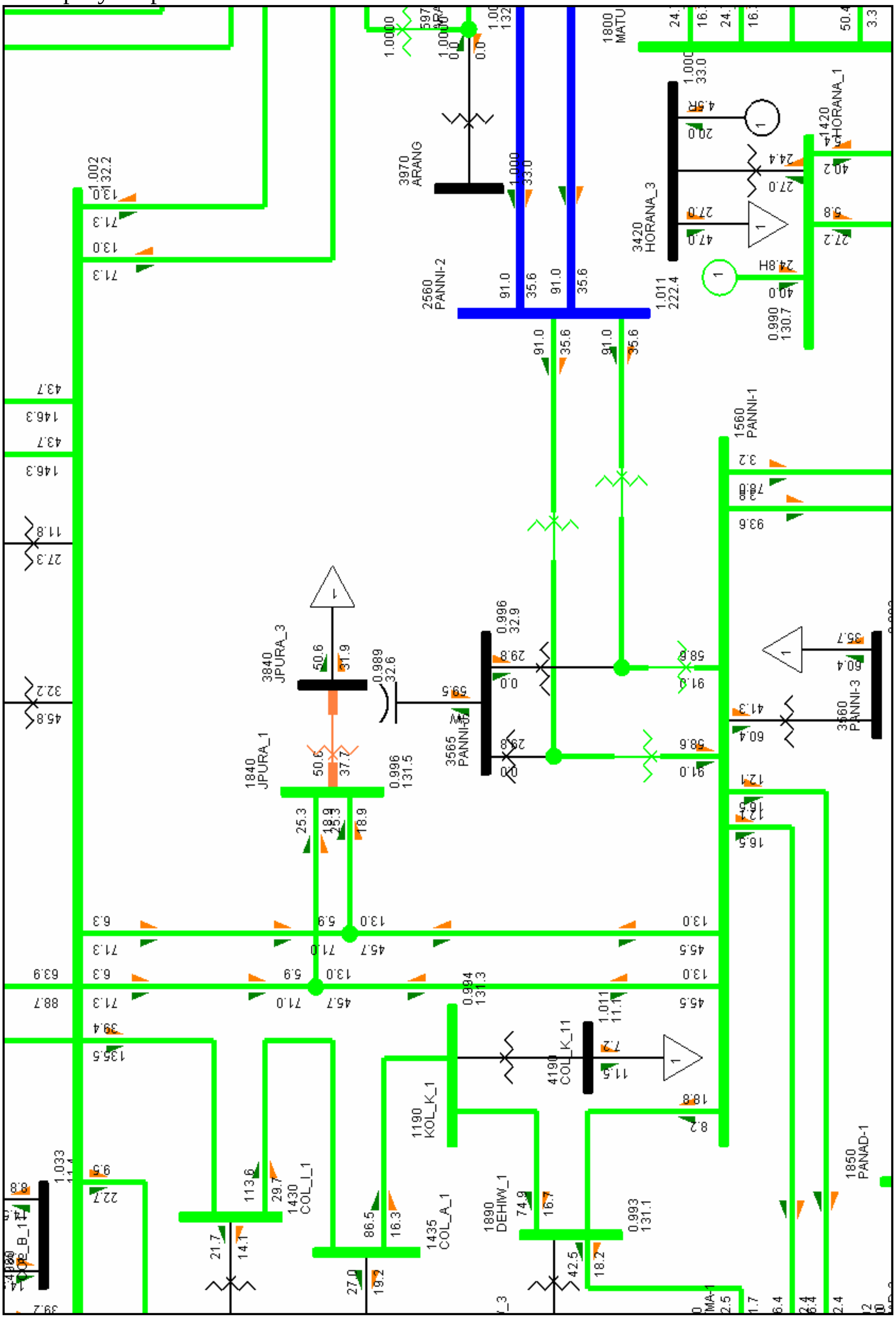
With Ampara capacitor



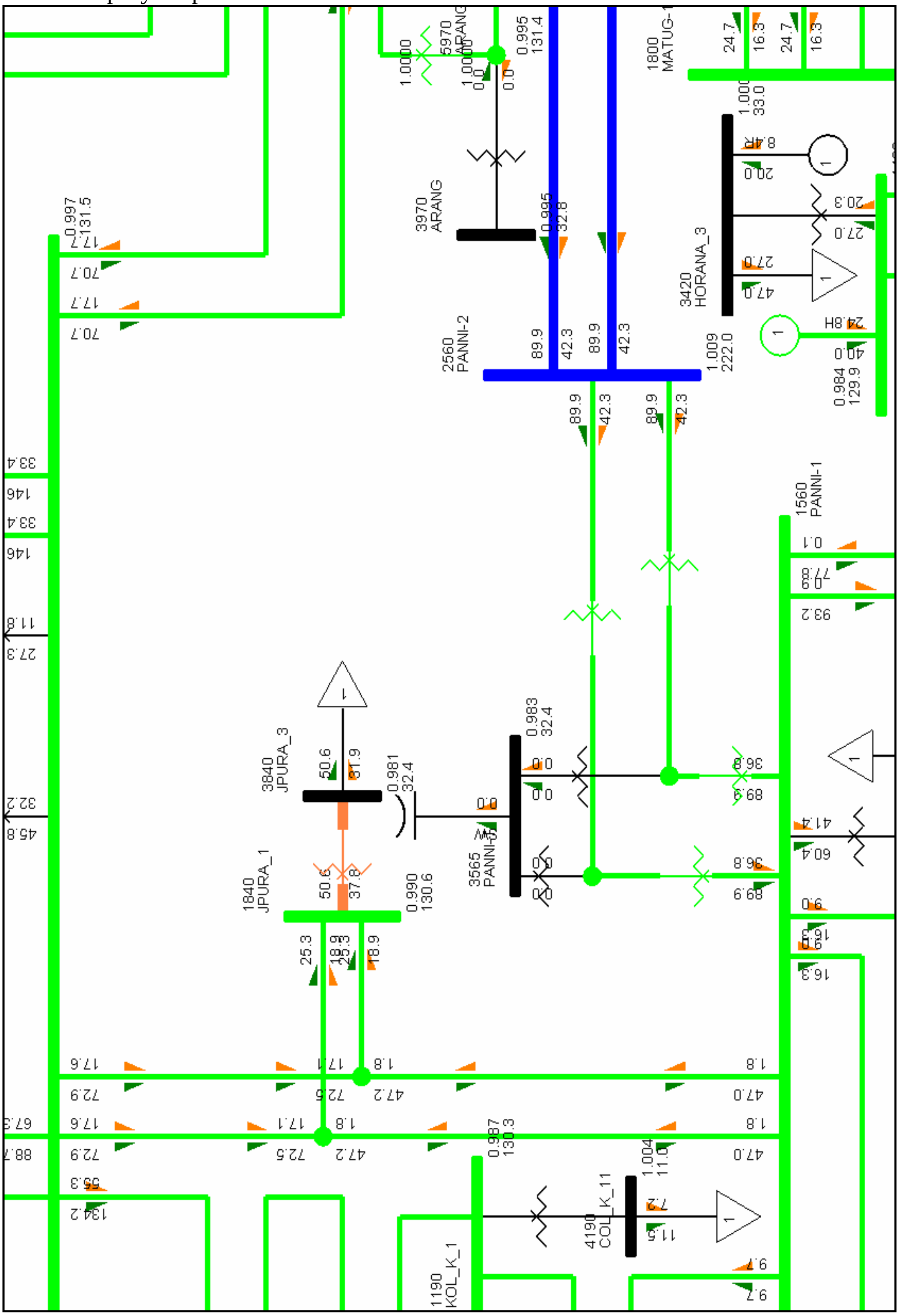
Without Ampara capacitor



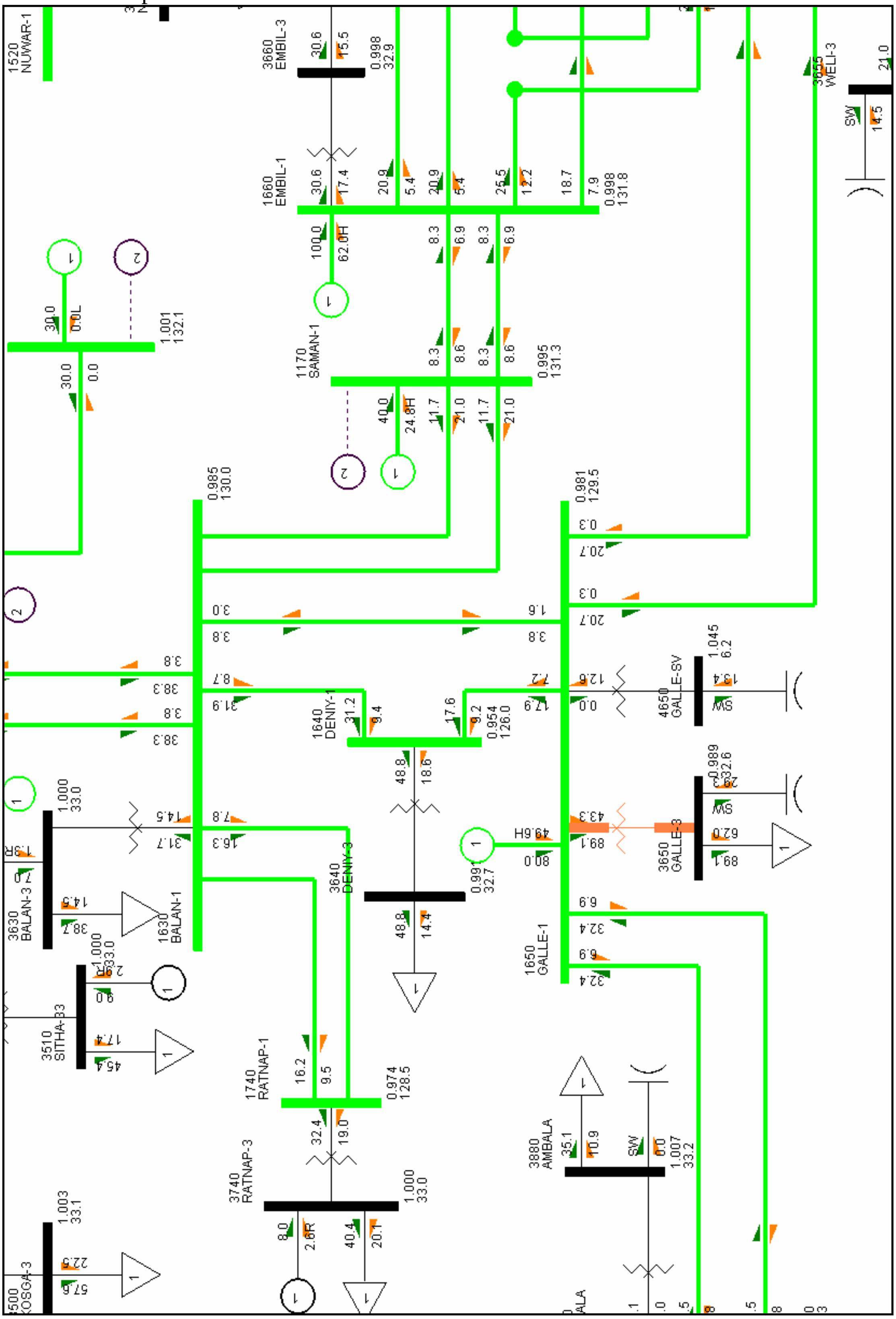
With Pannipitiya capacitor



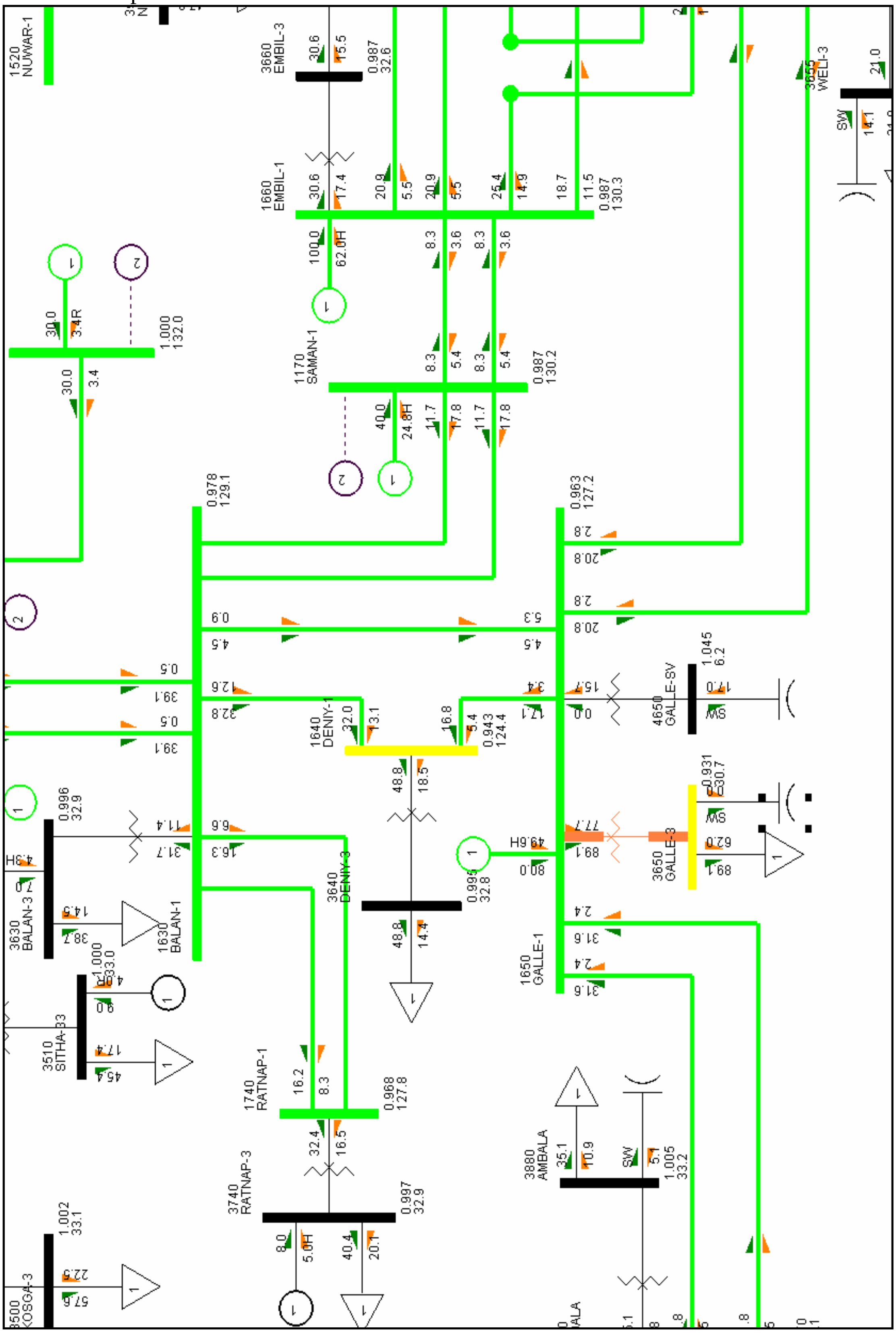
Without Pannipitiya capacitor



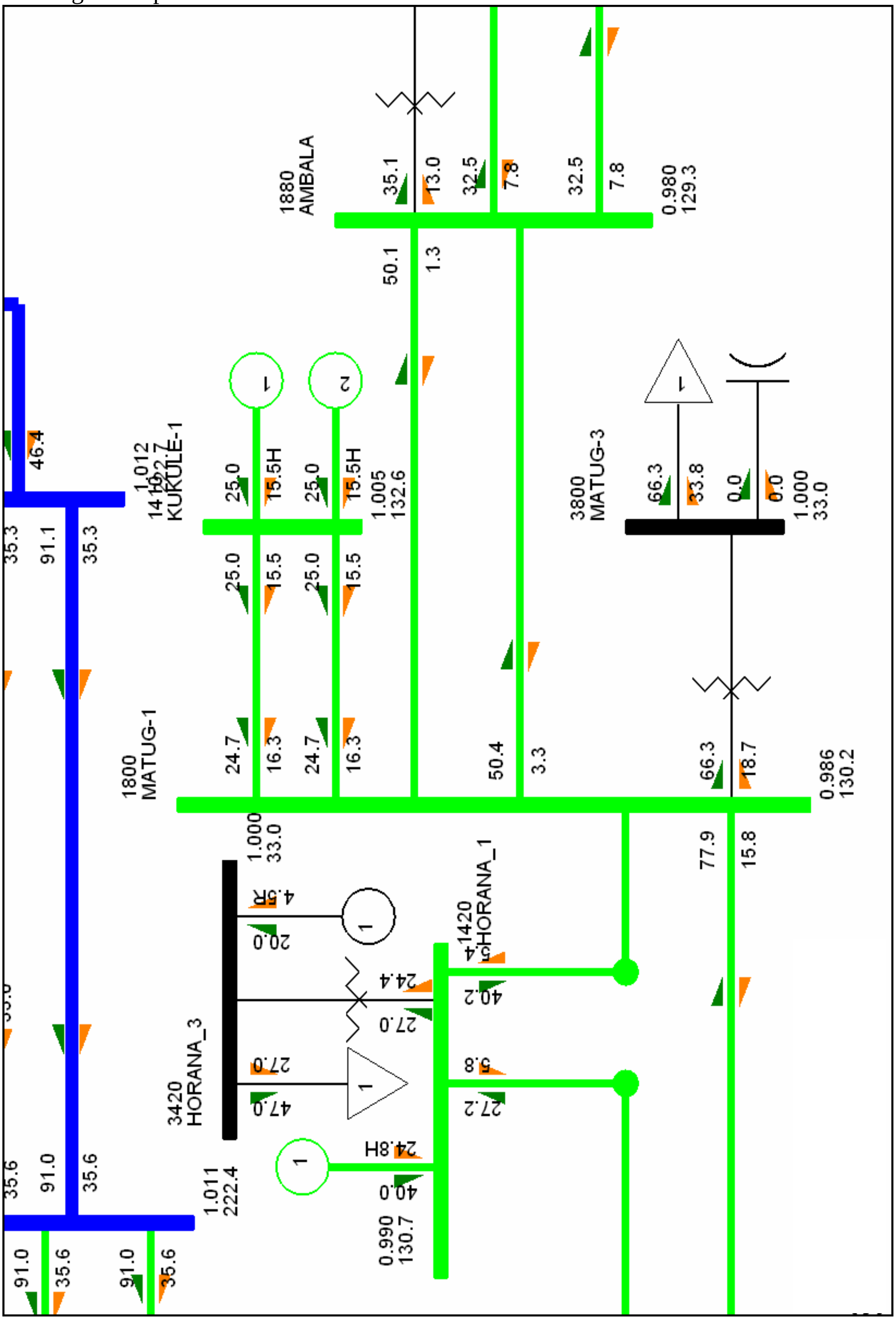
With Galle capacitor



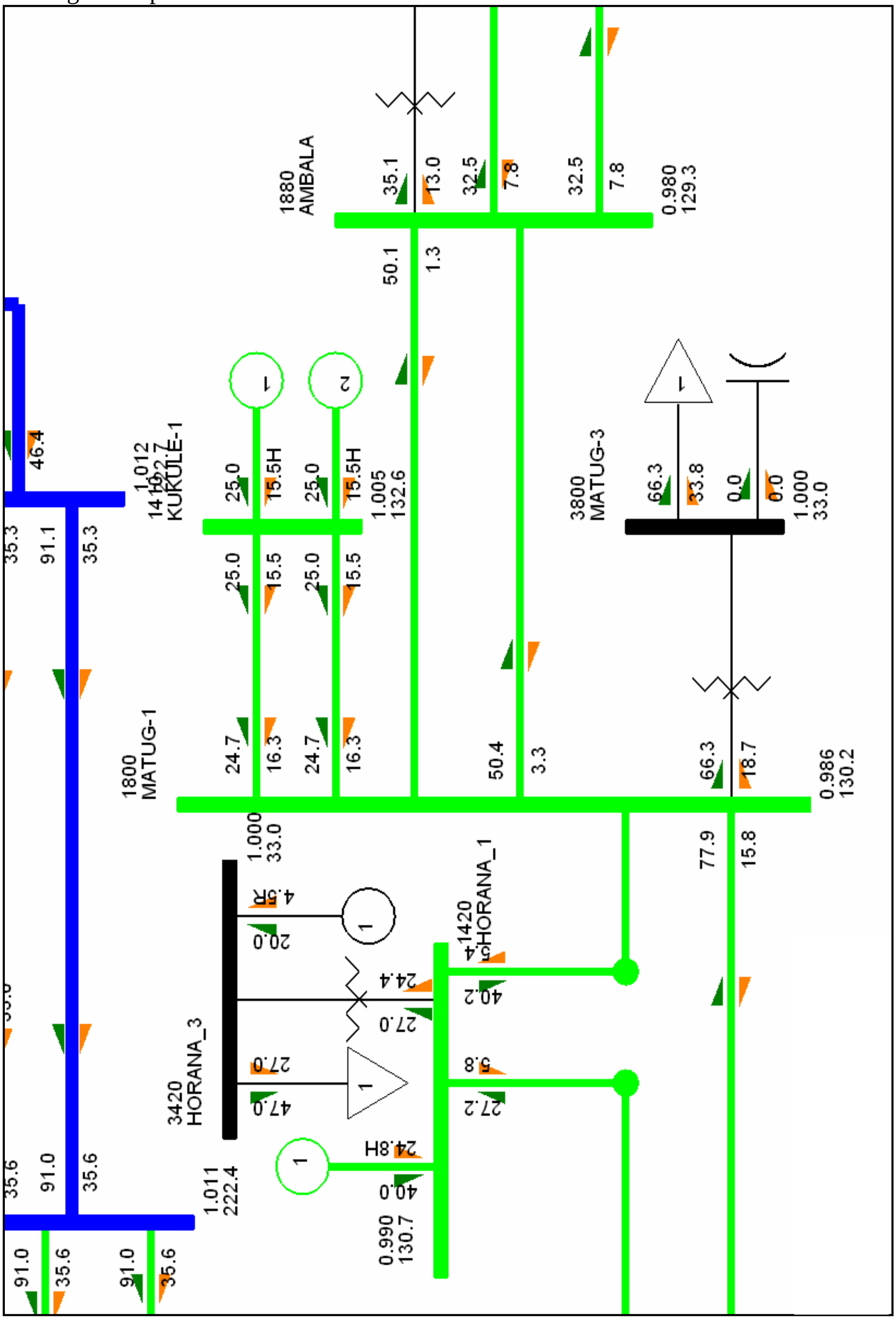
Without Galle capacitor



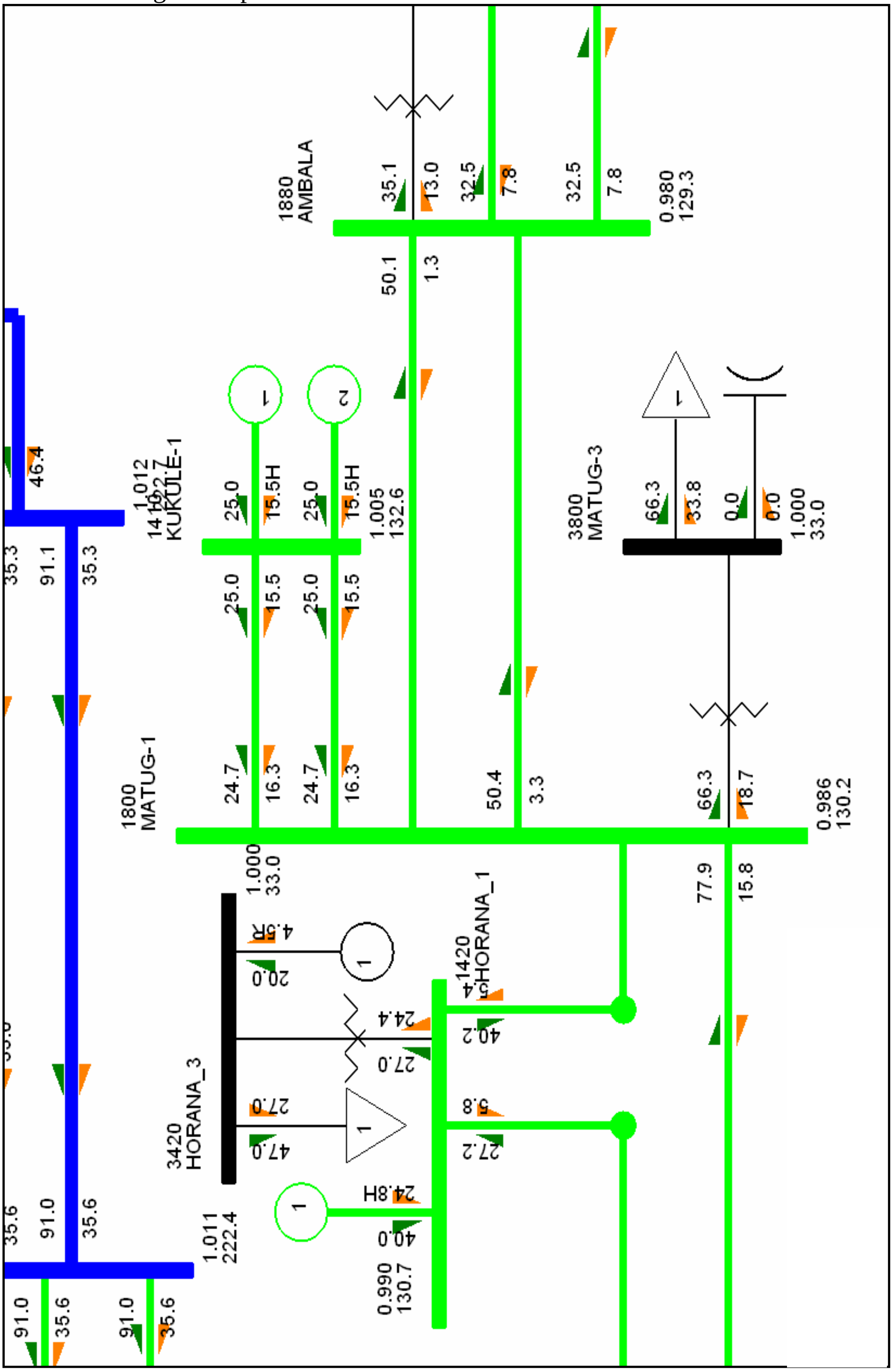
With Matugama capacitor



With Matugama capacitor

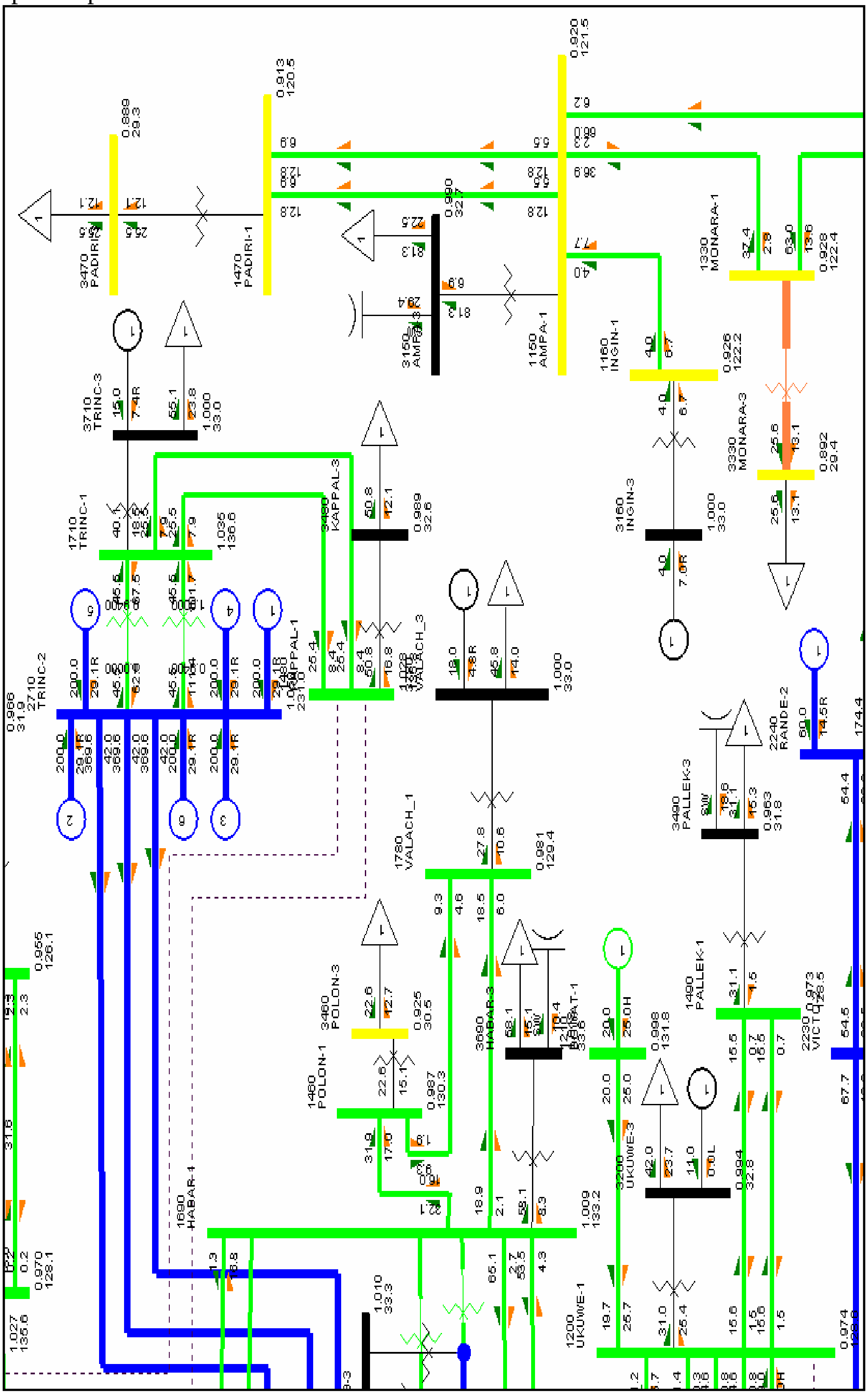


Without Matugama capacitor

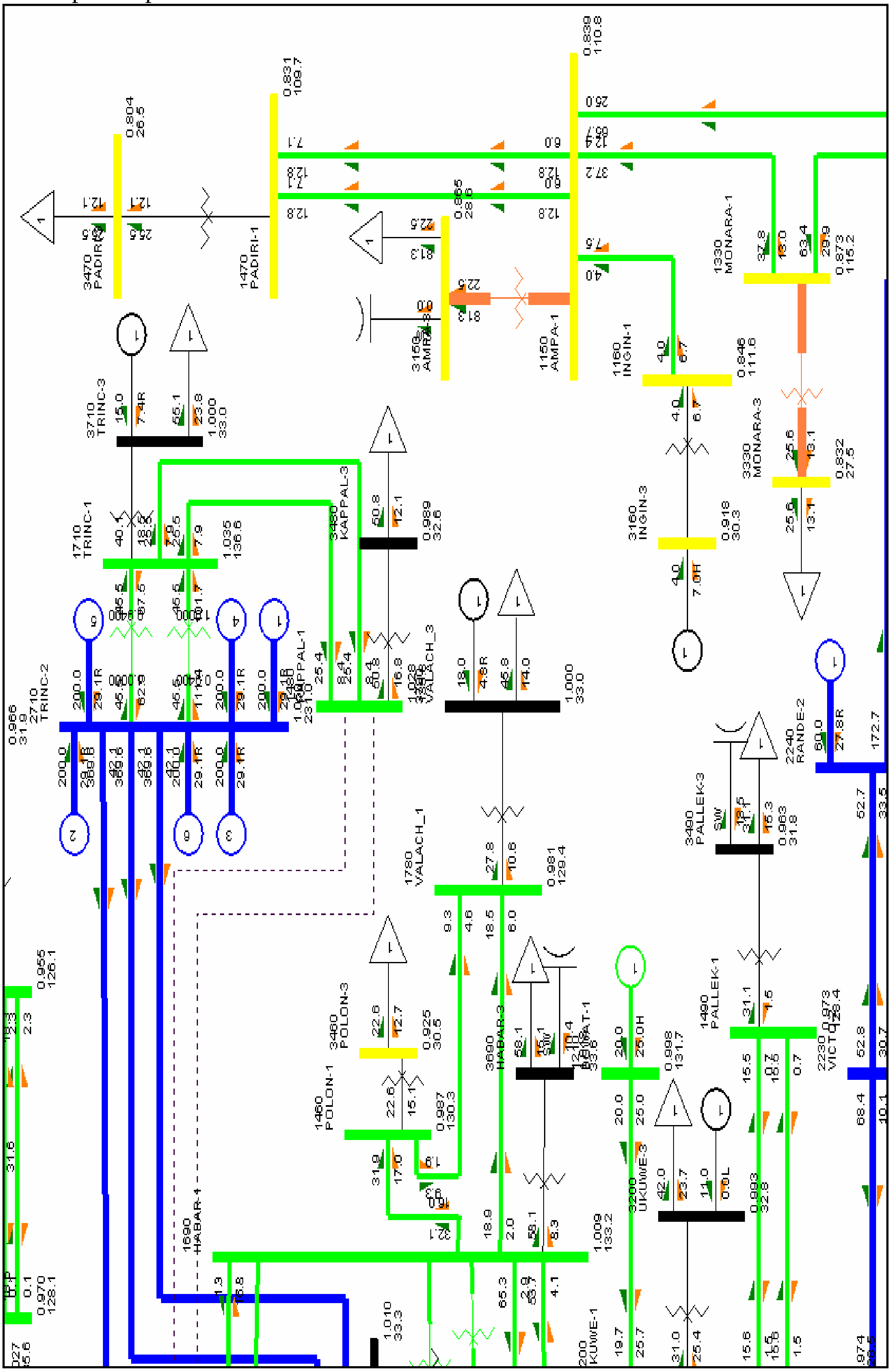


***( ii ) Year – 2016 :***

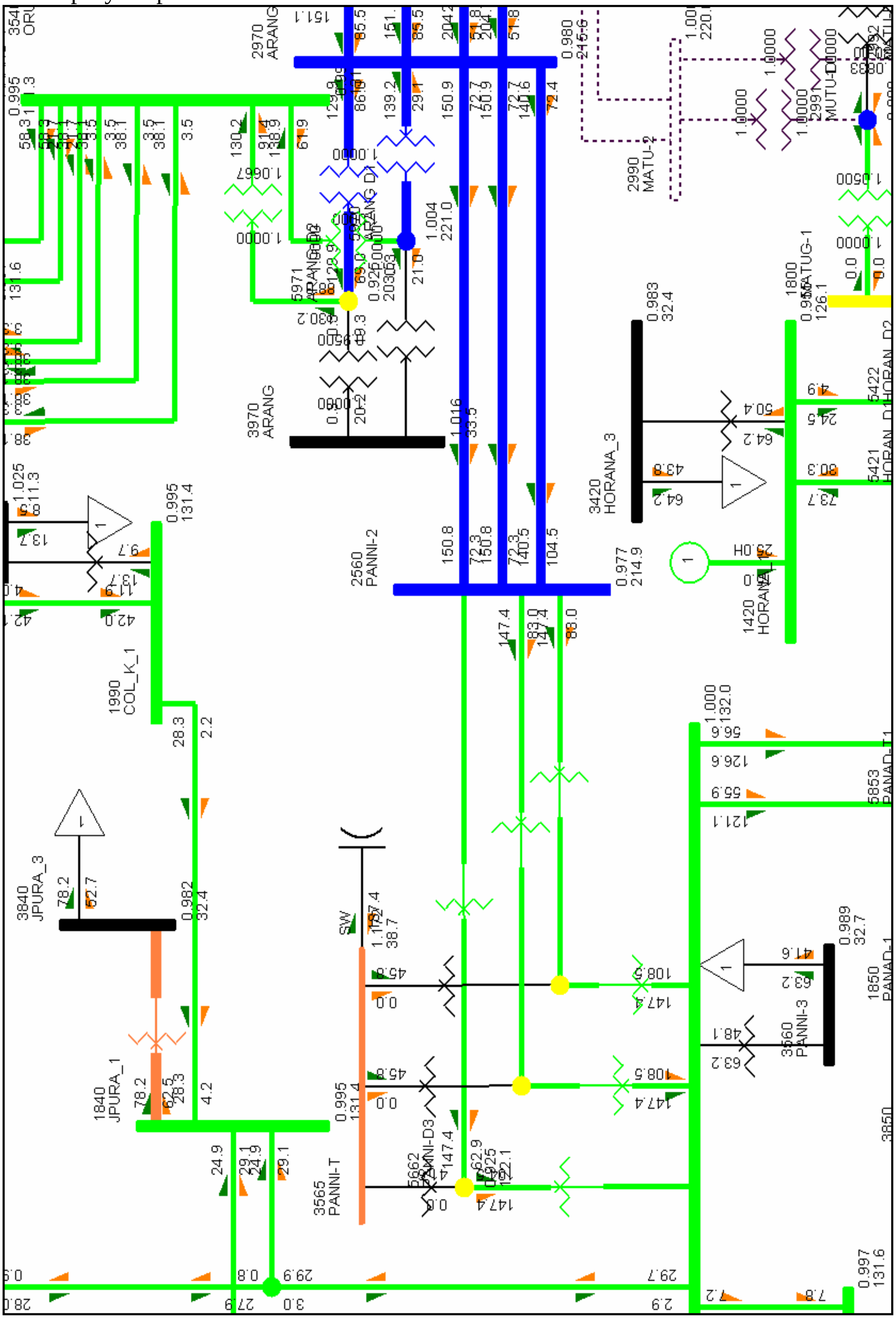
With Ampara capacitor



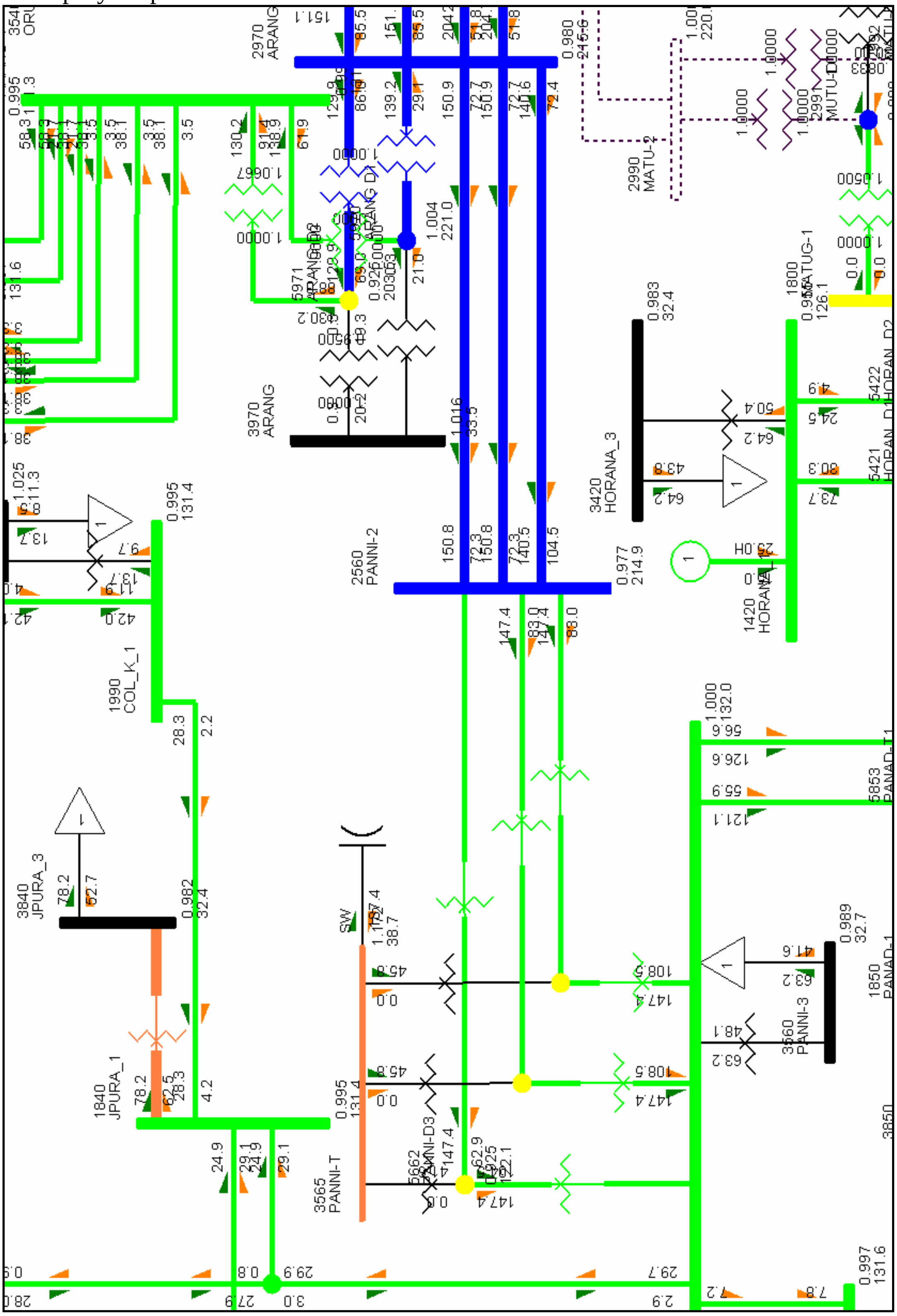
Without Ampara capacitor



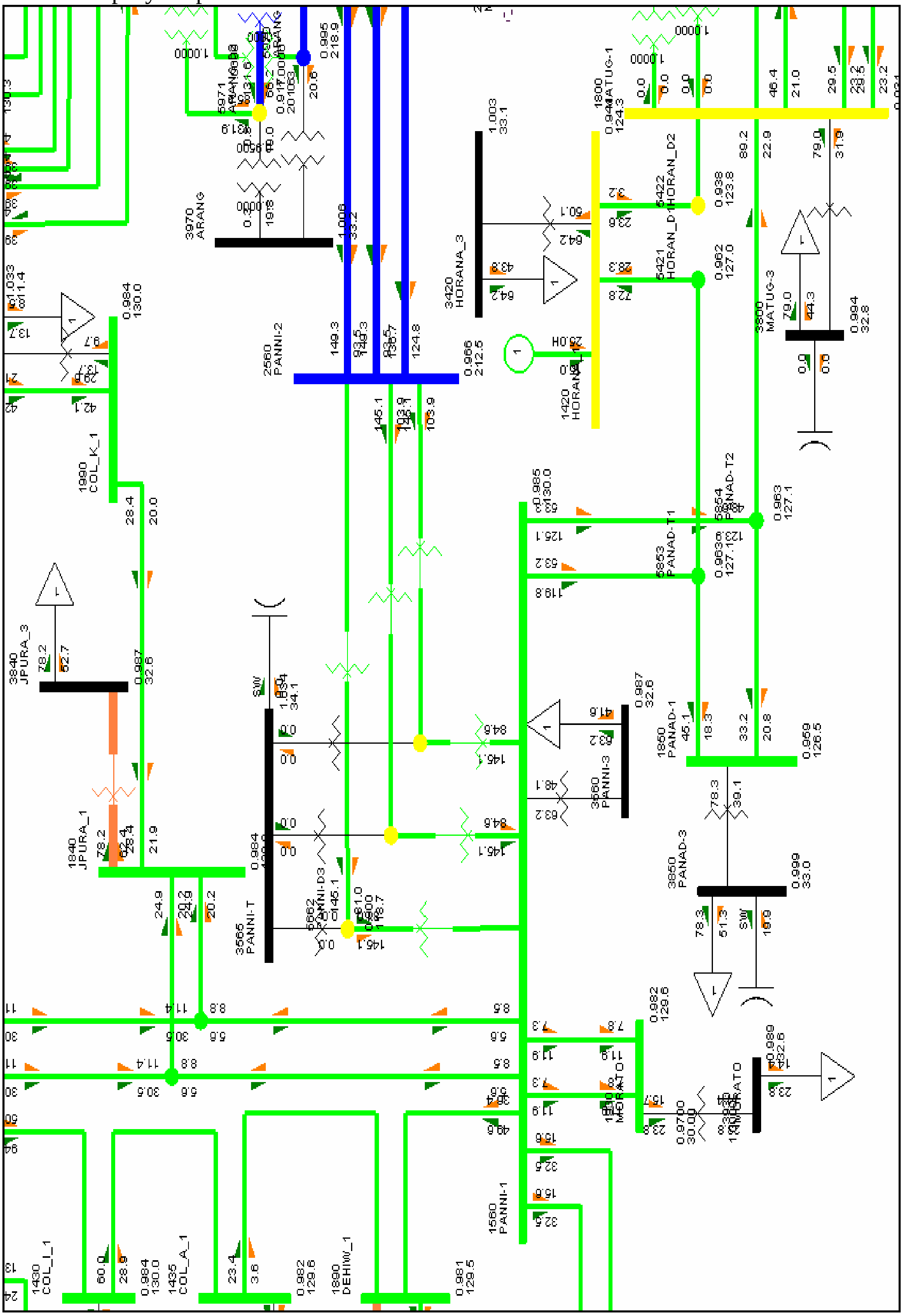
With Pannipitiya capacitor



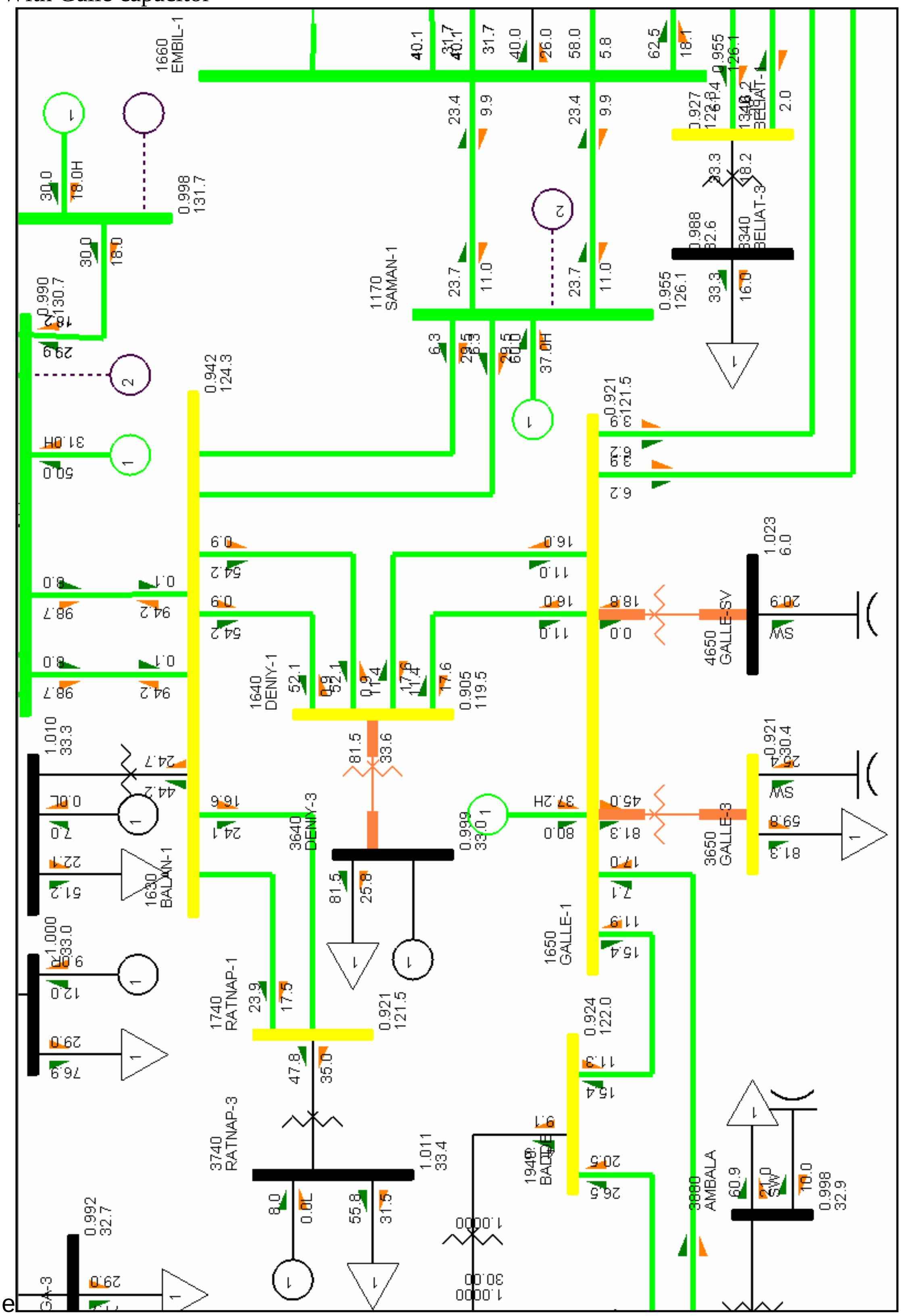
With Pannipitiya capacitor



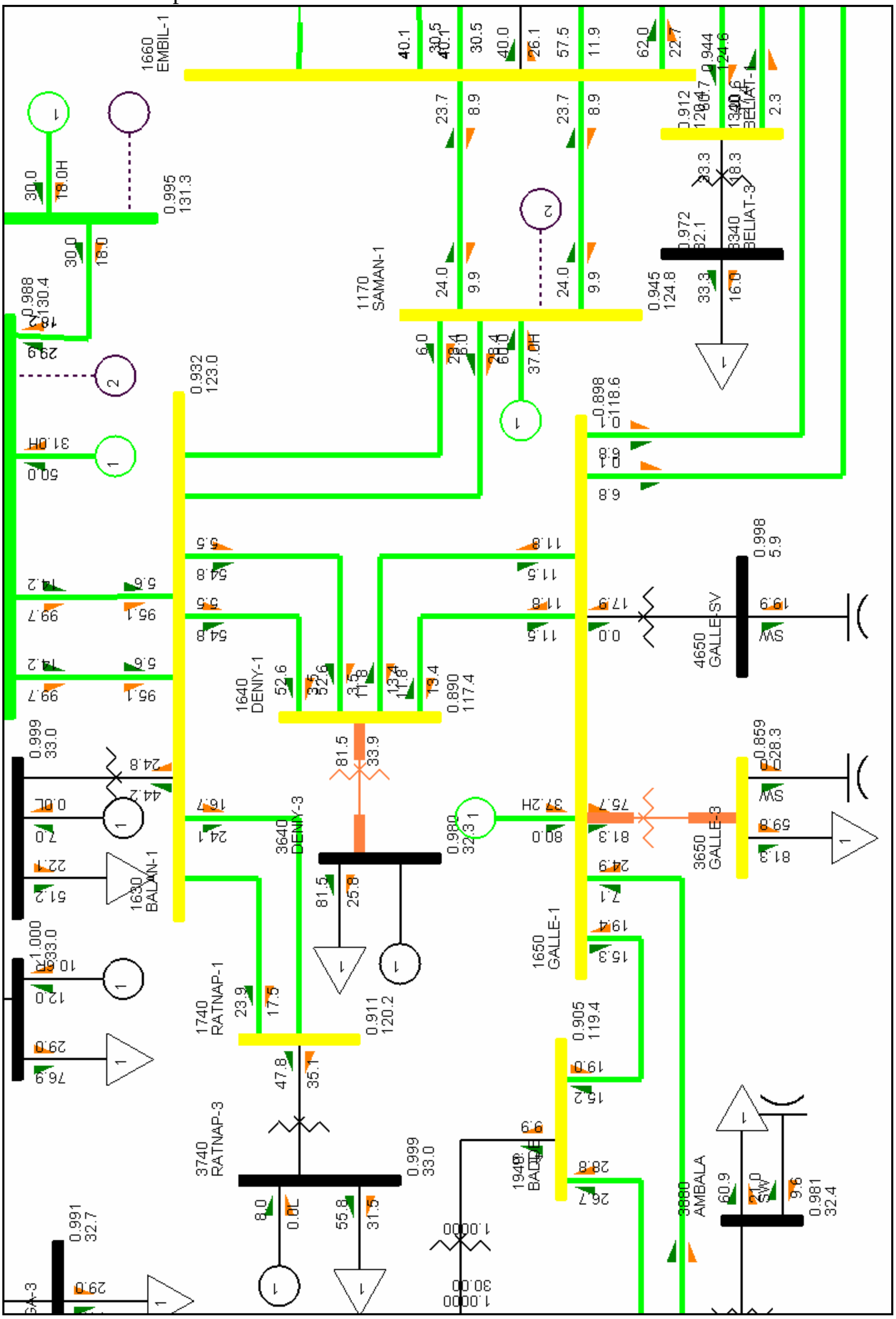
Without Pannipitiya capacitor



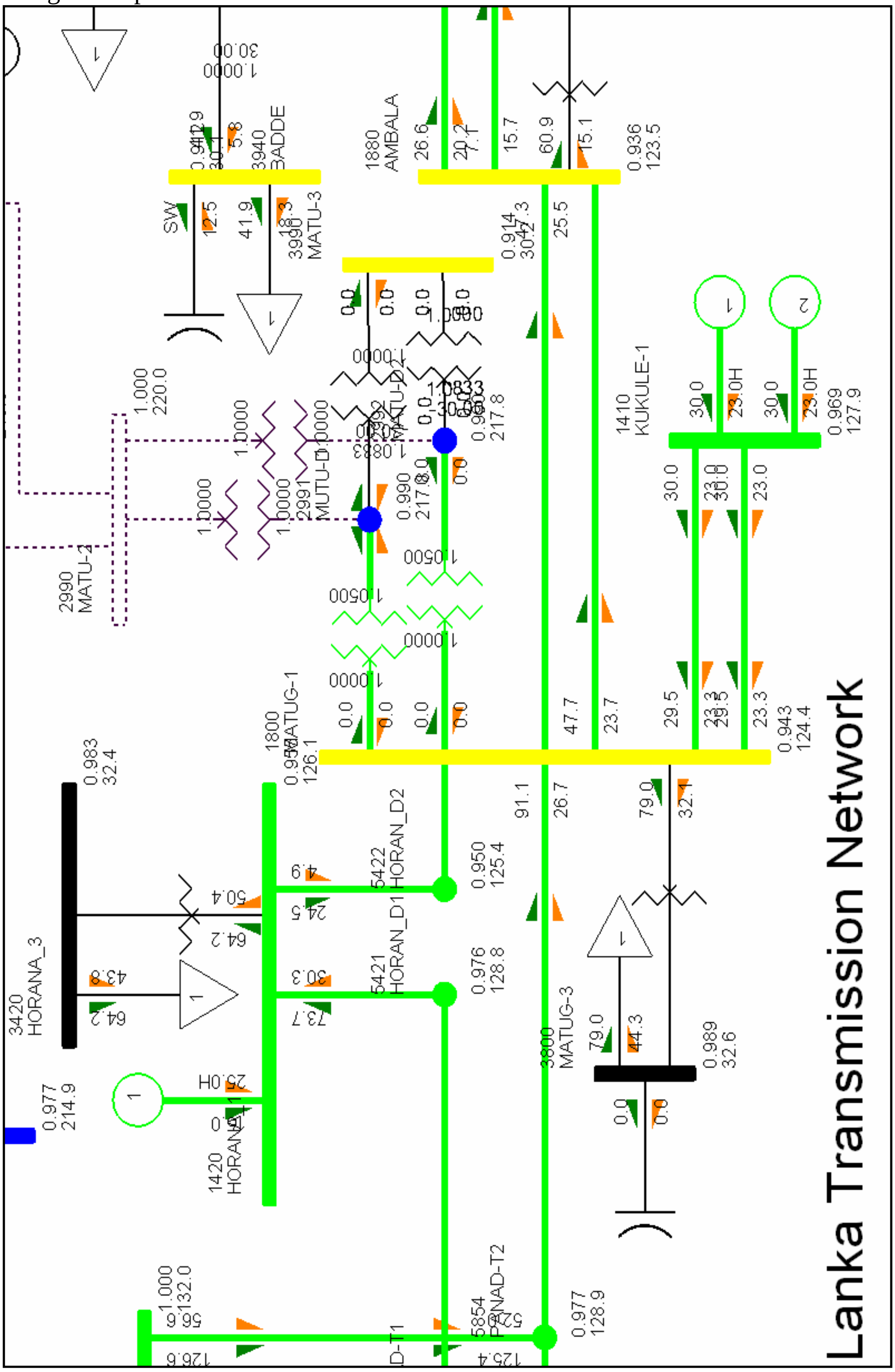
With Galle capacitor



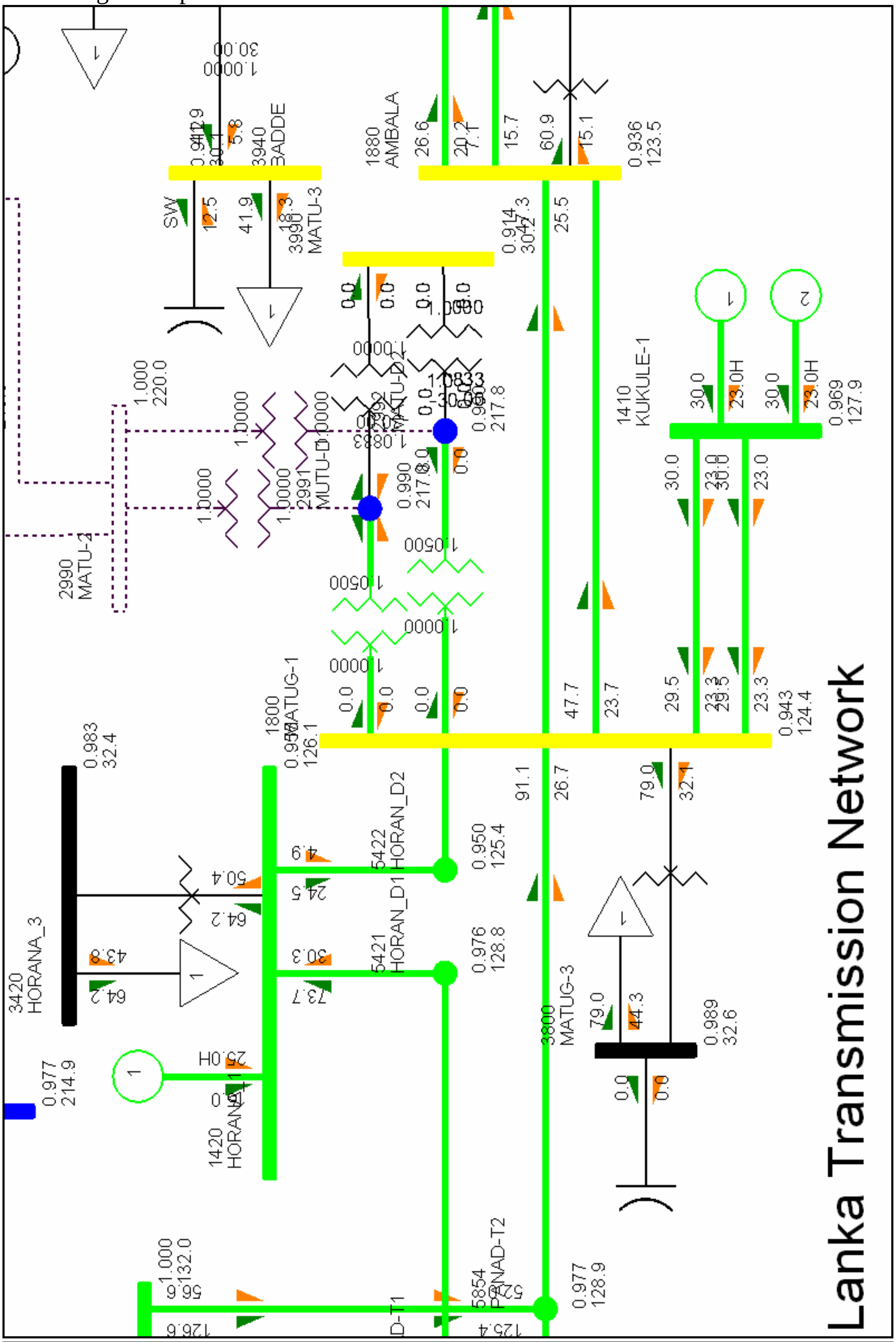
Without Galle capacitor



With Matugama capacitor



Without Matugama capacitor



# Chapter 9

# VOLTAGE CONTROL: STATIC VAR COMPENSATOR FOR STABILITY IMPROVEMENT

## 9.1 Introduction

Thyristor controlled shunt compensators are used primarily for voltage control in power systems. Inclusion of these has significant effect on the dynamic stability of power systems. Stability improvement through SVC has been indicated in this Section. Also, simulation studies of SVC on CEB System are performed and the results are enclosed.

## 9.2 Dynamic Stability Improvement through Suitable Location of SVC

**STATIC VAR COMPENSATOR MODEL**

The SVC is assumed to consist of a fixed capacitor and a Thyristor controlled reactor connected in anti-parallel as shown in Fig. 9.1.

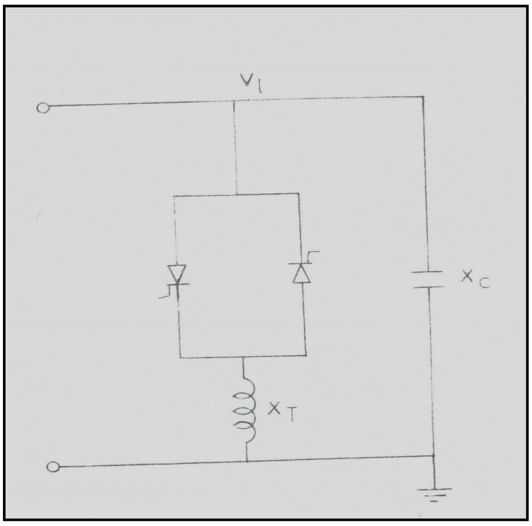



**Fig. 9.1 Elements of Static Var Compensator**

An analytical technique utilizing simplified (classical) models of machines and controllers was used to predict the influence of location of PSS in stabilizing the system. A Similar technique is proposed here to predict the influence of the location of SVC on effectiveness of stabilizing control. However, the classical model of synchronous machine is not adequate as SVC control acts through reactive power voltage loop (Q-V) and its coupling with the power angle loop (P-δ). Hence, the generator model should also include field winding and excitation control.

## AN OVERVIEW OF THE PROPOSED METHOD

Consider a power system with a single SVC at a particular location. The system can be described by the following equation.

$$p\,\underline{x} = A\,\underline{x} + \underline{b}_i\,u_i \qquad (1)$$

Where, $\underline{x}$ is the state vector and $u_i$ is the scalar control variable. For a simplified model of the SVC, the deviation in reactive power output ($\Delta Q_c$) can be treated as the control variable u. The subscript i in equation (1) characterizes the location of the SVC. With the auxiliary control of SVC, the control variable is obtained from a feedback of the output signal described by

$$u_i = Fi\, y_i \qquad (2)$$

$$y_i = \underline{C}_i^t\,\underline{x} + d_i\,u_i \qquad (3)$$

The output signal chosen for the SVC is the local bus frequency deviation $\Delta w_i$.

The objective of the controller is to increase the damping of a critical mode of oscillation by the proper choice of controller. If the critical eigenvalue of the open loop system is $\lambda_j$, the eigenvalue of the closed loop system ($\lambda_j^*$) can be expressed as

$$\lambda_j^* = \lambda_j + \frac{\partial \lambda_j^*}{\partial F_i}\,\Delta F_i + \text{higher order terms} \qquad (4)$$

The Eigen value sensitivity is calculated format he closed loop system matrix $[A_c]$ and is given by

$$[A_c] = [A] + \frac{\underline{b}_i\,F_i\,\underline{c}_i^t}{1-F_i\,d_i} \qquad (5)$$

The expression for the Eigen value sensitivity of a matrix with respect to the control parameter $F_i$ is given as

$$S_{ji} = \frac{\partial \lambda_j^*}{\partial F_i} = \frac{<\left(\frac{\partial A_c}{\partial F_i}\right)\underline{V}j, \underline{W}j>}{<\underline{V}j, \underline{W}j>} \qquad (6)$$

Where, $\underline{V}_j$ and $\underline{W}_j$ are the eigenvectors of $A_c$ and $A^t_c$ respectively corresponding to $j^{th}$ Eigen value evaluated at the initial value of $F_i$ which is assumed to be zero. $\left(\frac{\partial A_c}{\partial F_i}\right)$ is obtained from (5) as

$$\frac{\partial \underline{A}_c}{\partial F_i}\Bigg|_{F_i = 0} = \underline{b}_i \, \underline{c}^t_i$$

The effectiveness of a controller can be judged by the magnitude of real part of $S_{ji}$ and this is evident from (4) when higher order terms are neglected. Different locations of SVC give rise to different $\underline{b}_i$, $\underline{c}_i$ vectors and the influence of location on stabilizing control can be predicted from the real part of $S_{ji}$ evaluated at each location.

