DETERMINATION OF MAXIMUM POSSIBLE LOADING CAPACITY OF A SINGLE GENERATOR UNIT: A CASE STUDY FOR THE PRESENT SRI LANKAN POWER SYSTEM

Rathuge Sasanka Ranjitha

(139582H)

Degree of Master of Science

Department of Electrical Engineering

University of Moratuwa
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RATHUGE SASANKA RANJITHA

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Thesis submitted in partial fulfillment of the requirements for the degree Master of Science in Electrical Installations

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Declaration

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(Dr. W.D.A.S. Rodrigo)

Abstract

Present Sri Lankan power system consists of a rich energy mix and a vast diversity within all over the island, out of which hydro power generation is predominant. Even though hydro power generation is predominant and has least operational cost, the emerging consumer demand growth cannot be catered by hydro power generation only. In addition to hydro power, nearly 50% of country's energy demand is fulfilled by three number of coal power plants which are considered as largest capacity low cost thermal power plants in the country and are operated in base load basis.

Even though these large scale coal power plants are very much cost effective and have large net output power capacity, considering the system reliability, they cannot be dispatched in full load manner during certain demand conditions and different dispatch conditions which are currently practiced by Ceylon Electricity Board, which is the country's main power utility which has the authority to large scale electricity generation, transmission and distribution. The reason is when such a large generator gets tripped, the frequency stability and voltage stability would be highly vulnerable for resulting the system collapsing due to such large generation rejection from the system.

Recently the national power network has experienced several failures due to tripping of such large generators during certain demand condition under different dispatch conditions. Hence, it has become a challenging decision to determine the loading capacity of the large generators when it comes to system operations.

A model has been implemented with PSS/E software and has been validated with actual system incidents considering latest power system parameters. This validated model has been used for simulating generation rejections according to the appropriate generation percentages during all the dispatch scenarios considering worst case demand conditions. This study evaluates the capacity percentage range of the maximum loading capacity of single generator unit considering both frequency stability and voltage stability, compromising both power system operational cost and power system reliability as a case study which is carried out considering the parameters of operational guide lines of present Sri Lankan national power system.

Dedication

I dedicate this thesis to my beloved parents, who have guided and motivated me unconditionally to reach my best.

To all supporters who have encouraged me in various ways for achieving this life milestone.

Acknowledgements

First, I pay my sincere gratitude to Dr. Asanka Rodrigo who encouraged me and guided me to develop this research idea and journey so far up to preparation of final thesis.

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LIST OF ABBREVIATIONS

Abbreviation	**Description**
CEB	Ceylon Electricity Board
LECO	Lanka Electricity Company
GSS	Grid Sub Station
NCRE	Non Conventional Renewable Energy
LVPS	Lakvijaya Power Station
PSS/E	Power System Simulator for Engineers
KCCP	Kelanitissa Combined Cycle Plant
WCP	West Coast Plant
GT	Gas Turbine
Gen	Generator
T/F	Transformer
SCC	System Control Centre
PS	Power Station
UFLS	Under Frequency Load Shedding
SCADA	Supervisory Control And Data Acquisition
DFR	Digital Fault Recorder
IPP	Independent Power Producers

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Chapter 1

BACKGROUND

1.1 Introduction

Sri Lankan national power system is an islanding power system, which has a vast diversity of energy mix. Since the island is rich of natural water recourse, which is enriched by two tropical monsoons the hydropower generation is predominant. The present energy mix of the country consists of hydropower (large hydro and mini hydro), petroleum fuels, coal fuel, wind, solar, biomass and dendro.

At present, Sri Lankan power system consists of the total installed generation capacity of 4018MW including renewable energy sources at the end of the year 2016 [1]. Among them, the maximum capacity of a single generator unit is 300MW (gross output capacity) at Lakvijaya Coal Power Plant which has total installed capacity of 900MW. Renewable energy sources include mini hydro plants of 342MW and wind power plant of 128MW, which are owned and operated by private power sector [1]. Recorded day peak is around 2100MW and the recorded night peak is 2453MW at the end of the year 2016 [1]. Frequency control operation is done by one particular power station at a time, therefore it operates at lower governor droop setting (ep1-1.6% to 2.8%) and other machines operate at higher droop settings on free governor mode (ep2-4% to 8%). Allowable frequency deviation in Sri Lanka is specified, as +/- 1% of the 50Hz at the normal operational mode according to the Grid Code [2]. The minimum allowable system spinning reserve is 5% of total system generation. The maximum loading capacity of a single generator unit is 30%. The transmission network of the national power system is operated at 132kV and 220kV high voltages by the transmission licensee of CEB, with the maximum allowable voltage variation range of +/- 5% at the normal operational mode according to the Grid Code [2]. CEB-System Control Centre adheres to the above accords during carrying out the power system operations in such a way the utility maintains a healthy power system. CEB and LECO are the main utilities, which have the authority to distribute the electricity energy through 33kV and 11kV at medium voltage level, and 400V at low voltage level.