The computation of (6) is straight forward once the Eigen values and eigenvectors of the open loop system matrix A are calculated. As these remain invariant for various choices of the controller, the prediction of the effectiveness of the controller is simplified compared to the method based on simulation which requires repeated Eigen value analysis for each location of the controller with variation in the gain.

**SYSTEM MODEL**

To implement the method proposed in the previous section, the system model of multi-machine power system of the form given by (1) and (3) has to be constructed. It is advantageous to use simplified model of generator and SVC for this analysis. However, classical machine model is not adequate as it fails to account for the improvement in system damping due to reactive power control at a load bus. Hence, a fourth order model of the generator including the field winding and single time constant excitation system is considered here. Combining the equations of various generators in the system, we have

$$P\,\underline{X}_G = [A_G]\,\underline{X}_G + [B_G]\,\Delta\underline{S}_G \qquad (7)$$

Where,

$$\underline{X}^t_G = [\underline{x}^t_{g1} \ldots\ \underline{x}^t_{gi} \ldots\ \underline{x}^t_{gn}]$$

$$\underline{x}^t_{g1} = [\,\Delta E'_q \quad \Delta w \quad \Delta\delta \quad \Delta E_{fd}\,]$$

A multi-load model can be described as

$$\Delta\underline{S}_L = [K_V]\,\Delta\,\underline{V}_L + [K_F]\quad p\,\Delta\,\underline{\Theta}_L$$

Neglecting frequency dependence and assuming the var compensator to be located at ith load bus, the above equation gets modified to

$$\Delta\underline{S}_L = [K_V]\,\Delta\,\underline{V}_L - \underline{e}_i \quad \Delta\,Q_{ci} \qquad (8)$$

Where

$$\underline{e}^t_i = [\,0 \;\; 0 \;\; \ldots \;\; 0\; 1 \;\; \ldots\ldots \;\; 0 \;\; 0\,]$$

$i^{th}$ element

The output equation is given by

$$y_i = \Delta w_i = \underline{C}^t_i \;\; \underline{X}_G + d_i \; \Delta Q_{ci} \qquad (9)$$

Where

$$\underline{C}^t_i = k^t_i \; [F_{11}] \; [A]$$

$$d_i = [\, k^t_i \,] \; [F_{11}] \; \underline{b}_i$$

This equation is in the form given by (3).

**AN EXAMPLE**

A multi-machine power system is considered to illustrate the method proposed. The machine and exciter data are tabulated in Table 9.1.

**Table – 9.1**
The machine and exciter data for multi-machine system

| Machine No. | $x_d$ | $x^1_d$ | $T^l_{do}$ | H | $T_E$ | $K_E$ |
|---|---|---|---|---|---|---|
| 1 | 0.1460 | 0.0608 | 8.96 | 23.64 | 0.07 | 10.0 |
| 2 | 0.8958 | 0.1198 | 6.00 | 6.40 | 0.07 | 10.0 |
| 3 | 1.3125 | 0.1813 | 5.89 | 3.01 | 0.07 | 10.0 |

The multi-machine system has three generators and six load buses. Constant impedance load characteristics are assumed and the effects of transient saliency are ignored in this example. Without the compensator the eigenvalues corresponding to electromechanical oscillations are

$$\lambda_1 = -0.0161 \pm j13.3447$$

$$\lambda_2 = -0.0087 \pm j8.6605$$

The compensator is assumed to be located at one load bus at a time and the sensitivities of these eigenvalues with respect to the gain $F_i$ are evaluated.

Table 9.2 shows the sensitivities for different locations of the SVC.

**Table – 9.2**

Eigenvalue sensitivities of rotor oscillations at $F_i = 0.0$

| **Bus No.** | **$S_1$ ($\lambda_1$ = - 0.0161 + j13.3447)** | **$S_2$ ($\lambda_2$ = - 0.0087 + j8.6605)** |
|---|---|---|
| 4 | - 0.0355 - j0.0000 | - 0.0049 - j0.0005 |
| 5 | - 0.0419 + j0.0002 | - 0.4416 - j0.0051 |
| 6 | - 0.3177 - j0.0002 | - 0.3154 - j0.0039 |
| 7 | - 0.0058 + j0.0002 | - 1.5594 - j0.0135 |
| 8 | - 0.2433 + j0.0006 | - 1.4593 - j0.0136 |
| 9 | - 0.9826 - j0.0024 | - 1.0912 - j0.0099 |

Inspection of Table 9.2 shows that the sensitivity is maximum at bus No.9 for the eigenvalue corresponding to higher frequency. But for the eigenvalue corresponding to lower frequency, it is maximum at bus No.7. Since the sensitivity for the eigenvalue corresponding to higher frequency at but No.7 is very small, bus No.9 can be chosen as the optimum location for the compensator.

The location of SVC at bus 9 is optimal from stabilization point of view. This is also confirmed from Table 9.3 which compares the location at buses 7 and 9 for controller gain set at $F_i = 3.0$.

**Table – 9.3**

Eigenvalues corresponding to roter oscillation for locations No.7 and 9

| **Bus No.** | **$\Lambda_1$** | **$\lambda_2$** |
|---|---|---|
| 7 | - 0.0304 + j13.3110 | - 8.7261 + j11.2254 |
| 9 | - 5.9338 + j15.5043 | - 0.9973 + j10.9160 |

SVC at location 7 has significant effect on the damping of low frequency oscillation; it has negligible effect on the high frequency oscillation. SVC at bus No.9, in contrast, improves damping of both modes of oscillations although the damping of low frequency oscillation is less compared to that of high frequency. The presence of SVC at both places can be expected to improve the damping of both modes of oscillations significantly.

## 9.3 Simulation Studies of SVC on CEB System

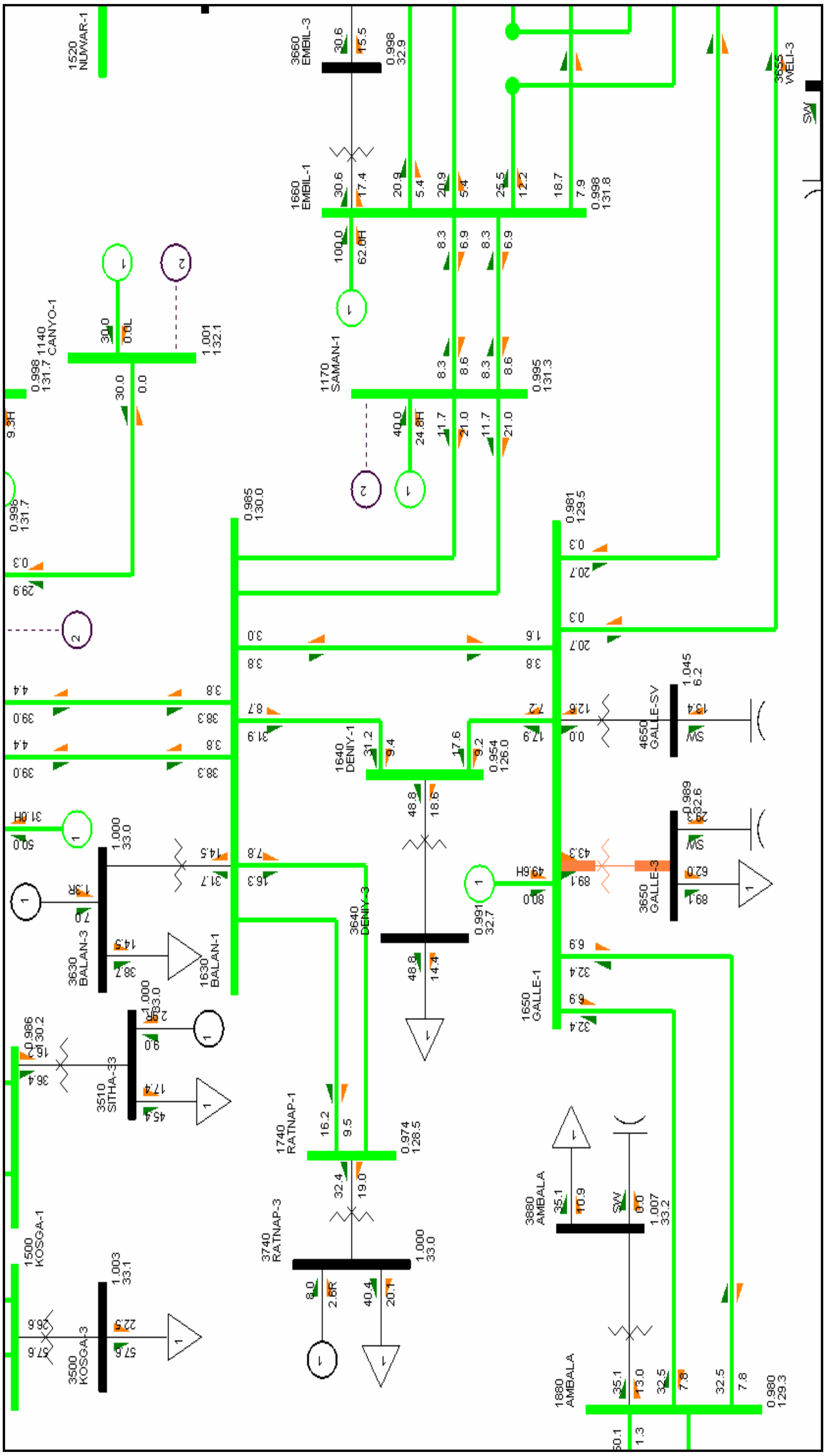
The following Simulation Studies are performed:

(1) Year – 2012: Without & with SVC at Galle;

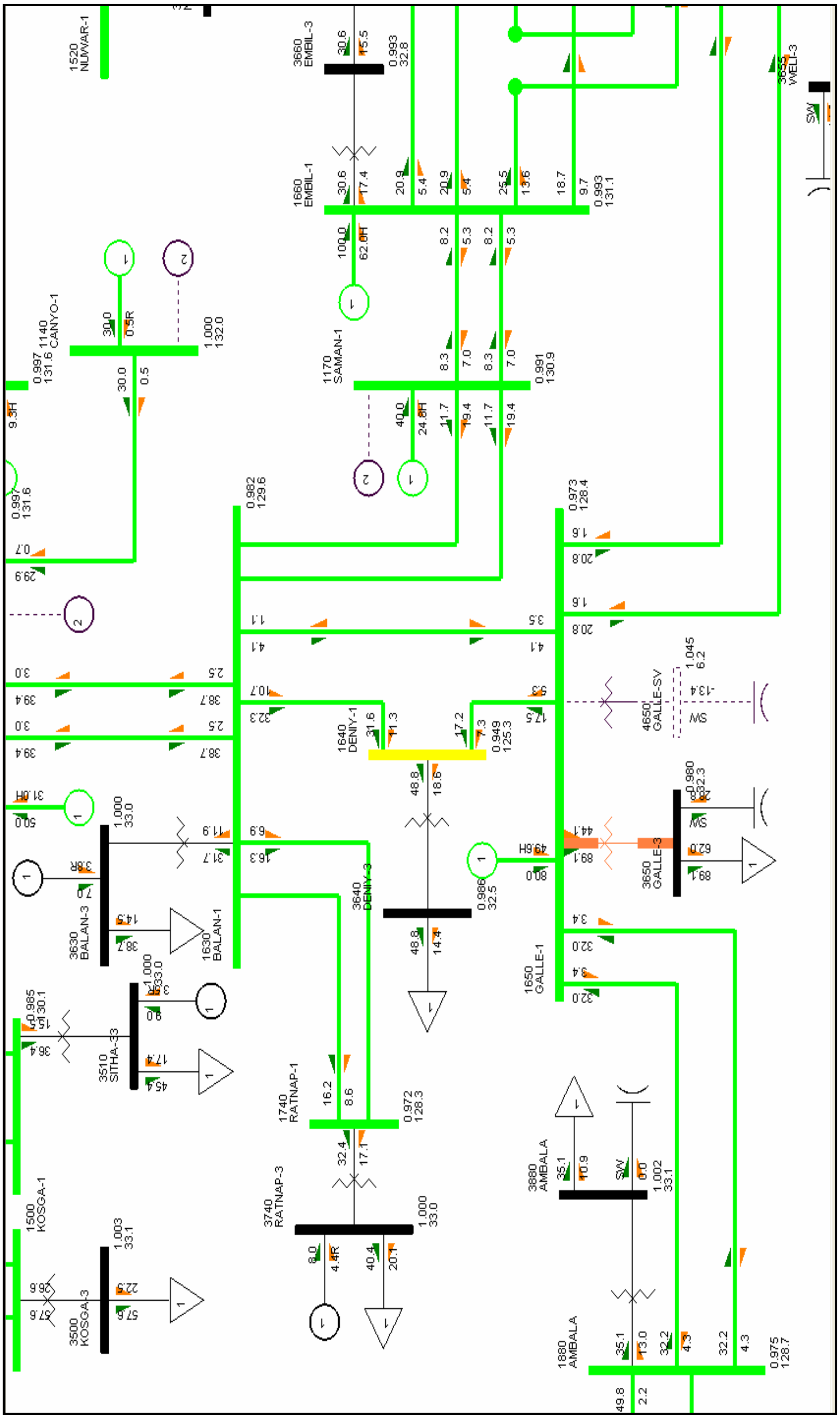
(2) Year – 2016:
  (a) Without & with SVC at Galle;
  (b) Without & with SVC at Kelanitissa;
  (c) Without & with SVC at Hambantota;

(3) Year – 2020: Without & with SVC at Galle

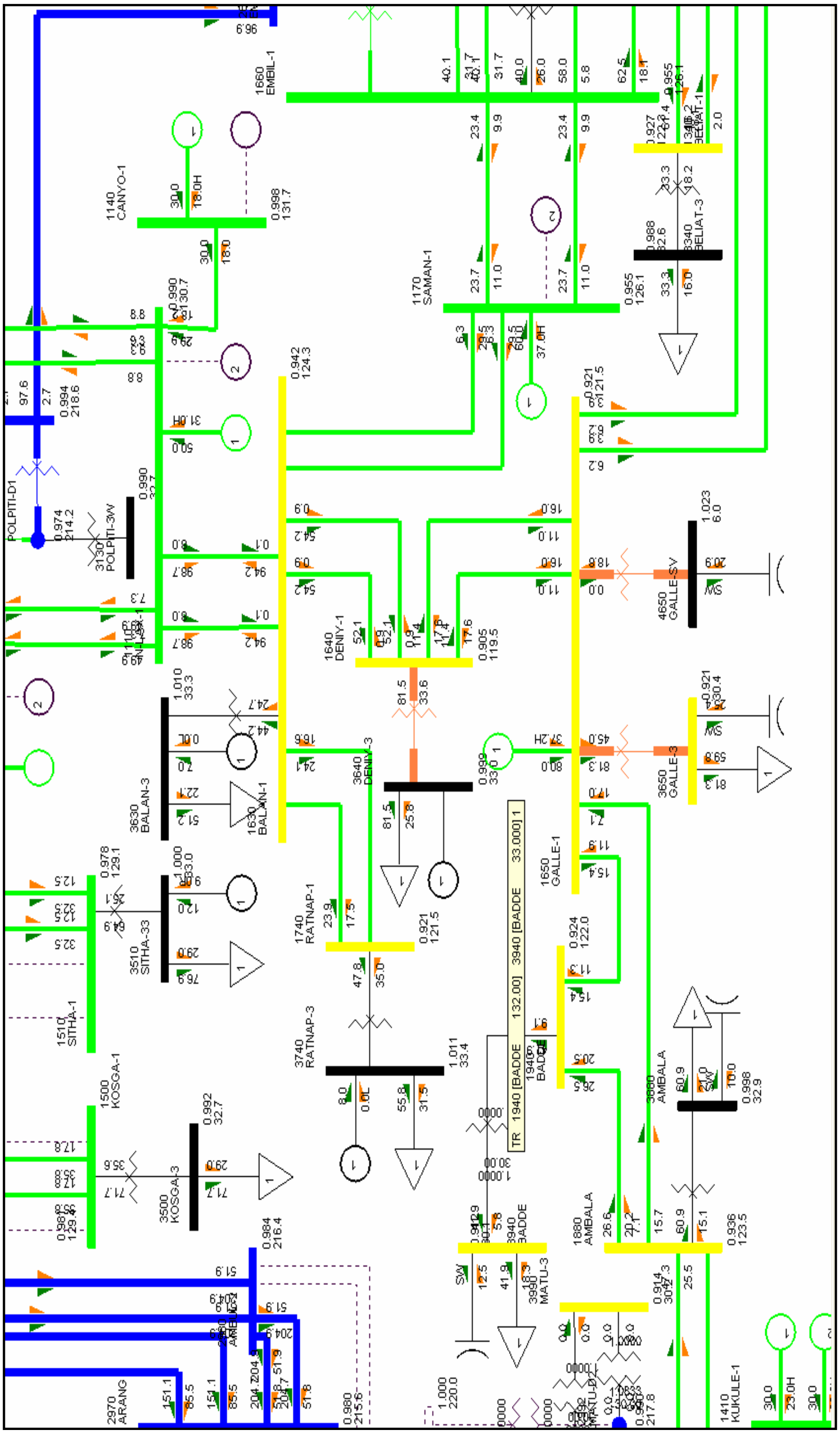
## ( i ) Year – 2012 : With Galle SVC



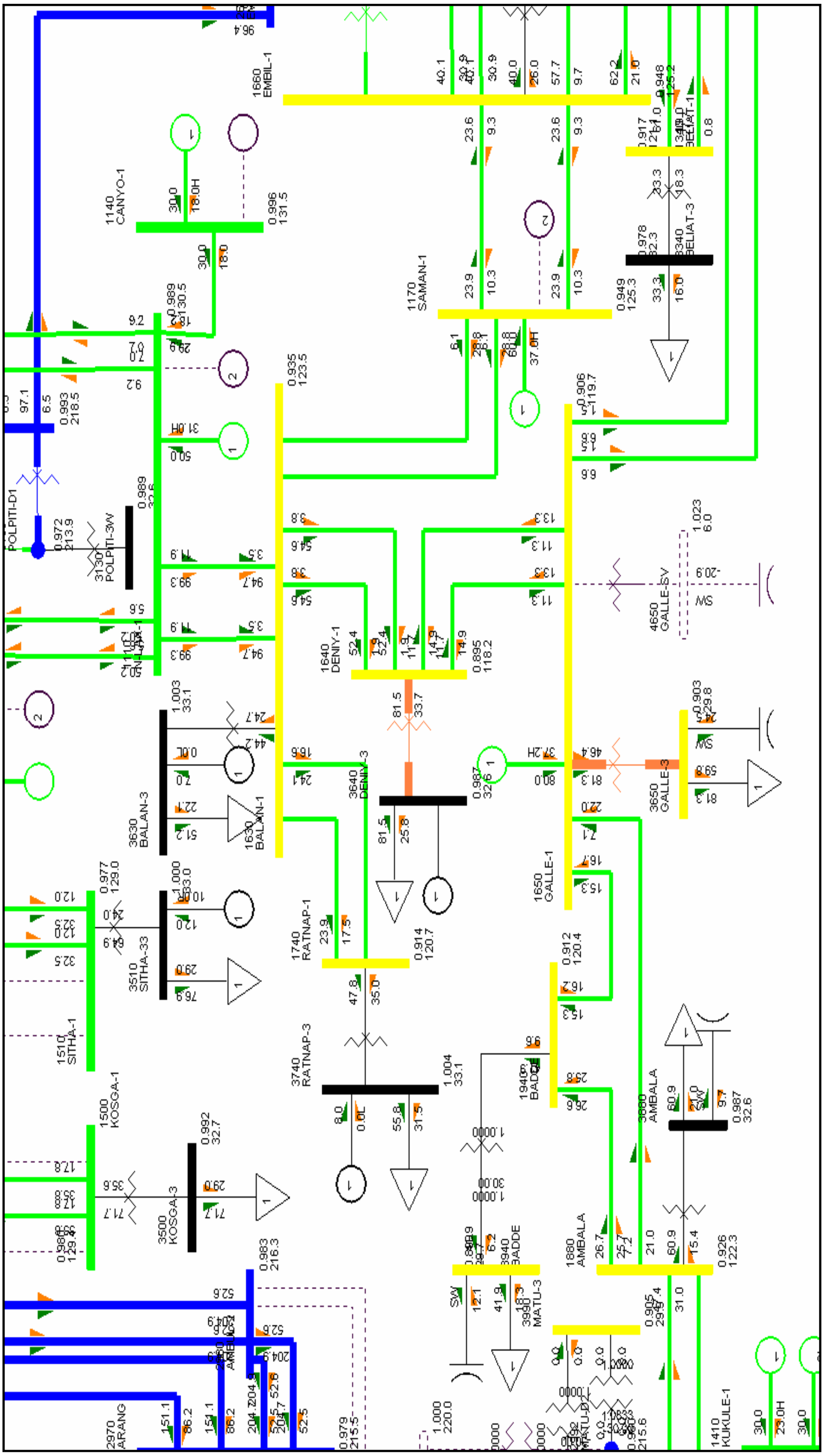
## Without Galle SVC



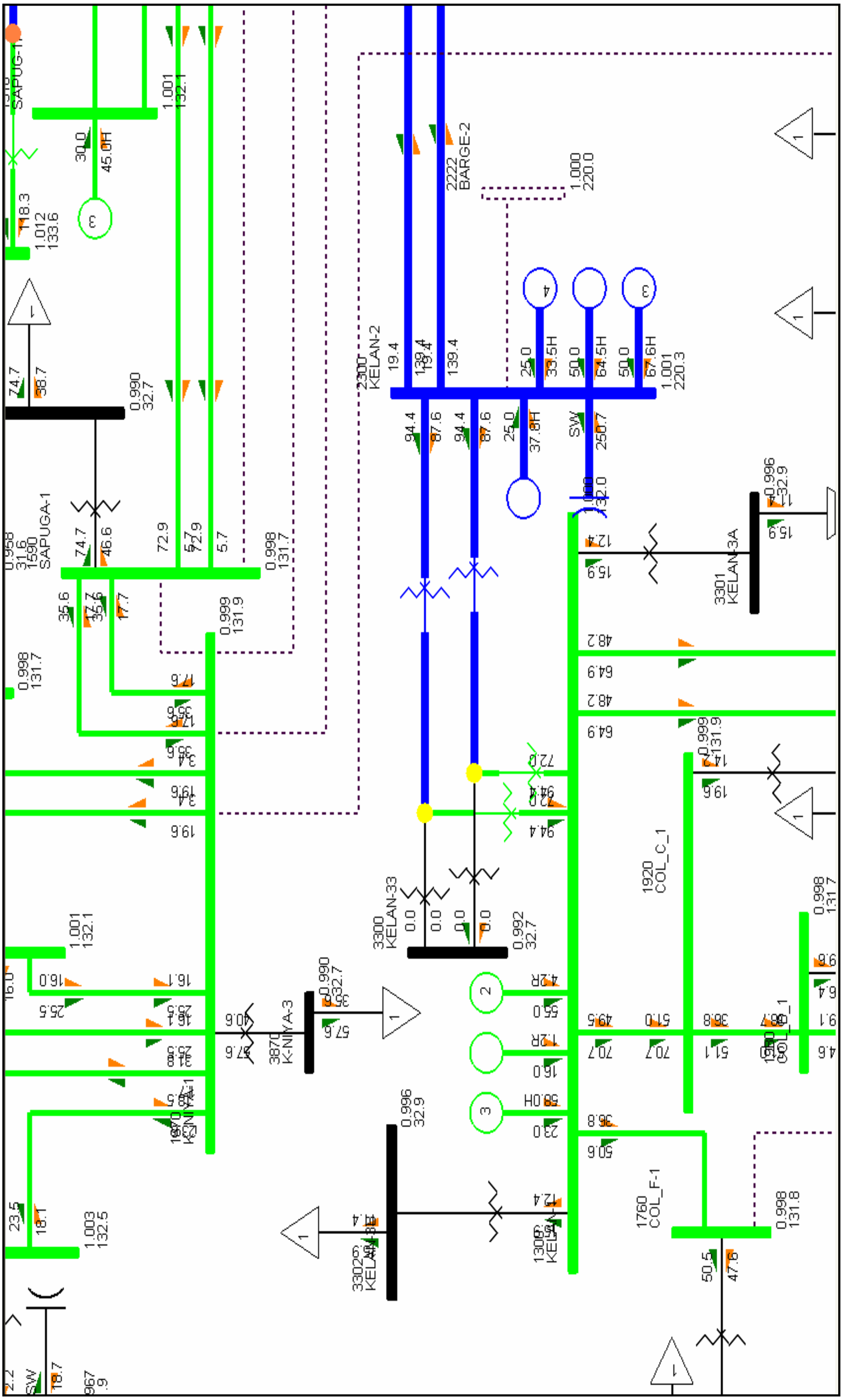
## ( ii ) Year – 2016: With Galle SVC



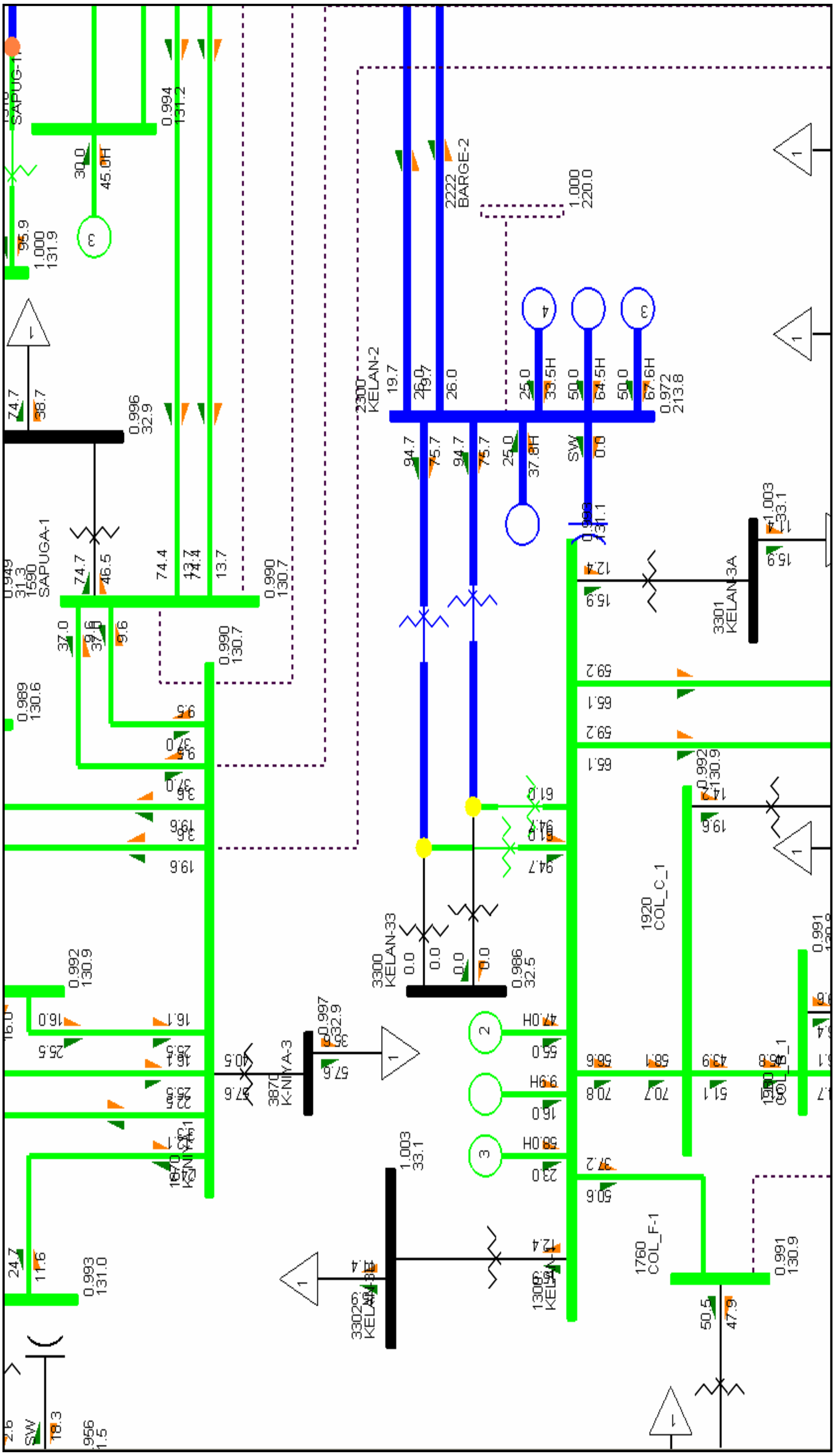
## Without Galle SVC



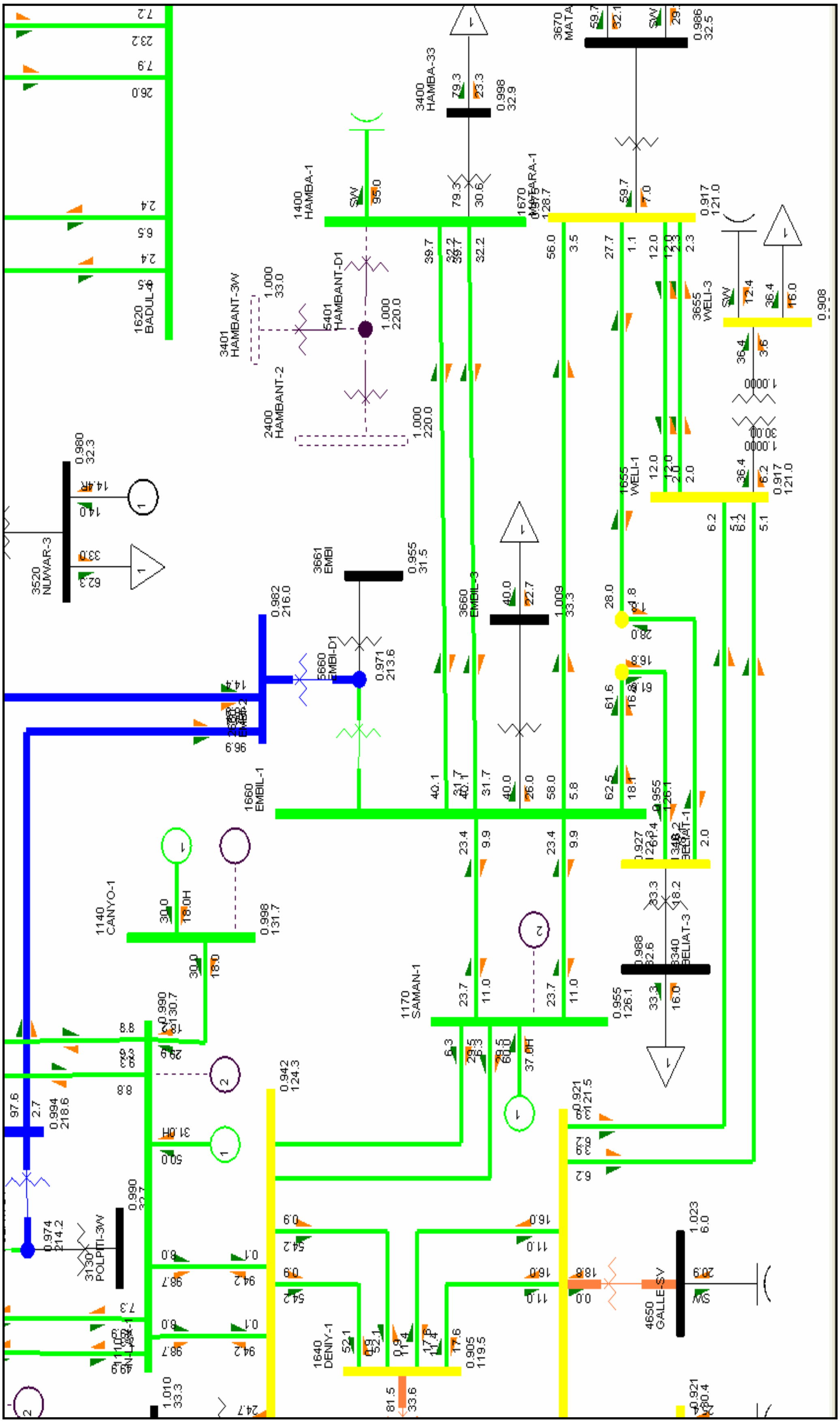
## With Kelanitissa SVC



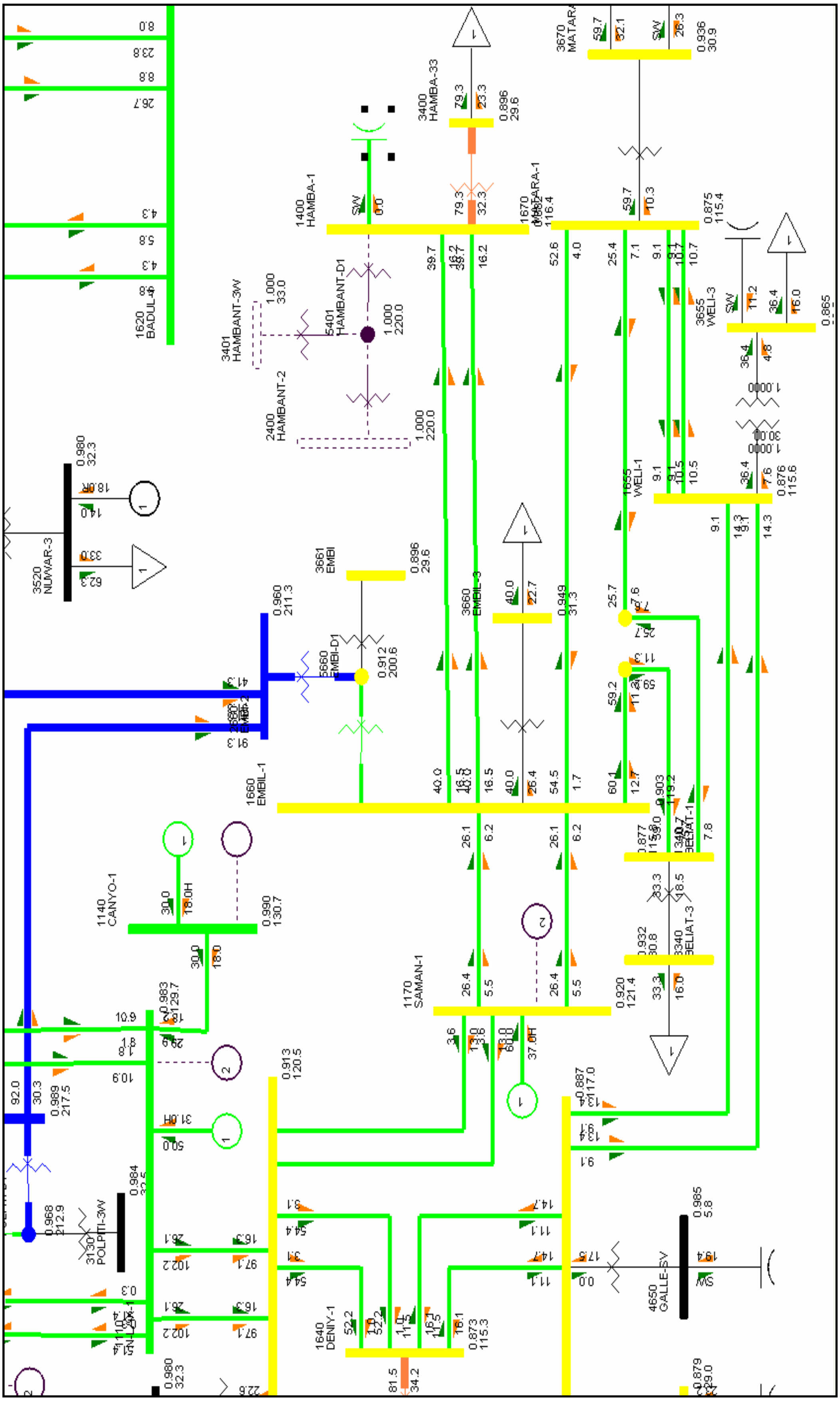
**Without Kelanitissa SVC**



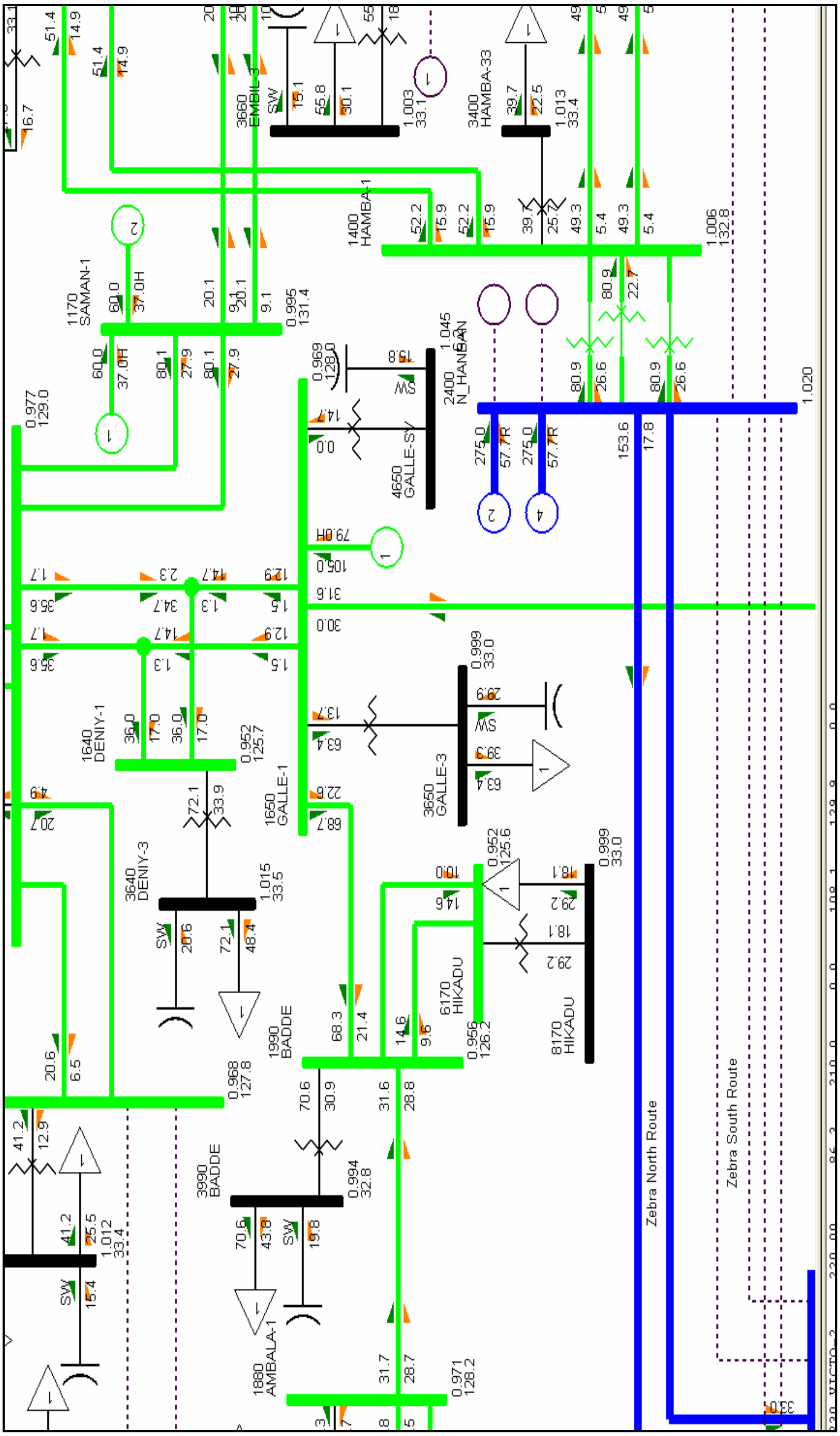
**With Hambantota SVC**



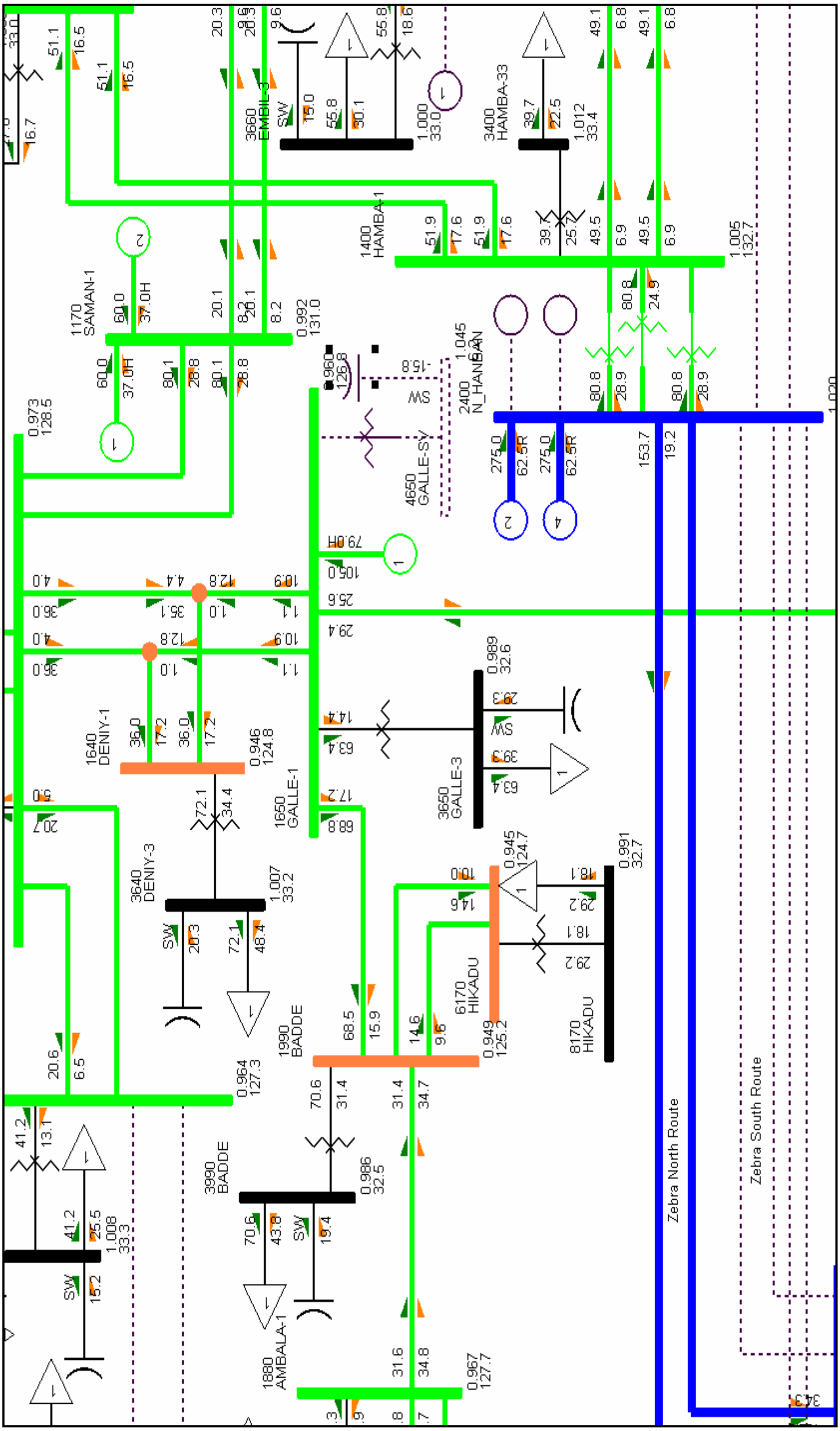
## Without Hambantota SVC



## ( iii ) Year – 2020:  With Galle SVC



**Without Galle SVC**



## 9.4 Observations and Recommendations

* Even though SVC is existing on the base-case CEB System, it is not found effective.

* Simulation studies are performed to obtain the effect of SVC at specific identified buses on Power Flows of CEB Systems corresponding to the Years 2012, 2016 and 2020 and the results are presented on the partial network.

* Improvement of reactive power flows in the neighboring sections and voltages at buses nearer to the location of SVC are observed.

* It is recommended to identify the effective locations for installing SVCs for improving the system dynamic stability, using the procedure suggested in this section.

# Chapter 10

# STABILITY IMPROVEMENT USING POWER SYSTEM STABILIZERS (PSS)

## 10.1 Introduction

Many of the modern large interconnected power systems tend to exhibit undamped or poorly damped oscillations when subjected to small perturbations about their operating point. This constitutes a severe threat to system security, and creates difficult operating problems. Hence, the need for the improvement of system damping has received much attention recently in the industry.

Analysis of dynamic stability can be performed by deriving a linearized state space model of the system in the following form:

$$p\,\underline{X} = A\,\underline{X} + B\,\underline{u} \qquad (1)$$

Where, the matrices A and B depend on the system parameters and the operating conditions. The Eigen values of the system matrix A determine the stability of the operating point. The Eigen-value analysis can be used not only for the determination of the stability regions, but also for the design of the controllers in the system.

The use of power system stabilizers with generating units for excitation control is well established as a means of improving the damping in the system. Power system stabilizers (PSS) are auxiliary feedback controllers which receive a signal from rotor velocity, frequency or accelerating power and provide a corrective input to the excitation system in order to damp out the oscillations in the system.

## 10.2 A Versatile System Model for Dynamic Stability Analysis of Large Scale Power Systems

The development of system model proceeds systematically by the development of the individual models of various components and subsystems and their interconnection through the network model. This approach retains the identity of the generating unit in the system model. Further, the changes in the system matrix caused by the changes in the system configuration can be easily accommodated.

### *10.2.1 Overview of the Proposed Method:*

Any complex power system can be represented, in general, as shown in Figure 10.1. This shows two types of buses in a power system: (i) Generator bus (G) and (ii) Load bus (L). Although only one bus or bus pair of each type is shown in figure, there can be a large number of generators and loads in a given system. At any bus k of an N-bus network the following equations apply

$$\Delta P_k = \sum_{j \in I_k} \left( \frac{\partial P_k}{\partial \theta_j} \Delta\theta_j + \frac{\partial P_k}{\partial V_j} \Delta V_j \right) \qquad (2)$$

$$\Delta Q_k = \sum_{j \in I_k} \left( \frac{\partial Q_k}{\partial \theta_j} \Delta \theta_j + \frac{\partial Q_k}{\partial V_j} \Delta V_j \right)$$

Where, $I_k$ is the set of buses that are connected to bus k.

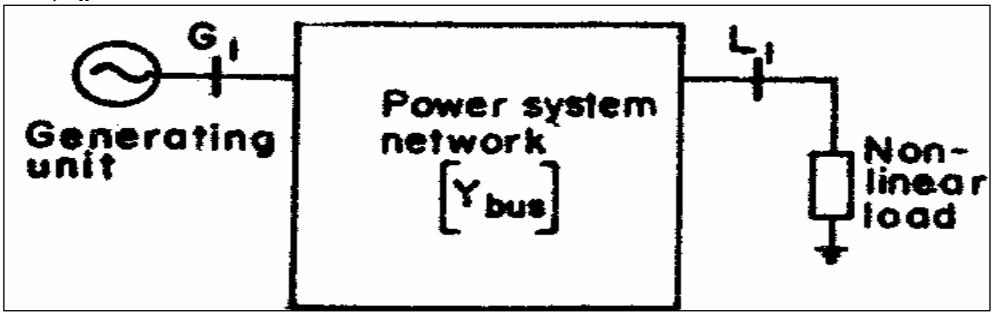



**Fig 10.1 Block diagram for Power System Network**

Also, it would be shown that for each bus, (ΔP, ΔQ) or (Δθ, ΔV) can be eliminated depending on the type of bus. This elimination procedure introduces the subset of generator output variables in the network equations. The remaining unknowns can thus be solved in terms of the system state variables.

The [A] matrix formulation is based on identifying the interconnections among the various subsystems of the power system as shown in Figure 10.2. Each generating unit comprises of three subsystems representing the synchronous machine, excitation and governor systems. Network is represented by its Jacobian matrix [J] of (2N x 2N) dimension. The effect of any non-linear voltage dependent load can be considered by modifying the corresponding diagonal block in [J]. All the generators are interconnected through the network.

In order to utilize the network equations given in the form of equation (2), the machine model has to be compatible. Hence the linearized machine representation is derived in a form such that $\Delta P_g$ and $\Delta Q_g$ are the input variables from the network and the machine terminal quantities, $\Delta\theta_g$ and $\Delta V_g$ are expressed in terms of the machine output variables and $\Delta P_g$, $\Delta Q_g$.

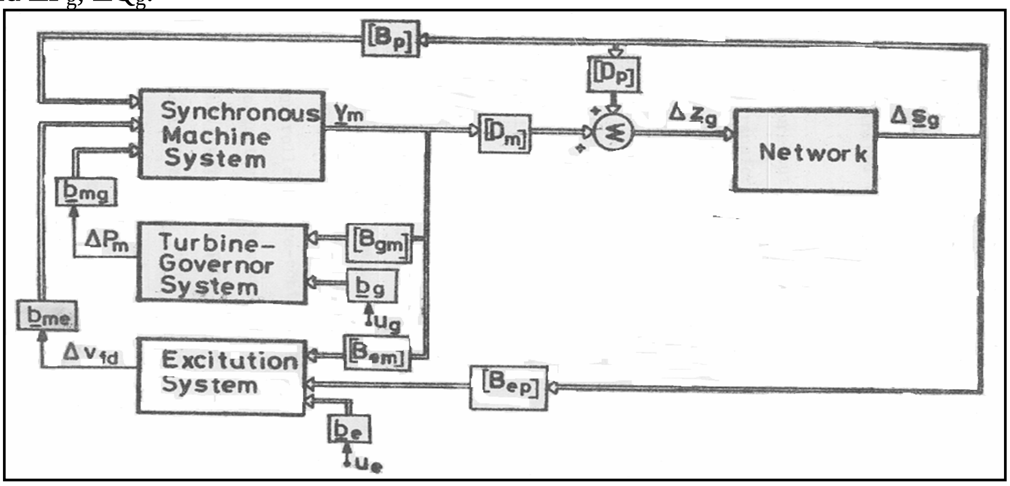



**Fig 10.2 Block diagram showing the interconnections among the various subsystems of power system**

Development of the system model is based on the formulation of the individual component models and identifying the various interconnections between the subsystems. The linearized network algebraic equations are solved in the terms of the system state variables resulting in the final system model.

### *10.2.2 State Space Model of the Overall System*

State space model of the overall system is obtained as, where all the components are matrices,

$$p\,\underline{X} = [A]\,\underline{X} + [B]\,\underline{U} \tag{3}$$

$$\underline{Y} = [C]\,\underline{X} \tag{4}$$

Where $\underline{X} = [\underline{X}_M^t \quad \underline{X}_E^t \quad \underline{X}_G^t]^t$

$\underline{U} = [\underline{u}_e^t \quad \underline{u}_g^t]^t$

$\underline{Y} = [\underline{Y}_M^t \quad \underline{Y}_E^t \quad \underline{Y}_G^t]^t$

$$[A] = \begin{bmatrix} A'_M & B_{ME} & B_{MG} \\ B'_{EM} & A_E & O \\ B_{GM} & O & A_G \end{bmatrix} \tag{5}$$

$$[B] = \begin{bmatrix} O & O \\ B_E & O \\ O & B_G \end{bmatrix} \tag{6}$$

$$[C] = \begin{bmatrix} C_M & & \\ & C_E & \\ & & C_G \end{bmatrix} \tag{7}$$

## 10.3 Dynamic Stability Improvement through Suitable Location of PSS

It can be shown that a proper choice of the location of PSS is essential to get the maximum benefits from the point of view of improving dynamic stability in a large interconnected system. In a large-scale power system, the optimal location of PSS is a complex problem, and it is normally decided by the economical and technical considerations. During the planning stages, various alternatives must be considered with different objectives for the selection of best location of the controllers. For each of the objectives, the system designer should have the information about the ranking (in order of preference) of all the possible locations of the controllers. This facilitates the system designer to select the best locations of the controllers that satisfy the various possible objectives in an optimum manner. The objective of this Section is to propose an analytical method to solve the problem of selection of PSS locations for the purpose of improving the dynamic stability.

While it would be advantageous to install the PSS on all the machines, the application of stabilizers on older units of the multimachine system can be ineffective and uneconomical in practice. Also, it may not be desirable from the point of view of coordination between various machines in a large system. For satisfactory system damping, it is sufficient to equip relatively few machines with PSS. It is suggested to use the eigenvalue analysis and the observation of mode shapes (eigenvectors) for the purpose of location of PSS.

In particular, two analytical methods are presented in this section based on two different assumptions namely:

1. the controller structure is not decided apriori;
2. the controller structure is decided in advance.

Both these methods have been tried on several examples and the results are discussed.

## 10.4 OUTLINE OF THE PROPOSED TECHNIQUE

Dynamic stability of power systems can be investigated with the help of a linear mathematical model expressed in the form

$$p\,\underline{X} = A\,\underline{X} + B\,\underline{u} \qquad (8)$$

$$\underline{Y} = C\,\underline{X} \qquad (9)$$

Where $\underline{X}$ is the state vector, $\underline{u}$ is the control vector and $\underline{Y}$ is the output vector. In deriving this model, the generating units are represented by differential equations and the power system network by algebraic equations. The degree of the detail used in the representation of generating unit can vary depending on the availability of data and the need for suitable accuracy. The model can be used for:

1. Prediction of the performance of the system under specified disturbances. The prediction of the stability characteristics is an important application and can be determined from eigenvalue analysis and is independent of the disturbances.

2. The design of suitable controllers. Normally, in control theory, the structure of the controller is specified in advance. In the case of feedback control, for example, it can be represented by

   $$\underline{u} = F\,\underline{Y} \qquad (10)$$

   Where, the elements of the matrix F have to be properly chosen.

In a power system, the selection of control vector $\underline{u}$ has to be made first before the controller can be designed. Assuming that there are a total of 'm' control vectors out of which one has to be selected, the problem can be stated as follows:

Select a control vector $u_i$ where i can range from l to m such that the system described by

$$p\,\underline{X} = A\,\underline{X} + B_i\,\underline{u_i} \qquad (11)$$

satisfies the control criterion in the most optimal manner among all possible choices of the control vector. In general, the solution to this problem requires the specification of the control criterion and the control structure such as that given by equation (10).

The control criterion in the dynamic stability problem is to increase the damping of the critical modes of oscillation. The objective can be stated in terms of achieving the maximum amount of damping through minimum control effort. To illustrate this, consider the transformation

$$\underline{X} = T\,\underline{Z} \tag{12}$$

which reduces the system of equations (11) to

$$\begin{aligned} p\,\underline{Z} &= [T^{-1} A\, T]\,\underline{Z} + [T^{-1} B_i]\,\underline{u}_i \\ &= [A]\,\underline{Z} + [\,B_i'\,]\,\underline{u}_i \end{aligned} \tag{13}$$

Where A is a diagonal matrix (with the assumption that all the eigenvalues are distinct) whose elements are the eigenvalues of the A matrix. The row in equation (13) corresponding to the critical eigenvalue (mode) $\lambda_j$ can be expressed as

$$p\,Z_j = \lambda_j Z_j + \underline{B}_{ji}'\ \underline{u}_i \tag{14}$$

Where, $\underline{B}_{ji}'$ is the jth row of $[B'_i]$

Assuming that the control law of $\underline{u}_i$ is going to be selected suitably in order to shift the eigenvalue $\lambda_j$ to the left in the complex plane (to increase the damping), it can be observed that the control effort would be minimum if a scalar norm of the vector $\underline{B}'_{ji}$ is maximum. If the control $\underline{u}_i$ is a scalar then $\underline{B}'_{ji}$ is also a scalar and the criterion for the best control is to maximum $|\,\underline{B}'_{ji}\,|$ over all possible values of the index i. It is to be noted that $\underline{B}'_{ji}$ is the scalar product of the eigenvector $\underline{W}_j$ (of the matrix $A^t$) and the vector $\underline{B}_i$.

## **<u>Selection of Control with Fixed Configuration</u>**

In the previous discussion the nature of the control law or the configuration of the controller has not been assumed apriori. In the alternate method of selection of the best control vector, the control law given by the equation (10) is assumed. For the single-input-single-output (SISO) case, the system equation (11) reduces to

$$p\,\underline{X} = (A + \underline{B}_i\ F_i\,\underline{C}^t_i)\,\underline{X} \tag{15}$$

Where the output $y_i = \underline{C}^t_i\,\underline{X}$ is used for feedback. The value of the scalar $F_i$ (feedback gain) is so chosen as to shift the open loop critical eigenvalue $\lambda_j$ to the left in the complex plane. This is to be achieved with the smallest possible value of gain. The closed loop eigenvalue $\lambda_j^*$ is given by

$$\lambda *_j = \lambda_j + \frac{\partial \lambda_j}{\partial F_i} F_i \ \text{+ higher order terms.}$$

If the higher order terms are neglected, the best control is determined by maximizing the absolute value of

$$\mathrm{Re}\left(\frac{\partial \lambda_j}{\partial F_i}\right)$$

The eigenvalue sensitivity ($\partial\lambda_j / \partial F_i$) is given by:

$$S_{ji} = \frac{\partial \lambda_j}{\partial F_i} = \frac{< \underline{B}_i \underline{C}^t{}_i \underline{V}_j, \underline{W}_j >}{< \underline{V}_j, \underline{W}_j >} \tag{16}$$

Where $\underline{V}_j$ and $\underline{W}_j$ are the eigenvectors of [A] and $[A]^t$ respectively corresponding to the jth eigenvalue.

## 10.5 Simplified Power System Models

In the dynamic stability analysis, the interest is mainly centered around damping of the electromechanical oscillations of the rotors of synchronous machines. For an ‘n’ machine system there are in general (n – 1) modes of oscillations. For planning studies it is admissible to use a simplified system model which contains only the relevant features that are of interest. Thus, it is possible to consider only classical models of the machine neglecting damper windings, voltage regulator and governor. The machine is represented by a constant voltage source behind its transient reactance.

The machine equations are given by

$$[M]\, P^2\, \Delta\underline{\delta}_g = \Delta\underline{P}_m - \Delta\underline{P}_g \tag{17}$$

For constant mechanical power input, $\Delta\underline{P}_m = \underline{O}$. The network equations can be written in the form

$$\begin{bmatrix} \Delta\underline{P}_g \\ \Delta\underline{P}_l \\ \Delta\underline{Q}_g \\ \Delta\underline{Q}_l \end{bmatrix} = \begin{bmatrix} J_{PA} & J_{PE} \\ J_{QA} & J_{QE} \end{bmatrix} \begin{bmatrix} \Delta\underline{\delta}_g \\ \Delta\delta_\ell \\ \Delta\underline{E}_g \\ \Delta\underline{E}_\ell \end{bmatrix} \tag{18}$$

Where, $J_{PA}$, $J_{PE}$, $J_{QA}$ and $J_{QE}$ are the component matrices of the Jacobian evaluated from the network power flow equations. The subscript refers to the internal buses of the generators. To simplify the analysis it is assumed that the effect of the voltage variations in the load buses is negligible.

Then, since only the active power component is required in the swing equation given by (17), the equation (18) can be written in the form given by

$$\begin{bmatrix} \Delta \underline{P}_g \\ \Delta \underline{P}_l \end{bmatrix} = [J_{PA}] \begin{bmatrix} \Delta \underline{\delta}_g \\ \Delta \underline{\delta}_l \end{bmatrix} + \begin{bmatrix} J_{E1} \\ J_{E3} \end{bmatrix} \Delta \underline{E}_g \qquad (19)$$

Where,

$$[J_{PA}] \underline{\underline{\Delta}} \begin{bmatrix} J_{A1} & J_{A2} \\ J_{A3} & J_{A4} \end{bmatrix} \quad \text{and} \quad [J_{PE}] \underline{\underline{\Delta}} \begin{bmatrix} J_{E1} & J_{E2} \\ J_{E3} & J_{E4} \end{bmatrix}$$

From equation (19), we have

$$\Delta\underline{\delta}_l = J^{-1}_{A4}\, \Delta\underline{P}_l - J^{-1}_{A4}\, J_{A3}\, \Delta\underline{\delta}_g - J^{-1}_{A4}\, J_{E3}\, \Delta\underline{E}_g \qquad (20)$$

Substituting the equation (20) in (19), we get

$$\Delta\underline{P}_g = [K]\ \Delta\underline{\delta}_g + [B'_d]\ \ \Delta\underline{P}_\ell + [B_S]\ \Delta\underline{E}_g \qquad (21)$$

Where $[K] = [J_{A1} - J_{A2}\ J_{A4}^{-1}\ J_{A3}]$

$[B'_d] = [J_{A2}\ \ J_{A4}^{-1}\ ]$

$[B_S] = [J_{E1} - J_{A2}\ \ J_{A4}^{-1}\ \ J_{E3}]$

The vector $\Delta\underline{P}_\ell$ is zero for the constant power type loads and it can also be treated to be zero for any other type of voltage dependent loads by suitably modifying the diagonal block of the Jacobian corresponding to the load buses.

The generator internal voltage is controlled by means of PSS control on the machine. Thus, the generator internal voltage vector $\Delta\underline{E}_g$ consists of non-zero elements corresponding only to the machines on PSS control.

The expression for $\Delta\underline{P}_g$ is given by the equation (21) when PSS is present. Hence, in equation (21),

i. if the PSS is absent, the vector $\Delta\underline{E}_g$ is zero.
ii. if the PSS is present, the vector $\Delta\underline{P}_\ell$ is zero.

**<u>System Model with PSS</u>**

For simplicity it is assumed that only one location for PSS is considered at a time. For the location of PSS on the ith generator, $\Delta\underline{E}_g$ is given by

$$\Delta\underline{E}_g = l_i\ \ u_{ei} \qquad (22)$$

Where $l_i = [0\ \ 0 \ldots\ldots\ldots 1^{\text{(ith gen)}}. \ldots\ldots 0]^t$
and $u_{ei}$ is the control corresponding to the ith machine. From the equations (21) and (22), we get

$$\Delta\underline{P}_g = [K]\ \Delta\underline{\delta}_g + \underline{b}'_{ei}\ \ u_{ei} \qquad (23)$$

Where

$$\underline{b}'_{ei} = [B_S]\ \underline{l}_i \qquad (24)$$

Using the equations (17) and (23), the state space form of the system model can be obtained and is given by

$$p\underline{X} = [A]\ \underline{X} + \underline{b}'_{ei}\ u_{ei} \qquad (25)$$

Where $\underline{X} = [\Delta\underline{\delta}^t_g \quad \Delta\underline{\omega}^t_g\ ]^t$

$$\underline{b}_{ei} = \begin{bmatrix} \underline{0} \\ -[M]^{-1} \quad \underline{b}'_{ei} \end{bmatrix} \ ; \quad [A] = \begin{bmatrix} 0 & I \\ P & 0 \end{bmatrix} \ ; \quad [P] = -[M]^{-1}K \qquad (26)$$

Normally, the rotor velocity of the machine is used as the feedback control signal for the PSS. This can be derived as

$$y_i = \underline{c}^t_{ei}\ \underline{X} \qquad (27)$$

$$\underline{c}^t_{ei} = [\underline{0} \quad \underline{\ell}^t_i\ ]$$

From the equation (10), for the SISO case, we get

$$u_{ei} = F_i \quad y_i \qquad (28)$$

## 10.6 Effect of the Location of PSS on Dynamic Stability – Illustration with Numerical Examples

### *10.6.1 Nine-Bus, Three-Machine Power System*

DATA:

| | | |
|---|---|---|
| Number of Buses | = | 9 |
| Number of Lines | = | 9 |
| Base MVA | = | 100.0 |
| Number of Machines | = | 3 |
| Number of Loads | = | 3 |
| Number of shunt capacitors | = | 0 |
| Number of voltage controlled buses | = | 0 |

**Table C.1: Line Data for the Nine-Bus, Three Machines System**

| Line No. | From Bus | To Bus | Line Impedance | | Half Line-Charging Admittance | Turns Ratio |
|---|---|---|---|---|---|---|
| | | | R | X | | |
| 1 | 1 | 4 | 0.0 | 0.0576 | 0.0 | 1.0 |
| 2 | 2 | 7 | 0.0 | 0.0625 | 0.0 | 1.0 |
| 3 | 3 | 9 | 0.0 | 0.0586 | 0.0 | 1.0 |
| 4 | 4 | 5 | 0.01 | 0.085 | 0.088 | 1.0 |
| 5 | 5 | 7 | 0.032 | 0.161 | 0.153 | 1.0 |
| 6 | 6 | 9 | 0.039 | 0.17 | 0.179 | 1.0 |
| 7 | 7 | 8 | 0.0085 | 0.072 | 0.0745 | 1.0 |
| 8 | 8 | 9 | 0.0119 | 0.1008 | 0.1045 | 1.0 |
| 9 | 4 | 6 | 0.017 | 0.092 | 0.079 | 1.0 |

All impedances are in pu on a 100-MVA base.

**Table C.2: Generator Data for the Nine-Bus, Three-Machine System**

| **Generator** | **1** | **2** | **3** |
|---|---|---|---|
| Rated MVA | 247.5 | 192.0 | 128.0 |
| kV | 16.5 | 18.0 | 13.8 |
| Power Factor | 1.0 | 0.85 | 0.85 |
| Type | Hydro | Steam | Steam |
| Speed | 180 rpm | 3600 rpm | 3600 rpm |
| $x_d$ | 0.1460 | 0.8958 | 1.3125 |
| $x'_d$ | 0.0608 | 0.1198 | 0.1813 |
| $x_q$ | 0.0969 | 0.8645 | 1.2578 |
| $x'_q$ | 0.0969 | 0.1969 | 0.25 |
| $x_l$ (leakage) | 0.0336 | 0.0521 | 0.0742 |
| $T_{do}'$ | 8.96 | 6.00 | 5.89 |
| $T_{qo}'$ | 0 | 0.535 | 0.600 |
| H (MW.s/100 MVA) | 23.64 s | 6.40 s | 3.01 s |

Reactance values are in pu on a 100-MVA base. All time constants are in secs.

Data for the Controllers

Excitation System (see Figure C.3)

$K_A$ = 50.0; $T_A$ = 0.02; $K_E$ = -0.037; $T_E$ = 0.146
$K_S$ = 0.057; $T_S$ = 0.45

$S_E = A_{ex} \exp^{B_{ex}\ V_{fd}}$

Where $A_{ex}$ = 0.015 and $B_{ex}$ = 0.6

Power System Stabilizer (PSS) (see Figure C.4)

$K_p$ = 96.0; $T_4$ = 3.0; $T_5$ = 0.15; $T_6$ = 0.05

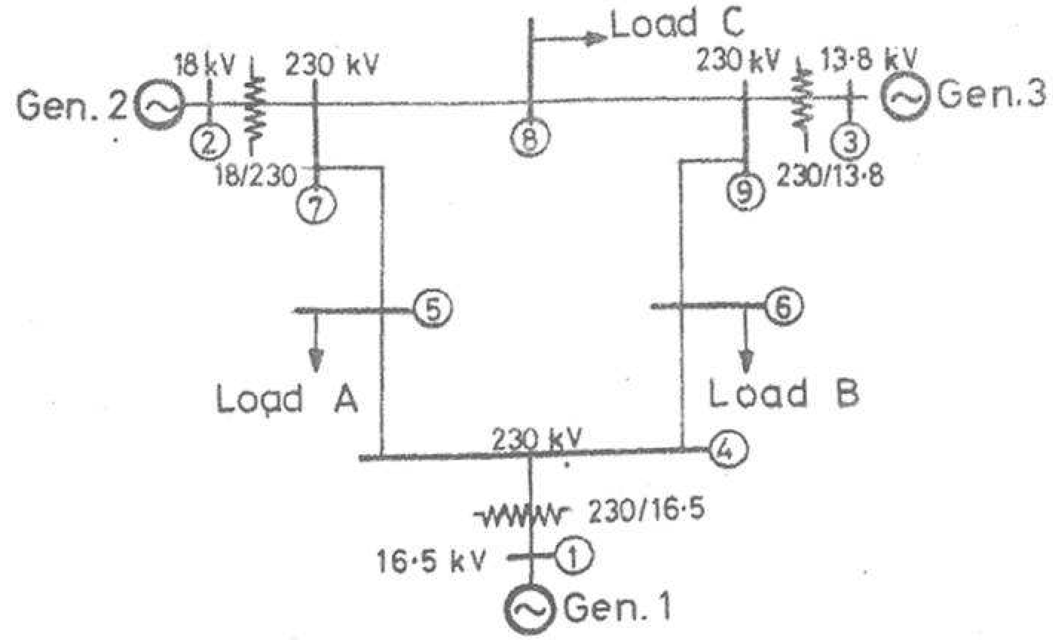



Fig. C.1 Single line diagram of nine-bus, three-machine power system

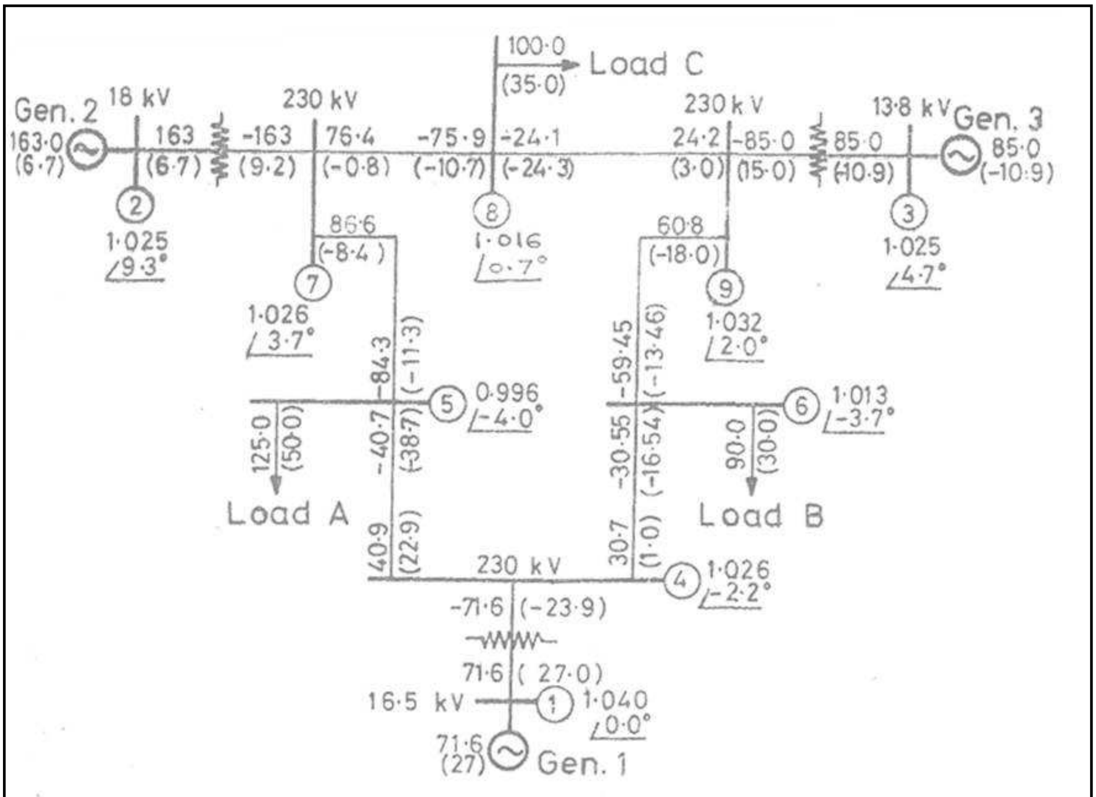



Fig. C·2 Load flow diagram showing prefault conditions of the nine-bus, three-machine system

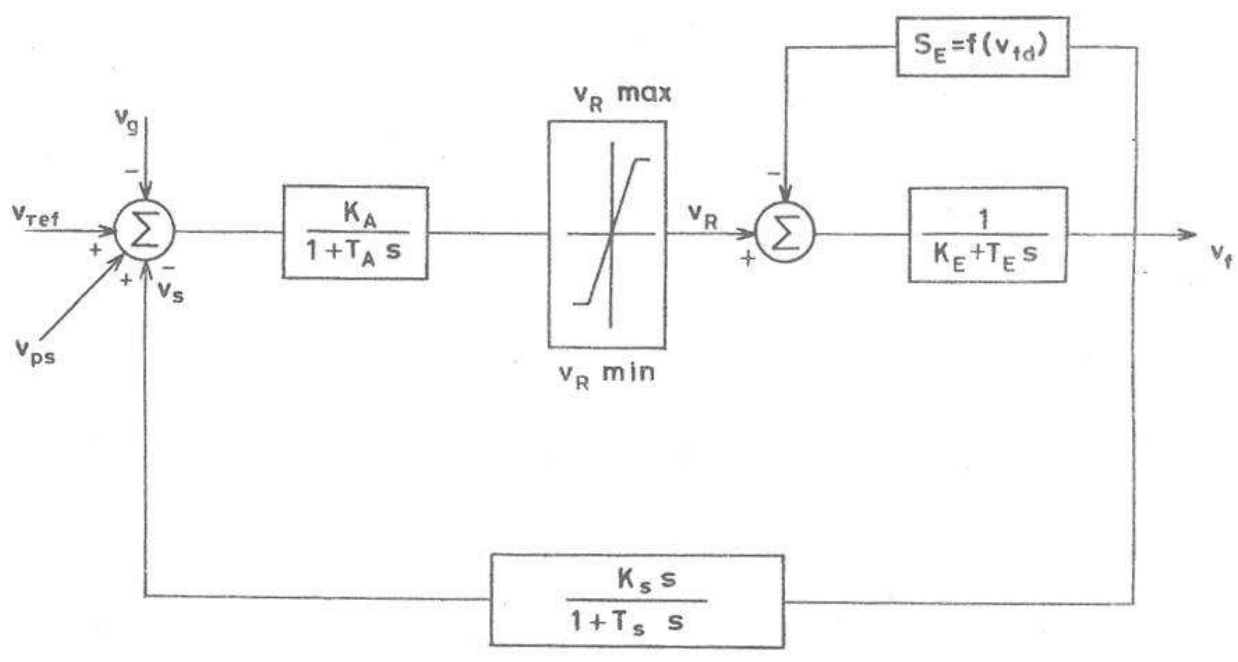



Fig. C·3 Block diagram of IEEE Type 1 excitation system

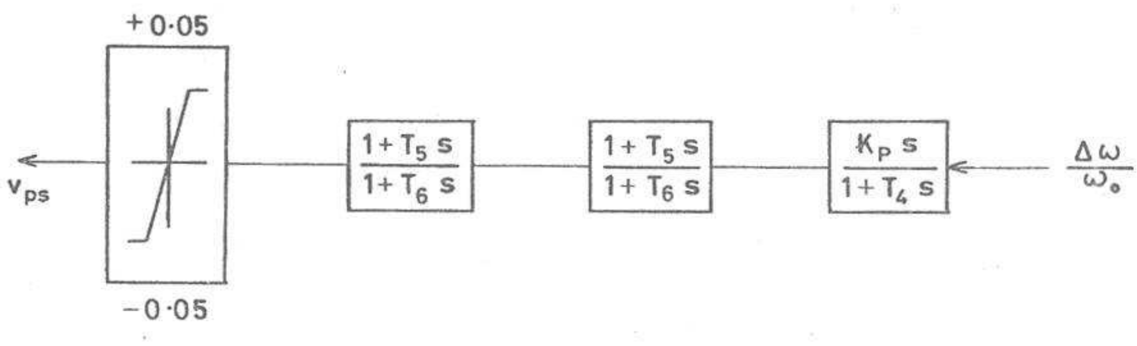



Fig. C-4 Block diagram of Power System Stabilizer

The multi-machine power system described above is considered. The single line diagram of the system is shown in the Figure C.1. The system model is formulated according to the procedure given in the Section 5. The eigenvalues for the system without the PSS and for the specified load conditions are calculated and found to be 0.0 $\pm$ j 8.6758; and 0.0 $\pm$ j 13.3973 corresponding to the rotor electromechanical oscillations. All the generators, taken one at a time are considered for the location of PSS with a view to damp the electromechanical oscillations.