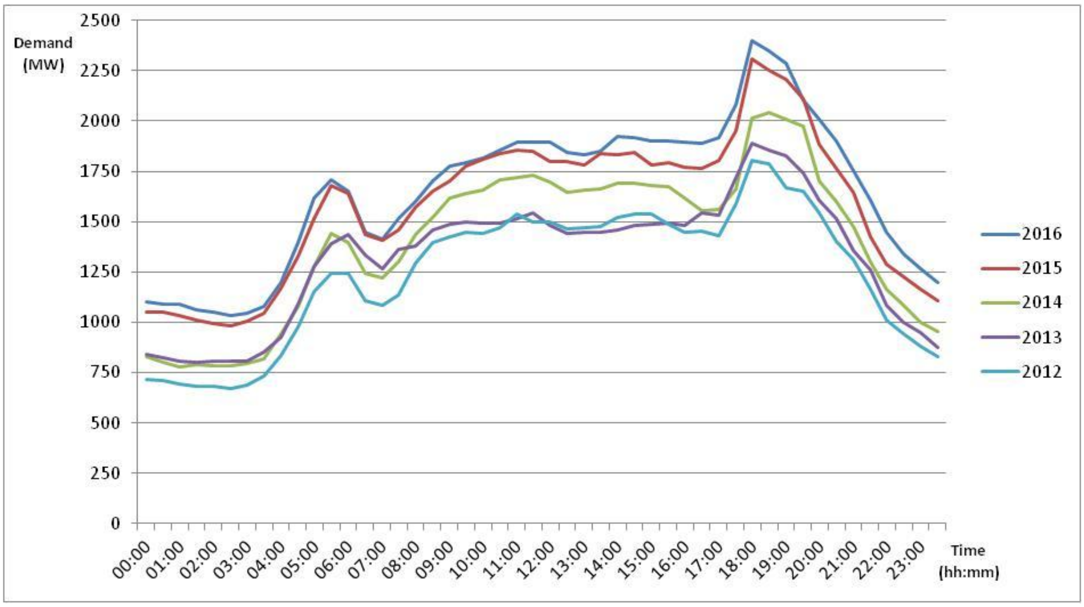


Figure 1.1: Average demand of a typical day variation of five years (2012 to 2016)

Even though the CEB generation sources are predominant by the hydro generation and petroleum fuel generation, the emerging demand growth cannot be fulfilled only through those resources. Even though the NCRE target is 20% from the total system generation at the year of 2020, it will not be sufficient to cater the demand growth.

The graph 1.1 depicts the average demand variation of a typical day, within 05 years from 2012 to 2016. At 2016 According to the above graph, the day peak which occurs around at 11:30hrs has increased around 400MW and the night peak which occurs around at 19:00hrs has increased around 600MW over the period of five years. (i.e. from 2012 to 2016).

In order to cater this significant demand growth, a scheme of 03 numbers of coal power plants which have 300MW each of gross generation (the largest electrical power generation scheme of Sri Lanka) were commissioned at Norochcholei in Puttalam district. The plant was named as Lakvijaya Power Station (which is known as LVPS) & was commissioned in the basis of 03 phases, out of which phase (I) was commissioned at 2011 March, phase (II) was commissioned at 2014 January and phase (III) was commissioned on 2014 September. At present, all 03 units contribute total gross generation of 900MW to the national power system as the least cost thermal power scheme.

1.2 Issues regarding the loading percentage of large capacity generators

Even though LVPS is the electrical generation scheme which has the largest capacity & is operated as the least unit cost thermal power plant within the generation mix of the national power system, there are restrictions which the each LVPS generator cannot be dispatched in full load manner. Because, tripping of such a large capacity power plant at light load conditions or off peak conditions would significantly affect to the power system stability. Therefore, it cannot be dispatched at it’s full load capacity at every time throughout the year even the scheme was initially designed as a full load running base load power plant.

Loading LVPS at it’s full load is very much cost effective when it comes to power system operation cost since LVPS is run by low cost coal fuel. Even though, in order to maintain system reliability at a tripping incident of such large machine affects the power system adversely. Therefore, considering both power system operation economy and power system reliability, there has to be a compromisation between these two factors.

The power system studies which had been carried out at the time when all three phases of LVPS were commissioned, with the proposed transmission network and the UFLS scheme, proved that the value of maximum loading capacity of a single generator unit could be enhanced up to 30%. Hence the CEB system control center used this value as 30%. Nevertheless, with occurrence of some generator tripping incidents and practical operational issues, the system operators have understood this value would be somewhat below the empirical value, which was obtained through the system studies. This can be due to the following reasons.

- Since this study had been carried out in off peak conditions, the practical load behavior of the off peak conditions according to the distinct scenarios could be much more complex and different.

- The system parameter inputs such as generator governor parameters, generator exciter parameters, etc can be deviated from the actual system or can be degraded with time.
- Unanticipated or unobserved mal-responses of generators and transformers might be possible when a particular disturbance happens.
- Unpredictable or unobserved mal-operation of 33kV feeder loads (due to setting the priority feeders of mal operation of feeder protection relays, etc.) when automatically disconnecting due to the operation of UFLS scheme, and when the reconnecting process while recovering back the system.
- Occurrence of worst system states to certain of an-avoidable phenomena. (Ex: Ferranti effect, etc.)

At present in some demand scenarios, it has been identified that the Sri Lankan national power system is being operated closer to their stability limits due to economic constraints when the percentage value maxim loading capacity of a single generator is used as 30%. Maintaining a stable and secure operation of the national power system is therefore very much crucial and a challenging issue. Due to these reasons at present, CEB System Control Centre uses the value of 25% as the maximum loading capacity of the single generator unit considering the system reliability at light load (both active power and reactive power demands) conditions.

1.3 Motivation

Sri Lankan Power system network contains of large number of generators which have been installed in distributed manner within the country. Besides catering the consumer demand, considering the economical dispatch and unit commitment is highly significant when it comes to the power system operational cost. Among the thermal power plants, the cheapest power generation is supplied by coal power plants which the country has three of them at Norochcholei with the net output capacity of 270MW.

Due to the restrictions of frequent start/stop s and the low operational cost, these three power plants are dispatched in base load basis. When a high capacity power plant gets tripped at a low system demand condition where the power system inertia tends to be significantly low, the system frequency drops drastically in such a way it activates the higher number of under frequency load shedding stages. Even though the UFLS scheme is capable of avoiding the power system frequency dropping down until the under frequency limit most of the times, due to the tripping of higher number of 33kV feeders (i.e. power system active and reactive power demand), this disturbance leads to nuisance frequency overshoots and voltage overshoots which would cause to tripping of more number of generators and backbone transmission lines. This phenomenon would lead the power system in to major system failure or even towards to total system blackout. Because of that, the loading process of such a high capacity generator should compromise both power system operational cost and power system stability.

The power system analysis which have been carried out in early 2012 with the generation and transmission parameters, which CEB had proposed the maximum loading capacity of a single generator unit should be less than or equal 30% out of the total system demand. Even though, some of the actual power system failures which had occurred in certain low demand conditions have proven that there can be a mismatch of some of power system parameters and because of that, this value should be somewhat less than the 30% during certain low demand conditions. Due to this reason, power system operators operate the power system in such a way that the maximum loading capacity of a single generator is less than or equal to 25% in certain low load conditions. And also during certain worst low demand conditions, they are compelled to maintain this percentage, even at a lesser value, in order to maintain system reliability at desired level according to their previous practical experiences.

Therefore, a detailed analysis of loading percentage of a single high capacity power plant during each dispatch scenario and demand scenario, has a great value for the utility operations and the country’s economy.

1.4 Objective of the Study

The main objective of this study is to determining the maximum possible loading capacity of a single generator unit (i.e. loading capacity percentage range of a particular generator, considering the total system demand at any particular time of the day) for each dispatch scenario analyzing both frequency stability and voltage stability, considering the prevailing UFLS scheme.

In this study, along with the possible dispatch scenarios it has been considered the worst case demand scenarios which the power system is highly vulnerable.

1.5 Outcomes of the study

The findings of the research will enable followings.

- When it comes to real time power system operations, under any dispatch and demand scenario at any given time, maintaining the system frequency at a desired level during steady state operations with study proposed model, while the operational cost is maintained at minimum.
- When it comes to real time power system operations, under any dispatch and demand scenario at any given time, maintaining the system voltage at a desired level during steady state operations with study proposed model, while the operational cost is maintained at minimum.
- When it comes to real time power system operations, under any dispatch and demand scenario at any given time, maintaining the system frequency stability within desired level during dynamic state operation after tripping of a single high capacity generator while the operational cost is maintained at minimum.
- When it comes to real time power system operations, under any dispatch and demand scenario at any given time, maintaining the system voltage stability within desired level during dynamic state operation after tripping of a single high capacity generator while the operational cost is maintained at minimum.

1.6 Scope of the study work

- Modeling of the Sri Lanka power system-2017 by using Power System Simulator for Engineers (PSS/E) software (Licensed software which used at System Control Centre-CEB).
- Validating steady state properties of the model considering actual system parameters.
- Validating dynamic properties of the model considering actual single generator tripping incidents.
- Simulate the validated model with all dispatch scenarios and demand scenarios which are currently practiced at CEB-System Control Centre.
- Derive the frequency stability for both steady state and transient state while the operational cost is kept at minimum considering the prevailing UFLS scheme.
- Derive the voltage stability for both steady state and transient state while the operational cost is kept at minimum considering the prevailing UFLS scheme.
- Evaluation of power system stability for both frequency and voltage when a high capacity generator is tripped while the operational cost is maintained at minimum.
- Selection of optimum capacity range of a high capacity generator where it can be loaded at it maximum considering both system operational cost and system reliability, for each dispatch scenario.

Chapter 2

PRESENT GENERATION DISPATCH SCENARIOS AND DEMAND SCENARIOS

2.1 Generation Dispatch Scenarios

There are 03 numbers of generation dispatch scenarios (known as dispatch Scenarios) in Sri Lankan power system considering the various generation dispatch patterns. Generation dispatch scenarios are basically diversified according to the prevailing weather conditions at a certain period of a year. These dispatch scenarios are defined for every week of the year by System Control Centre of CEB.

Until 2016, there were 02 main generation dispatch scenarios.

1. Hydro Maximum Scenario – During rainy seasons when there are plenty of hydro reservoir levels and high inflows to the run of the river machines. The swing generator is a hydro generator.
2. Thermal Maximum Scenario – During dry seasons when there are no rain, less hydro reservoir and run of the river pond levels. The swing generator is a hydro generator.

Even though during 2017 severe drought, system Control Centre of CEB has introduced another dispatch scenario which is called Extreme Thermal Maximum Scenario. The differences of Extreme Thermal Maximum scenario comparing with Thermal Maximum scenario are, in Extreme Thermal Maximum scenario there are much less number of hydro machines (most probably, must run hydro plants only) and the frequency controlling is done by a gas turbine or a combine cycle power plant (KCCP). Therefor year of 2017 on words, there are 03 main generation dispatch scenarios.

1. Hydro Maximum Scenario – During rainy seasons when there are plenty of hydro reservoir levels and high inflows to the run of the river machines. The swing generator is a hydro generator.

2. Thermal Maximum Scenario – During dry seasons when there are no rain and less hydro reservoir and run of the river pond levels. The swing generator is a hydro generator.
3. Extreme Thermal Maximum Scenario – During extreme dry seasons when there are very lesser hydro reservoir and run of the river pond levels. The swing generator is a gas turbine or a combine cycle power plant (KCCP).

2.2 Demand Scenarios

There are 03 numbers of Demand Scenarios per day related to Sri Lankan power system. Demand Scenarios are basically diversified according to the peak values (i.e. maximum or minimum) of the demand patterns of the consumers of the country considering a single typical day.

There are four numbers of Demand Scenarios per day which are known as Morning Peak, Day Peak, Night Peak and Off Peak. Since Morning Peak is not that much significant comparing with Day Peak, the Morning Peak can be omitted when it’s considered the study purposes. Therefore, there can be classified the 03 number of demand scenarios as follows.

1. Day Peak – This maximum demand occurs at day time around 12:00hrs of a certain day. Typical average maximum demand is 1900MW in 2017[4].
2. Night peak – This maximum demand occurs at night time around 19:00hrs of a certain day. Typical average maximum demand is 2300MW in 2017[4].
3. Off Peak – This minimum demand occurs at night time around 3:00hrs of a certain day. Typical average maximum demand is 1000MW in 2017[4].