In the first method, the magnitude of the scalar product of the reciprocal eigenvector ($\underline{W}_j$) and the vector $\underline{b}_{ei}$ is calculated for each of the complex pair of eigenvalues and for different locations of the PSS. In the second method, the eigenvalue sensitivity ($S_j$) is calculated for each of the complex pairs of eigenvalues and for different locations of the PSS. The local feedback of rotor velocity of the machine is considered as the feedback control signal in this method.

The results obtained for these two methods are shown in the Table 10.1.

**Table 10.1:** Scalar Products in Method 1 and the Eigenvalue Sensitivities in Method 2, for Different Locations of the PSS in the 3 – Machine System. Feedback Control Signal in Method 2; Local Feedback of the Absolute Value of ω of the Machine.

| **Location (Gen.) No.** | **Scalar Products in the Method 1** | | **Eigenvalue Sensitivities in the Method 2 Re. ($S_j$), j = 1, 2** | |
|---|---|---|---|---|
| | **Lower Frequency Mode (ω = 8.6758)** | **Higher Frequency Mode (ω = 13.3973)** | **Lower Frequency Mode (ω = 8.6758)** | **Higher Frequency Mode (ω = 13.3973)** |
| 1 | 0.8141 | 0.5652 | + 2.1029 | + 0.1808 |
| 2 | 2.6195 | 1.1609 | - 17.6790 | - 2.7518 |
| 3 | 1.3260 | 2.6012 | - 5.1410 | -19.8580 |

**<u>Validation of the Results</u>**

In order to test the results obtained from the study regarding the effective location, an eigenvalue analysis is performed. The eigenvalues obtained for a controller gain of F =

0.2 pu/rad. per sec with the feedback signal obtained locally from the $\omega$ of the corresponding machine, taken one at a time, are shown in the Table 10.2. The results given in the Table 2 validate the conclusions regarding the effective location of the PSS.

**Table 10.2:** Eigenvalues Corresponding to the Electromechanical Oscillations for Different Locations of the PSS, with Local Feedback of Rotor Velocity of the Machine.

| Location (Gen.) No. | Feedback Control Structure | Eigenvalues | |
|---|---|---|---|
| | | Lower Frequency Oscillation | Higher Frequency Oscillation |
| 1 | $\Delta E_i = F_i \, \Delta\omega_i$ | $+0.3712 \pm j8.8029$ | $+0.0356 \pm j13.4020$ |
| 2 | | $-3.3580 \pm j6.6445$ | $-0.2331 \pm j13.1140$ |
| 3 | | $-0.9392 \pm j9.2990$ | $-3.9201 \pm j10.8501$ |

### *10.6.2 Six – Bus, 4 – Machine System*

An example of a 4 – machine system described in another reference is considered here. The single line diagram of the system is shown in the Figure C.5. The generator data, bus data and the line data are given below:

Data given here is in pu on a 100 MVA base.

**Table C.3: Generator Data for the 4-Machine System**

| Generator | $x_d$ | $x'_d$ | $x_q$ | $T'_{do}$ (sec.) | Inertia Constant H (sec.) |
|---|---|---|---|---|---|
| 1 (Infinite Bus) | 0.0 | 0.0 | 0.0 | - | - |
| 2 | 0.761 | 0.084 | 0.75 | 7.3 | 10.36 |
| 3 | 0.609 | 0.092 | 0.524 | 7.5 | 11.30 |
| 4 | 0.302 | 0.046 | 0.262 | 7.5 | 22.65 |

**Table C.4: Bus Data for the 4-Machine System**

| Bus No. | Bus Voltage Magnitude (pu) | Bus Voltage Phase Angle (Degrees) | Generation | | Load | |
|---|---|---|---|---|---|---|
| | | | MW | MVAR | MW | MVAR |
| 1 | 1.07 | 0.0 | 861.0 | 480.0 | 0.0 | 0.0 |
| 2 | 1.04 | 2.1 | 180.0 | 49.0 | 30.0 | 15.0 |
| 3 | 1.05 | -1.4 | 275.0 | 150.0 | 60.0 | 40.0 |
| 4 | 1.05 | 4.4 | 400.0 | 94.0 | 110.0 | 80.0 |
| 5 | 0.91 | -14.5 | 0.0 | 0.0 | 1060.0 | 400.0 |
| 6 | 1.00 | -4.5 | 0.0 | 0.0 | 400.0 | 170.0 |

**Table C.5: Line Data for the 4-Machine System**

| Line | From Bus | To Bus | Line Impedance | | Line Charging | Turns Ratio |
|---|---|---|---|---|---|---|
| | | | Resistance | Reactance | | |
| a | 4 | 6 | 0.0101 | 0.0615 | 0.8 | 1.0 |
| b | 3 | 6 | 0.0057 | 0.046 | 0.098 | 1.0 |
| c | 3 | 5 | 0.0836 | 0.236 | 0.1856 | 1.0 |
| d | 1 | 3 | 0.0628 | 0.11 | 0.3654 | 1.0 |
| e | 1 | 5 | 0.0033 | 0.0313 | 1.144 | 1.0 |
| f | 2 | 5 | 0.0255 | 0.172 | 0.65 | 1.0 |
| g | 2 | 4 | 0.0836 | 0.236 | 0.1856 | 1.0 |

**Results for the Effective Location of PSS**

The system model is formulated as per the procedure indicated earlier. The eigenvalues for the system without the PSS and for the specified load conditions are computed and found to be 0.0 $\pm$ j6.1907; 0.0 $\pm$ j10.2067; 0.0 $\pm$ j12.2026.

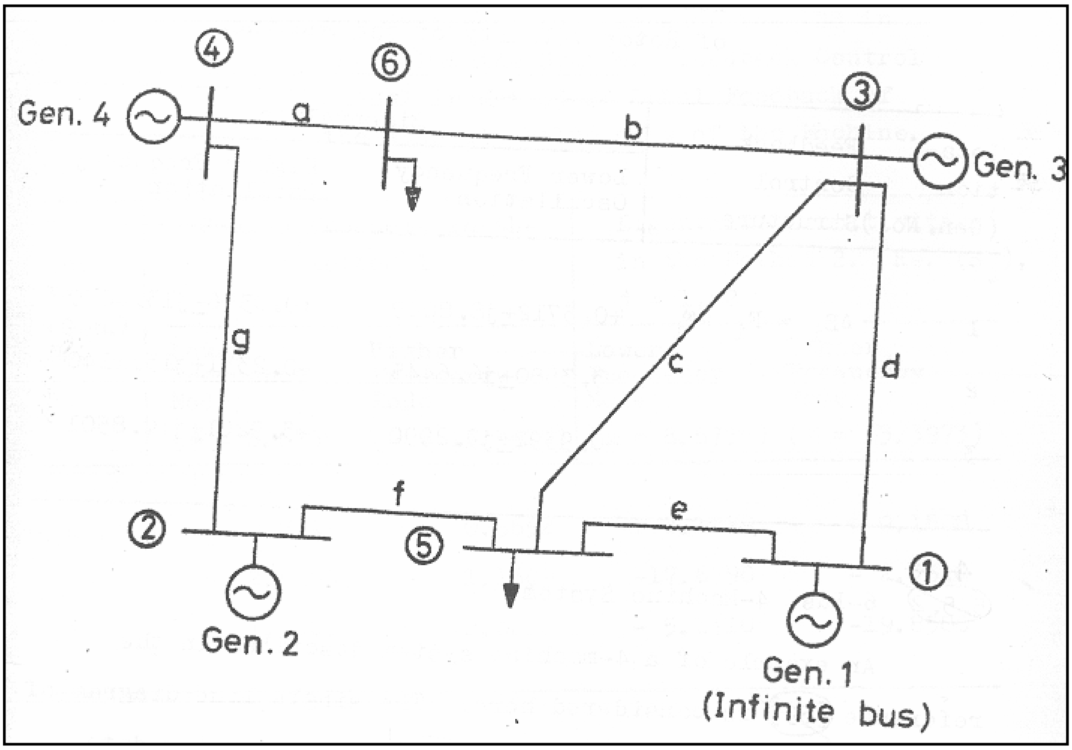



**Fig: C.5 Single line diagram of the 4- machine system**

Corresponding to the rotor electromechanical oscillations, all the generators, taken one at a time, are considered for the location of PSS with a view to damp these oscillations. Both the methods proposed are applied. The scalar products obtained in the method 1 and the eigenvalue sensitivities obtained in the method 2 are shown in the Table 10.3, for different locations of the PSS.

## Validation of the Results

In order to verify the results obtained above for the effective location of PSS, an eigenvalue analysis is performed. The eigenvalues obtained for a controller gain for F = 0.2 pu/rad. per sec. are shown in Table 10.4. The eigenvalues given in the Table 10.4 validate the results obtained above.

**Table 10.3:** Scalar Products in Method 1 and the Eigenvalue Sensitivities in Method 2, for Different Locations of the PSS in the 4 – Machine System. Feedback Control Signal in Method 2; Local Feedback of the Absolute Value of ω of the Machine.

| Location (Gen.) No. | Scalar Products in the Method 1 | | | Eigenvalue Sensitivities in the Method 2. Re. ($S_j$), j = 1, 2, 3 | | |
|---|---|---|---|---|---|---|
| | 1st Mode (ω=6.1907) | 2nd Mode (ω=10.2067) | 3rd Mode (ω=12.2026) | 1st Mode (ω=6.1907) | 2nd Mode (ω=10.2067) | 3rd Mode (ω=12.2026) |
| 2 | 2.4429 | 9.4447 | 0.1787 | -4.0323 | -15.9540 | -0.0180 |
| 3 | 3.4251 | 2.9018 | 2.5331 | -3.8275 | -0.8659 | -14.4114 |
| 4 | 7.7206 | 7.8656 | 0.2536 | -17.5471 | -3.8410 | -0.3547 |

**Table 10.4:** Eigenvalues Corresponding to the Electromechanical Oscillations for Different Locations of the PSS in the 4-Machine System. Feedback control structure: $E_i = F_i \Delta\omega_i$, i = 2, 3, 4

| Location (Gen.) No. | Eigenvalues for Different Modes of Oscillations | | |
|---|---|---|---|
| | 1st ($\lambda_1 = \pm j6.1907$) | 2nd ($\lambda_2 = \pm j10.2067$) | 3rd ($\lambda_3 = \pm j12.2026$) |
| 2 | -0.6237±j6.6510 | -3.3764±j8.8315 | -0.0008±j12.2011 |
| 3 | -0.7497±j6.4438 | -0.0745±j10.2974 | -2.9968±j11.1401 |
| 4 | -4.0114±j5.0504 | -0.3083±j9.7999 | -0.0288±j12.1675 |

**Discussion of the Results**

The methods proposed for the determination of the effective location of PSS are demonstrated with two power system examples. In these two examples considered here, both the methods suggest similar results for identifying an effective location of the PSS and, from an inspection of the Tables 10.1 to 10.4, the effective locations of the PSS for each of the modes of oscillations are summarized here.

In the 3-machine system, the lower and higher frequency modes of oscillations are effectively damped by providing the PSS on the machines 2 and 3 respectively. In the 4-machine system, the modes of oscillations corresponding to ω = 6.1907, ω = 10.2067, and ω = 12.2026 are effectively damped by providing the PSS on the machines 4, 2 and 3 respectively.

It is interesting to observe that if PSS is provided on machine one (in the 3-machine system) the feedback gain has to be negative in order to damp the oscillations. The present practice in the industry of designing PSS utilizing simplified system models (that of a single machine connected to infinite bus) always results in the selection of positive feedback gains and applied to the present case would result in negative damping of the system.

### 10.7 Recommendations

(i) Improvement in the damping of electromechanical oscillations can be obtained by using PSS.

(ii) It is found from the study reported here that the proper location of PSS is important for it to be effective in damping the oscillations.

(iii) Any one of the two approaches suggested here for selecting the optimum location of PSS may be employed. The first method is independent of the controller structure; and the second one is based on eigenvalue sensitivity.

(iv) It is observed that in a large system, no individual PSS may be expected to perform satisfactorily in the absence of proper coordination between various controllers in the system.

(v) CEB Power System Network-equivalent corresponding to the mesh-connected system (say, 220 KV and 132 KV buses, taking into account the effect of all radial feeders incident at the appropriate buses present in the meshed-network) may be obtained using PSS / E software module. Using the Linearized Dynamic Simulation module of PSS / E software, power system [A], [B] & [C] matrices may be obtained for the desired CEB System. Then, any one of the Approaches suggested above may be applied to identify effective locations for installing PSS, by ranking the effectiveness of PSS locations for improving the damping of selected modes of oscillations.

# Chapter 11

# VOLTAGE STABILITY ANALYSIS

## 11.1 Introduction to Voltage Stability

### *11.1.1 Power System Stability Classifications*

An IEEE paper published in May 2004[1] has proposed the following three classifications of power system stability:

- Rotor angle stability
- Frequency stability
- Voltage stability

When a particular system is undergoing system instability, more than one of the above types of instability can be present. The primary purpose of classifying power system stability phenomenon is to aid in its analysis as different techniques are employed to ferret out the underlying causes of the symptoms of a particular disturbance. A brief overview of the above classifications is provided next.

***Rotor Angle Stability***

Rotor angle stability is commonly analyzed in the electric utility industry through the use of time-domain simulations. Rotor angle instability occurs when there is a loss of synchronism at one or more synchronous generators.

***Frequency Stability***

The system is considered frequency stable when the total generation output matches system load and loss demand. Frequency instability, commonly analyzed through the use of time-domain simulations, may occur as a result of a significant loss of load or generation within a given system.

***Voltage Stability***

Voltage instability, the focus of this section, is generally characterized by loss of a stable operating point as well as by the deterioration of voltage levels in and around the electrical center of the region undergoing voltage collapse. Voltage collapse, a form of voltage instability, commonly occurs as a result of reactive power deficiency. Unmitigated rotor angle instability can also result in voltage instability.

Voltage stability is commonly analyzed by employing two techniques, namely time-domain (dynamic) simulation and steady-state analysis. Depending on the stability phenomenon or phenomena under investigation, one or both of these techniques may be applied. For example, if steady-state analysis reveals that voltages at the buses at or near induction motor loads drop by more than 10% of their pre-disturbance value, time-domain (dynamic) analysis should be undertaken to assess the potential for motor stalling (steady-state analysis will not directly yield this information). This may involve extending the model to incorporate aggregate induction motor models at lower voltage buses as necessary.

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[1] P. Kundur, J. Paserba, V. Ajjarapu, G. Anderson, A. Bose, C. Canizares, N. Hatziargyriou, D. Hill, A. Stankovic, C. Taylor, T. V. Custem, V. Vittal, "Definition and Classification of Power System Stability", *IEEE Transactions on Power Systems*, vol. 19, no. 2, pp. 1387 – 1401, May 2004

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### *11.1.2 Voltage Stability and the Timeframes of Interest*

This section provides an overview of the various timeframes of interest when studying voltage stability. Power system equipment such as transformer automatic load tap changers (LTC), Static VAr compensators and automatic switched capacitor banks behave with certain time-constants that need to be considered when studying voltage stability. The following timeframes are of interest when studying voltage stability:

- Short-term
- Mid-term
- Long-term

The subsections that follow provide a general overview of the power system equipment and the typical timeframes that they may operate in.

***Short-Term Timeframe***

Short-term timeframe involves the time taken between the onset of a system disturbance to just prior to the activation of the automatic LTC. Rotor angle instability and voltage instability can occur within this timeframe. The following fast acting, automatically controlled power system equipment may be considered in assessing system performance within this timeframe:

- Synchronous Condensers
- Automatic switched shunt capacitors
- Induction motor dynamics
- Static VAr Compensators
- Flexible AC Transmission System (FACTS) devices
- Excitation system dynamics
- Voltage-dependent loads

The extent to which each of the above components needs to be examined depends upon the size of the disturbance being considered relative to the stiffness of the power system.

*Mid-Term Timeframe*

Mid-term timeframe refers to the time from the onset of the automatic LTC operation to just prior to the engagement of over-excitation limiters (OEL). During this time, frequency and voltage stability may be of interest.

*Long-Term Timeframe*

Long-term timeframe refers to the time after OELs engage and includes manual operator-initiated action. During this timeframe, longer-term dynamics come into play such as governor action and load-voltage and/or load-frequency characteristics in addition to operator-initiated manual system adjustments.

### *11.1.3 Determination of Critical Bus or Busses*

A key element of voltage stability studies is the determination of a critical bus or a cluster of critical busses. These busses can then be monitored as they will invariably form the electrical centroid of a voltage collapse.

In a radial transmission system consisting of a generator serving several loads along a transmission line, the critical or weak bus is generally located electrically and physically furthest away from the generator[2]. In a networked or meshed transmission system, finding the weakest bus or a cluster of weak busses is not as intuitive. Industry experience has demonstrated that the weakest bus or set of busses are generally located in locations with reactive power deficiencies.

According to the WECC publication "Voltage Stability Criteria, under voltage Load Shedding Strategy, and Reactive Power Reserve Monitoring Methodology" (1998), the critical bus exhibits one or more of the following characteristics under the worst single or multiple contingency:

- has the highest voltage collapse point on the V-Q curve
- has the lowest reactive power margin
- has the greatest reactive power deficiency
- has the highest percentage change in voltage

The publication also confirms one of the well-known characteristics of the power-flow Jacobian at the 'nose' (also known as the saddle-node bifurcation) point - the weakest bus will tend to have the highest ($\partial Q/ \partial V$) component3 (i.e., highly sensitive reactive power consumption). The WECC document "Under voltage Load Shedding Guidelines", published in 1999 provides an example for selecting the critical bus(es).

#### *11.1.3.1 Static versus Dynamic Analysis*

The two most common methods employed within the electric utility industry for analyzing power system stability are static and dynamic analysis. These are briefly discussed next.

[2] O.O. Obadina, G.J. Berg, "Identifying electrically weak and strong segments of a power system from a voltage stability viewpoint", IEE Proceedings, Vol. 137, Pt. C, No. 3, May 1990

[3] For further explanation, please refer to: Kundur, P, "Power System Stability and Control", McGraw-Hill Inc., 1994 – or - "Voltage Stability Assessment: Concepts, Practices and Tools," IEEE Catalog Number SP101PSS, August, 2002.

***Static Analysis***

Static analysis (also referred to as load-flow or steady-state analysis) reveals equilibrium points of a system under study. The power flow equations employed in static analysis assume constant system frequency; in other words, generation output equals load demand plus losses. Voltage stability studies are frequently undertaken through the use of static analysis. A common use of this is the development of P-V curves as shown in Figure 11.1.

The graph is obtained in power-flow simulation by monitoring a voltage at a bus of interest and varying the power in small increments until power-flow divergence is encountered. Each equilibrium point shown represents a steady-state operating condition. In other words, each point may be considered as representing a system that has been in a stable operating point for over ½ hour. This means that the generation real-power dispatch and all voltage support equipment have been established such that the system meets the required reliability criteria for each operating point on the graph up to and including the operating limit point indicated on the graph. Beyond the operating limit, further increase in power may result in a breach of one or more of the reliability criteria. A series of curves can be produced, each one as shown in Figure 1, with each curve depicting one or more transmission outages.

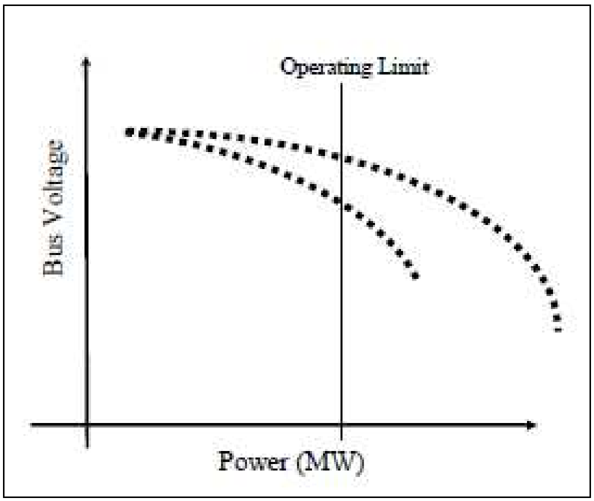



**Figure 11.1: Typical Power Versus Voltage Curves**

Given that each operating point on the P-V curve represents a unique steady-state operating condition, a pessimistic but realistic generation dispatch is normally employed as load is increased.

### *Dynamic Analysis*

Dynamic analysis (also referred to as time-domain analysis) is commonly employed in the study of power system stability to reveal system trajectory after a disturbance. In contrast to static analysis in which equilibria points of a P-V curve are not time-dependent, dynamic analysis method reveals the transient and/or the longer-term stability of a power system under study.

### *11.1.3 Study Methodology*

Voltage stability analysis is generally conducted by employing two methodologies, namely static and dynamic analysis. Static analysis reveals loss of system equilibrium and is a snapshot in time (i.e., not time dependent). Dynamic analysis, also referred to as time-domain analysis, reveals the system trajectory immediately following a disturbance. Both these methods should be used in a complementary manner thereby providing an overall assessment of the voltage stability of the area under consideration.

This section outlines the methodology for assessing a particular area’s or a particular transfer path’s conformity with planning standard using P-V and V-Q analysis. P-V analysis of a particular area or of a particular transfer path reveals the static stability margin of that area or of that path while V-Q analysis yields the reactive power margin at a particular bus in the power system under consideration.

## 11.2 Performing PV/QV Analyses through PSS / E

The PV/QV analyses that are described in this chapter are designed for studies of slow voltage stability, which could be analyzed as a steady-state problem. They are load flow based analyses used to assess voltage variations with active and reactive power change. Two methods are used to determine the loading limits imposed by voltage stability under the steady-state conditions.

The PV/QV analyses do not provide solutions to specific problem but function as tools that can be directed by the user to perform analyses in the solution of problems associated with the steady-state voltage stability of power systems.

## 11.3 Basic Engineering Guide to PV and QV Curves Applications

### 11.3.1 Objective

The objective of a PV and QV curves is to determine the ability of a power system to maintain voltage stability at all the buses in the system under normal and abnormal steady state operating conditions. They are useful, for example:

- To show the voltage collapse point of the buses in the power system network
- To study the maximum transfer of power between buses before voltage collapse point
- To size the reactive power compensation devices required at relevant buses to prevent voltage collapse
- To study the influence of generator, loads and reactive power compensation devices on the network

The PV and QV curves are obtained through a series of AC load flow solutions. The PV curve is a representation of voltage change as a result of increased power transfer between two systems, and the QV curve is a representation of reactive power demand by a bus or buses as voltage level changes.

### 11.3.2 PV Analysis (PV Curves) Applications

PV curves are parametric study involving a series of AC load flows that monitor the changes in one set of load flow variables with respect to another in a systematic fashion. This approach is a powerful method for determining transfer limits which account for voltage and reactive flow effects. As power transfer is increased, voltage decreases at some buses on or near the transfer path. The transfer capacity where voltage reaches the low voltage criterion is the low voltage transfer limit.

Transfer can continue to increase until the solution identifies a condition of voltage collapse; this is the voltage collapse transfer limit.

The plot of the relationship between voltage at the receiving end, VR, and the load power, PR, as the power transfer is increased due to increased loading, gives the PV curves similar in characteristic to the curve shown in Figure 11.2.

PV curves are typically used for the "knee curve analysis".  It is as named because of its distinctive shape at the point of voltage collapse as the power transfer increases, as shown in Figure 11.2.

Depending on the transfer path, different buses have different knee point. The buses closer to the transfer path will normally exhibit a more discernible knee point.

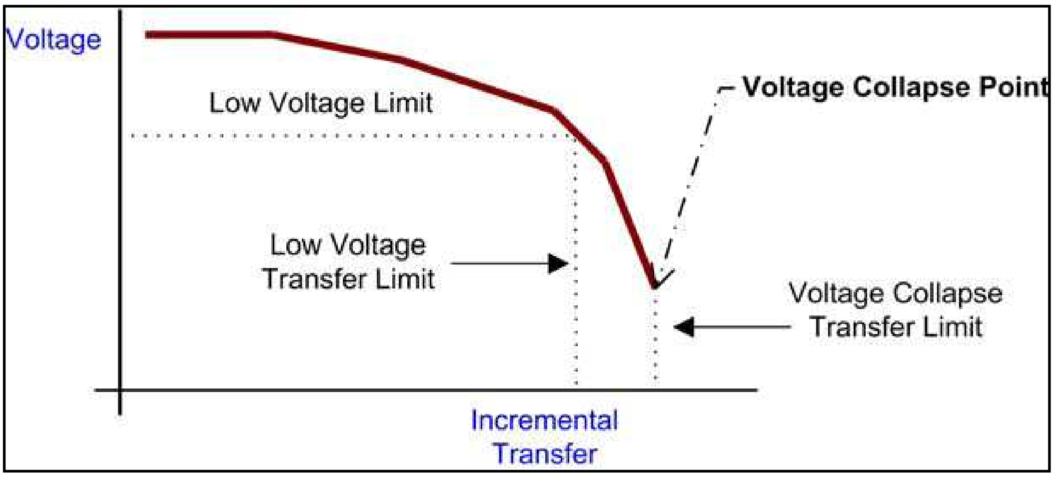



**Figure 11.2: PV Curves Voltage and Incremental Power Transfer Characteristics**

Voltage instability occurs at the "knee point" of the PV curve where the voltage drops rapidly with an increase in the transfer power flow. Load flow solution will not converge beyond this limit, indicating voltage instability. Operation at or near the stability limit is impractical and a satisfactory operating condition must be ensured to prevent voltage collapse.

In PSS/E, the PV curves are generated by selecting two subsystems where the power transfer between the subsystems is incremented in a defined step size for a series of AC load flow calculations while the bus voltages, generator outputs and the branch flows of the system are monitored.

When the bus voltages are plotted as a function of the incremental power transfer the PV curves are obtained. One of the subsystems in the study must be defined as the study (source) system and another as the opposing (sink) system. The power flows from the study subsystem to the opposing subsystem.

## 11.4 QV Analysis (QV Curves) Applications

In the PV curve analysis, the effect of active power flow on voltage instability is demonstrated.

However, it is observed that the power factor of the load has a significant impact on the overall equations. This is to be expected since the voltage drop in the line is a function of both active and reactive power transfer. Hence, the QV curves may also be used to assess voltage stability of the system.

QV curves are used to determine the reactive power injection required at a bus in order to vary the bus voltage to the required value. The curve is obtained through a series of AC load flow calculations. Starting with the existing reactive loading at a bus, the voltage at the bus can be computed for a series of power flows as the reactive load is increased in steps, until the power flow experiences convergence difficulties as the system approaches the voltage collapse point.

Figure 11.3 is a typical of the QV curves that will be generated for a system that is stable at moderate loading and unstable at higher loadings.

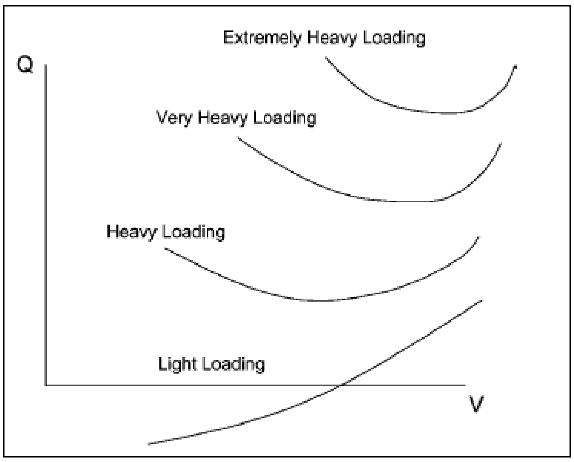



**Figure 11.3: QV Curves for a Range of System Loading**

The bottom of the QV curve, where the change of reactive power, Q, with respect to voltage, V (or derivative dQ/dV) is equal to zero, represents the voltage stability limit. Since all reactive power compensator devices are designed to operate satisfactorily when an increase in Q is accompanied by an increase in V, the operation on the right side of the QV curve is stable, whereas the operation on the left side is unstable. Also, voltage on the left side may be so low that the protective devices may be activated.

The bottom of the QV curves, in addition to identifying the stability limit, defines the minimum reactive power requirement for the stable operation. Hence, the QV curve can be used to examine the type and size of compensation needed to provide voltage stability. This can be performed by superimposing the QV characteristic curves of the compensator devices on that of the system. For instance the capacitor characteristic can be drawn over the system's QV curves as shown in Figure 11.4.

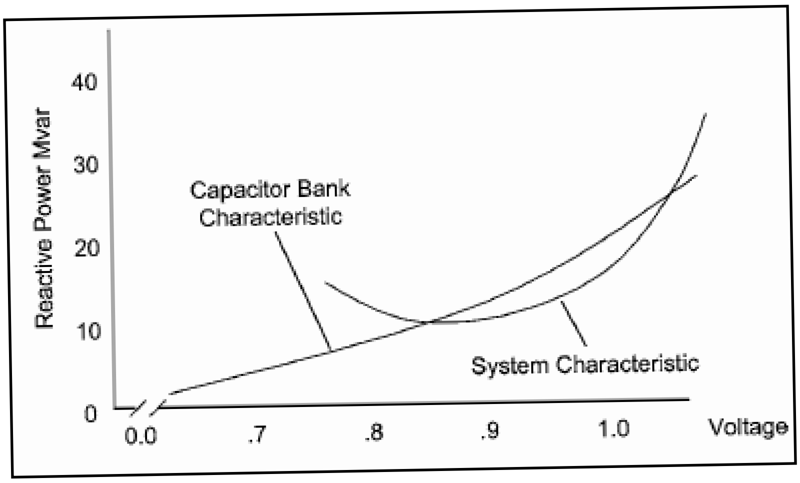



**Figure 11.4: QV Curves and Characteristics of a Capacitor Bank Required at Stable Operating Point**

Figure 11.5 shows the QV curves for a range of capacitor banks with different rating superimposed on the system's QV curves under different loading conditions. From the plot we can determine that capacitor rating of 300 Mvar is required to maintain 1 pu voltage at loading of 1300 MW, 450 Mvar at 1500 MW and so on. For the case of very high loading at 1900 MW, even though the capacitor bank rating of 950 Mvar can maintain a voltage of 1 pu, point B is not a stable operating point. If there is a drop in voltage from point B to B', the ability of the capacitor to supply reactive power is decreased more than the drop in requirement of the system. This will result in continuous drop in voltage. Alternatively, if the voltage is increased above point B, the capacitor will supply more reactive power than the increase in requirement of the system. This will result in continuous rise in voltage.

Hence, the criterion for stable operating point when using a reactive power compensator is as follow:

System (dQ/dV) > Compensator (dQcomp/dV)
Where:

(dQ/dV) is the change of the system's reactive power, Q, with respect to voltage, V.

(dQcomp/dV) is the change of the compensator's reactive power output, Qcomp, with respect to voltage, V.

For the case of light loading at 1300 MW with capacitor rating of 300 Mvar, point A is a stable operating point. If the voltage is increased from point A to A', the capacitor will supply less reactive power than the increase in system's demand, hence reducing the voltage to 1 pu. Alternatively, if the voltage is decreased from point A towards the bottom of the QV curve, the capacitor will supply more reactive power than the system's demand, hence returning the voltage to 1 pu.

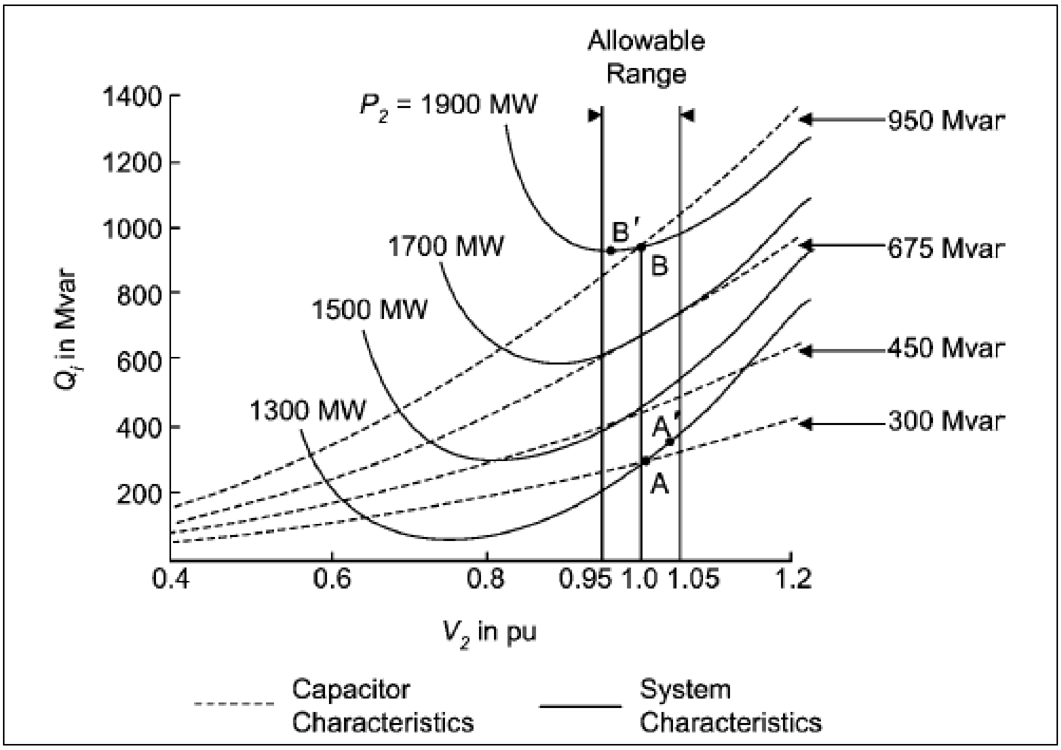



**Figure 11.5: Compensator Operations and Size on Voltage Stability using QV Curves**

In PSS/E, the QV curves are generated by artificially introducing a synchronous condenser, with high reactive power limits, at a bus to make this a PV bus. As the scheduled voltage set point (bus voltage) of the PV bus is varied in steps for a series of AC load flow calculations, the reactive power output from the condenser is monitored. When the reactive power is plotted as a function of the bus voltage QV curves are obtained.

QV curves are commonly used to identify voltage stability issues and reactive power margin for specific locations in the power system under various loading and contingency conditions. The QV curves are also used as a method to size shunt reactive compensation at any particular bus to maintain the required scheduled voltage.

The shape of the QV curves can also be used to determine the load characteristic, and study the effect of load tap changer (LTC) transformer on the system. It is observed that the QV curves are slightly shaped like an 'S'. The S-shape characteristics are due to the load type in the system and the action of the LTC transformer as illustrated in Figure 11.6.

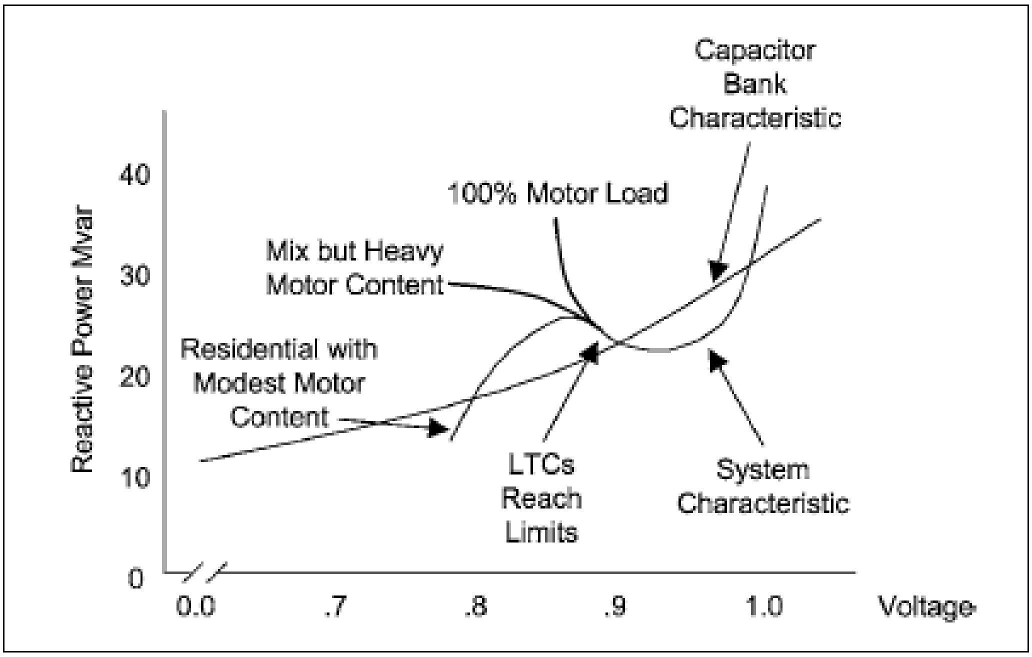



**Figure 11.6: QV Curves for Different Load Type with Consideration of LTC**

## 11.5 Voltage Stability Analysis using MATLAB Simulation {Voltage Stability Toolbox (VST)} on Standard Sample IEEE Test System:

### 11.5.1 Voltage Stability Toolbox (VST)

Voltage Stability Toolbox (VST) has been developed to investigate stability and bifurcation issues in power systems. The VST integrates the symbolic and numeric computations with a graphical menu-driven interface based on MATLAB and its Extended Symbolic Toolbox. It implements symbolic computations to build exact load flow equations and Jacobian matrices including 2$^{nd}$ –order derivatives, required to implement numerical computations such as Newton-Raphson (NR) and Newton-Raphson-Seydel (NRS) for bifurcation analysis. The numerical calculations of solutions for power system equations are performed and controlled via a graphical user interface (GUI). The GUI makes the complex theoretical backgrounds readily accessible to power system engineers who use them to solve practical problems. It has proved to be a useful tool for education and research in the area of power system stability analysis. Even a user not well versed in the mathematics of bifurcation analysis can easily experiment with standard test systems or construct one of his/her own. An experienced user can exploit MATLAB's open architecture to implement and experiment with alternative computational algorithms. Fig 11.7 shows a schematic of the VST.

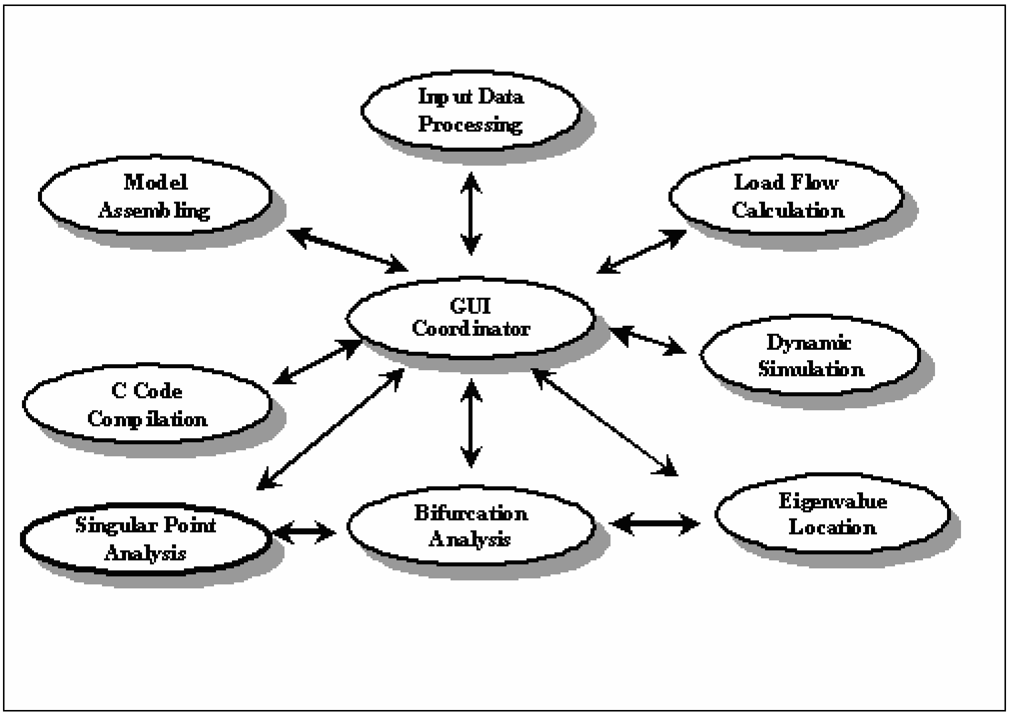



**Fig 11.7: The schematic of VST**

The following analysis can be performed with the VST, as can be seen in Fig 11.8:

- Load flow analysis
- Time domain simulations
- Static bifurcation analysis
- Dynamic bifurcation analysis
- Singularity analysis
- Eigenvalue analysis

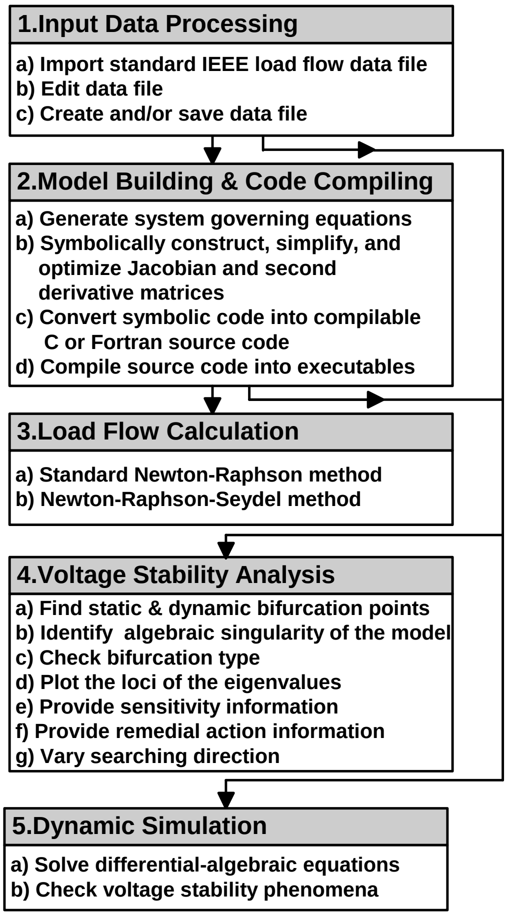



**Fig 11.8: Flowchart of VST**

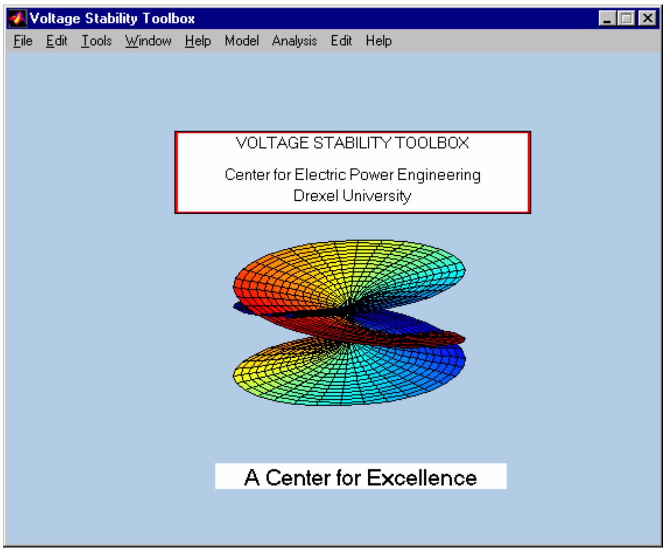



**Fig 11.9: The VST main window**

### 11.5.2 Analysis Pull-Down Menu

This section describes the options available on the Analysis pull-down menu, as shown in Fig 11.10.

**Load Flow**

It implements the Newton-Raphson algorithm for power flow studies.

**Simulation**

It implements the time-domain simulation for differential-algebraic classical power system model.

**Static Bifurcation**

It implements a two-stage algorithm consisting of the Newton-Raphson (NR) and Newton-Raphson-Seydel (NRS) methods to compute the equilibria up to the saddle node bifurcation point.

**Dynamic Bifurcation Analysis**

**Zoom around nose point:** It implements a two-stage algorithm (NR→NRS) to compute the system equilibria and their corresponding bifurcations, including Hopf and singularity induced bifurcations, and characterizes the stability features of the system equilibria along the nose curve.

**Zoom lower part:** It implements a three-stage algorithm (NR→NRS→NR) to compute the system equilibria and their corresponding bifurcations, including Hopf and singularity induced bifurcations, and characterizes the stability features of the system equilibria along the nose curve.

**Eigen value of system matrix**

It plots the Eigen values of the system matrix of $\dot{x} = [A_{SYS}]x$.

**Sensitivity around the saddle node bifurcation**

It plots the absolute values of the components of the right and left eigenvectors corresponding to the zero Eigen value of the load flow Jacobian matrix evaluated at the saddle node bifurcation point.

**Singular Point Analysis**

It implements the NR and NRS algorithms starting at an upper equilibrium point of the nose curve at a fixed parameter to compute the singular points of the DAE model as shown in Fig 11.11.