2.3 Economical cost analysis of loading operations of LVPS capacity under different dispatch scenarios

2.3.1 Hydro Maximum Scenario

In hydro maximum scenario, at off peak condition the only dispatched thermal generators are LVPS three generators under normal conditions. The remaining thermal generators are replaced by CEB hydro generators and NCRE embedded generation. Since LVPS is a base load running plant, in these type scenarios the deloading operations for LVPS has to be carried out only if occurs low demand or for system stability concerns. Using proper hydro generation mix and deloading costlier thermal generators (i.e. LVPS) as much as possible (Normally when it comes to practical operations, reaching the minimum load of all 04 numbers of coal mills of a single plant is sufficient in order to cater the off peak load at hydro maximum scenario) is the most cost effective method where there are plenty of embedded NCRE generation and sufficient hydro reservoir and pond levels.

2.3.2 Thermal Maximum Scenario

In thermal maximum scenario at off peak condition, the deloading operation of LVPS can be done through loading a low cost thermal generator instead, which are situated closer but below to the LVPS, in the merit order list which is prepared by the System Control Centre ,CEB. Such plants are Sapugaskanda Diesel power plants (A side and B side),power barge and Uthuru Janani.

Deloading 1MW from LVPS and loading 1MW of the second cheapest power generator (i.e. Sapugaskanda Diesel B side) will be cost as follows.

Average time per day for the consideration = 6hrs

The capacity of deloading from LVPS power station = 1MW

The average unit cost reduction due to the above operation
(unit cost of LVPS) = Rs.7.29

The energy cost per day due to the above
dispatch method = RS.(1 x 1000 x 6 x 7.29)
= Rs.43,740.00

The capacity of loading from,
Sapugaskand-B power station = 1MW

The cost addition due to the above operation,
(unit cost of Sapugaskanda-B) = Rs.17.80

The energy cost per day due to the above dispatch

method = RS,(1 x 1000 x 6 x 17.80)

= Rs.106,800.00

The loss per day due to the entire dispatch operation = Rs.(106,800-43,740)

= Rs.63,060.00

Since this is extreme thermal maximum scenario, it can be assumed that the plant has been already dispatched before the off peak occurs. Unless, the start/stop cost are also has to be taken in to the account. Assuming that this dispatch method has been carried out through an entire month at the thermal maximum scenario, deloading 1MW from LVPS and loading 1MW from the second cheapest thermal power plant would affect an economical loss of approximately 1.9 million rupees per month for the utility.

2.3.3 Extreme Thermal Maximum Scenario

In extreme thermal maximum scenario at off peak condition, the deloading operation of LVPS can be done through loading a low cost combine cycle thermal generator instead (In extreme thermal maximum scenario, most of the time all the combine cycle power plants are dispatched at off peak), which has the least incremental cost according to the merit order list which is prepared by the System Control Centre, CEB. Such plants are KCCP, Sojitz power plant (formerly known as AES-Kelanitissa power plant) and WCP (Yugadhanavi power plant).

Deloading 1MW from LVPS and loading 1MW from the power plant which has the second cheapest incremental cost, (i.e. It is Sojitz-Kelanitissa power plant since the gas turbine of KCCP power plant has been dispatched as the swing generator) will be expensed as follows.

Average time per day for the consideration = 6hrs

The capacity of deloading from LVPS power station = 1MW

The average unit cost reduction due to the above operation

(unit cost of LVPS) = Rs.7.29

The energy cost per day due to the above-

dispatch method = RS.(1 x 1000 x 6 x 7.29)

= Rs.43,740.00

The capacity of loading from,

Sojitz-Kelanitissa power station = 1MW

The cost addition due to the above operation

(unit cost of Sojitz-Kelanitissa) = Rs.13.86

The energy cost per day due to the above dispatch-

method = RS,(1 x 1000 x 6 x 13.86)

= Rs.83,160.00

The loss per day due to the entire dispatch operation = Rs.(83,160-43,740)

= Rs.39,420.00

Since this is extreme thermal maximum scenario, it can be assumed that the plant has been already dispatched before the off peak occurs. Unless, the start/stop cost also has to be taken in to the account. Assuming that this dispatch method has been carried out through an entire month at the extreme thermal maximum scenario, deloading 1MW from LVPS and loading 1MW from the second cheapest thermal power plant would affect an economical loss of approximately 1.2 million rupees per month for the utility.

2.4 Determination of contribution percentage range of a single LVPS generator, at off peak demand scenario under each dispatch scenario

2.4.1 Methodology of calculation LVPS generation contribution

The accurate method of calculating the LVPS generation contribution at a specific instance is considering the net generator output to the national transmission grid, deducting the plant in house generation from the plant total output generation.

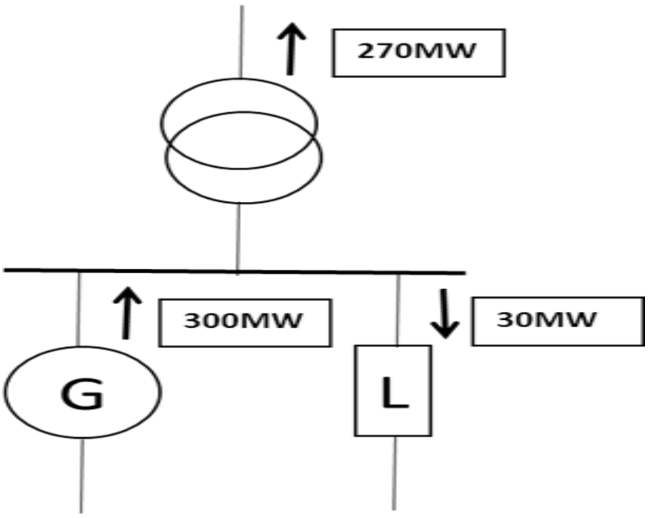


Figure 2.1: Graphical represent of LVPS single unit contribution to the national grid

According to the figure 2.1**,** when a single generator of LVPS is dispatched at it's full load capacity the generation contribution to the national transmission grid is as follows.

Total output gross generation = 300MW

LVPS single generator net output generation = 270MW

LVPS single generator contribution = (300-30)MW

= 270MW

Assuming that the total system generation is equal to $\text{Gen}_{\text{Total}}$ MW, when a single generator of LVPS is dispatched at it's full load capacity, the generation contribution percentage out of the total generation is as follows.

Total System generation = $\text{Gen}_{\text{Total}}$ MW

LVPS single generator net output generation = 270MW

LVPS single generator contribution = $\underline{\underline{(270/ \text{Gen}_{\text{Total}}) \times 100\%}}$

2.4.2 LVPS contribution percentage at Off Peak demand scenario under Hydro Maximum Scenario

The calculation for determining the LVPS contribution percentage at Off Peak demand scenario under Hydro Maximum Scenario, considering machine restrictions and the actual system data is as follows.

Typical minimum off peak System demand = 800MW
LVPS Minimum net generator output (machine constraint) = 150MW
LVPS Maximum net generator output (machine constraint) = 270MW
Study lower limit % contribution of a single LVPS generator = 150/800 = 18.75%
Study upper limit % contribution of a single LVPS generator = 270/800 = 33.75%

LVPS single unit Contribution Range is 19% - 33% -----(1)

2.4.3 LVPS contribution percentage at Off Peak demand scenario under Thermal Maximum Scenario

The calculation for determining the LVPS contribution percentage at Off Peak demand scenario under Hydro Maximum Scenario, considering machine restrictions and the actual system data is as follows.

Typical minimum off peak System demand = 1000MW
LVPS Minimum net generator output (machine constraint) = 150MW
LVPS Maximum net generator output (machine constraint) = 270MW
Study lower limit % contribution of a single LVPS generator = 150/1000 = 15%
Study upper limit % contribution of a single LVPS generator = 270/1000 = 27%

LVPS single unit Contribution Range is 15% - 27% -----(2)

2.4.4 LVPS contribution percentage at Off Peak demand scenario under Extreme Thermal Maximum Scenario

The calculation for determining the LVPS contribution percentage at Off Peak demand scenario under Hydro Maximum Scenario, considering machine restrictions and the actual system data is as follows.

The only difference between the generator dispatching of thermal maximum scenario and extreme thermal maximum scenario is the selection of swing generator. In thermal maximum scenario the swing generator is a hydro generator and in extreme thermal maximum scenario the swing generator is a gas turbine.

Typical minimum off peak System demand = 1000MW
LVPS Minimum net generator output (machine constraint) = 150MW
LVPS Maximum net generator output (machine constraint) = 270MW
Study lower limit % contribution of a single LVPS generator = 150/1000 = 15%
Study upper limit % contribution of a single LVPS generator = 270/1000 = 27%

LVPS single unit Contribution Range is 15% - 27% -----(3)

2.4.5 Study range consideration

In order to consider a common study range, considering above all dispatch scenarios under 2.4.2, 2.4.3, 2.4.4 {i.e. Equations (1),(2) and(3)}, this study evaluates LVPS single generator unit contribution from 19% to 27% out of the total system generation at off peak conditions.

Chapter 3

Existing Transmission System of Sri Lanka

3.1 Existing Power system and the maximum loading capacity of a single generator unit

Until the end of the year 2011, the maximum loading capacity of a single generator unit had been restricted up to 20% of the total system generation to ensure the system stability with the prevailed UFLS scheme. However, after the commissioning of LVPS-Stage 01 at 2011, the prevailed UFLS scheme had to be revised in order to maximize the coal generation through LVPS (Planed net output generation was 270MW) which provides the cheapest cost power generation after hydropower generation.

The power system studies which had been carried out at the time when the early stages of LVPS commissioning, with the proposed transmission network at the time and the UFLS scheme proved that the value of maximum loading capacity of a single generator unit can be enhanced up to 30%. Hence, the CEB System Control Center used this value as 30%. Nevertheless, with occurrence of some practical experiences and issues, the system operations have become so much crucial and challenging.

Due to these reasons, at present system control Centre use the value of 25% as the maximum loading capacity of the single generator unit. However, occurrence of disturbances at certain worst demand scenarios compels the system operators to operate this value far more below the above values. By operating the system in such a way, the system operators could avoid the major system failures and near miss incidents including total system failures.

3.2 Frequency criteria of Sri Lanka

The present frequency criteria used by the Transmission Planning branch of Ceylon Electricity Board for voltage tolerance are defined for power system under normal operating conditions and under emergency conditions.

Table 3.1 : Allowable frequency variation

Bus Bar Nominal Voltage	Planned Maximum Frequency Variation	
	Normal Operating Condition	Emergency operating Condition
50Hz	+/- 1%	+/- 5%

Source: Transmission Plan, Ceylon Electricity Board March 2015

Even though the emergency operation condition of frequency has listed in the table 3.1 as +/-5% (i.e 47.50Hz to 52.50Hz), later on certain generators have been programmed their over frequency protection settings less than the upper limit of the range (i.e. +5%).Therefore, it has to be considered the machine frequency limitations as well over the frequency limitations in table 3.1, when it comes to practical power system operations.

3.3 Voltage criteria of Sri Lanka

The present voltage criteria used by the Transmission Planning branch of Ceylon Electricity Board for voltage tolerance are defined for power system under normal operating conditions and under emergency conditions.