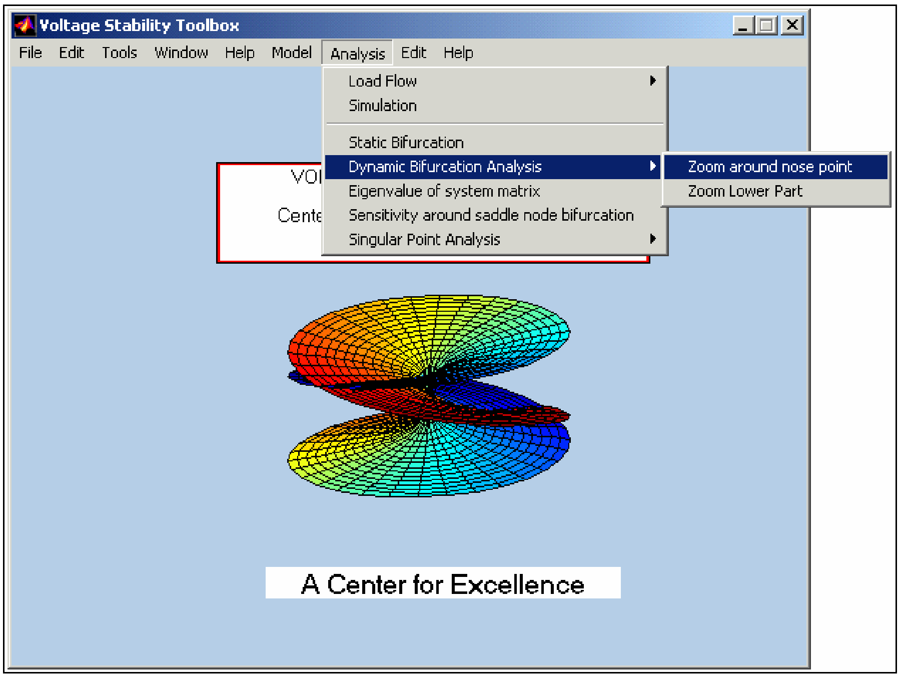



**Fig 11.10: The Analysis pull-down menu**

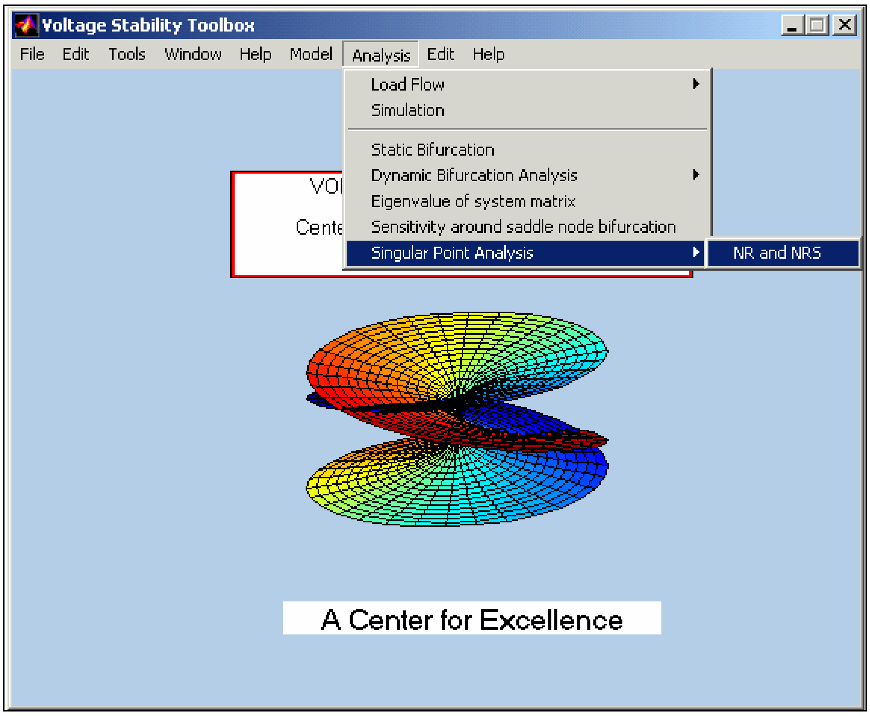


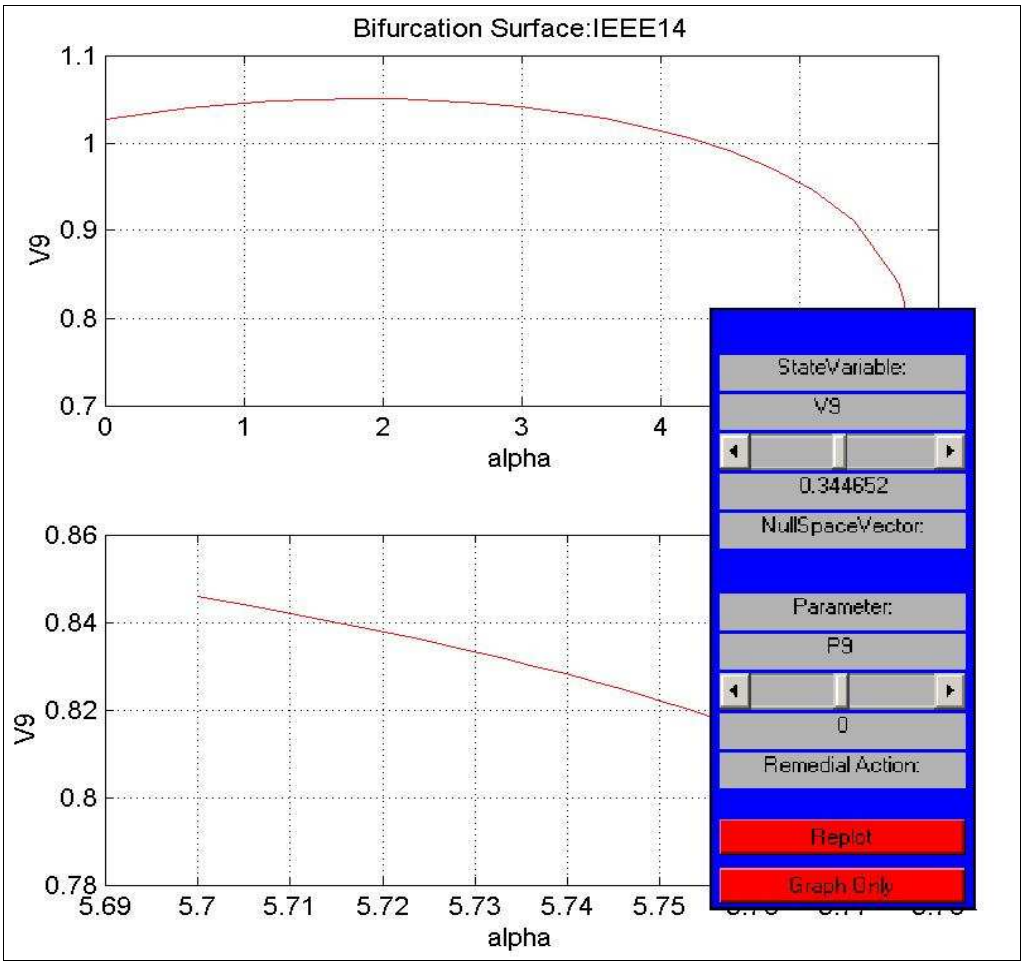

**Fig 11.11: The Singular Point Analysis menu item**

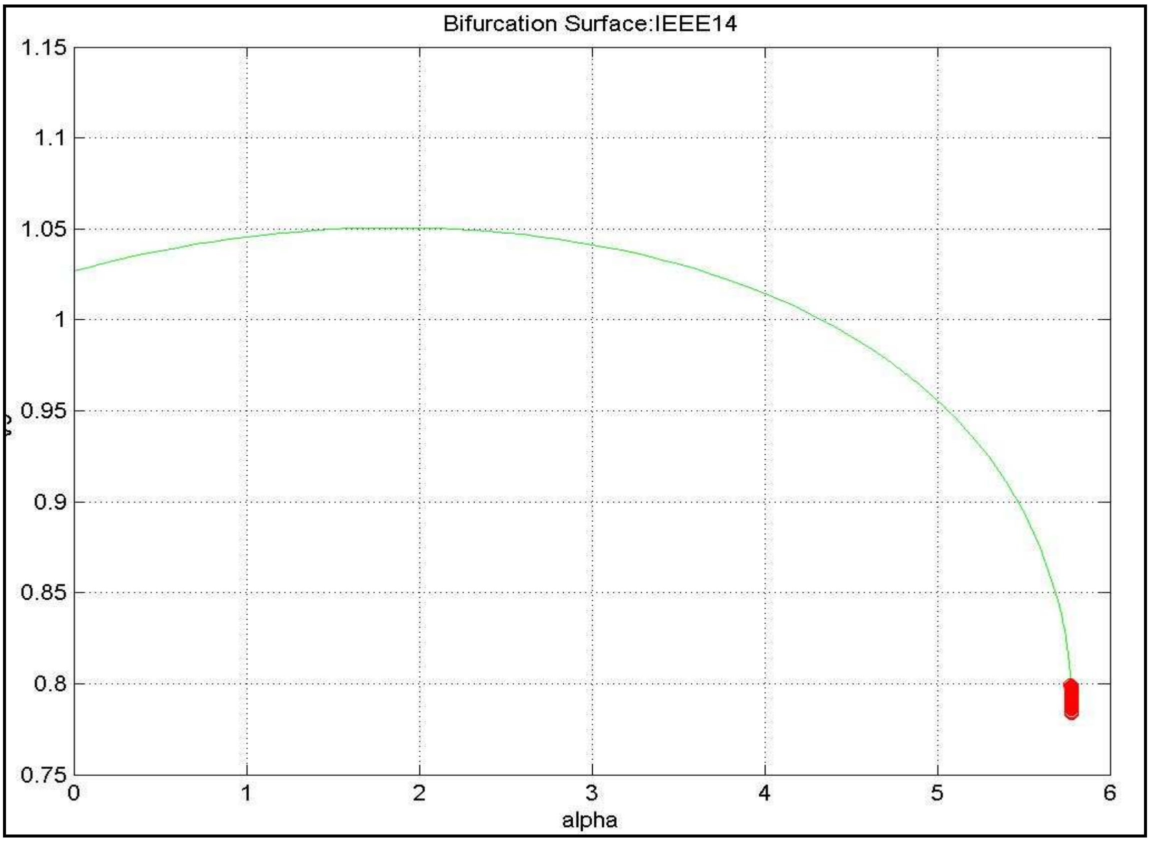
### Software and System Requirements

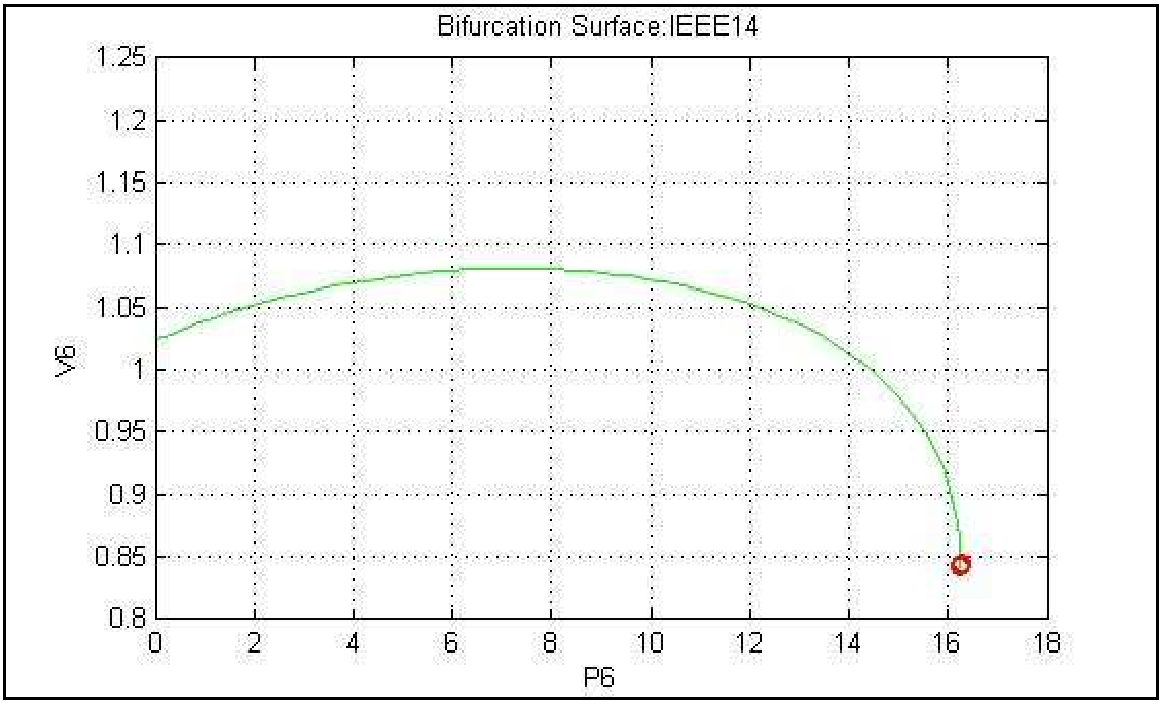
To be able to use the Voltage Stability Toolbox, one needs to have the following:

- Matlab Version 5 (available from The MathWorks)
- Matlab Extended Symbolic Toolbox (available from the MathWorks)
- Windows 95 Windows, NT Workstation 4.0 or UNIX
- Voltage Stability Toolbox files that are available at our homepage: http://power.ece.drexel.edu/

### 11.5.3 Results of Sample IEEE Test System (14 – Bus)




Bifurcation Surface:IEEE14
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
0
1
2
3
4
5
6
alpha


Bifurcation Surface:IEEE14
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
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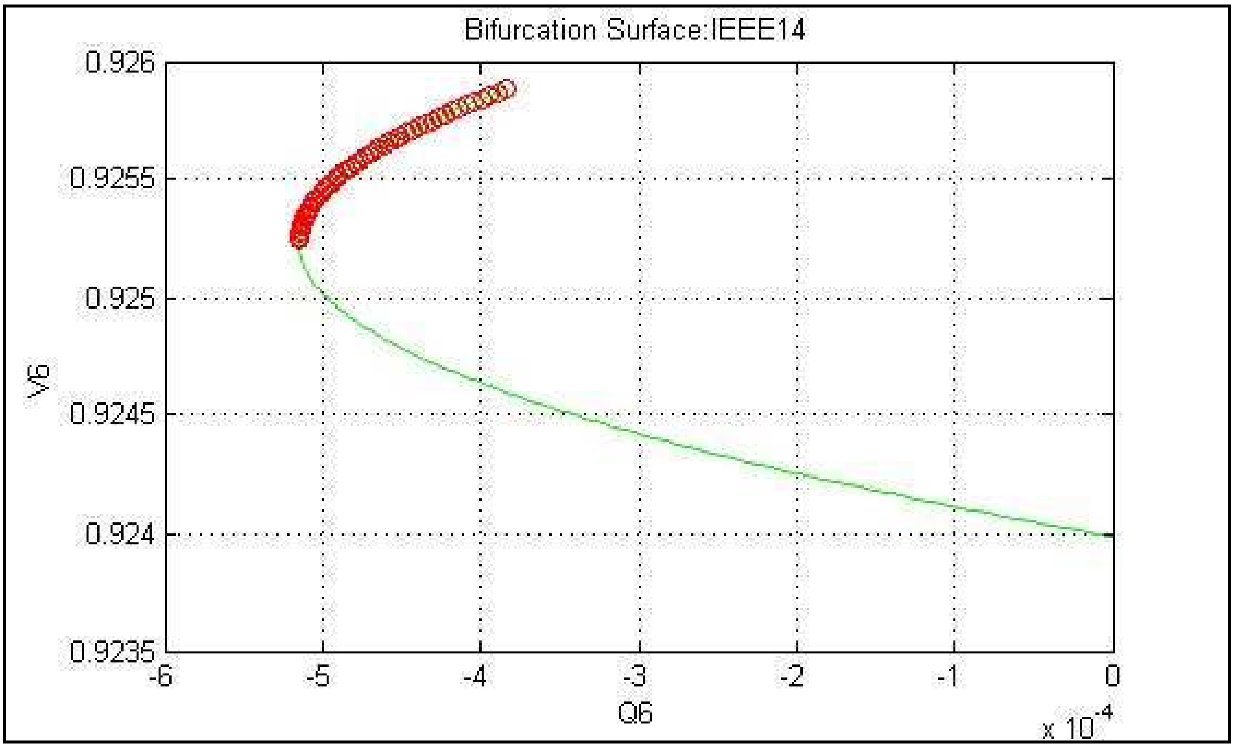
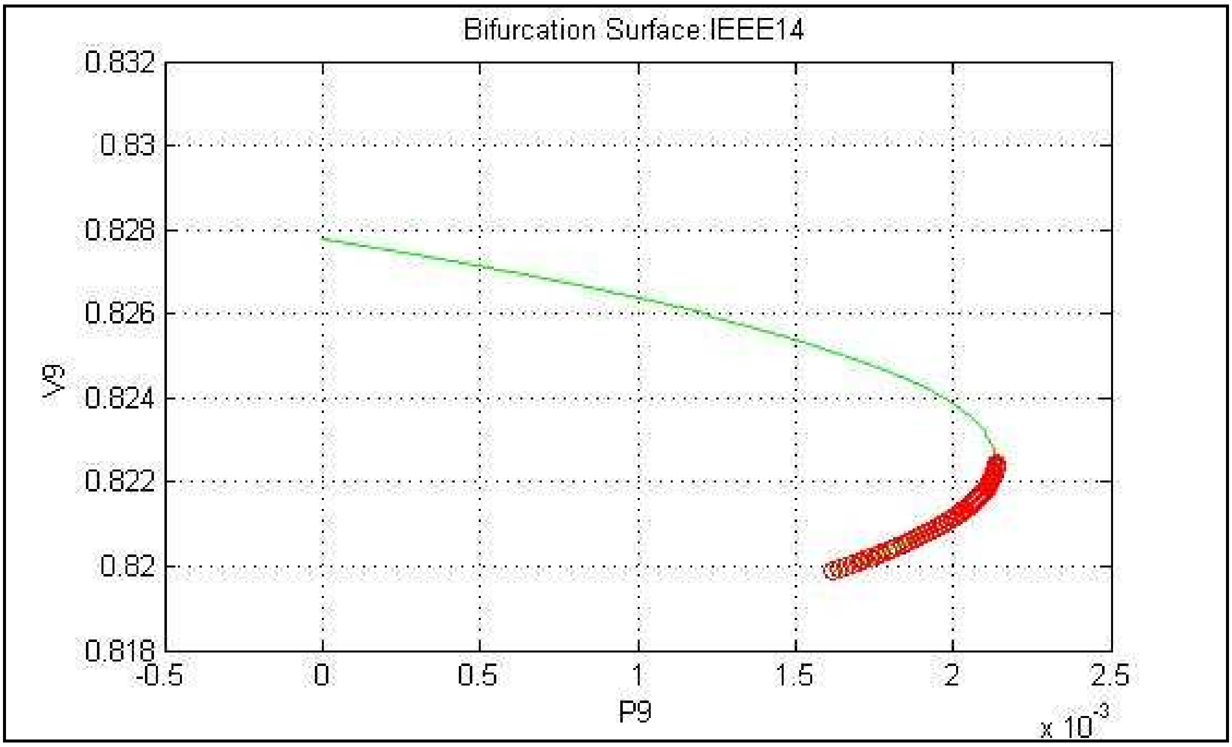
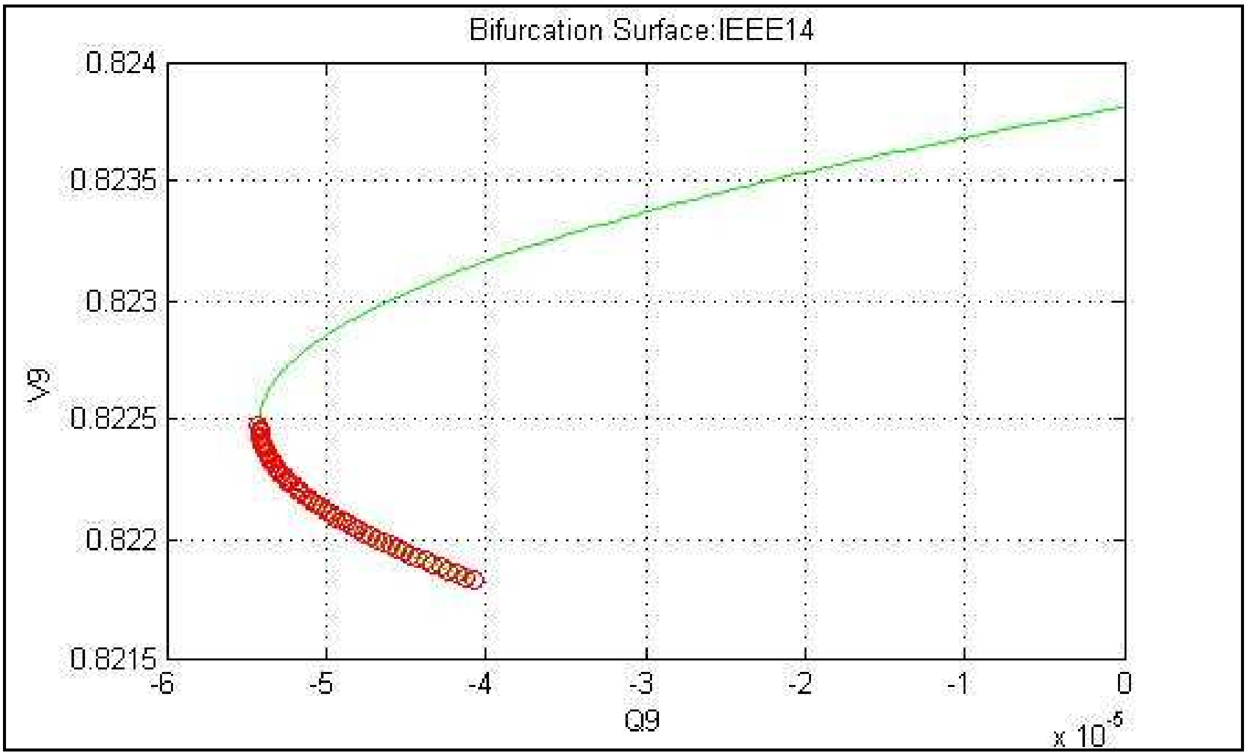
10
12
14
16
18
P6



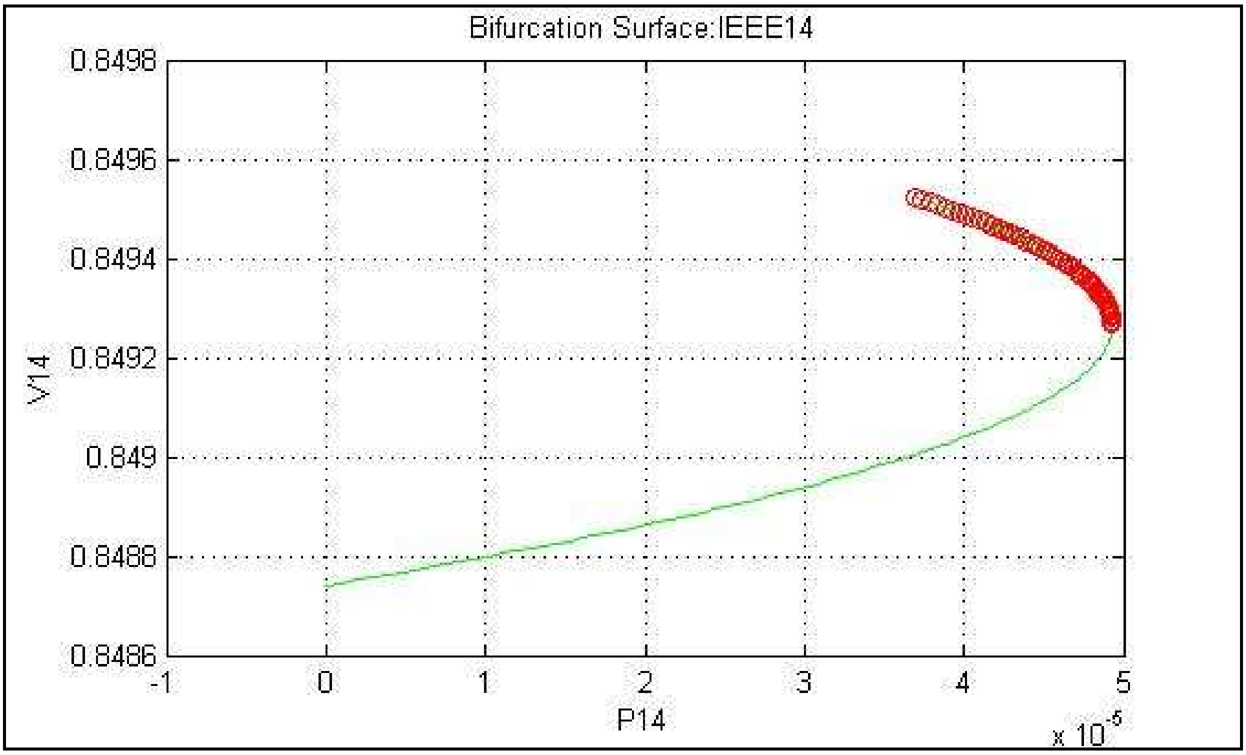
Bifurcation Surface:IEEE14
0.926
0.9255
0.925
0.9245
0.924
0.9235
V6
-6
-5
-4
-3
-2
-1
0
Q6
x 10-4

Bifurcation Surface:IEEE14
0.832
0.83
0.828
0.826
0.824
0.822
0.82
0.818
V9
-0.5
0
0.5
1
1.5
2
2.5
P9
x 10-3



Bifurcation Surface:IEEE14
0.824
0.8235
0.823
0.8225
0.822
0.8215
V9
-6
-5
-4
-3
-2
-1
0
Q9
x 10^-5

Bifurcation Surface:IEEE14
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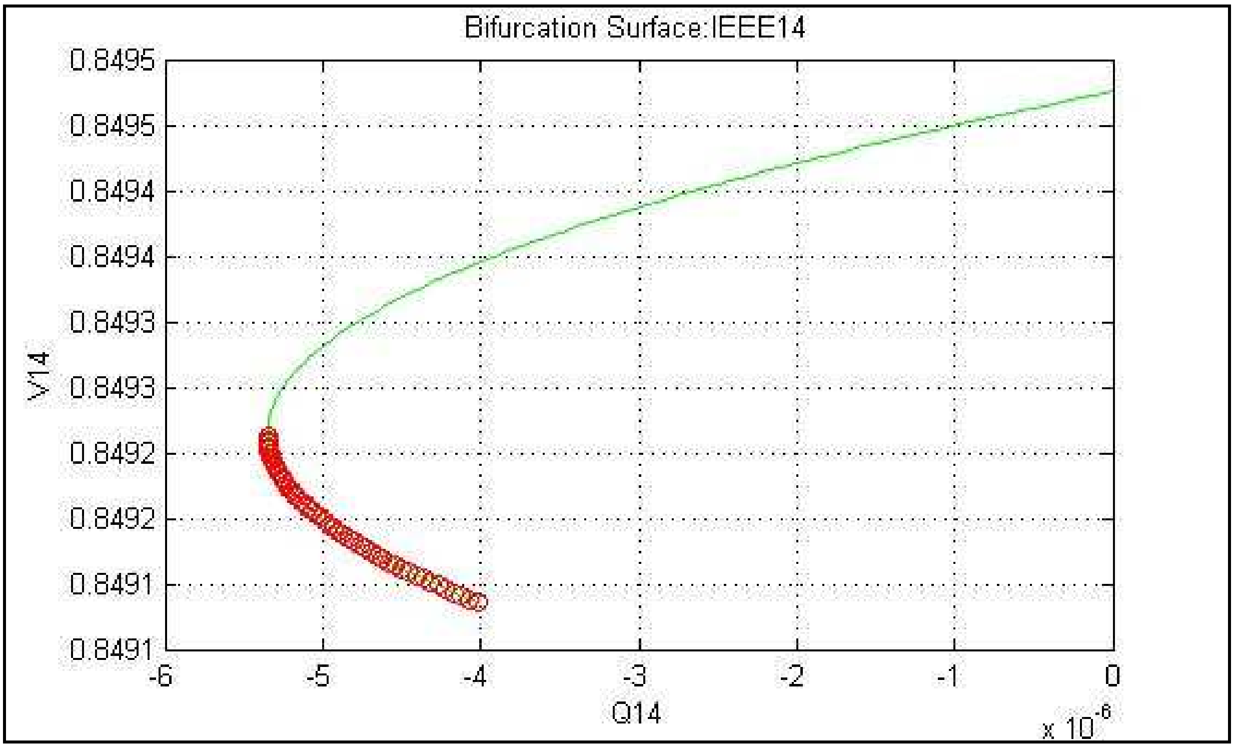
0.8496
0.8494
0.8492
0.849
0.8488
0.8486
V14
-1
0
1
2
3
4
5
P14
x 10^-5




**IEEE 14 – Bus System Data:**

14

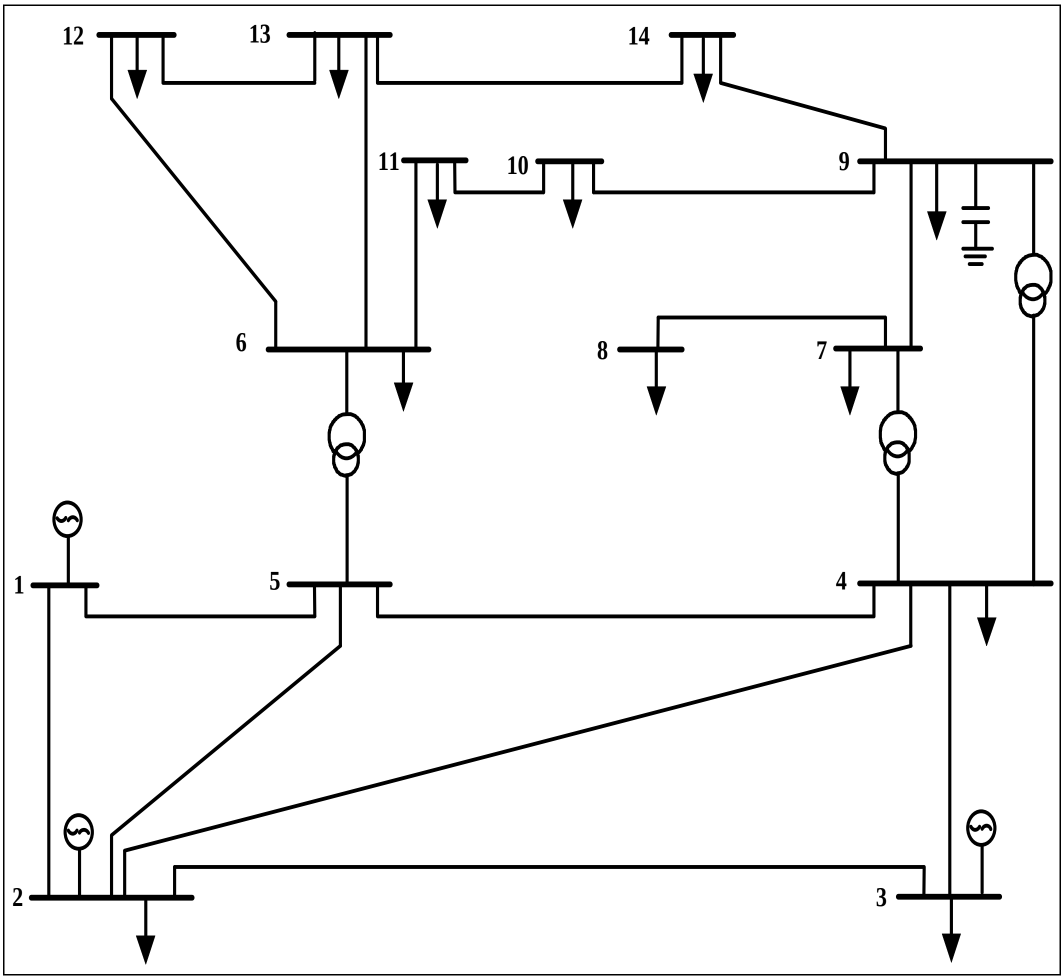
| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 Bus 1 | HV 3 | 2.3240 | -0.1690 | 0.0000 | 0.0000 | 1.0600 | 0.0000 |
| 2 | 2 Bus 2 | HV 2 | 0.1830 | 0.2970 | 0.0000 | 0.0000 | 1.0450 | -0.0869 |
| 3 | 3 Bus 3 | HV 2 | -0.9420 | 0.0440 | 0.0000 | 0.0000 | 1.0100 | -0.2220 |
| 4 | 6 Bus 6 | LV 2 | -0.1120 | 0.0470 | 0.0000 | 0.0000 | 1.0700 | -0.2482 |
| 5 | 8 Bus 8 | TV 2 | 0.0000 | 0.1740 | 0.0000 | 0.0000 | 1.0900 | -0.2332 |
| 6 | 4 Bus 4 | HV 1 | -0.4780 | 0.0390 | 0.0000 | 0.0000 | 1.0190 | -0.1803 |
| 7 | 5 Bus 5 | HV 1 | -0.0760 | -0.0160 | 0.0000 | 0.0000 | 1.0200 | -0.1532 |
| 8 | 7 Bus 7 | ZV 1 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 1.0620 | -0.2334 |
| 9 | 9 Bus 9 | LV 1 | -0.2950 | -0.1660 | 0.0000 | 0.1900 | 1.0560 | -0.2608 |
| 10 | 10 Bus 10 | LV 1 | -0.0900 | -0.0580 | 0.0000 | 0.0000 | 1.0510 | -0.2635 |
| 11 | 11 Bus 11 | LV 1 | -0.0350 | -0.0180 | 0.0000 | 0.0000 | 1.0570 | -0.2581 |
| 12 | 12 Bus 12 | LV 1 | -0.0610 | -0.0160 | 0.0000 | 0.0000 | 1.0550 | -0.2630 |
| 13 | 13 Bus 13 | LV 1 | -0.1350 | -0.0580 | 0.0000 | 0.0000 | 1.0500 | -0.2646 |
| 14 | 14 Bus 14 | LV 1 | -0.1490 | -0.0500 | 0.0000 | 0.0000 | 1.0360 | -0.2800 |

-999

20

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 0 | 0.019380 | 0.059170 | 0 | 0.0000 | 0.0000 | 0.0000 |
| 1 | 7 | 0 | 0.054030 | 0.223040 | 0 | 0.0000 | 0.0000 | 0.0000 |
| 2 | 3 | 0 | 0.046990 | 0.197970 | 0 | 0.0000 | 0.0000 | 0.0000 |
| 2 | 6 | 0 | 0.058110 | 0.176320 | 0 | 0.0000 | 0.0000 | 0.0000 |
| 2 | 7 | 0 | 0.056950 | 0.173880 | 0 | 0.0000 | 0.0000 | 0.0000 |
| 3 | 6 | 0 | 0.067010 | 0.171030 | 0 | 0.0000 | 0.0000 | 0.0000 |
| 6 | 7 | 0 | 0.013350 | 0.042110 | 0 | 0.0000 | 0.0000 | 0.0000 |
| 6 | 8 | 1 | 0.000000 | 0.209120 | 0 | 0.0000 | 0.0000 | 0.0000 |
| 6 | 9 | 1 | 0.000000 | 0.556180 | 0 | 0.0000 | 0.0000 | 0.0000 |
| 7 | 4 | 1 | 0.000000 | 0.252020 | 0 | 0.0000 | 0.0000 | 0.0000 |
| 4 | 11 | 0 | 0.094980 | 0.198900 | 0 | 0.0000 | 0.0000 | 0.0000 |
| 4 | 12 | 0 | 0.122910 | 0.255810 | 0 | 0.0000 | 0.0000 | 0.0000 |
| 4 | 13 | 0 | 0.066150 | 0.130270 | 0 | 0.0000 | 0.0000 | 0.0000 |
| 8 | 5 | 0 | 0.000000 | 0.176150 | 0 | 0.0000 | 0.0000 | 0.0000 |
| 8 | 9 | 0 | 0.000000 | 0.110010 | 0 | 0.0000 | 0.0000 | 0.0000 |
| 9 | 10 | 0 | 0.031810 | 0.084500 | 0 | 0.0000 | 0.0000 | 0.0000 |
| 9 | 14 | 0 | 0.127110 | 0.270380 | 0 | 0.0000 | 0.0000 | 0.0000 |
| 10 | 11 | 0 | 0.082050 | 0.192070 | 0 | 0.0000 | 0.0000 | 0.0000 |
| 12 | 13 | 0 | 0.220920 | 0.199880 | 0 | 0.0000 | 0.0000 | 0.0000 |
| 13 | 14 | 0 | 0.170930 | 0.348020 | 0 | 0.0000 | 0.0000 | 0.0000 |

-999




## 11.6 Observations and Recommendations:

* In the sample illustration here, appropriate MATLAB Tool Box modules are applied to obtain PV and QV curves for Voltage Stability Analysis.

* *Recommendation:* Procedure indicated in the above Sections 2, 3 and 4 (from PSS/E Manual) can be applied using PSS/E software modules for Voltage Stability Analysis of CEB System.

# Chapter 12

# WIND PENETRATION: STUDY OF FREQUENCY AND VOLTAGE CONTROL ASPECTS

## 12.1 Introduction

Wind power generation is increasing throughout the world where sufficient wind velocity exists. NREL study estimates considerable wind potential in Sri Lanka. CEB has set up a 3 MW wind power plant integrated to the grid. There are several requests being received by the CEB for interconnection.

The **frequency and voltage control** aspects of future power system scenarios from 2012 onwards with wind power generation are studied and the results and analysis are presented in this chapter.

Simulation has been carried out by CEB engineers using PSS/E.

## 12.2 Operational Issues with Wind Power Plants

Wind power is intermittent as the wind velocity can wary depending on the season. So the power balance in the power system gets disturbed and frequency fluctuates.

At off-peak loads wind power plant may replace hydro or thermal power plant. If wind power plant gets tripped frequency may fall and frequency control becomes a problem.

Some wind turbine generators are of induction type and these draw reactive power from the grid. Modern wind turbine generators with power electronics-based controls do not have this problem as reactive power can be controlled.

The inertia of the wind turbine generator with inverter connection to grid does not get reflected on the power system inertia. Thus frequency control can be affected.

There are different wind turbine generating systems are currently installed as shown in the Table with the distinctive features of each.

Variable speed wind turbines with doubly fed induction generator (DFIG) are widely being used. Most of the modern wind power plants being set up in the recent times are with power electronics based controls. In these systems active and reactive power outputs can be controlled.

**Table 12.1 Wind Turbines Configurations**

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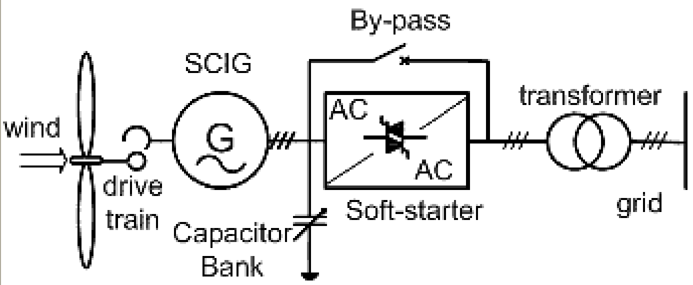
<tr>
<td>


Fixed-speed directly-grid connected wind turbine
</td>
<td>

- operates at constant speed (1-2 % speed variation)
- both passive and active stall are used
- requires a stiff grid in order to enable stable operation
- implies an more expensive mechanical construction in order to absorb high mechanical stress
- exhibits periodic power pulsations in addition to the stochastic power pulsations caused by the wind
- very robust and cheap solution

</td>
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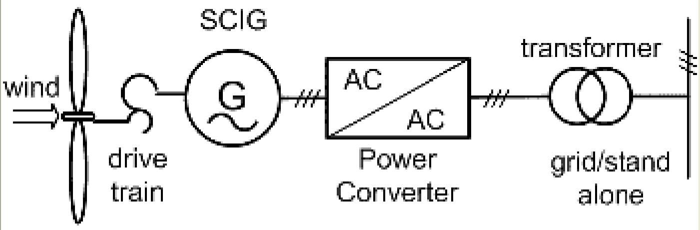

Variable-speed wind turbine with squirrel-cage induction generator
</td>
<td>

- operates at variable speed
- a bi-directional power converter can assure the full control of active and reactive power
- power converter designed to carry full load
- preferred for low and medium power applications both stand-alone and grid-connected

</td>
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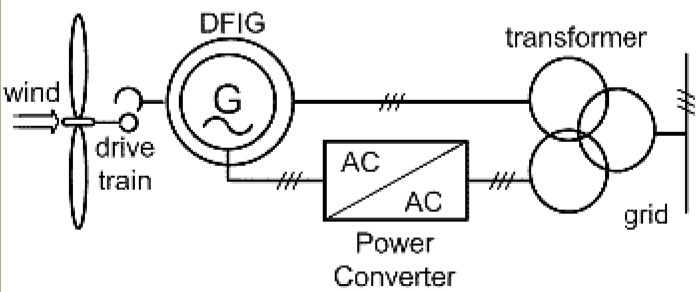
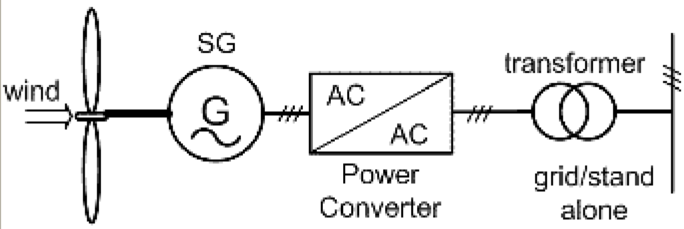
<tr>
<td>


Variable-speed wind turbine with doubly-fed induction generator
</td>
<td>

- operates in a wide speed range
- a bi-directional power converter in the rotor circuit can assure the full control of active and reactive power
- power converter rating is around 25% of the total generator power
- preferred for low and medium power applications both stand-alone and grid-connected

</td>
</tr>
</table>




Variable-speed direct-driven synchronous generator

- operates at variable speed
- a bi-directional power converter can assure the full control of active and reactive power
- power converter designed to handle the full generated power
- the gearbox is eliminated
- large and relatively heavy generator

## 12.3 Wind penetration study using PSS/E

### Main objective

Simulation has been carried out to study

- the effect of wind generation on CEB power system operation
- the safe  proportion of generation that can be using wind generation

### Wind generator model

The wind turbine generator model considered is that of GE 1.5 MW as provided in PSS/E.  The wind turbine stability model simulates performance of a wind turbine employing a doubly fed induction generator (DFIG) with the active control by a power converter connected to the rotor terminals. This is typical of modern wind turbine generators being manufactured by major companies like GE, Gamesa, Vestas etc.

The wind turbine generator scheme with controls is shown in Fig 12.1.

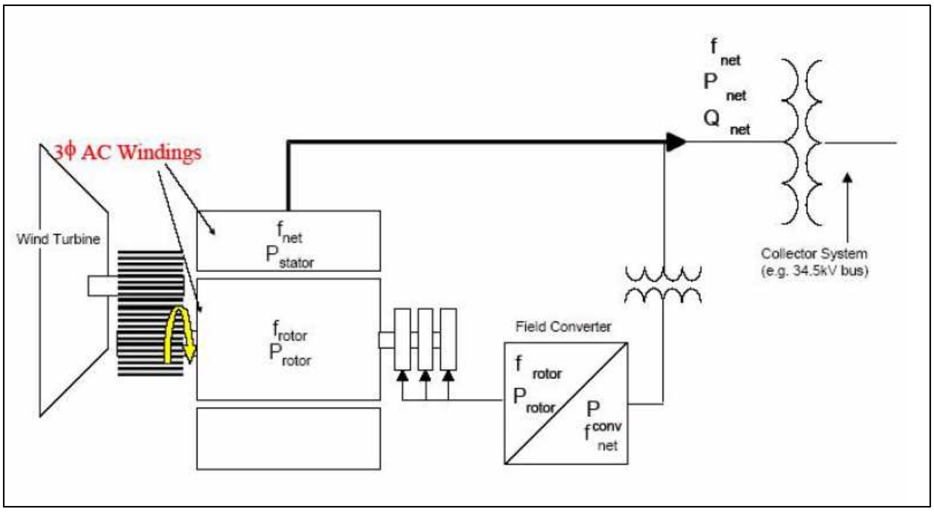



**Fig 12.1 Wind turbine generator model with controller**

### 12.4 Isolated Wind power system: Fault Ride through Capability

To study the effect of wind generation a sample system as shown in Fig. around a wind power plant at Puttalam is considered. A three phase fault is simulated on 132 KV line at t= 2 sec. and the fault is cleared at t= 2.12 seconds. At 2.62 seconds line is reconnected.

It would be of interest to see how the isolated power system with wind model behaves with regard to transients in frequency, voltage and power outputs.

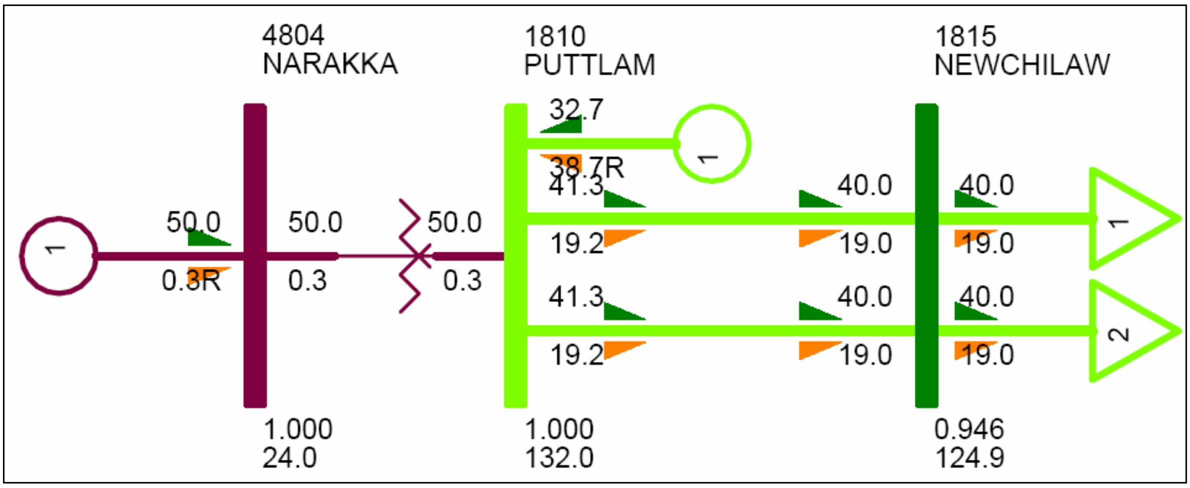



**Fig 12.2 Isolated power system with wind power plant at Narakka**

The variation in frequency of the isolated power system is shown in Fig 12.3 below. It is observed that frequency returns to the normal value quickly without oscillations.