Table 3.2: Allowable voltage variation

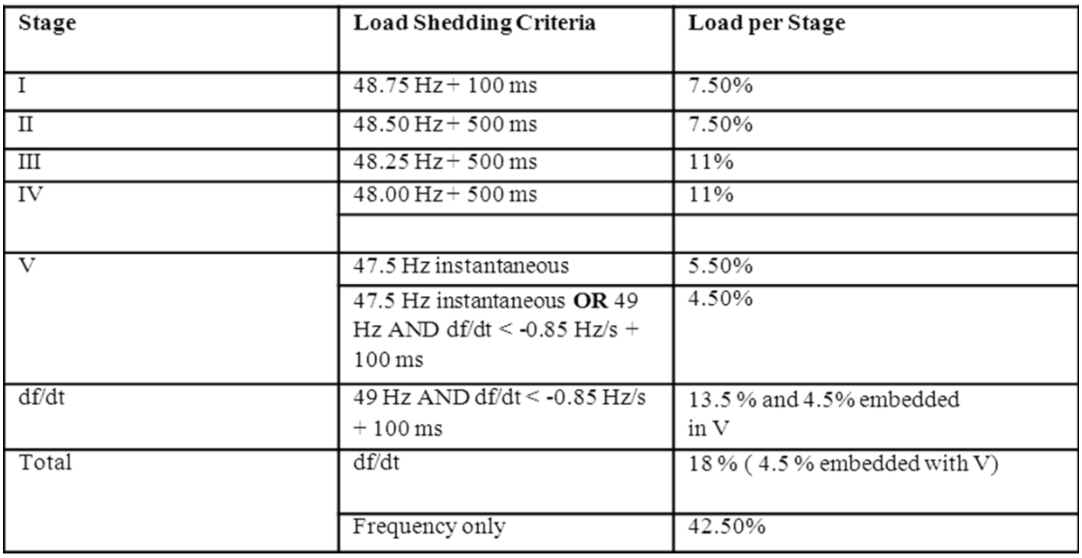
Bus Bar Nominal Voltage	Planned Maximum Voltage Variation	
	Normal Operating Condition	Emergency operating Condition
220kV	+/- 5%	+/- 10%
132kV	+/- 5%	+/- 10%

Source: Transmission Plan, Ceylon Electricity Board March 2015

Even though the normal operation condition of voltage has listed in the table 3.2 as +/-5% (i.e 209kV to 231kV), it is a challenging task to maintain the voltage within that range during certain periods. Some examples are, periods when high Mvar contribution thermal machines (KCCP, WCP, Sojitz Kelanithissa, Barge mounted PS, Sapugaskanda PS, etc) are at planned/forced outages, light load conditions at off peak conditions, etc. Therefore, the practical normal operation condition is considered as +/-10% when it comes to the practical system operations.

3.4 Present UFLS scheme

Table 3.3: Prevailing Under frequency load shedding scheme



Stage	**Load Shedding Criteria**	**Load per Stage**
I	48.75 Hz + 100 ms	7.50%
II	48.50 Hz + 500 ms	7.50%
III	48.25 Hz + 500 ms	11%
IV	48.00 Hz + 500 ms	11%
V	47.5 Hz instantaneous	5.50%
	47.5 Hz instantaneous **OR** 49 Hz AND df/dt < -0.85 Hz/s + 100 ms	4.50%
df/dt	49 Hz AND df/dt < -0.85 Hz/s + 100 ms	13.5 % and 4.5% embedded in V
Total	df/dt	18 % (4.5 % embedded with V)
	Frequency only	42.50%

Source: Transmission Plan, Ceylon Electricity Board March 2015

The present UFLS scheme is shown at table 3.3. It can be elaborate as follows.

- If the frequency reaches up to 48.75Hz for 100ms the UFLS stage (I) would get activated rejecting 7.5% of the total demand, provided that the rate of change of frequency is less than 0.85Hz/s.
- Further, if the frequency doesn’t get recovered and the frequency reaches up to 48.50Hz for 500ms the UFLS stage (II) would get activated rejecting 7.5% of the total demand, provided that the rate of change of frequency is less than 0.85Hz/s.
- Further, if the frequency doesn’t get recovered and the frequency reaches up to 48.25Hz for 500ms the UFLS stage (III) would get activated rejecting 11%

of the total demand, provided that the rate of change of frequency is less than 0.85Hz/s.

- Further if the frequency doesn’t get recovered and the frequency reaches up to 48.00Hz for 500ms the UFLS stage (IV) would get activated rejecting 11% of the total demand, provided that the rate of change of frequency is less than 0.85Hz/s.
- Further, if the frequency does not get recovered and the frequency reaches up to 47.75Hz instantaneously, the UFLS stage (V) would get activated rejecting 5.5% of the total demand, provided that the rate of change of frequency is less than 0.85Hz/s. Considering this same case, when the rate of change of frequency is greater than 0.85Hz/s or the frequency reaches up to 49.00Hz for 100ms, the same UFLS scheme {i.e. UFLS stage (V)} would get activated rejecting 4.5% of the total system demand.

When the frequency reaches up to 49.00Hz and the rate of change of frequency is greater than 0.85Hz/s (i.e. This can be happened duo to a rejection of a large generation portion from the system) it would shed 18% {embedded with UFLS scheme (V)} from the total load, as the load shedded considering the rate of change of frequency only. The total shedded load considering the frequency value only is 42.50%.

3.5 Dispatch Scenario consideration and demand scenario considerations for the study

As discussed in the section 2.1, considering Sri Lankan power system, there are there dispatch scenarios (Hydro Maximum, Thermal Maximum and Extreme Thermal Maximum) and three demand scenarios (Day Peak, Night Peak, Off Peak). It should be clearly identified according to which dispatch scenario/scenarios & under which demand scenario/scenarios that the research should be continued with.

Table 3.4: Features of different dispatch Scenarios

Condition	System Demand	System Inertia	Spinning Reserve percentage	Free governor action capability	Reactive power absorption capability
Hydro Maximum	Low	Low	High	High	High
Thermal Maximum	High	High	Low	Low	Low
Extreme Thermal Maximum	High	High	Low	Very Low	Very Low

According to the table 3.4, it can be clearly identified how each 03 dispatch scenarios would have their own varieties of system parameters and hence the different dynamic response when a disturbance happens. Therefore, it is clear that it should be critically analyzed how the system would response, when a generation rejection happens under all the above mentioned dispatch scenarios.

Table 3.5 Typical average demand values of different demand scenarios under different dispatch scenarios in 2017

Scenario	Hydro Maximum (Average System Demand in MW)	Thermal Maximum (Average System Demand in MW)	Extreme Thermal Maximum (Average System Demand in MW
Day Peak	1750	2100	2100
Night Peak	2100	2400	2400
Off Peak	800	1000	1000

Source: Generation Summary Reports, SCC-CEB

Table 3.6 : Largest generator (LVPS) capacity percentages when dispatched full load, during different demand scenarios under different dispatch scenarios in 2017

Scenario	Hydro Maximum (LVPS % when dispatched full load)	Thermal Maximum (LVPS % when dispatched full load)	Extreme Thermal Maximum (LVPS % when dispatched full load)
Day Peak	15.43	12.86	12.86
Night Peak	12.86	11.25	11.25
Off Peak	33.75	27.00	27.00

Source: Generation Summary Reports, SCC-CEB

Table 3.5 represents the typical demand values under each dispatch scenarios at each demand scenario. Correlating with table 3.5, table 3.6 represents the typical demand values percentages under each dispatch scenarios at each demand scenario assuming that LVPS single unit is a largest generator which has been dispatched at the corresponding demand scenario. According to table 3.6, it can be clearly understood that among the all 03 demand scenarios, the power system is so much vulnerable for possible initiations of collapsing, when a fully loaded LVPS generator gets tripped at the off peak demand scenario. Therefore, it’s clear that it should be analyzed how the system would response, when a generation rejection happens only at off peak conditions since it is the worst case demand scenario and the results obtained through that could be correlated to the other demand scenarios as well.

3.6 Power system limitations

3.6.1 Frequency limitations

Following over frequency and under frequency trip settings have been installed for the protection purposes of the generators in following machines from 06/03/2017 onwards.

- LVPS unit 01 –51.83Hz (3110 rpm) - Instantaneous
- LVPS unit 02 –51.30Hz (3078 rpm) - Instantaneous
- LVPS unit 03 –51.67Hz (3100 rpm) - Instantaneous
- Kelanithissa Combined cycle plant (KCCP) – 48.0Hz for 03 seconds

3.6.2 Voltage limitations

Following over voltage trip settings have been installed for the protection purposes of the 220/132/33kV auto transformers from 04/03/2017 onwards.

- New Anuradhapura 220/132/33kV T/F 01 & T/F 02 – 264kV –for 10 seconds
- Biyagama 220/132/33kV T/F 01 & T/F 02 – 264kV –for 10 seconds
- Rantambe 220/132/33kV T/F 01 & T/F 02 – 264kV –for 10 seconds
- Pannipitiya 220/132/33kV T/F 01 & T/F 02 – 264kV –for 10 seconds
- Kelanithissa 220/132/33kV T/F 01 & T/F 02– 264kV –for 10 seconds

Following over voltage trip setting has been installed for the protection purposes of the 220kV transmission network at following transmission line from 04/03/2017 onwards.

- New Anuradhapura – Kothmale 220kV circuit 02 –253kV –05 seconds

These are the latest trip settings [3] and power system limitations, which would be considered throughout this study.

3.7 System cascade disturbances occurred with related to maximum loading capacity of a single generator unit

There exists several number of cascade near-miss system disturbances which had been avoided by the system operators by using the maximum loading capacity of a single generator unit value below the predefined standard percentage value. One such incident is as follows.

3.7.1 Tripping incident initiated with of Kosgama – Kolonnawa 132kV single circuit on 18.02.2017

The Sri Lankan power system experienced a major cascade disturbance in the terms of both frequency stability and voltage stability on 18th February of 2017 at 02:10hrs.

Just before the failure initiated, the system was delivering 998MW total active power and 70Mvar lagging reactive power through the generators. The dispatch scenario was extreme thermal maximum and the swing generator was KCCP gas turbine. At that time all 03 numbers of LVPS generator units had been full load dispatched and LVPS all generators were being deloaded up to 250MW in order to maintain the generator contribution at 25%. Just before the failure initiated, a single LVPS unit had reached 250MW and remaining two generators were at 260MW while the deloading process was going on. The failure initiated with the tripping of Kosgama - Kolonnawa 132kV circuit due to a single phase solid earth fault at Kolonnawa grid substation. Due to the low impedance at the fault, the sudden frequency overshoot was drastic such that it reached 51.35Hz which is slightly greater than the of the over frequency protection setting of LVPS unit – 02 (Over frequency protection trip setting was 51.30Hz). Due to exceeding it’s over frequency protection limit, LVPS unit-02 tripped and that sudden generation loss (i.e. frequency drop down) coursed of activation of the UFLS scheme up to stage 04. Because of the rejection of 33kV loads due to activation of UFLS scheme, the frequency again roused until 51.60Hz and the system could be recovered with the involvement of system operators’ actions as well. The second frequency overshoot was slightly below to the over frequency protection trop setting of LVPS unit 03 (Over frequency protection trip setting was 51.67Hz). If the second over frequency overshoot reached 51.67Hz, another LVPS generator could have tripped and thereafter, the entire power system might have faced towards a total system failure.

The frequency variation during the disturbance period is illustrated at figure 3.1.