The effect of three phase fault on frequency is insignificant.

Similar is the case with voltage as shown in Fig12.4. However there are few oscillations in the active and reactive powers as seen in Fig 12.5. These oscillations are only transient and die down quickly.

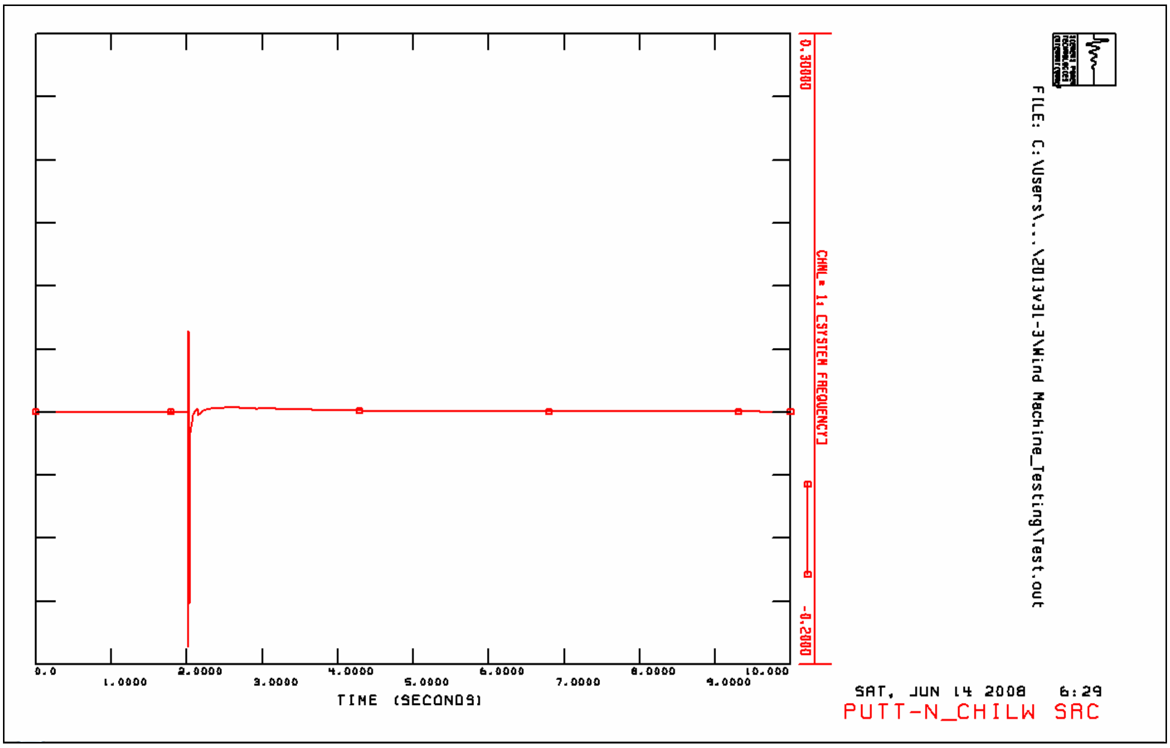



**Fig 12.3 Frequency variation following 3-phase fault**

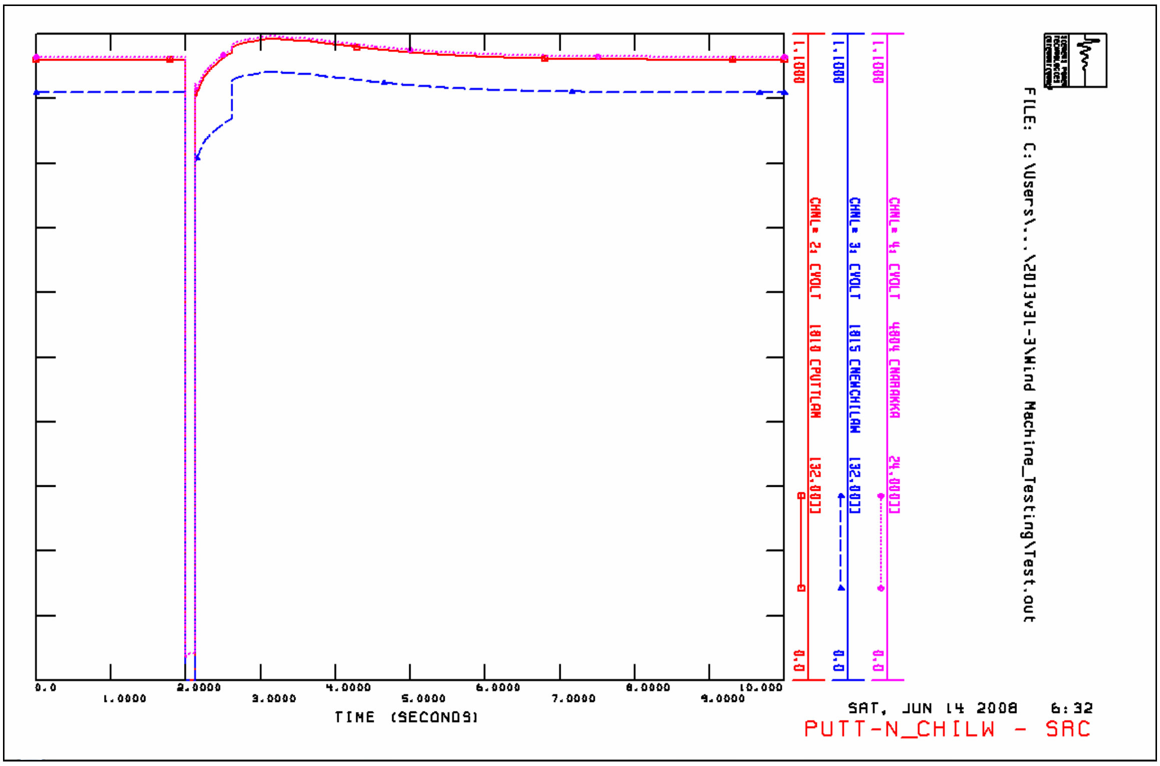



**Fig 12.4 Voltage variation following 3-phase fault**

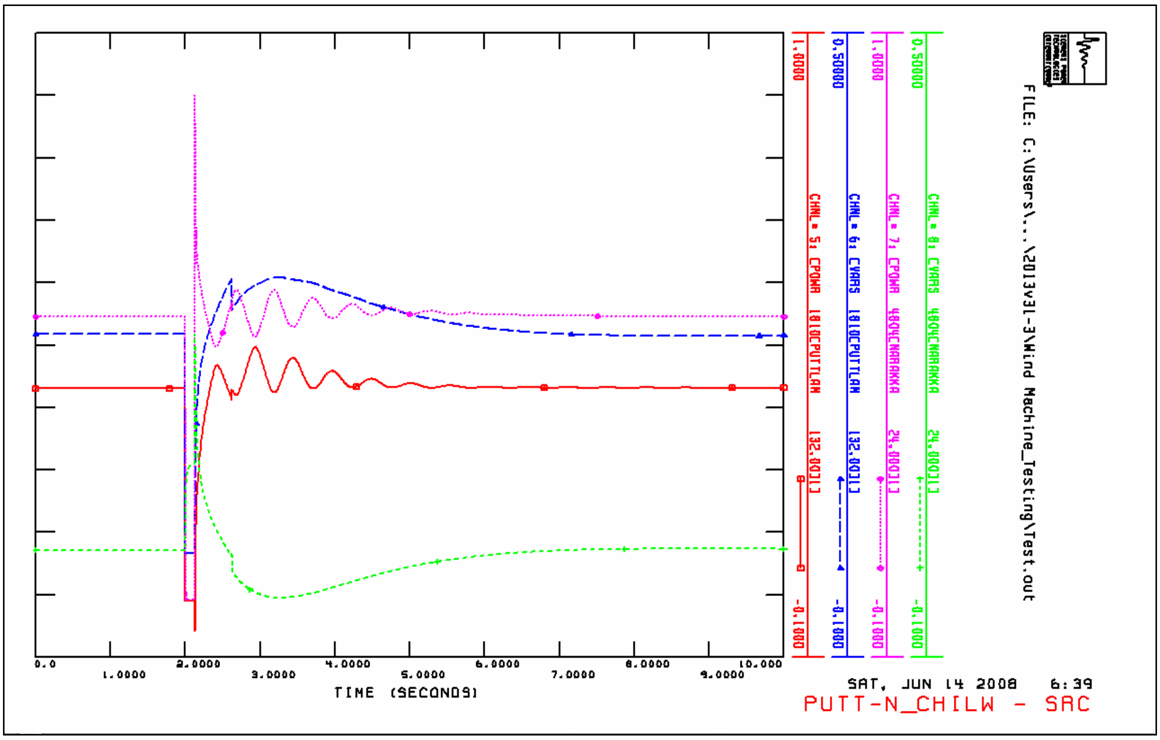



*Fig 12.5 Variations in Active and reactive power outputs following 3-phase fault*

## 12.5 Effect of Wind Power Plant Trip on FREQUENCY and VOLTAGES

The planned power system for 2016 with thermal maximum night peak (TMNP) is considered for studying the effects of wind turbine trip on frequency and voltage.

Forecasted peak load for the year 2016 is 3726.7 MW and the base load for year 2016 is 1490.7 MW (assuming 40% of peak load).

For the purpose of simulation 20% of base load is considered as the wind generation at a single point.

A portion of the CEB power system with 285 MW (1.5 MW x 90 units) wind generation connected to Putalam is shown in the Fig.6. At the point of common coupling the voltage is 33 kV.

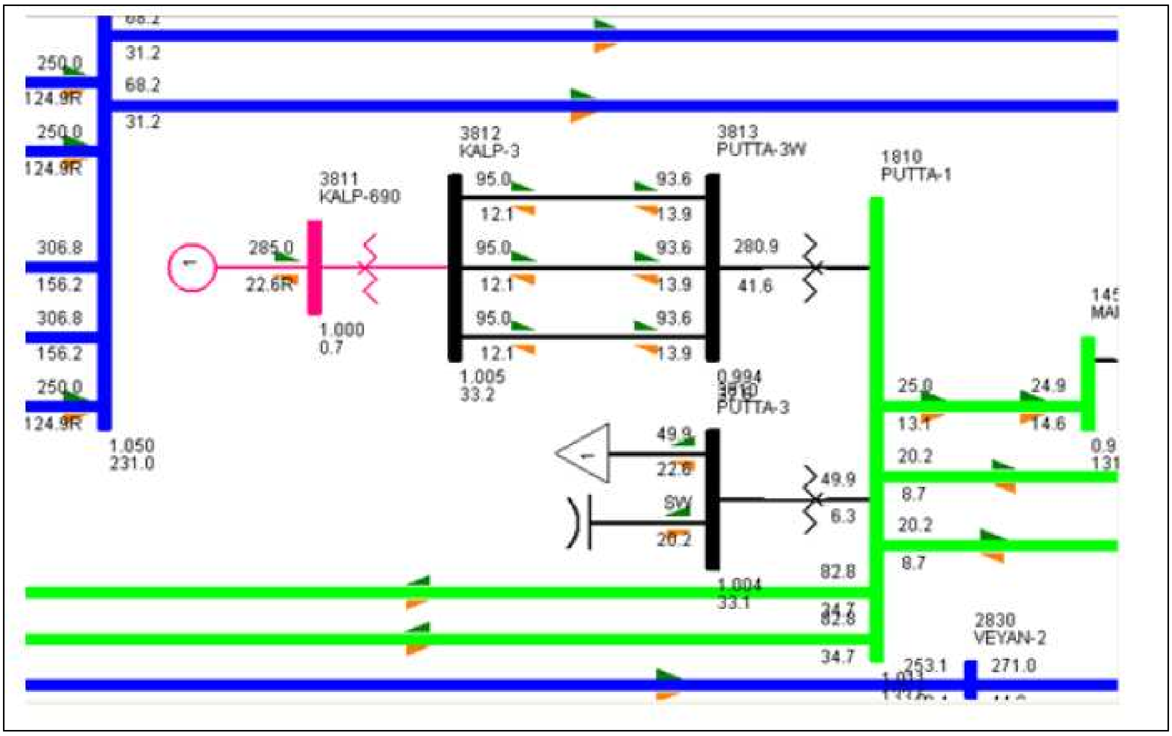



**Fig 12.6 Portion of power system with 285 MW Wind generator**

## Wind power plant trip: Frequency variation

The variation in power system frequency when the 285 MW wind power plant suddenly trips is shown in Fig 12.7. The frequency falls to 2.4% in about 25 second i.e. to 48.8 Hz which is more than the load shedding frequency limit.

With all governors in action and with Victoria hydro machines participating in frequency control, the simulation result is shown in Fig 12.8. Frequency falls to 0.5% below 50 Hz and gets settled at 0.4% below rated frequency.

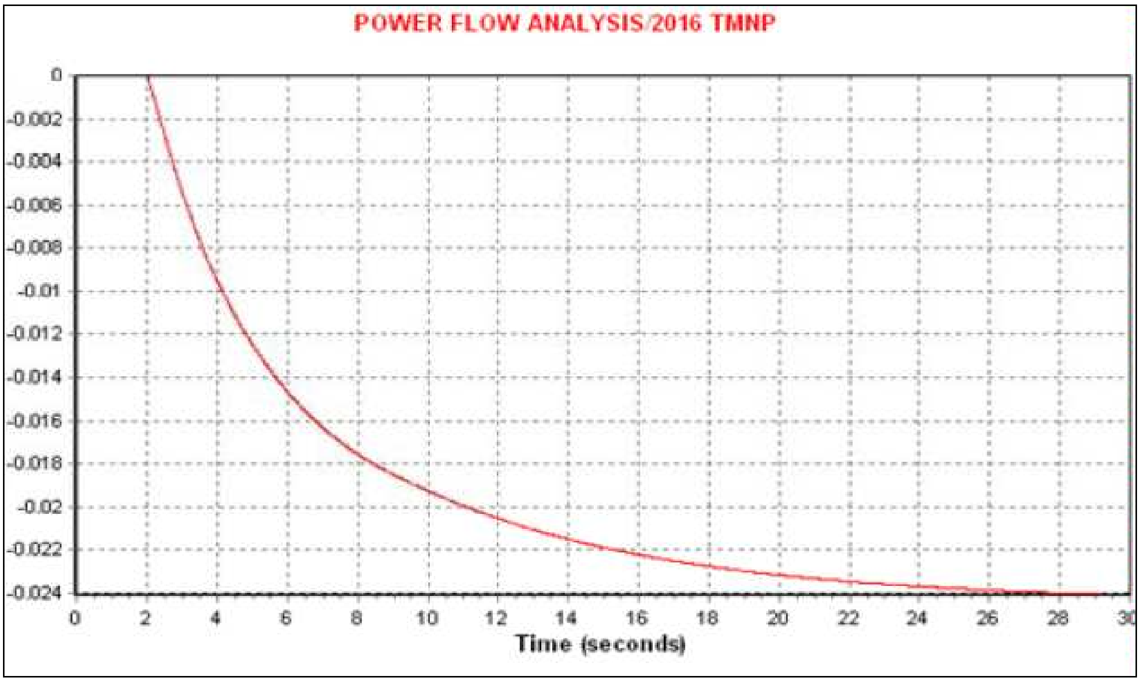



**Fig 12.7 Frequency variation for 285 MW wind power plant trip (2016 case) WITHOUT governors**

Frequency Plot- With all Governors (Victoria at 1.6% and other governors at 5% droop)

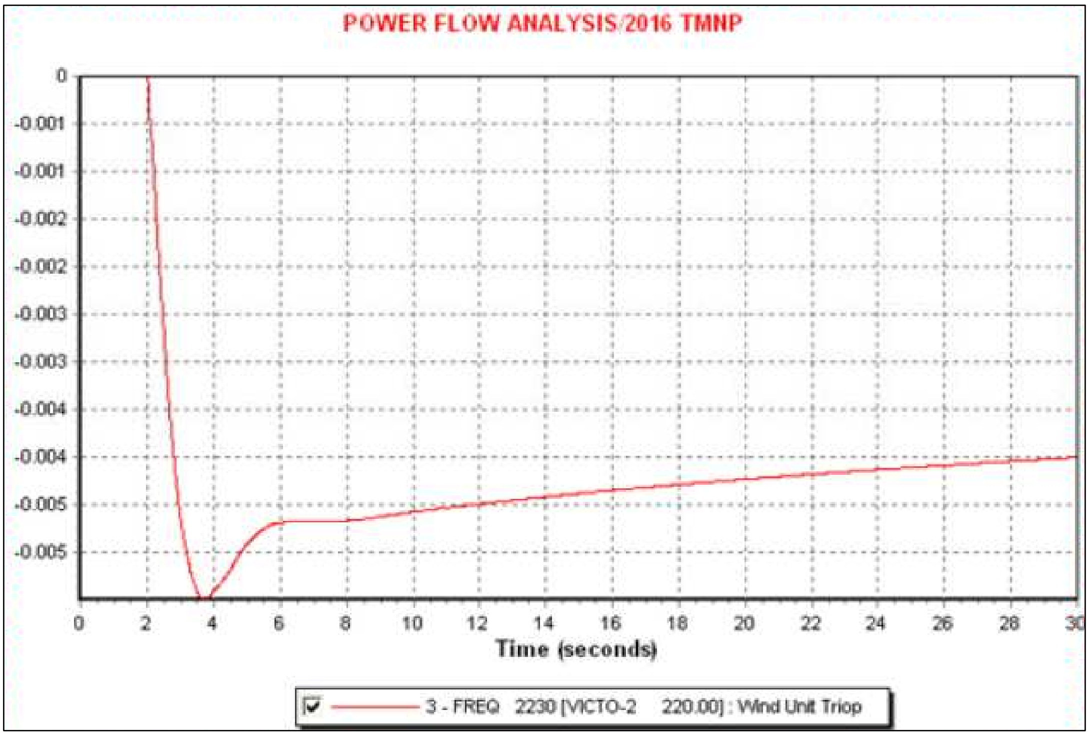



**Fig 12.8 Frequency variation for 285 MW wind power plant trip (2016 case) WITH governors**

**Wind power plant trip: Voltage variation**

For the trip of 285 MW wind power plant on the 2016 peak load case, the variations in voltages are shown in Fig 12.9. The voltages at various Puttalam buses fall and settle down quickly after few oscillations. The simulation result shows that voltage control is not a serious problem for trip of 10% wind generation trip.

It is interesting to see that WITH governors in control the voltage variations improve as shown in Fig 12.10.

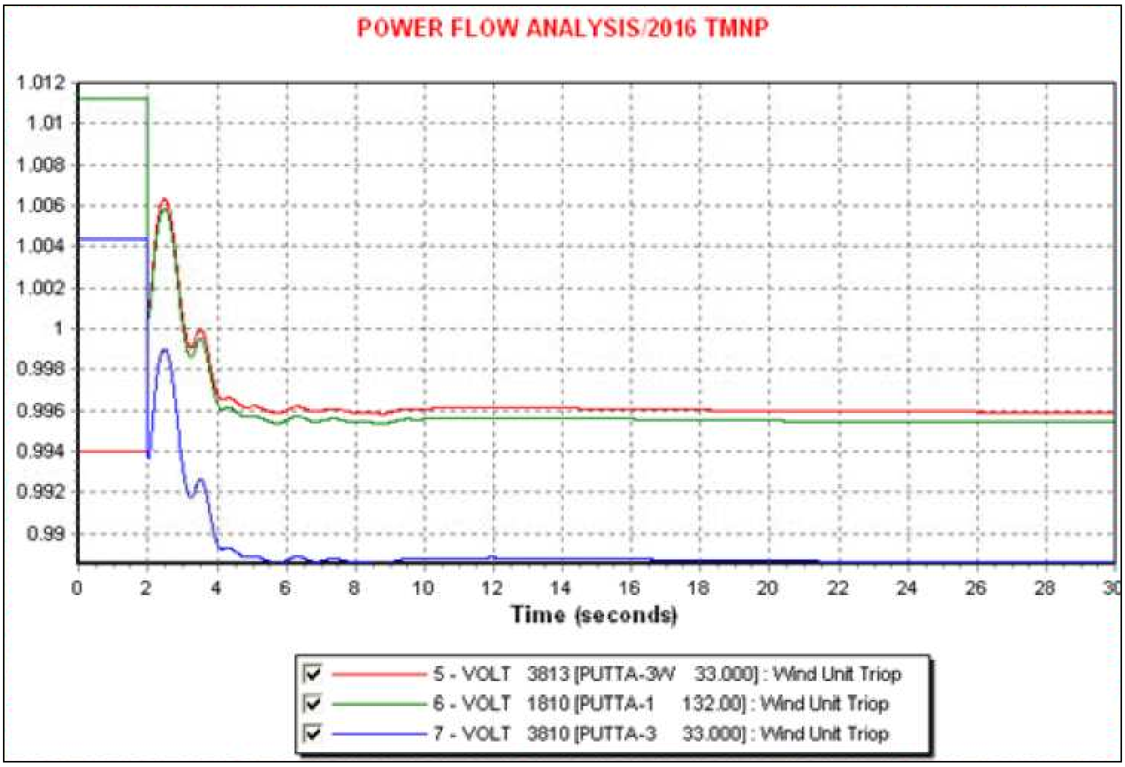



**Fig 12.9 Voltage variation for 285 MW wind power plant trip (2016 case) WITHOUT governors**

Voltage Plots – With all Governors (Victoria at 1.6% and other governors at 5% droop)

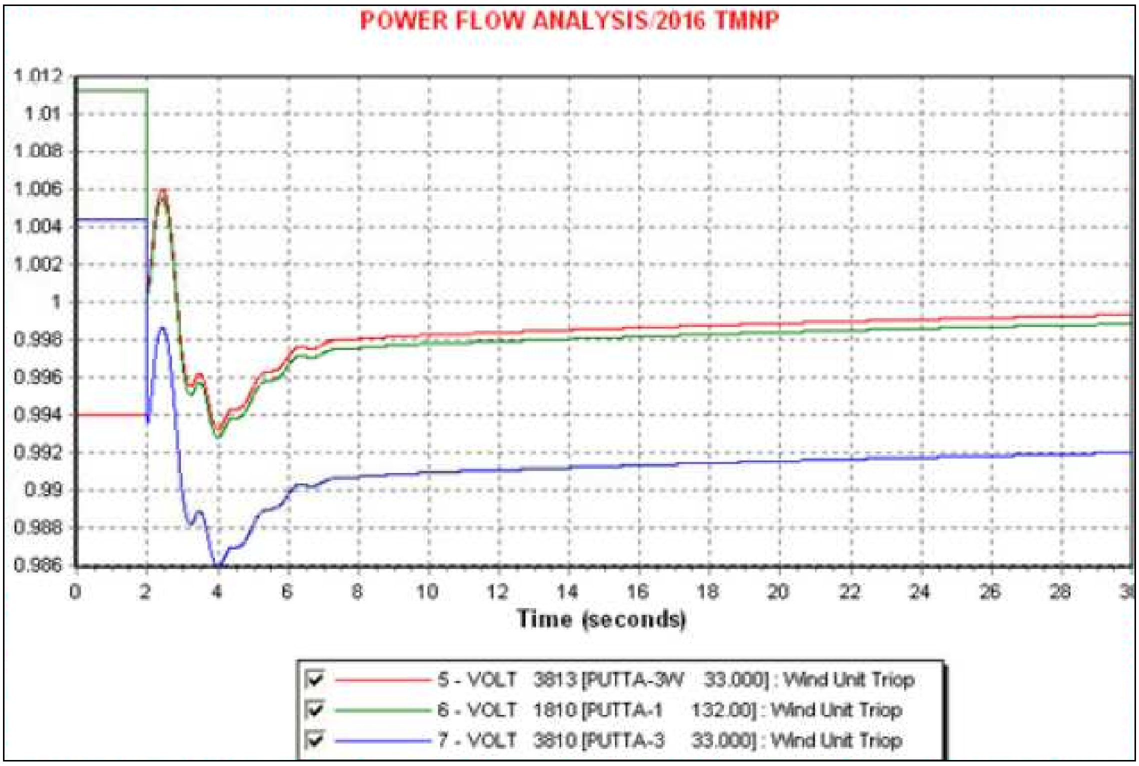



**Fig 12.10 Voltage variation for 285 MW wind power plant trip (2016 case) WITH governors**

## 12.6 Effect of Three Phase Fault on 2016 case with wind power: Voltage variations

For the 2016 case power system with 285 MW wind power, a fault is simulated on the 132 kV transmission line and the voltage variations are studied. These cases are repeated WITH and WITHOUT governors for thermal maximum night peak load and base laod as shown in Fig 12.11 to Fig 12.14. The variations in voltages are less than 1%.

Fault: Three phase short circuit at Puttlam – New-Chilaw 132kV transmission line-unsuccessful re-closing is assumed

Night peak loading condition - With all Governors

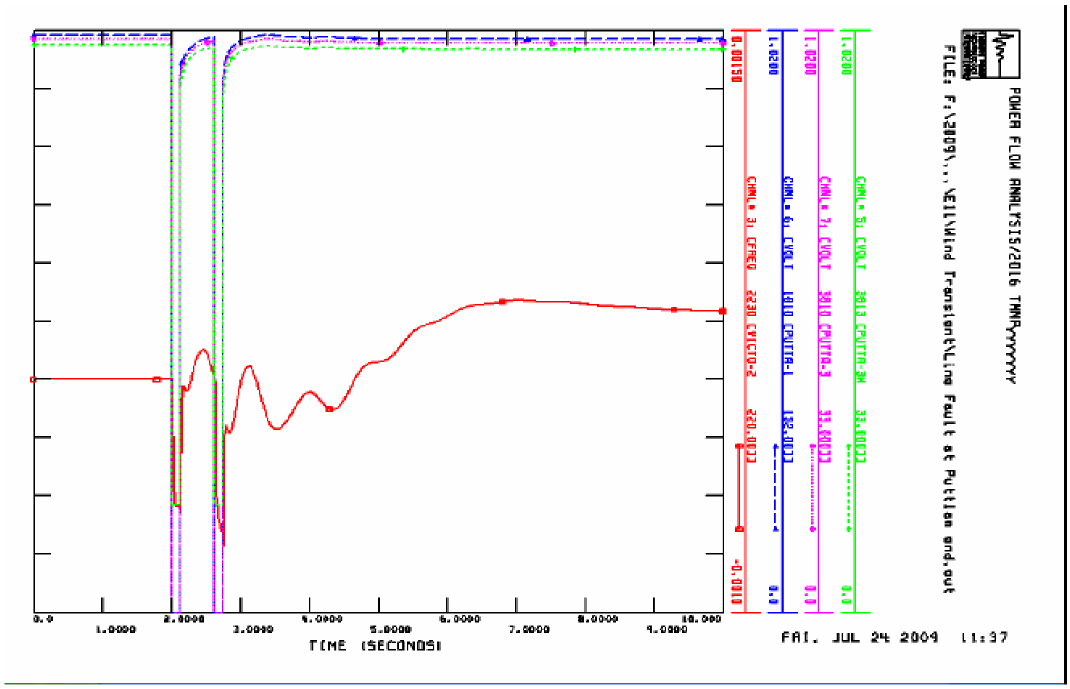



**Fig 12.11 Voltage variation for fault on 132 KV line (2016 case) WITH governors**

Night peak loading condition – Without Governors

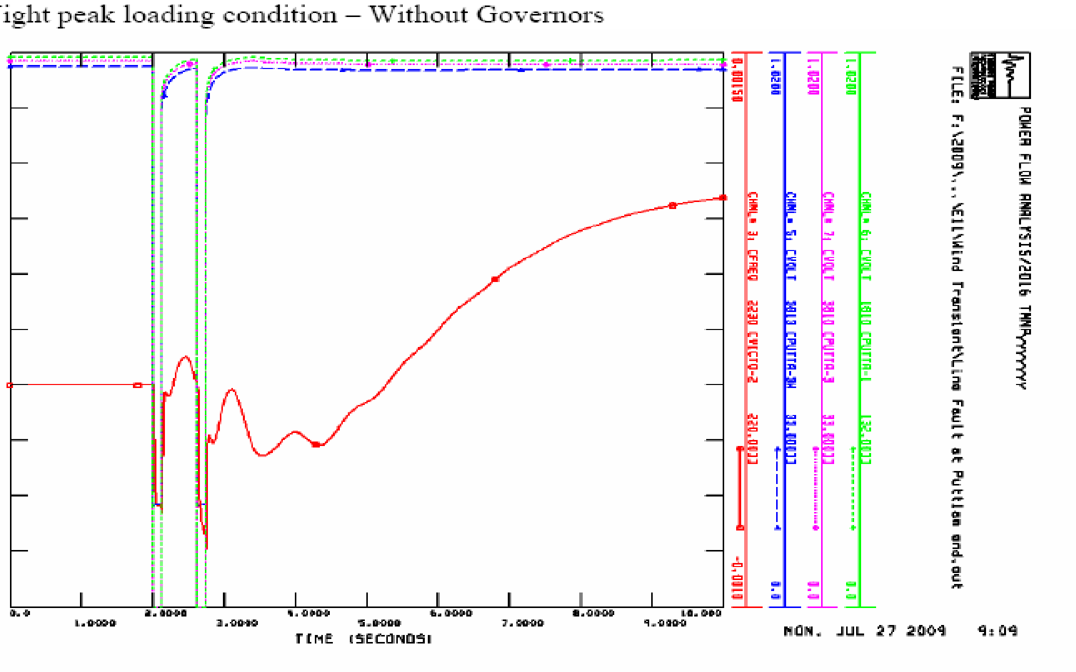



**Fig 12.12 Voltage variation for fault on 132 KV line (2016 case) WITHOUT governors**

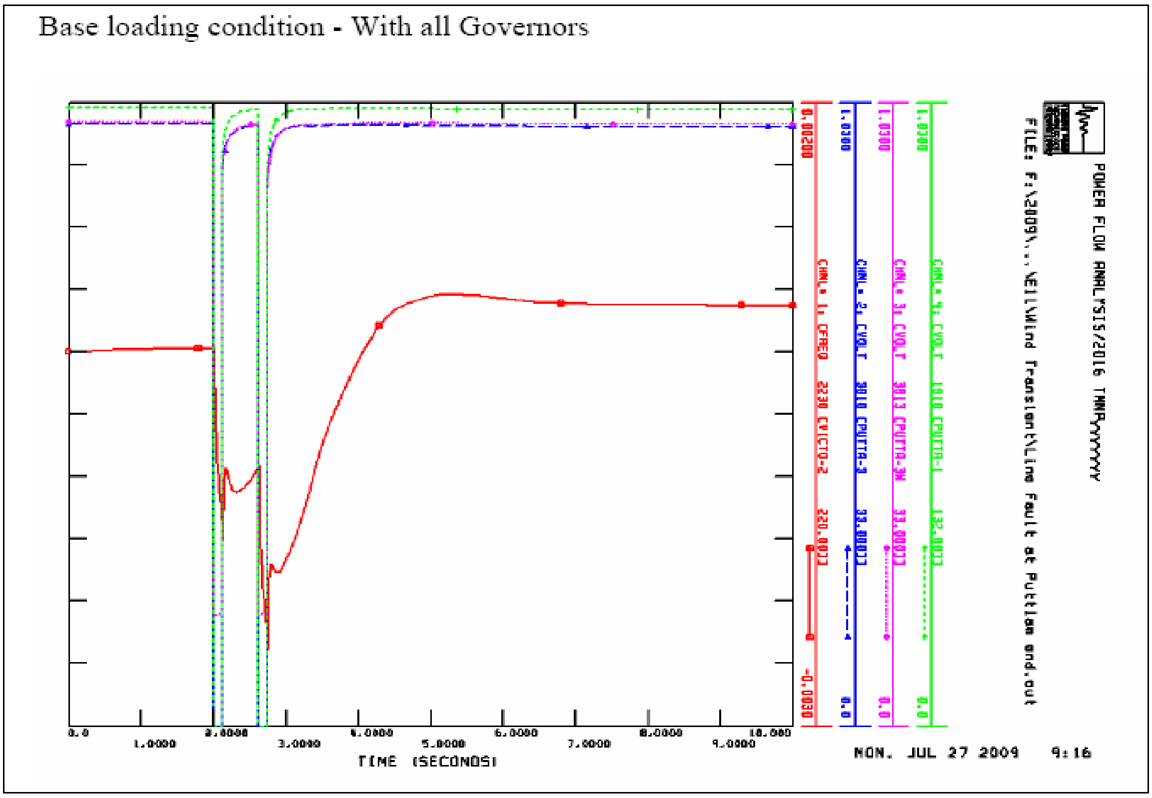



**Fig 12.13 Voltage variation for fault on 132 KV line (2016 BASE case) WITH governors**

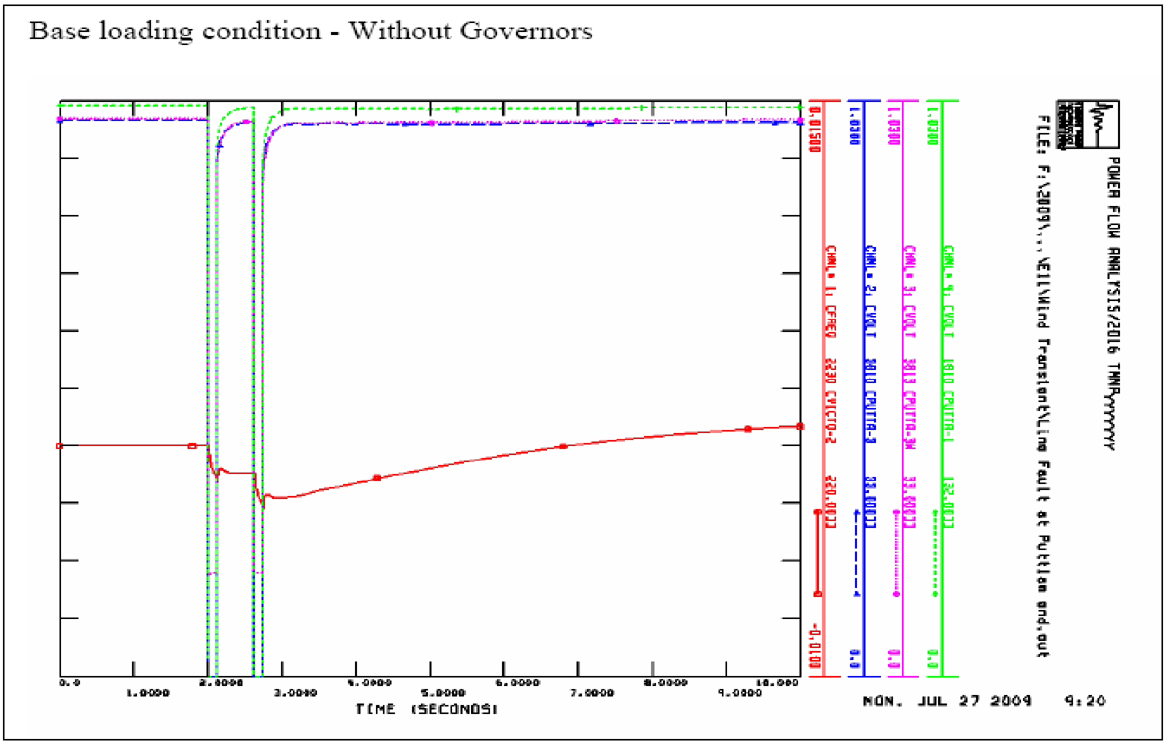



**Fig 12.14 Voltage variation for fault on 132 KV line (2016 BASE case) WITHOUT governors**

## 12.7 Study of the Effects of Different Wind Penetration Levels

For the CEB 2016 power system off-peak cases have been studied, as the wind power at low load level can destabilize the system. Frequency and voltage variations have been simulated for various wind penetration levels: 5%, 10% and 20%.

**5% wind penetration: Wind generator trip**

A portion of the CEB power system with wind generation at Puttalam is shown in Fig 12.15. About 50 MW (5% of off-peak load) is the wind generation.

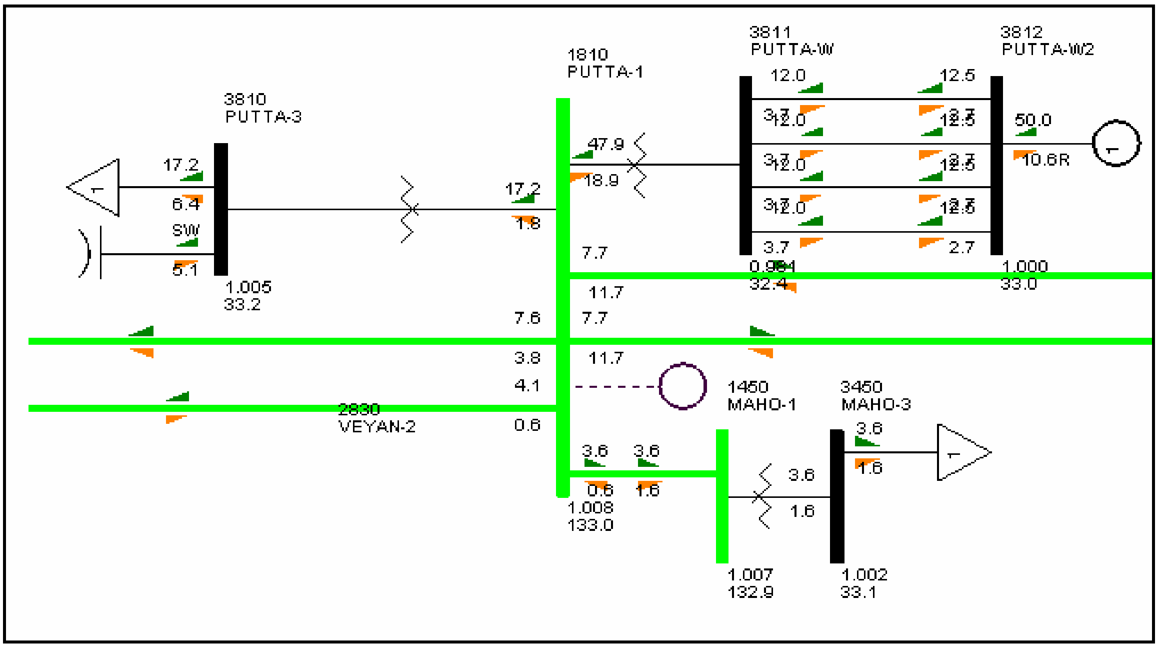



*Fig 12.15 CEB power system around Puttalam with wind generation*

The frequency variation WITH and WITHOUT governors is shown in Fig 12.16 and Fig 12.17. The effect on frequency is insignificant.

The voltage variations at various buses are shown in Fig 12.18. At the Puttalam 33 KV bus there is a rise in voltage of about 2% but the voltage settles down quickly.

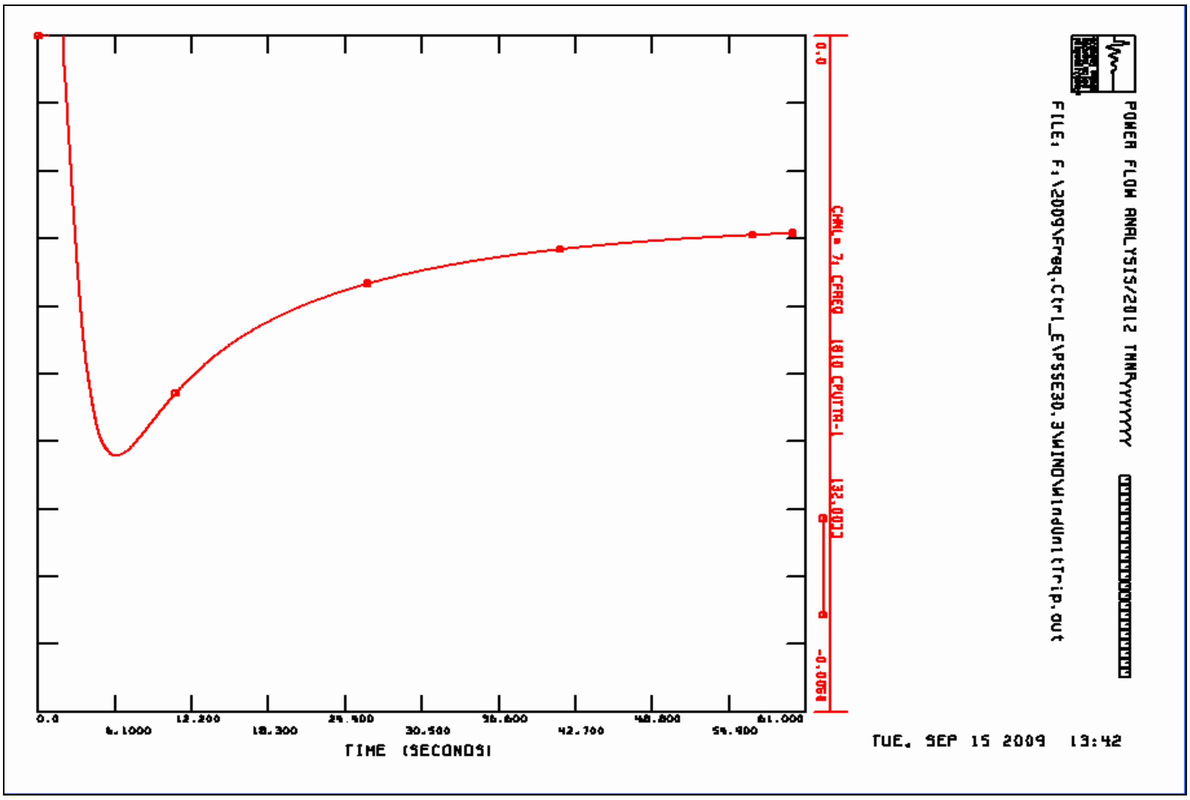



**Fig 12.16 Wind generation trip: 5% of off-peak load: WITH governors**

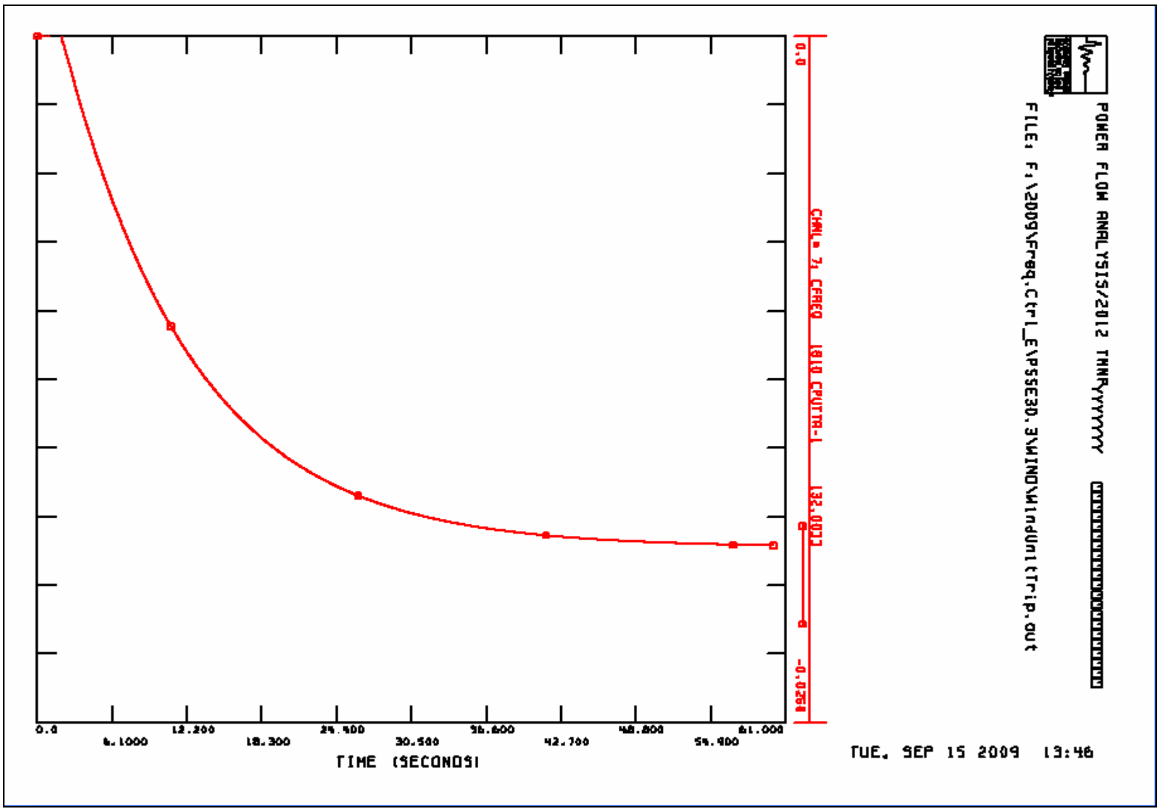



**Fig 12.17 Wind generation trip: 5% of off-peak load: WITHOUT governors**

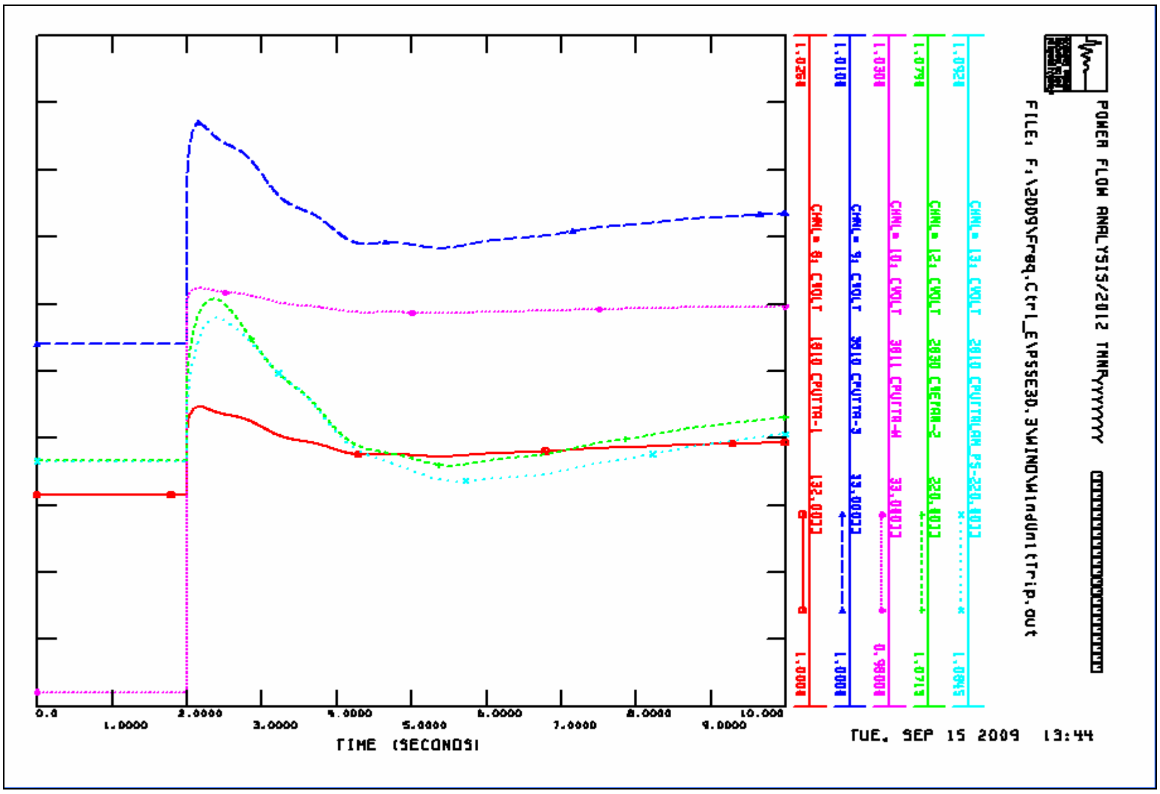


*Fig 12.18 Wind generation trip: 5% of off-peak load: VOLTAGE variation*

## 5% wind penetration: Coal Unit trip

The effect of tripping a large power generating unit at Puttalam of 115 MW capacity when the wind penetration level is 5% on 2016 off-load case is simulated to see whether frequency and voltage variations are within permissible limits or not. There is no significant effect.

Puttlam Coal Power Plant Tripping – 114MW

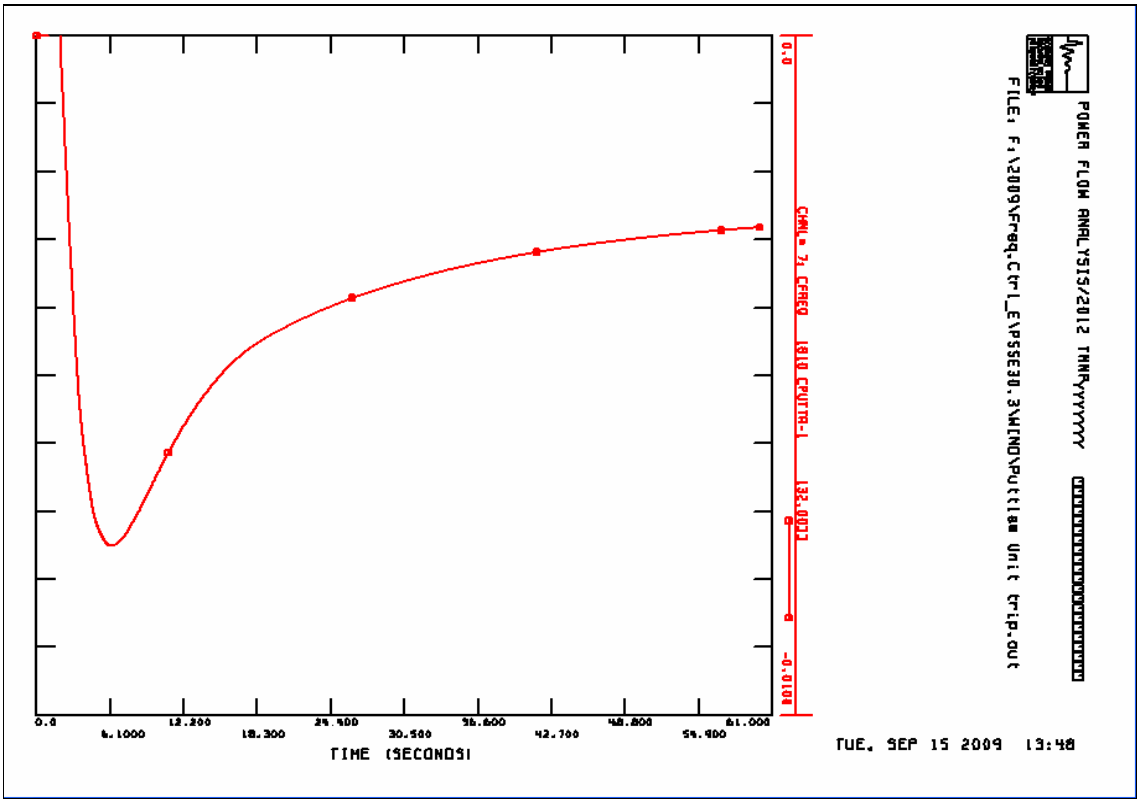



**Fig 12.19 Coal unit trip: 5% wind penetration: Frequency variation**

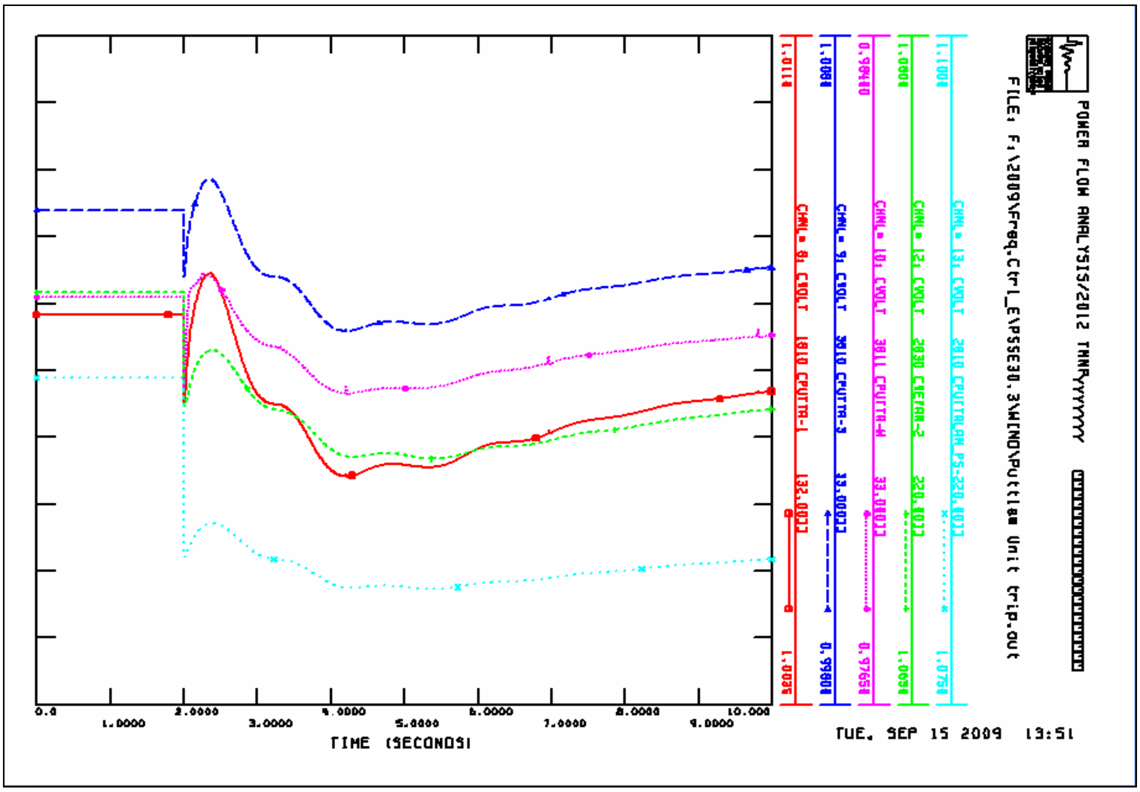



**Fig 12.20 Coal unit trip: 5% wind penetration: Voltage variation**

## 10% wind penetration: Wind generator trip and Coal Unit trip

The penetration level is increased to 10% of off-peak load. And the simulation using PSS/E is carried out for

- 100 MW wind generator trip
- coal unit trip

Fig 12.21 shows the frequency variation following a trip of wind generator with a capacity of 100 MW (10%) on a lightly loaded system. The peak frequency fall is only about 0.5%.

Similarly when the coal unit of 115 MW trips (with 10% wind penetration level), the frequency variation is not significant as shown in Fig 12.22.

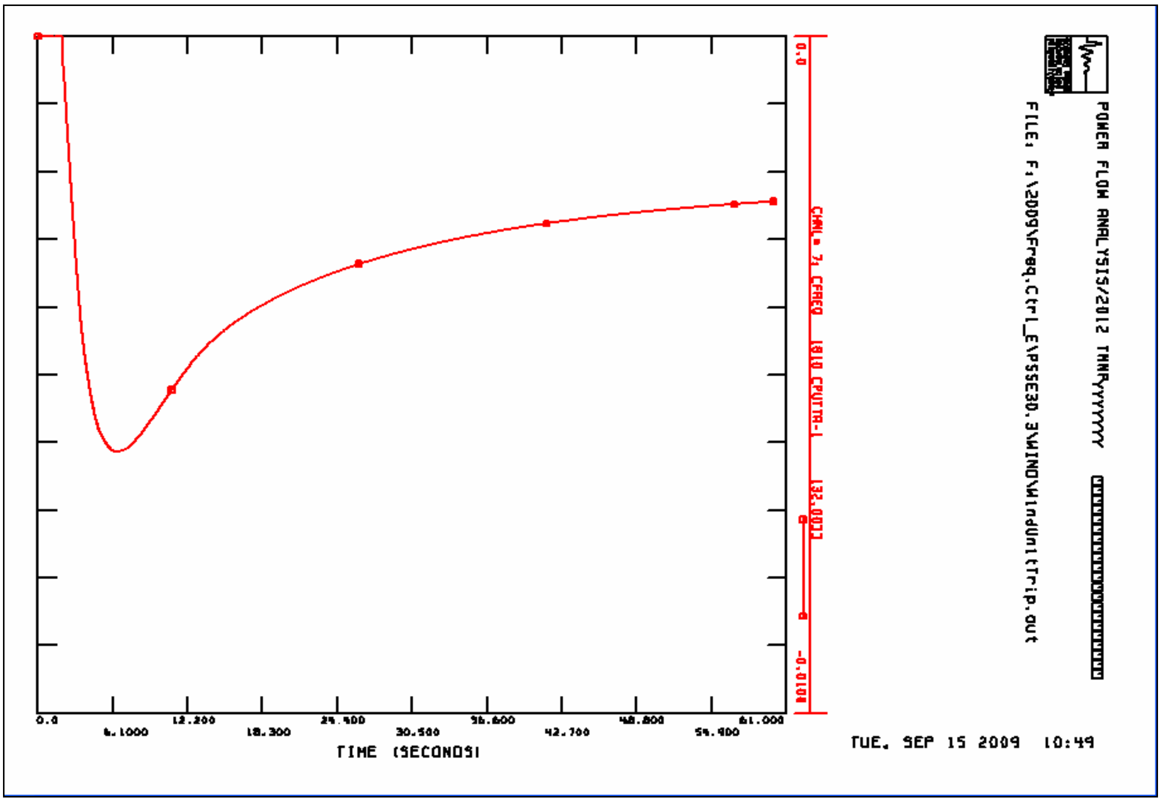



**Fig 12.21 Wind generator trip: 10% wind penetration: Frequency variation**

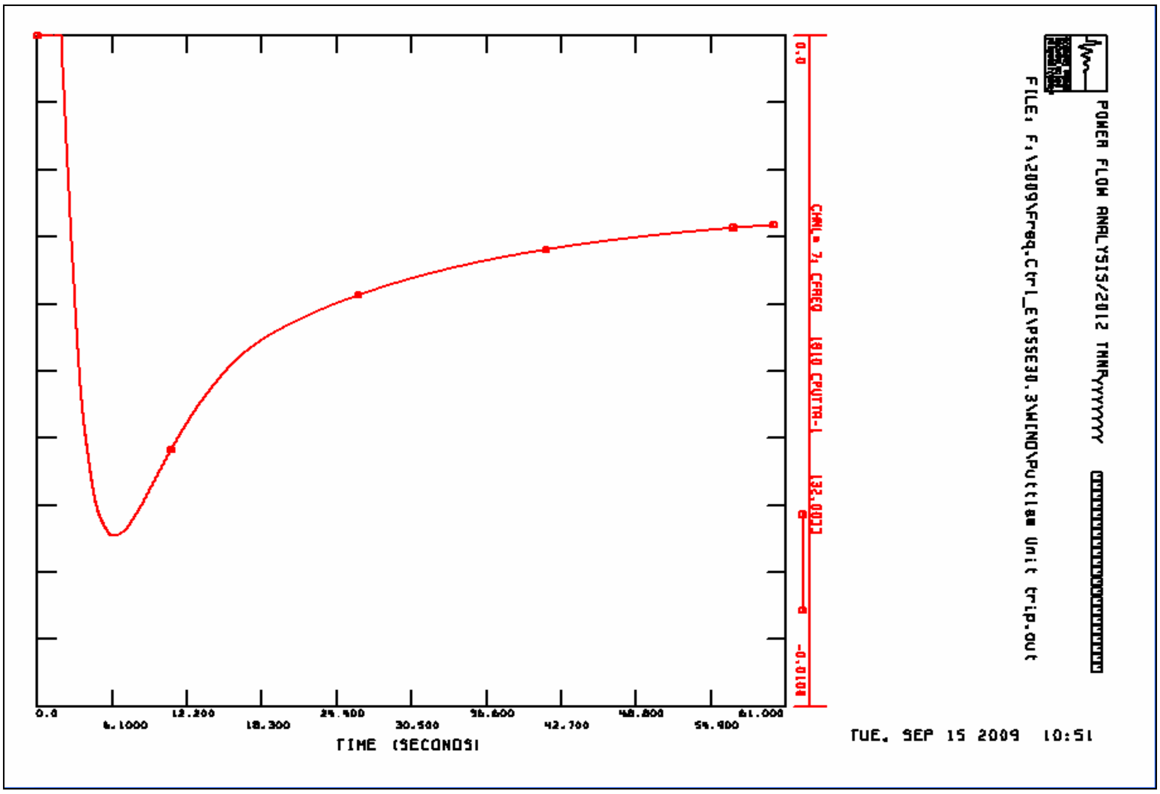



**Fig 12.22 Coal Unit 114 MW trip: 10% wind penetration: Frequency variation**

## Voltage variation with 10% wind penetration

When wind generator of 100 MW capacity trips there is a small variation at Puttalam and other buses which get restored very soon as shown in Fig 12.23.

Similarly for the trip of coal unit of 114 MW with penetration level of 10%, the effect on bus voltages nearby is very less as shown in Fig 12.24.

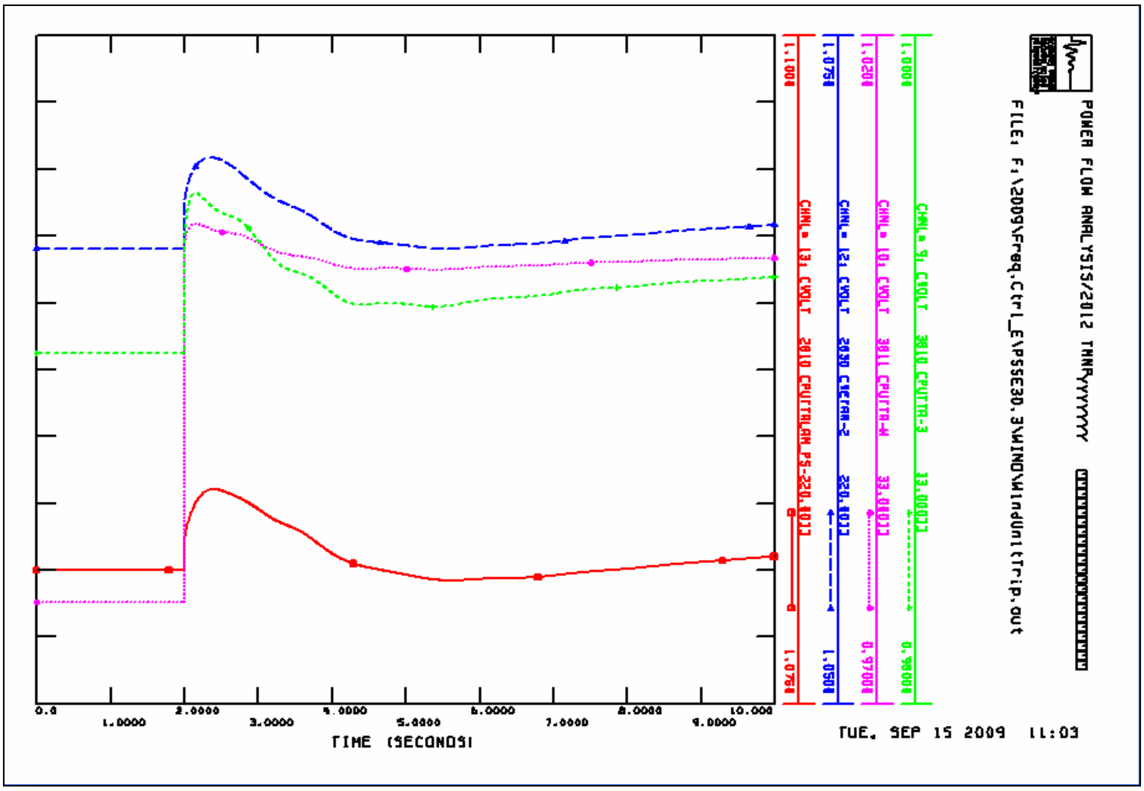


Fig 12.23 Wind generator trip: 10% wind penetration: Voltage variation

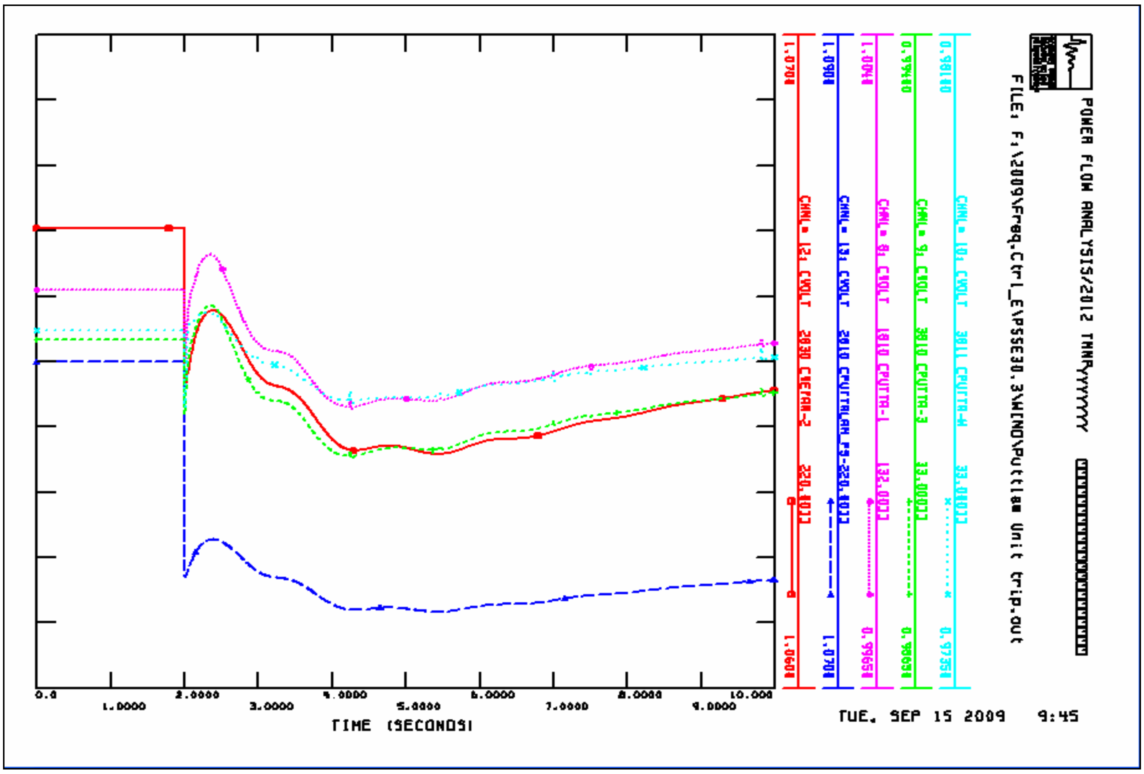


Fig 12.24 Coal Unit trip : 10% wind penetration: Voltage variation

## 20% wind penetration: Wind generator trip

It has been observed that at off-peak 2016 loads the effects of 5% and 10% wind penetration on frequency and voltage for trips of wind generator or for the trip of a large generating unit like 115 MW coal unit are negligible.

When wind generator trips, the frequency falls to 1.75% below the rated frequency with all turbines in free governor mode and finally frequency settles at 0.5% below rated frequency as shown in Fig 12.25.

There is a transient voltage variation of about 2% at buses near wind connected bus (Fig 12.26).

When the governors are not in auto, the frequency falls by 7.5%, as shown in Fig 12.27, which is considerable. Load shedding has to be resorted to.

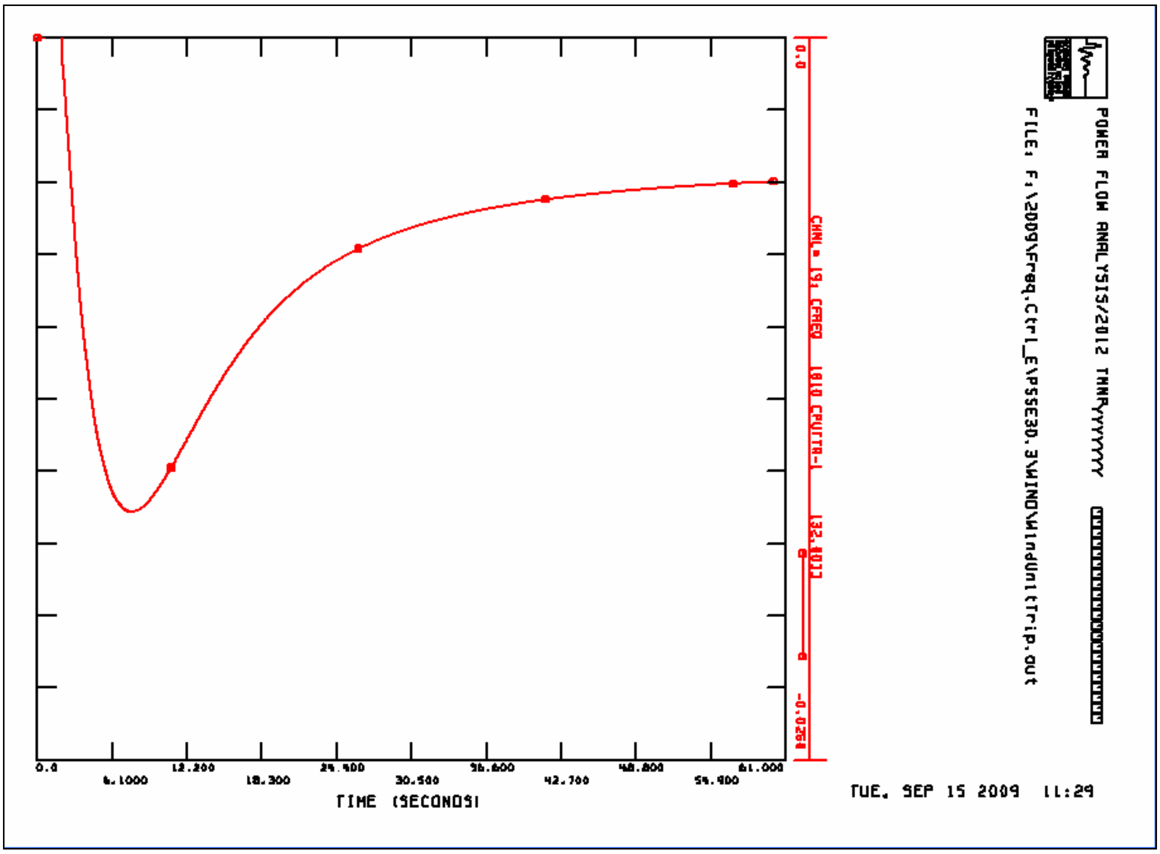



**Fig 12.25 Wind Unit trip: 20% wind penetration: Frequency variation**

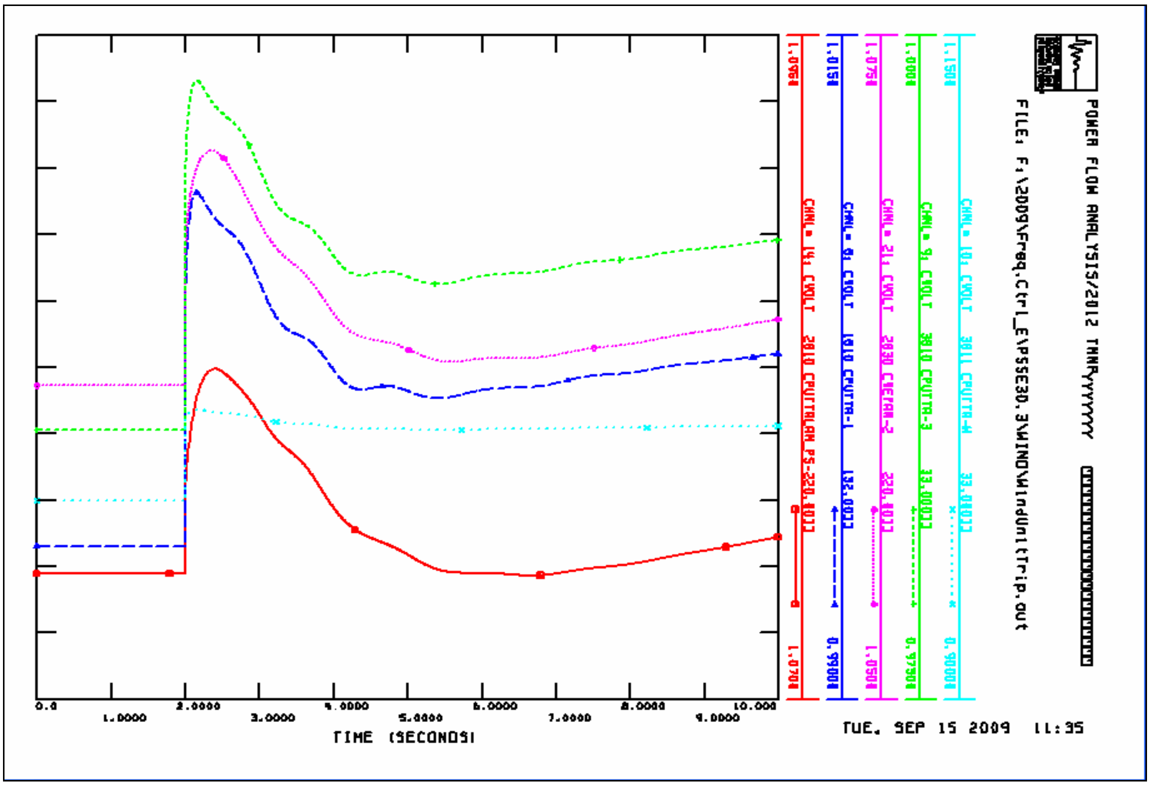



**Fig 12.26 Wind Unit trip: 20% wind penetration: Voltage variation**

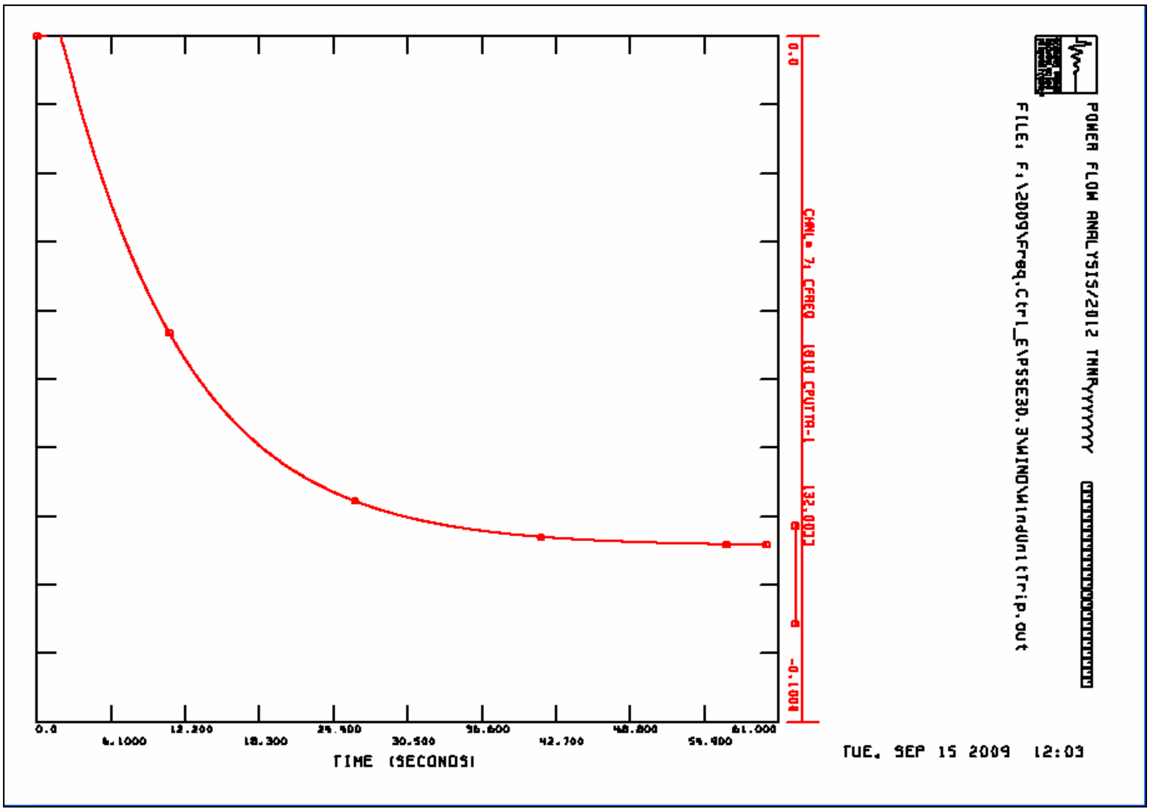



**Fig 12.27 Wind Unit trip: 20% wind penetration: Frequency variation: NO governors**

## 12.8 Analysis of Wind Penetration

### Summary of Simulation Studies

Wind penetration studies are being carried out through out the world on various aspects of power system operation. The emphasis in this study has been on the frequency and voltage variations. The simulation studies carried out on CEB 2016 power system showed that system can withstand wind penetration levels in excess of 10%. Simulation has been carried out by CEB engineers using the PSS/E with Wind turbine model of GE 1.5 MW built in.

### Costs of wind penetration

In USA and Europe the power systems are very large and deregulated. With frequency and voltage regulations being considered as ancillary service several complications arise.

The costs due to wind penetration are divided into two categories:

- incremental reserve requirements and
- imbalance costs.

The incremental reserve category accounted for the estimated cost of increasing the level of operating reserves necessary to maintain system reliability with a relatively large penetration of wind capacity. The imbalance cost category was intended to capture the difference in operating costs that may occur because of additional unit start-ups, a higher rate of incurring bid-ask spread penalties, or operating a unit at a less efficient point on the heat-rate or power curve.

To assess the incremental reserve requirement, the wind generation is treated as a negative load. This approach recognizes that each individual resource does not need to be balanced as long as the overall system is in balance.

### Mitigation Measures

To address the intermittency of wind and increase the wind capacity that can be added to the system there are some mitigations measures being considered:

- power electronics and line compensation to control power factor and improve power quality;
- ultra capacitors to absorb short-term fluctuations
- resistors and power electronics to provide low-voltage ride-through (LVRT) capability and allow large wind plants to continue operating after momentary line faults

### Operating reserve and load following capabilities

Studies carried out on Ireland power system suggested that with 16 to 27% wind penetration level, operating reserve is to be increased by 10 to 12% and load following capability is to be increased by 30%.

Due to $CO_2$ restrictions on conventional power plants, many wind power plants are being planned in Germany. The load following capability was suggested to be increased by 200% for 20% wind penetration level.

In Denmark presently about 21% of energy consumed is supplied by wind turbines alone. Penetrations of wind power into local grids have at times gone up to 60% in good windy season.

In Tamil Nadu, 33% wind power exists on installed power basis. With 50% PLF in high wind season, penetration level of 18% on an average is there.

In general, many countries are gearing up to achieve wind penetration level of 20%.

### 12.9 Recommendation on wind penetration level for CEB power system

i. Based on the simulation studies of the CEB power system and the experiences of various countries with wind power, it is recommended that CEB may safely allow wind generation up to 10% of off-peak load. The frequency and voltage stability can be maintained with this level.

ii. Presently the operating reserves are provided for frequency regulation in Victoria and other hydro power stations. The operating reserves are to be increased for safe control capabilities.

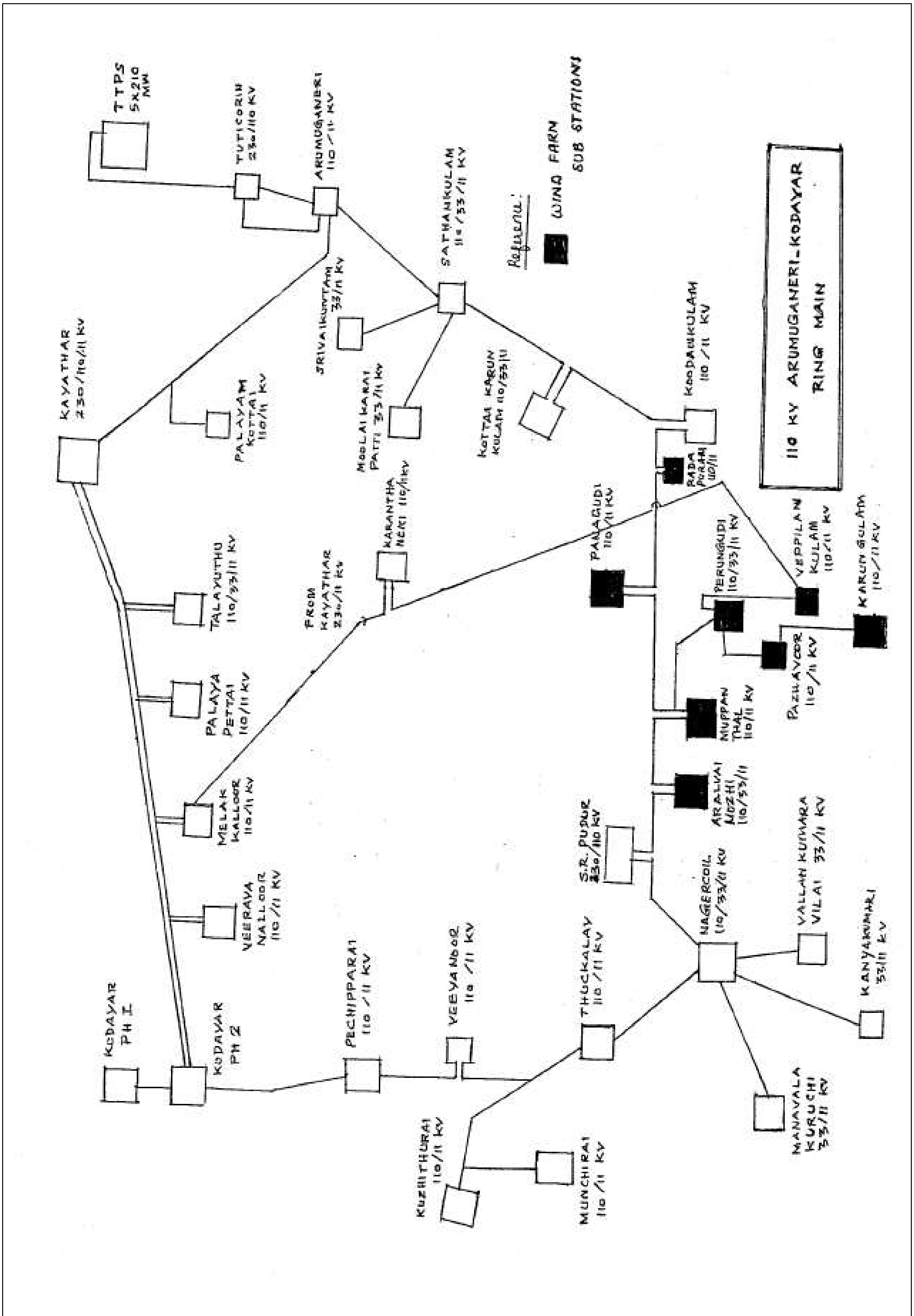
iii. Various studies are to be carried out for individual cases of wind connection requests like

   - power flow and contingency studies
   - fault analysis
   - transfer limit analysis
   - dynamic analysis and
   - harmonic analysis

iv. If the wind farms are connected at connected at the 11 KV/ 33 KV levels impacts on power quality (harmonics, flicker etc.) at the local distribution system level have to be assessed.

v. With wind generation in excess of 10% being planned, provision of storage facilities like advanced batteries and fly wheels have to be considered for future power system.

vi. Voltage level of grid connection in India: Tamil Nadu has large concentration of wind power plants. A sketch is enclosed showing the local grid connection of 386 MW of in the Muppandal area (in the year 2000) with 110 KV ring main. This scheme might be helpful for planning engineers of CEB.


TTPS 5x210 MW
TUTICORIN 230/110 KV
ARUMUGANERI 110/11 KV
SATHANKULAM 110/33/11 KV
Reference:
WIND FARM SUB STATIONS
110 KV ARUMUGANERI-KODAYAR RING MAIN
KAYATHAR 230/110/11 KV
SRIVAIKUNTAM 33/11 KV
PALAYAM KOTTAI 110/11 KV
MOOLAIKARAI PATTI 33/11 KV
KOTTAI KARUN KULAM 110/33/11
KOODANKULAM 110/11 KV
RADA PURAM 110/11
PANAGUDI 110/11 KV
KARANTHA NERI 110/11KV
FROM KAYATHAR 230/11 KV
TALAYUTHU 110/33/11 KV
PERUNGUDI 110/33/11 KV
VEPPILAN KULAM 110/11 KV
KARUNGULAM 110/11 KV
PAZHAVOOR 110/11 KV
PALAYA PETTAI 110/11 KV
MUPPAN THAL 110/11 KV
ARALVAI MOZHI 110/33/11
MELAK KALLOOR 110/11 KV
S.R. PUDUR 230/110 KV
VEERAVA NALLOOR 110/11 KV
NAGERCOIL 110/33/11 KV
VALLAN KUMARA VILAI 33/11 KV
KANYAKUMARI 33/11 KV
KODAYAR PH I
KODAYAR PH 2
PECHIPPARAI 110/11 KV
VEEYANOOR 110/11 KV
THUCKALAY 110/11 KV
MANAVALA KURUCHI 33/11 KV
KUZHITHURAI 110/11 KV
MUNCHIRAI 110/11 KV

# Chapter 13

# REQUIREMENTS OF SOFTWARE AND CONSULTANCY SERVICES

The PTI Power System Simulator (PSS/E) is a package of programs for studies of power system transmission network and generation performance in both steady-state and dynamic conditions. PSS/E handles power flow, fault analysis (balanced and unbalanced), network equivalent construction, and dynamic simulation.

Ceylon Electricity Board has licensed Power System simulator for Engineering (PSS/E) from Siemens. PSS/E is used by several utilities world wide. It is considered to be a robust program for analysis of power system network with several thousands of buses.

The load flow analysis and dynamic simulation are the two components that have been used for the frequency and voltage control aspects of study reported in this report. The simulation has been carried out by the CEB engineers under the direction of GECE consultants.

## 13.1 Additional Software Requirements

### i) PSS/MUST from Siemens

Considering the future growth of the Sri Lanka power system with plans for addition of coal based thermal power plants, wind power plants etc., and the deregulation the software expansion , it is preferable to procure the program Power System Simulator for Managing and Utilizing System Transmission (PSS/MUST) supplied by Siemens.

It is used to calculate electric transmission transfer capabilities and the impact of transactions and generation dispatch. It helps in managing the effect of power transactions and dispatch changes. The capability to move power from one part of the transmission grid to another is a key commercial and technical concern in the restructured electric utility environment. Engineers determine transmission transfer capability by simulating network conditions with equipment outages during changing network conditions. Many uncertainties remain in the process, most importantly, Source/sink transactions different than those assumed in the initial (base) calculation, Generation dispatch patterns different from those assumed in the initial calculation.

PSS/MUST is considered to be efficient in calculating transaction impacts on transmission areas, interfaces, monitored elements, or flow gates and generation redispatch factors for relieving overloads. Incremental transfer capability (FCITC) and its variations with respect to network changes, transactions, and generation dispatch are also efficiently calculated.

PSS/MUT complements Siemens PTI’s Power System Simulator for Engineering (PSS/E) and uses advanced data handling and analysis functions with the most advanced linear.

**ii) PSS/TPLAN from Siemens**

Another program in the PSS suite that will be useful for Transmission planning is TPLAN. It can be used for testing deterministic reliability as in the (n-1) criterion, and others of this type such as (n-2), (n-1-1), etc. PSS/TPLAN provides for detailed modeling of remedial action schemes, effective identification of voltage collapse conditions, and automatic handling of re-dispatch and load shedding requirements.

Keeping the future growth of Sri Lanka power system, it is recommended that CEB may acquire PSS/MUST and PSS/TPLAN.

**iii) Wind interconnection study module**

CEB will be receiving several proposals for interconnection of wind power plants. There are various manufacturers of modern wind turbines and their controllers like GE, Vestas, Suzlon, Gamesa etc. The control configurations and wind generator configurations are different depending on the manufacturer. Siemens is reported to be updating the modules in the model library of PSS/E. It is recommended that CEB procure the additional modules required for wind interconnection study.

**iv) Transient analysis Software**

Power System Transients can be classified as:

- **Ultra Fast Transient**: Lightning, switching surges, etc. that can lead to short circuits and insulation break down.
- **Medium Fast Transient**: Short circuits that can cause loss of synchronization
- **Slow Transient**: Electromechanical phenomena that results in 2-3 oscillations to several per minutes and loss of synchronization.

PSS/E can be used for medium and slow transient studies. But for ultra fast transient studies another software is required. Various softwares like EMTP available commercially are being studied. Final recommendation will be given in the Final Simulation report.

### 13.2 Software for system control and operational support

i) PSS/E is a powerful program for transmission planning. But for operation and control, load flow analysis with powerful visuals is available in PowerWorld simulator. Often operating engineers have to take quick decisions. PowerWorld Simulator is beneficial for this purpose. It is recommended that CEB may procure PowerWorld Simulator software which is also not quite expensive.

ii) There are going to be many coal based/ oil based thermal power plants. Present diesel generator sets are not used much for 'despatch' purpose. So it is recommended that CEB may acquire Economic Despatch software which takes care of constraints also. ETAP, Cyme and other vendors supply the economic dispatch softwares.

# Chapter 14

# TRAINING OF CEB ENGINEERS

Presently there are only two engineers trained on PSS/E on limited aspects of power system planning. It is necessary to have 10 to 12 trained engineers trained on various aspects of power system studies using PSS/E and other well known programs.

## 14.1 Preparatory Course

Prior to the training on PSS/E, a general appreciation course covering the analysis of the power system and its controls is necessary. With the consultation of CEB engineers a 10-day training program on "Power system analysis and operation" is proposed as given in Table.

**PROPOSED TRAINING PROGRAM FOR CEB ON "POWER SYSTEM ANALYSIS AND OPERATION"**

| Day | Forenoon Session | | Afternoon Session | |
|---|---|---|---|---|
| **1** | Introduction to power system and its components | Power system Representation using one line diagram | Basic power flow equations | Power Flow Analysis - 1 |
| **2** | Power Flow Analysis - 2 | | Power Flow Analysis - 3 | |
| **3** | Contingency Analysis | | Optimal Power Flow | Power Transfer Capability Limits |
| **4** | Dynamic Simulation Principles | Synchronous Machine Models - 1 | Synchronous Machine Models - 2 | Generator Capability curve |
| **5** | Excitation System and Controller Models | Modeling of Automatic Voltage Regulators (AVR) | Modeling of Power System stabilizer (PSS) | Modeling of transmission lines and transformers |
| **6** | Modeling of Hydro turbine and its governing system | Modeling of Steam turbine governing System | Modeling of Gas turbine and its control system | Modeling of Diesel engine governing System |
| **7** | Modeling of wind turbine generator and its control System | Load Modeling | Tuning of governor parameters | Tuning of AVR parameters |

| Day | Forenoon Session | | Afternoon Session | |
|---|---|---|---|---|
| **8** | Dynamic Stability analysis (Small - signal Stability analysis) | | Transient Stability analysis | Static VAR Compensator and its Modeling |
| **9** | Reactive Power Management | Voltage Stability analysis - 1 | Voltage Stability analysis - 2 | Automatic Generation Control (AGC) - 1 |
| **10** | Automatic Generation Control - 2 | HVDC System modeling | Impact of Wind Generation | Energy Management System and its application programs |

## 14.2 PSS/E Training

Siemens – PTI conducts training with various modules dealing with PSS/E basics like: power flow modeling, creating one-line diagrams, Power flow solution and reports.

The topics like Contingency and transfer limit analyses, Balanced switching, Fault analysis, Network reduction and PV and QV analyses should also be included.

Hands-on experience on IPLAN programming and Python language will also be useful.

Another course ‘Introduction to Dynamic Simulation using PSS/E’ offered by Siemens will be very useful, as the present study on frequency and voltage control aspects used dynamic simulation module of PSS/E extensively. The training should include modeling aspects of governors, AVRs using PSS/E along with the modeling aspects of generators, transformers etc.

## 14.3 Long Term Training

Various Power System training modules that can be considered for long term training are listed in the Appendix 3 based on the experience of GECE consultants.

# Chapter 15

# CONCLUSIONS AND RECOMMENDATIONS

The 'frequency control' and 'voltage control' aspects of the power system of Sri Lanka for various scenarios of 2008, 2012, 2016 and 2020 have been studied using PSS/E (Power System Simulator for Engineering) program with the assistance of Ceylon Electricity Board (CEB). The data for the study has been provided by CEB.

The load flow analysis is the starting point for the dynamic simulation study using PSS/E. The data for the dynamic simulation includes the data for prime movers, generators, transmission lines, substation devices and various control systems like governors and automatic voltage regulators (AVR). Most of the data used for the steady state and dynamic simulation has already been incorporated in the PSS/E program by CEB and verified by the JICA study team as part of Master Plan study. Wherever data is not there suitable values have been considered.

The following conclusions can be drawn from the simulation study.

## 15.1 Frequency Control

The frequency of the Sri Lanka power system is generally maintained within the permissible limits of 50 Hz ± 1%.

In the *primary regulation* the governors of all the prime movers- hydro turbines, diesel engines and steam and gas turbines respond. The hydro turbine governors at Victoria are made to respond faster and pick up more share of the load change by reducing the permanent droop to 1.6% whereas all other governors have 5% droop. But the frequency for load changes cannot return back to the normal value unless an Automatic Load Frequency control (LFC) scheme is provided.

## 15.2 Automatic Generation Control

It is recommended that an Automatic Generation control system be provided with the following functions:

- Load frequency control (LFC)
- Economic Dispatch (ED) and
- Interchange Scheduling (IS)

CEB is already planning to upgrade the System Control Center with advanced SCADA/ EMS. CEB should include the application programs for AGC and necessary field devices to manipulate the governor load set points automatically for generating units participating in frequency regulation.

There is already a plan to upgrade to Energy Management System (EMS) at the System Control Center. The ALFC runs as an application program along with economic dispatch (ED) and interchange scheduling (IS). CEB presently do not have many thermal units with boilers and steam turbines. But when the power generation system expands with proposed coal based units this ED function becomes a necessity.

### 15.3 Droop (Permanent droop) setting

The permanent droop is set uniformly at 5% in CEB generating stations except those used for secondary frequency regulation. Same value is reflected in the dynamic data used for simulation. In other countries also it is uniformly set at 4% or 5% to facilitate sharing of power in proportion to the capacities. There is no need to deviate from this philosophy.

### 15.4 Tuning of governor parameters

The hydro governor adjustable parameters are temporary droop and recovery time in the case of temporary droop type governor and PID gains in the case of PID governor. From the simulation study, it has been observed that the values provided for various hydro machines in the PSS/E data yield stable response. But whether the same values are in the field are to be checked. Some of the data like water inertia constant values are to be checked from the hydro power equipment manufacturers or the hydraulic network designers. In one case (Laxpana) it is found that water inertia constant provided by the Toshiba documentation is different than the value provided in the PSS/E dynamic data. It can be reasonably presumed that the rotor inertia constant values provided as part of generator data are correct.

In the report guidelines for tuning of the governor parameters are given as per the established norms and published literature.

### 15.5 Voltage Control

- **Dynamic Simulation:**

  The voltage control aspects of the CEB power system has been studied considering the total CEB power system data.  Disturbances like three phase faults have been simulated on typical 220 kV and 132 kV lines and the variations in voltages, power flows, and rotor angles at various buses have been studied by using PSS/E.

  All cases of rotor angle deviations exhibit stable responses for the studies performed. Though some transient oscillations are observed, system stability is not endangered.

- **AVR :**

  The effects of automatic voltage regulator (AVR) parameters like amplifier gain, stabilization loop gain etc., have been studied on the selected generator models using MATLAB - Simulink program. The effects of parameter changes in AVR have been studied.  The existing practice of Voltage Control has been reviewed through discussions with the policy making engineers of CEB and also by simulation study.

- **VAR Scheduling :**

The following studies are performed to analyze the issue of VAR Scheduling:

After observing the Base Case Voltage Control Element Status, the following options are considered for the study: Changing AVR set points; Tap change control; AVR Set - points and Tap Positions; Switched Shunt Controls; and with all controls.

Study of reactive power management is conducted with orientation towards VAR Scheduling for the combined operation of Generator AVR and Grid Transformer Tap-control (GTTC) and the suitability of present practice adopted has been checked and study to find adequacy of present strategy for future system is found satisfactory, using PSS/E software with the assistance of trained staff of CEB.

- **SVC:**

Even though SVC is existing on the base-case CEB System, it is found not effectively operational. Simulation studies are performed to obtain the effect of SVC at specific identified buses on Power Flows of CEB Systems corresponding to the Years 2012, 2016 and 2020 and the results are presented by displaying on the partial network. Improvement of reactive power flows in the neighbouring sections and voltages at buses nearer to the location of SVC are observed. It is recommended to identify the effective locations for installing SVCs for improving the system dynamic stability, using the procedure suggested here.

- **Effectiveness of PSS :**

Improvement in the damping of electromechanical oscillations can be obtained by using PSS. It is found from the study reported here that the proper location of PSS is important for it to be effective in damping the oscillations. Based on the proven philosophy suitable approaches are suggested for the selection of effective locations for installing Power System Stabilizer.
***Suggestion:*** CEB Power System Network-equivalent corresponding to the mesh-connected system (say, 220 KV and 132 KV buses, taking into account the effect of all radial feeders incident at the appropriate buses present in the meshed-network) may be obtained using PSS/E software module. Using the Linearized Dynamic Simulation module of PSS/E software, power system [A], [B] and [C] matrices may be obtained for the desired CEB System. Then, the Approach suggested here may be applied to identify effective locations for installing PSS, by ranking the effectiveness of PSS locations for improving the damping of selected modes of oscillations.

- **Voltage Stability :**

The methodology for maintaining voltage stability has been suggested based on research experience and published literature.

Appropriate MATLAB Tool Box modules may be applied to obtain PV and QV curves for Voltage Stability Analysis.

***Suggestion:*** Procedure indicated in PSS/E Manual can be applied using PSS/E software modules for Voltage Stability Analysis of CEB System.

- **CEB Power System for the Year – 2020 :**

  The simulation of the frequency control and voltage control aspects of expanded power system up to the Year 2020 has been carried out and analyzed. Similarly the effect of wind penetration on the power system operation has been studied and appropriate suggestions are indicated.

- **Data Validation :**

  The settings of automatic voltage regulators (AVR) provided with various generators as in the PSS/E dynamic data have been reviewed and these values do not need to be changed. But it was noticed that different types of AVRs are used in the power stations and the mathematical model does not reflect these differences in the AVR design. So it is recommended that the AVR and excitation system parameters provided at the power stations be checked by suitable tests and measurements.

- **Suggested Future Policy Recommendation :**

  Deregulation of the existing vertically integrated structure may be considered as a policy issue. The concept of Reactive Power as an 'ancillary service' with its own compensation and charges may be examined. The perspective is that CEB should aim to procure reactive power in a way that results in the most efficient investments in and dispatch of reactive power resources, including both generation and non – generation resources.

## 15.6 Wind penetration study

Detailed studies have been carried out on the permissible wind penetration levels based on the frequency and voltage considerations. The frequency drop for the trip of the connected wind turbine is the main limitation. With DFIG type wind turbine generators with power electronics controls, voltage stability is not a big problem. Considering the size of the CEB power system, it is recommended that wind generation may be limited to less than 10% of off-peak load. Though penetration levels of more than 20% are there in some power systems, the grid inertia is much more in those power systems than in Sri Lanka. Also CEB has to gain experience on the wind technologies before higher penetration levels are allowed.

## 15.7 Dispatch with higher penetration of renewable sources

Though at the level of 10% to 15% of renewable energy in the grid there is no problem of frequency control and voltage control, it is recommended to increase the operating reserve to meet any eventualities. For the power system beyond 2016, storage technologies using advance batteries and fly wheels can be considered as they are already being incorporated in western grids.

## 15.8 Software inadequacies

The PSS/E is a popular program among the utilities world- wide. For the studies involving load flows etc., it is quite convenient. The PSS/MUST and TPLAN programs offered by Siemens will be quite valuable for transmission planning and calculation of electric transmission transfer capabilities and the impact of transactions and generator dispatch. Hence it is recommended that CEB may procure PSS/MUST and TPLAN also. TPLAN provides for an easy, friendly but comprehensively-featured environment for testing deterministic reliability as in the (n-1) criterion, and others of this type such as (n-2) etc. PSS/TPLAN features easy configuration, detailed modeling of remedial action schemes, effective identification of voltage collapse conditions, and automatic handling of re-dispatch and load shedding requirements.

It is also suggested that CEB may procure Economic Despatch calculation software and PowerWorld Simulator software for the benefit of System Control and Operation engineers in taking quick informed decisions.

Additional model library required for the study of various types of wind turbines is recommended as part of PSS/E license. This will help the planners to analyze the interconnection requests received from the wind power plant operators thoroughly.

## 15.9 Training requirements

Presently there are only two engineers trained on PSS/E on limited aspects of power system planning. It is necessary to have 10 to 12 trained engineers trained on various aspects of power system studies using PSS/E and other well known programs. Prior to the training on PSS/E a general appreciation course covering the theoretical aspects of the power system analysis is necessary and a proposal has been given in the report.

It is also recommended to carry out tests at power stations and other sites to ascertain the control system parameters for tuning the same optimally. The PSS/E developers PTI-Siemens may be contacted for such practical tuning studies.

## 15.10 Tuning of the governor and AVR parameters at site

The droop value reflects the relationship between power and frequency. For old power stations this value may not be the real value as the relationships change due to wear and tear. It is better to do measurements at sites. The tuning parameters as in the dynamic data give stable response. Services of PSS/E software developers like Siemens may be entrusted with this task.

# Chapter 16

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# APPENDICES

## Appendix 1: Data used for the study

**BASE CASE STUDY – YEAR 2008 – THERMAL MAXIMUM NIGHT PEAK:** Generation Data

| Bus No | Bus Name | ID | Code | In Ser. | Pout | Pmax | Pmin | Qout | Qmax |
|---|---|---|---|---|---|---|---|---|---|
| 1100 | LAX-1 132.00 | 1 | -2 | 1 | 25.0 | 25.0 | 0 | 15.5 | 15.5 |
| 1100 | LAX-1 132.00 | 2 | -2 | 0 | 25.0 | 25.0 | 0 | 9.3 | 15.5 |
| 1110 | N-LAX-1 132.00 | 1 | -2 | 1 | 50.0 | 50.0 | 0 | 31.0 | 31.0 |
| 1110 | N-LAX-1 132.00 | 2 | -2 | 0 | 40.0 | 50.0 | 0 | 0.4 | 24.8 |
| 1120 | WIMAL-1 132.00 | 1 | -2 | 1 | 25.0 | 25.0 | 0 | 15.5 | 15.5 |
| 1120 | WIMAL-1 132.00 | 2 | -2 | 0 | 20.0 | 25.0 | 0 | 0.0 | 12.4 |
| 1130 | POLPI-1 132.00 | 1 | -2 | 1 | 37.5 | 37.5 | 0 | 23.2 | 23.2 |
| 1130 | POLPI-1 132.00 | 2 | -2 | 0 | 22.0 | 37.5 | 0 | 19.8 | 13.6 |
| 1140 | CANYO-1 132.00 | 1 | -2 | 1 | 30.0 | 30.0 | 0 | 0.0 | 18.6 |
| 1140 | CANYO-1 132.00 | 2 | -2 | 0 | 20.0 | 30.0 | 0 | 0.0 | 12.4 |
| 1170 | SAMAN-1 132.00 | 1 | -2 | 1 | 60.0 | 60.0 | 0 | 37.2 | 37.2 |
| 1170 | SAMAN-1 132.00 | 2 | -2 | 0 | 40.0 | 60.0 | 0 | 24.8 | 24.8 |
| 1200 | UKUWE-1 132.00 | 1 | -2 | 1 | 19.0 | 19.0 | 0 | 11.8 | 11.8 |
| 1200 | UKUWE-1 132.00 | 2 | -2 | 0 | 19.0 | 19.0 | 0 | 3.1 | 11.8 |
| 1210 | BOWAT-1 132.00 | 1 | -2 | 1 | 25.0 | 40.0 | 0 | 15.5 | 15.5 |
| 1300 | KELAN-1 132.00 | 1 | -2 | 1 | 16.0 | 16.0 | 0 | 0.0 | 9.9 |
| 1300 | KELAN-1 132.00 | 3 | -2 | 1 | 115.0 | 115.0 | 0 | 0.0 | 71.3 |
| 1310 | SAPUG-1P 132.00 | 1 | -2 | 1 | 32.0 | 36.0 | 0 | 0.0 | 19.8 |
| 1310 | SAPUG-1P 132.00 | 2 | -2 | 1 | 32.0 | 36.0 | 0 | 0.0 | 19.8 |
| 1310 | SAPUG-1P 132.00 | 3 | -2 | 1 | 72.0 | 72.0 | 0 | 0.0 | 44.6 |
| 1410 | KUKULE-1 132.00 | 1 | -2 | 1 | 35.0 | 35.0 | 0 | 0.0 | 21.7 |
| 1410 | KUKULE-1 132.00 | 2 | -2 | 1 | 35.0 | 35.0 | 0 | 0.0 | 21.7 |
| 1595 | KHD -1 132.00 | 1 | -2 | 1 | 51.0 | 51.0 | 0 | 0.0 | 31.6 |
| 1660 | EMBIL-1 132.00 | 1 | 2 | 1 | 100.0 | 100.0 | 0 | 7.1 | 62.0 |
| 1810 | PUTTA-1 132.00 | 1 | -2 | 1 | 100.0 | 100.0 | 0 | 0.0 | 62.0 |
| 2220 | KOTMA-2 220.00 | 1 | 2 | 1 | 45.0 | 67.0 | 0 | 18.5 | 27.9 |
| 2220 | KOTMA-2 220.00 | 2 | 2 | 1 | 45.0 | 67.0 | 0 | 18.5 | 27.9 |
| 2220 | KOTMA-2 220.00 | 3 | 2 | 1 | 45.0 | 67.0 | 0 | 18.5 | 27.9 |
| 2222 | BARGE-2 220.00 | 1 | -2 | 1 | 60.0 | 60.0 | 0 | 0.0 | 37.2 |
| 2230 | VICTO-2 220.00 | 1 | 3 | 1 | 176.8 | 210.0 | 0 | 24.3 | 109.6 |
| 2240 | RANDE-2 220.00 | 1 | -2 | 1 | 35.0 | 60.0 | 0 | 21.7 | 21.7 |
| 2240 | RANDE-2 220.00 | 2 | -2 | 1 | 35.0 | 60.0 | 0 | 21.7 | 21.7 |
| 2300 | KELAN-2 220.00 | 1 | 2 | 1 | 104.0 | 104.0 | 0 | 37.9 | 64.5 |
| 2300 | KELAN-2 220.00 | 2 | 2 | 1 | 61.0 | 61.0 | 0 | 22.2 | 37.8 |
| 2300 | KELAN-2 220.00 | 3 | 2 | 1 | 109.0 | 109.0 | 0 | 39.7 | 67.6 |
| 2300 | KELAN-2 220.00 | 4 | 2 | 1 | 54.0 | 54.0 | 0 | 19.7 | 33.5 |
| 2305 | KERAWALA_2 220.00 | 1 | 2 | 1 | 100.0 | 170.0 | 0 | 60.6 | 62.0 |
| 3120 | WIMAL-3 33.000 | 1 | -2 | 1 | 2.3 | 7.0 | 0 | 1.4 | 1.4 |
| 3200 | UKUWE-3 33.000 | 1 | 2 | 1 | 2.6 | 7.7 | 0 | 0.0 | 1.6 |
| 3250 | RANTE-3 33.000 | 1 | -2 | 1 | 0.0 | 1.0 | 0 | 0.0 | 0.0 |
| 3301 | KELAN-3A 33.000 | 1 | -2 | 1 | 45.0 | 48.0 | 0 | 0.0 | 27.9 |
| 3302 | KELAN-3B 33.000 | 1 | 2 | 1 | 30.0 | 32.0 | 0 | 2.2 | 18.6 |
| 3420 | HORANA_3 33.000 | 1 | 2 | 1 | 24.0 | 24.4 | 0 | 5.7 | 14.9 |
| 3510 | SITHA-33 33.000 | 1 | -2 | 1 | 4.1 | 12.3 | 0 | 0.0 | 2.5 |
| 3520 | NUWAR-3 33.000 | 1 | -2 | 1 | 4.1 | 12.2 | 0 | 2.5 | 2.5 |
| 3530 | THULH-3 33.000 | 1 | -2 | 1 | 4.7 | 14.0 | 0 | 2.9 | 2.9 |
| 3590 | SAPUG-3A 33.000 | 1 | -2 | 1 | 22.5 | 22.5 | 0 | 0.0 | 13.9 |
| 3620 | BADUL-3 33.000 | 1 | -2 | 1 | 4.3 | 12.9 | 0 | 2.7 | 2.7 |
| 3630 | BALAN-3 33.000 | 1 | 2 | 1 | 10.0 | 30.0 | 0 | 5.8 | 6.2 |
| 3640 | DENIY-3 33.000 | 1 | 2 | 1 | 4.0 | 12.0 | 0 | 1.0 | 2.5 |
| 3670 | MATARA-3 33.000 | 1 | -2 | 1 | 20.0 | 24.0 | 0 | 12.4 | 12.4 |
| 3740 | RATNAP-3 33.000 | 1 | -2 | 1 | 4.4 | 13.2 | 0 | 2.7 | 2.7 |
| 3770 | KIRIB-3 33.000 | 1 | -2 | 1 | 5.0 | 15.0 | 0 | 0.0 | 3.1 |
| 4251 | RANTE-G1 12.500 | 1 | 2 | 1 | 18.0 | 27.0 | 0 | 8.6 | 11.2 |
| 4252 | RANTE-G2 12.500 | 1 | 2 | 1 | 18.0 | 27.0 | 0 | 8.6 | 11.2 |
| **System Total** | | | | | **2138.3** | | | **573.8** | |

**Load Data**

| Bus No. | Bus Name | P | Q | P+dP | Q+qQ |
|---|---|---|---|---|---|
| 3120 | WIMAL-3 33.000 | 14.8 | 3.5 | 14.8 | 3.5 |
| 3121 | WIMAL-3B 33.000 | 7.1 | 1.7 | 7.1 | 1.7 |
| 3150 | AMPA-3 33.000 | 61.8 | 9.8 | 61.8 | 9.8 |
| 3160 | INGIN-3 33.000 | 0 | 0 | 0 | 0 |
| 3200 | UKUWE-3 33.000 | 37.2 | 14.8 | 37.2 | 14.8 |
| 3240 | VAVUN-33 33.000 | 12.5 | 1.5 | 12.5 | 1.5 |
| 3250 | RANTE-3 33.000 | 6.1 | 2.1 | 6.1 | 2.1 |
| 3301 | KELAN-3A 33.000 | 18.5 | 10.3 | 18.5 | 10.3 |
| 3302 | KELAN-3B 33.000 | 18.5 | 10.3 | 18.5 | 10.3 |
| 3400 | HAMBA-33 33.000 | 14 | 1.6 | 14 | 1.6 |
| 3420 | HORANA_3 33.000 | 33.4 | 16.1 | 33.4 | 16.1 |
| 3500 | KOSGA-3 33.000 | 46.4 | 17.8 | 46.4 | 17.8 |
| 3510 | SITHA-33 33.000 | 26 | 9.8 | 26 | 9.8 |
| 3520 | NUWAR-3 33.000 | 34.6 | 15.3 | 34.6 | 15.3 |
| 3530 | THULH-3 33.000 | 47.7 | 22.7 | 47.7 | 22.7 |
| 3540 | ORUWA-3 33.000 | 0 | 0 | 0 | 0 |
| 3550 | KOLON-3A 33.000 | 31.3 | 10.1 | 46.6 | 16.9 |
| 3551 | KOLON-3B 33.000 | 39.9 | 23.4 | 55.2 | 30.2 |
| 3560 | PANNI-3 33.000 | 38.5 | 20 | 38.5 | 20.0 |
| 3570 | BIYAG-3 33.000 | 82.2 | 37.3 | 101.3 | 45.8 |
| 3580 | KOTUG-3 33.000 | 108.3 | 62.2 | 123.6 | 69.0 |
| 3590 | SAPUG-3A 33.000 | 71.3 | 43.9 | 90.4 | 52.4 |
| 3600 | BOLAW-3 33.000 | 54.2 | 25.9 | 54.2 | 25.9 |
| 3620 | BADUL-3 33.000 | 48.9 | 11.5 | 48.9 | 11.5 |
| 3630 | BALAN-3 33.000 | 24.4 | 6.9 | 24.4 | 6.9 |
| 3640 | DENIY-3 33.000 | 28.7 | 7.5 | 28.7 | 7.5 |
| 3650 | GALLE-3 33.000 | 61.5 | 46.4 | 61.5 | 46.4 |
| 3660 | EMBIL-3 33.000 | 24 | 10.2 | 24 | 10.2 |
| 3670 | MATARA-3 33.000 | 54.8 | 19.6 | 54.8 | 19.6 |
| 3680 | KURUN-3 33.000 | 47.7 | 14.9 | 47.7 | 14.9 |
| 3690 | HABAR-3 33.000 | 52.2 | 14.2 | 52.2 | 14.2 |
| 3700 | ANURA-3A 33.000 | 15.2 | 2.9 | 15.2 | 2.9 |
| 3701 | ANURA-3B 33.000 | 9.7 | 1.8 | 9.7 | 1.8 |
| 3705 | NEWANU-3 33.000 | 20.8 | 4.1 | 20.8 | 4.1 |
| 3710 | TRINC-3 33.000 | 35.7 | 14.2 | 35.7 | 14.2 |
| 3740 | RATNAP-3 33.000 | 26.6 | 11 | 26.6 | 11 |
| 3770 | KIRIB-3 33.000 | 70.2 | 27.9 | 70.2 | 27.9 |
| 3780 | VALACH_3 33.000 | 30.1 | 8 | 30.1 | 8 |
| 3790 | RATMA-3A 33.000 | 54 | 27.8 | 54 | 27.8 |
| 3800 | MATUG-3 33.000 | 54.7 | 26.4 | 54.7 | 26.4 |
| 3810 | PUTTA-3 33.000 | 33.9 | 10.1 | 33.9 | 10.1 |
| 3820 | ATURU-3 33.000 | 17.1 | 11 | 17.1 | 11 |
| 3830 | VEYAN-33 33.000 | 46.4 | 22.4 | 61.7 | 29.2 |
| 3840 | JPURA_3 33.000 | 51.2 | 30.5 | 51.2 | 30.5 |
| 3850 | PANAD-3 33.000 | 55 | 30.1 | 55.0 | 30.1 |
| 3860 | MADAM-3 33.000 | 48.8 | 24.9 | 48.8 | 24.9 |
| 3870 | K-NIYA-3 33.000 | 18.2 | 10.3 | 27.8 | 14.5 |
| 3880 | AMBALA 33.000 | 20.5 | 5.7 | 20.5 | 5.7 |
| 3890 | DEHIW_3 33.000 | 32.6 | 17.5 | 51.7 | 26.0 |
| 3900 | PANNAL 33.000 | 14.9 | 6.4 | 43.6 | 19.1 |
| 3910 | ANIYA 33.000 | 20.5 | 9.1 | 51.1 | 22.6 |
| 4430 | COL_I_11 11.000 | 11.9 | 6.2 | 11.9 | 6.2 |
| 4435 | COL_A_11 11.000 | 17.6 | 8.9 | 17.6 | 8.9 |
| 4750 | COL_E-11 11.000 | 30.8 | 22.4 | 30.8 | 22.4 |
| 4760 | COL_F-11 11.000 | 27.1 | 15.2 | 27.1 | 15.2 |
| **System Total** | | **1910.0** | **846.1** | **2097.2** | **929.0** |

**Dynamic Data**

| | | | R (speed droop) | T1 (>0) (sec) | T2 (>0) (sec) | T3 (>0) (sec) | Ambient temperature load limit, AT | KT | VMAX | VMIN | Dturb | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1300 | 'GAST' | 1 | 0.05 | 0.4 | 0.1 | 3 | 1 | 2 | 0.95 | -0.05 | 0 | / | | | |
| 1300 | 'GAST' | 3 | 0.05 | 0.4 | 0.1 | 3 | 1 | 2 | 0.95 | -0.05 | 0 | / | | | |
| | | | R, permanent droop | r, temporary droop | Tr (>0) governor time constant | Tf (>0) filter time constant | Tg (>0) servo time constant | VELM, gate velocity limit | GMAX, maximum gate limit | GMIN, minimum gate limit | TW (>0) water time constant | At, turbine gain | Dturb, turbine damping | qNL, no load flow | |
| 1100 | 'HYGOV' | 1 | 0.05 | 0.3 | 5.2 | 0.05 | 0.5 | 0.2 | 0.95 | 0 | 1.3 | 1.1 | 0.5 | 0.08 | / |
| 1100 | 'HYGOV' | 2 | 0.05 | 0.3 | 5.2 | 0.05 | 0.5 | 0.2 | 0.95 | 0 | 1.3 | 1.1 | 0.5 | 0.08 | / |
| 1110 | 'HYGOV' | 1 | 0.05 | 0.3 | 5.2 | 0.05 | 0.5 | 0.2 | 0.95 | 0 | 1.3 | 1.1 | 0.5 | 0.08 | / |
| 1110 | 'HYGOV' | 2 | 0.05 | 0.3 | 5.2 | 0.05 | 0.5 | 0.2 | 0.95 | 0 | 1.3 | 1.1 | 0.5 | 0.08 | / |
| 1120 | 'HYGOV' | 1 | 0.05 | 0.43 | 5.2 | 0.05 | 0.5 | 0.2 | 1 | 0 | 1.3 | 1.1 | 0.5 | 0.08 | / |
| 1120 | 'HYGOV' | 2 | 0.05 | 0.43 | 5.2 | 0.05 | 0.5 | 0.2 | 1 | 0 | 1.3 | 1.1 | 0.5 | 0.08 | / |
| 1130 | 'HYGOV' | 1 | 0.05 | 0.43 | 5.2 | 0.05 | 0.5 | 0.2 | 0.95 | 0 | 1.3 | 1.1 | 0.5 | 0.08 | / |
| 1130 | 'HYGOV' | 2 | 0.05 | 0.43 | 5.2 | 0.05 | 0.5 | 0.2 | 0.95 | 0 | 1.3 | 1.1 | 0.5 | 0.08 | / |
| 1140 | 'HYGOV' | 1 | 0.05 | 0.43 | 5.2 | 0.05 | 0.5 | 0.2 | 1 | 0 | 1.3 | 1.1 | 0.5 | 0.08 | / |
| 1140 | 'HYGOV' | 2 | 0.05 | 0.43 | 5.2 | 0.05 | 0.5 | 0.2 | 1 | 0 | 1.3 | 1.1 | 0.5 | 0.08 | / |
| 1210 | 'HYGOV' | 1 | 0.05 | 0.43 | 5.2 | 0.05 | 0.5 | 0.2 | 1 | 0 | 1.3 | 1.1 | 0.5 | 0.08 | / |
| 1410 | 'HYGOV' | 1 | 0.05 | 0.46 | 8 | 0.05 | 0.5 | 0.2 | 1 | 0 | 1.3 | 1.1 | 0.5 | 0.08 | / |
| 1410 | 'HYGOV' | 2 | 0.05 | 0.46 | 8 | 0.05 | 0.5 | 0.2 | 1 | 0 | 1.3 | 1.1 | 0.5 | 0.08 | / |
| 2230 | 'HYGOV' | 1 | 0.05 | 0.3 | 5.2 | 0.05 | 0.5 | 0.2 | 0.95 | 0 | 1.3 | 1.1 | 0.5 | 0.08 | / |
| 2240 | 'HYGOV' | 1 | 0.05 | 0.3 | 5.2 | 0.05 | 0.5 | 0.2 | 0.95 | 0 | 1.3 | 1.1 | 0.5 | 0.08 | / |
| 2240 | 'HYGOV' | 2 | 0.05 | 0.3 | 5.2 | 0.05 | 0.5 | 0.2 | 0.95 | 0 | 1.3 | 1.1 | 0.5 | 0.08 | / |
| 4251 | 'HYGOV' | 1 | 0.05 | 0.43 | 5.2 | 0.05 | 0.5 | 0.2 | 0.95 | 0 | 1.3 | 1.1 | 0.5 | 0.08 | / |

| | | | TA/TB | TB (>0) (sec) | K | TE (sec) | EMIN (pu on EFD base) | EMAX (pu on EFD base) |
|---|---|---|---|---|---|---|---|---|
| 1410 | 'SCRX' | 1 | 0.1 | 10 | 200 | 0.05 | 0 | 4.5 |
| 1410 | 'SCRX' | 2 | 0.1 | 10 | 200 | 0.05 | 0 | 4.5 |
| | | | **TA/TB** | **TB (>0) (sec)** | **K** | **TE (sec)** | **EMIN (pu on EFD base)** | **EMAX (pu on EFD base)** |
| 1100 | 'SEXS' | 1 | 0.1 | 10 | 300 | 0.05 | 0 | 3 |
| 1100 | 'SEXS' | 2 | 0.1 | 10 | 300 | 0.05 | 0 | 3 |
| 1110 | 'SEXS' | 1 | 0.1 | 10 | 300 | 0.05 | 0 | 3 |
| 1110 | 'SEXS' | 2 | 0.1 | 10 | 300 | 0.05 | 0 | 3 |
| 1120 | 'SEXS' | 1 | 0.1 | 10 | 300 | 0.05 | 0 | 3 |
| 1120 | 'SEXS' | 2 | 0.1 | 10 | 300 | 0.05 | 0 | 3 |
| 1130 | 'SEXS' | 1 | 0.1 | 10 | 300 | 0.05 | 0 | 3 |
| 1130 | 'SEXS' | 2 | 0.1 | 10 | 300 | 0.05 | 0 | 3 |
| 1140 | 'SEXS' | 1 | 0.1 | 10 | 300 | 0.05 | 0 | 3 |
| 1140 | 'SEXS' | 2 | 0.1 | 10 | 300 | 0.05 | 0 | 3 |
| 1210 | 'SEXS' | 1 | 0.1 | 10 | 300 | 0.05 | 0 | 3 |
| 1300 | 'SEXS' | 1 | 0.1 | 10 | 300 | 0.05 | 0 | 3.25 |
| 1300 | 'SEXS' | 3 | 0.1 | 10 | 300 | 0.05 | 0 | 3 |
| 1310 | 'SEXS' | 1 | 0.1 | 10 | 300 | 0.05 | 0 | 5 |
| 1310 | 'SEXS' | 2 | 0.1 | 10 | 300 | 0.05 | 0 | 9 |
| 1310 | 'SEXS' | 3 | 0.1 | 10 | 300 | 0.05 | 0 | 9 |
| 2230 | 'SEXS' | 1 | 0.1 | 10 | 300 | 0.05 | 0 | 3 |
| 2240 | 'SEXS' | 1 | 0.1 | 10 | 300 | 0.05 | 0 | 3 |
| 2240 | 'SEXS' | 2 | 0.1 | 10 | 300 | 0.05 | 0 | 3 |
| 2300 | 'SEXS' | 1 | 0.1 | 10 | 200 | 0.05 | 0 | 3 |
| 2300 | 'SEXS' | 2 | 0.1 | 10 | 200 | 0.05 | 0 | 3 |
| 2300 | 'SEXS' | 3 | 0.1 | 10 | 200 | 0.05 | 0 | 3 |
| 2300 | 'SEXS' | 4 | 0.1 | 10 | 200 | 0.05 | 0 | 3 |
| 3590 | 'SEXS' | 1 | 0.1 | 10 | 300 | 0.05 | 0 | 6 |
| | | | **TA/TB** | **TB (>0) (sec)** | **K** | **TE (sec)** | **EMIN (pu on EFD base)** | **EMAX (pu on EFD base)** |
| 4252 | 'SEXS' | 1 | 0.1 | 10 | 300 | 0.05 | 0 | 3 |
| 2222 | 'SEXS' | 1 | 0.1 | 10 | 100 | 0.05 | 0 | 4 |

| | | | R | T1 (>0) (sec) | VMAX | VMIN | T2 (sec) | T3 (>0) (sec) | Dt | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3590 | 'TGOV1' | 1 | 0.05 | 0.5 | 0.85 | 0.3 | 1 | 1 | 0 | / | | | |
| | | | T'do (>0) (sec) | T"do (>0) (sec) | T'qo (>0) (sec) | T"qo (>0) (sec) | Inertia, H | Speed damping, D | Xd | Xq | X'd | X'q | X"d = X"q | Xl |
| 1300 | 'GENROU' | 1 | 6.97 | 0.03 | 1.09 | 0.16 | 4.5 | 0.5 | 1.79 | 1.72 | 0.23 | 1.2 | 0.147 | 0.1 |
| 1300 | 'GENROU' | 3 | 6.85 | 0.032 | 1 | 0.16 | 4.5 | 0.5 | 1.75 | 1.72 | 0.27 | 1.31 | 0.179 | 0.1 |
| 2300 | 'GENROU' | 1 | 6.85 | 0.032 | 1 | 0.16 | 4 | 0.5 | 1.75 | 1.68 | 0.2262 | 0.437 | 0.163 | 0.0875 |
| 2300 | 'GENROU' | 2 | 6.85 | 0.032 | 1 | 0.16 | 4 | 0.5 | 1.75 | 1.68 | 0.2262 | 0.437 | 0.153 | 0.0875 |
| 2300 | 'GENROU' | 3 | 6.85 | 0.032 | 1 | 0.16 | 4 | 0.5 | 1.75 | 1.68 | 0.2262 | 0.437 | 0.163 | 0.0875 |
| 2300 | 'GENROU' | 4 | 6.85 | 0.032 | 1 | 0.16 | 4 | 0.5 | 1.75 | 1.68 | 0.2262 | 0.437 | 0.153 | 0.0875 |
| 3301 | 'GENROU' | 1 | 6.97 | 0.029 | 1.09 | 0.15 | 4.5 | 0.5 | 1.79 | 1.72 | 0.23 | 1.2 | 0.147 | 0.1 |
| 3302 | 'GENROU' | 1 | 6.97 | 0.029 | 1.09 | 0.15 | 4.5 | 0.5 | 1.79 | 1.72 | 0.23 | 1.2 | 0.149 | 0.1 |
| 1810 | 'GENROU' | 1 | 6.64 | 0.049 | 1.18 | 0.066 | 8 | 0.5 | 1.81 | 1.77 | 0.259 | 0.344 | 0.237 | 0.1 |
| | | | T'do (>0) (sec) | T"do (>0) (sec) | T"qo (>0) (sec) | Inertia, H | Speed damping, D | Xd | Xq | X'd | X"d = X"q | Xl | S(1.0) | S(1.2) |
| 1100 | 'GENSAL' | 1 | 5.2 | 0.068 | 0.12 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.16 | 0.1 | 0.03 | 0.25 |
| 1100 | 'GENSAL' | 2 | 5.2 | 0.068 | 0.12 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.21 | 0.1 | 0.03 | 0.25 |
| 1110 | 'GENSAL' | 1 | 6.7 | 0.056 | 0.12 | 4.3 | 0.5 | 1.03 | 0.63 | 0.29 | 0.15 | 0.1 | 0.03 | 0.25 |
| 1110 | 'GENSAL' | 2 | 6.7 | 0.056 | 0.12 | 4.3 | 0.5 | 1.03 | 0.63 | 0.29 | 0.15 | 0.1 | 0.03 | 0.25 |
| 1120 | 'GENSAL' | 1 | 5.2 | 0.074 | 0.13 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.147 | 0.1 | 0.03 | 0.25 |
| 1120 | 'GENSAL' | 2 | 5.2 | 0.074 | 0.13 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.147 | 0.1 | 0.03 | 0.25 |
| 1130 | 'GENSAL' | 1 | 5.2 | 0.084 | 0.15 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.156 | 0.1 | 0.03 | 0.25 |
| 1130 | 'GENSAL' | 2 | 5.2 | 0.084 | 0.15 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.156 | 0.1 | 0.03 | 0.25 |
| 1140 | 'GENSAL' | 1 | 5.2 | 0.06 | 0.11 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.18 | 0.1 | 0.03 | 0.25 |
| 1140 | 'GENSAL' | 2 | 5.2 | 0.06 | 0.11 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.18 | 0.1 | 0.03 | 0.25 |
| 1170 | 'GENSAL' | 1 | 6.7 | 0.07 | 0.15 | 4.3 | 0.5 | 1.03 | 0.63 | 0.29 | 0.135 | 0.1 | 0.03 | 0.25 |
| 1170 | 'GENSAL' | 2 | 6.7 | 0.07 | 0.15 | 4.3 | 0.5 | 1.03 | 0.63 | 0.29 | 0.135 | 0.1 | 0.03 | 0.25 |
| 1200 | 'GENSAL' | 1 | 5.2 | 0.061 | 0.11 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.22 | 0.1 | 0.03 | 0.25 |
| 1200 | 'GENSAL' | 2 | 5.2 | 0.061 | 0.11 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.22 | 0.1 | 0.03 | 0.25 |
| 1210 | 'GENSAL' | 1 | 5.2 | 0.073 | 0.13 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.148 | 0.1 | 0.03 | 0.25 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1310 | 'GENSAL' | 1 | 4.3 | 0.05 | 0.2 | 3.2 | 0 | 1.98 | 1.9 | 0.31 | 0.21 | 0.099 | 0.1 | 0.3 |
| 1310 | 'GENSAL' | 2 | 4.3 | 0.05 | 0.19 | 3.2 | 0 | 1.98 | 1.9 | 0.31 | 0.21 | 0.099 | 0.1 | 0.3 |
| 1310 | 'GENSAL' | 3 | 4.3 | 0.05 | 0.19 | 3.2 | 0 | 1.98 | 1.9 | 0.31 | 0.21 | 0.099 | 0.1 | 0.3 |
| 1410 | 'GENSAL' | 1 | 5 | 0.05 | 0.11 | 2.84 | 0 | 1.12 | 0.84 | 0.23 | 0.2 | 0.112 | 0.19 | 0.7 |
| 1410 | 'GENSAL' | 2 | 5 | 0.05 | 0.11 | 2.84 | 0 | 1.12 | 0.84 | 0.23 | 0.2 | 0.112 | 0.19 | 0.7 |
| 2220 | 'GENSAL' | 1 | 6.7 | 0.049 | 0.11 | 4.3 | 0.5 | 1.03 | 0.63 | 0.29 | 0.17 | 0.1 | 0.03 | 0.25 |
| 2220 | 'GENSAL' | 2 | 6.7 | 0.049 | 0.11 | 4.3 | 0.5 | 1.03 | 0.63 | 0.29 | 0.17 | 0.1 | 0.03 | 0.25 |
| 2220 | 'GENSAL' | 3 | 6.7 | 0.049 | 0.11 | 4.3 | 0.5 | 1.03 | 0.63 | 0.29 | 0.17 | 0.1 | 0.03 | 0.25 |
| 2230 | 'GENSAL' | 1 | 6.7 | 0.051 | 0.11 | 4.3 | 0.5 | 1.03 | 0.63 | 0.29 | 0.165 | 0.1 | 0.03 | 0.25 |
| 2240 | 'GENSAL' | 1 | 6.7 | 0.04 | 0.088 | 4.3 | 0.5 | 1.03 | 0.63 | 0.29 | 0.185 | 0.1 | 0.03 | 0.25 |
| 2240 | 'GENSAL' | 2 | 6.7 | 0.04 | 0.088 | 4.3 | 0.5 | 1.03 | 0.63 | 0.29 | 0.185 | 0.1 | 0.03 | 0.25 |
| 3120 | 'GENSAL' | 1 | 5.2 | 0.059 | 0.1 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.185 | 0.1 | 0.03 | 0.25 |
| 3200 | 'GENSAL' | 1 | 5.2 | 0.059 | 0.1 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.185 | 0.1 | 0.03 | 0.25 |
| 3250 | 'GENSAL' | 1 | 5.2 | 0.059 | 0.1 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.185 | 0.1 | 0.03 | 0.25 |
| 3420 | 'GENSAL' | 1 | 3.8 | 0.027 | 0.09 | 0.83 | 0.5 | 2.34 | 1.13 | 0.381 | 0.258 | 0.1 | 0.093 | 0.242 |
| 3510 | 'GENSAL' | 1 | 5.2 | 0.059 | 0.1 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.185 | 0.1 | 0.03 | 0.25 |
| 3520 | 'GENSAL' | 1 | 5.2 | 0.059 | 0.1 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.185 | 0.1 | 0.03 | 0.25 |
| 3530 | 'GENSAL' | 1 | 5.2 | 0.059 | 0.1 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.185 | 0.1 | 0.03 | 0.25 |
| 3590 | 'GENSAL' | 1 | 3.6 | 0.021 | 0.09 | 0.53 | 0 | 2.2 | 1.06 | 0.358 | 0.241 | 0.1 | 0.093 | 0.242 |
| 3620 | 'GENSAL' | 1 | 5.2 | 0.059 | 0.1 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.185 | 0.1 | 0.03 | 0.25 |
| 3630 | 'GENSAL' | 1 | 5.2 | 0.059 | 0.1 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.185 | 0.1 | 0.03 | 0.25 |
| 3640 | 'GENSAL' | 1 | 5.2 | 0.059 | 0.1 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.185 | 0.1 | 0.03 | 0.25 |
| 3670 | 'GENSAL' | 1 | 3.6 | 0.021 | 0.09 | 0.53 | 0 | 2.2 | 1.06 | 0.358 | 0.262 | 0.1 | 0.093 | 0.242 |
| 3740 | 'GENSAL' | 1 | 5.2 | 0.059 | 0.1 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.185 | 0.1 | 0.03 | 0.25 |
| 3770 | 'GENSAL' | 1 | 5.2 | 0.059 | 0.1 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.185 | 0.1 | 0.03 | 0.25 |
| 4251 | 'GENSAL' | 1 | 5.2 | 0.059 | 0.1 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.185 | 0.1 | 0.03 | 0.25 |
| 4252 | 'GENSAL' | 1 | 5.2 | 0.059 | 0.1 | 3 | 0.5 | 1.1 | 0.66 | 0.32 | 0.185 | 0.1 | 0.03 | 0.25 |
| 1595 | 'GENSAL' | 1 | 5.5 | 0.049 | 0.14 | 1 | 0.5 | 2.38 | 1.51 | 0.44 | 0.23 | 0.1 | 0.03 | 0.25 |
| 1660 | 'GENSAL' | 1 | 3.6 | 0.033 | 0.06 | 7.704 | 0.5 | 1.77 | 0.88 | 0.48 | 0.16 | 0.15 | 0.1 | 0.3 |
| 2222 | 'GENSAL' | 1 | 4.9 | 0.056 | 0.1 | 1.62 | 0.1 | 1.35 | 0.77 | 0.39 | 0.29 | 0.18 | 0.111 | 0.436 |

# Appendix 2

**Activities on 'Voltage control study'**

1. Familiarization of CEB power system
2. Familiarization of PSS/E Software
3. Identifying study system of CEB and components: present and planned for 2020
4. Review of data collected/ compiled by CEB on individual generators, AVRs, transformers, PSS etc., and system-wide data
5. Assumption of values for missing data
6. Identification of PSS/E modules required for voltage control study
7. Simulation study of individual AVR, PSS (if any) control loops of generators
8. Recommendations on the tuning of AVR settings and Grid transformer Tap changers (to be completed)
9. Study of automatic voltage control strategies and VAR scheduling (to be completed)
10. Preparing modeling frame- work for voltage control study
11. Identifying PSS/E modules for simulation of voltage control of present system
12. Development of required modeling of components to incorporate in studies using PSS/E
13. Preliminary simulation using Matlab/ Simulink or any other suitable software for individual generator control systems (where required)
14. Preliminary simulation using Matlab/ Simulink or any other suitable software for power system voltage control on sample system
15. Preparation of interim simulation and analysis report
16. Simulation of power system voltage control using PSS/E with CEB assistance
17. Recommendations on voltage control strategies for the current system
18. Simulation of power system voltage control of 2020 system using PSS/E with CEB assistance
19. Recommendations on voltage control strategies for the proposed system
20. Recommendations on the PSS to be introduced in Excitation systems of Generators
21. Review of software adequacies and suggestion for improvements/ enhancements
22. Preparation of final simulation report giving model details, recommendations on current system and future system
23. Recommendations on the scope for additional studies desired to be performed in future on CEB system

**Frequency Control Study Activities**

1. Familiarization of CEB power system
2. Familiarization of PSS/E
3. Identifying study system and components: present and planned for 2020
4. Review of data collected/ compiled by CEB on individual turbine governors, system-wide data
5. Assumption of missing data
6. Study of identifying modules required for frequency study
7. Study of individual governor control loops for hydro, thermal, combined cycle gas turbine and diesel machine Frequency Control Study Activities
8. Recommendations on the tuning of governor settings
9. Study of automatic frequency control mechanism
10. Preparing modeling frame work for frequency control
11. Identifying PSS/E modules for simulation of load frequency control of present system
12. Development of required modeling components to incorporate in PSS/E
13. Preliminary simulation using Matlab/ Simulink for individual governing systems (where required)
14. Preliminary simulation using Matlab/ Simulink for power system load frequency control
15. Preparation of interim simulation and analysis report
16. Simulation of power system load frequency control using PSS/E with CEB assistance
17. Recommendations on frequency control strategies for the current system
18. Simulation of power system load frequency control of 2020 system using PSS/E with CEB assistance
19. Study of the influence of non- centrally dispatched units on frequency regulation using Matlab/ Simulink
20. Simulation of frequency control with non-centrally dispatched units with CEB assistance
21. Recommendations on frequency control strategies for the proposed system
22. Review of software adequacies and suggestion for improvements/ enhancements
23. Preparation of final simulation report giving model details, recommendations on current system and future system

# Appendix 3

Various Power System training modules that can be considered for long term training are listed below based on the experience of GECE consultants.

1. Basic modeling aspects of power system components and sub-systems
2. Synchronous machine representation
3. Generator capability curve
4. Automatic voltage regulator (AVR)
5. Grid transformer with tap change control (GTTC)
6. Static VAR compensator system (SVC)
7. Power system stabilizer (PSS)
8. Hydro turbine and its governing system
9. Steam turbine and its governing system
10. Diesel engine governing system
11. Gas turbine and its control system
12. Wind turbine control system
13. Load representation
14. Transmission line representation
15. Network representation
16. Load frequency control system
17. Reactive power control system
18. Load Flow Analysis
19. Contingency Analysis
20. Transient stability analysis
21. Dynamic stability analysis including eigenvalue analysis (small signal stability analysis).
22. Voltage Stability Analysis.
23. Simulation using Matlab/ Simulink
24. Description of components included in Energy management system like, state estimation(SE), security analysis (SA), Automatic Generation Control (AGC) which includes load frequency control (LFC) and economic dispatch (ED) and Reactive Power Management (RPM).
25. General control system analysis techniques and tuning methodologies.
26. HVDC system studies
27. Study of embedded generation
28. Protection systems

29. Optimal Power Flow
30. Harmonics and Power Quality Studies
31. Switching Transient Studies
32. Smart Electric grids
33. Power System operation and electricity trading.

**PA Government Services Inc.**
DLF Cyber City
Building No. 9B, 11th Floor
Gurgaon - 122 002
Haryana, India.
Tel: +91 124 4737400
Fax: +91 124 4737444
**www.paconsulting.com**