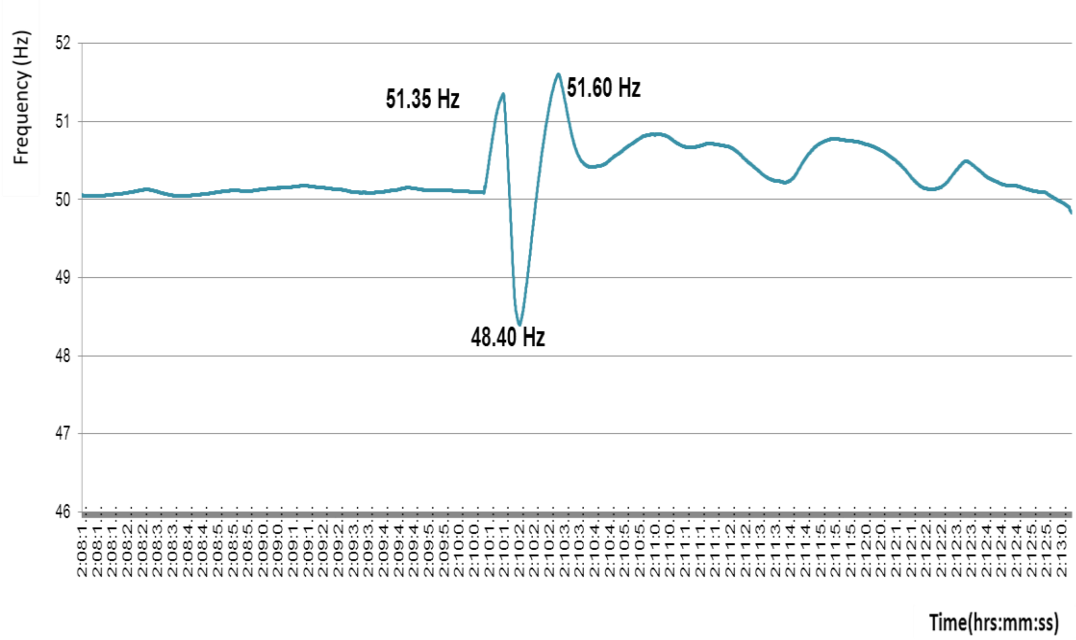


Figure 3.1: Frequency variation during the disturbance period at Biyagama 220kV bus

These kind of abnormal frequency responses and latest trip settings of the transmission and genaration network should be critiaclly considered, when it comes to determination of maximum loading capacity of a single geneartor unit.

The 220kV voltage variation was also abnormal during the failure period. At the failure moment, initially the system voltage drastically dropped down due to the rejection of high Mvar generation from the tripped LVPS plant. But after the activation of UFLS scheme, the voltage rising was abnormal due to the complex load behavior and the Ferranti effect.

The 220kV voltage variation during the disturbance period is illustrated in figure 3.2.

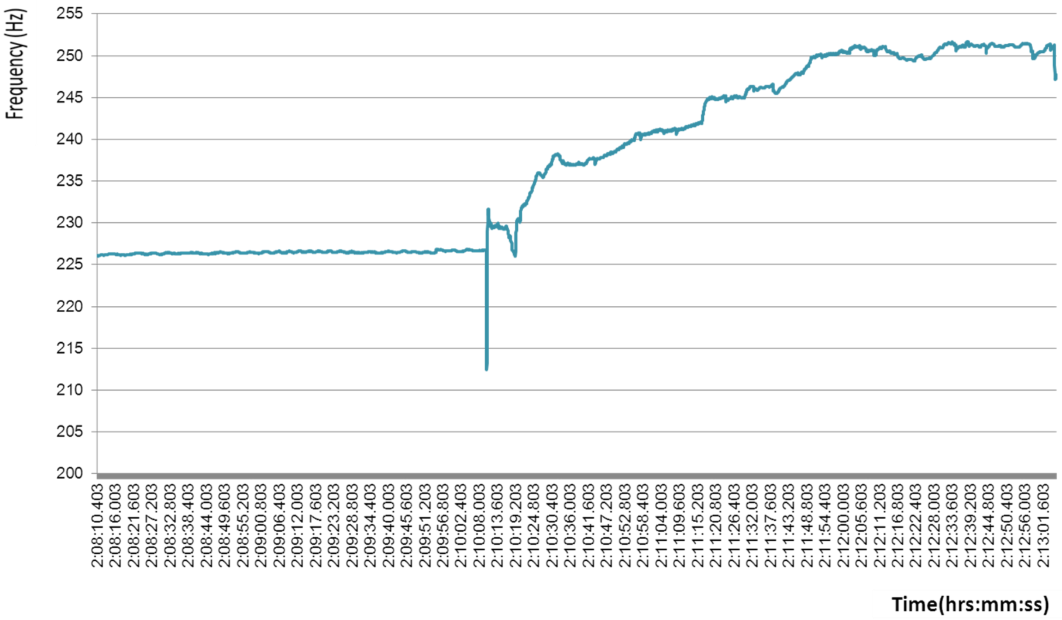


Figure 3.2: Voltage variation during the disturbance period at New Anuradhapura 220kV bus

These kind of abnormal voltage responses when a generator tripping happens, latest trip settings of the transmission and genaration network and certain adverse phenomena such as Ferranti effect, etc should be critiaclly considered,when it comes to determination of maximum loading capacity of a single geneartor unit.

3.7.2 LVPS governor responding behavior during the failure period

The active power response, due to the free governor operation of LVPS generators was also abnormal during the failure period. Due to the frequency overshoot, until it reached the over frequency protection trip setting of LVPS generator 02, it tripped and hence the system frequency went down drastically until 48.40Hz. At this time, the remaining two LVPS generators automatically activated their free governor action and contributes to the system an approximately 100MW all together.

But this incident happed when the system frequency was high, due to the activation of UFLS scheme. These phenomena caused to maximize the system frequency much more (I.e. Increasing of generation around 100MW at low demand condition while the system frequency is high) and obviously it led the system into a severe condition such that, if the frequency overshoot reached 51.67Hz, the remaining LVPS one unit might have tripped and hence the total system failure could have occurred. This could be definitely happened if the maximum loading capacity of a single generator unit value had been used as 30%. (i.e. If the 03 LVPS generators had been dispatched in full load). Since there was used the value as 25% according to the previous experiences of System Control Centre, an another total system failure had been avoided.

The frequency variation and the active power response of LVPS all units during the disturbance period are illustrated in figure 3.3.

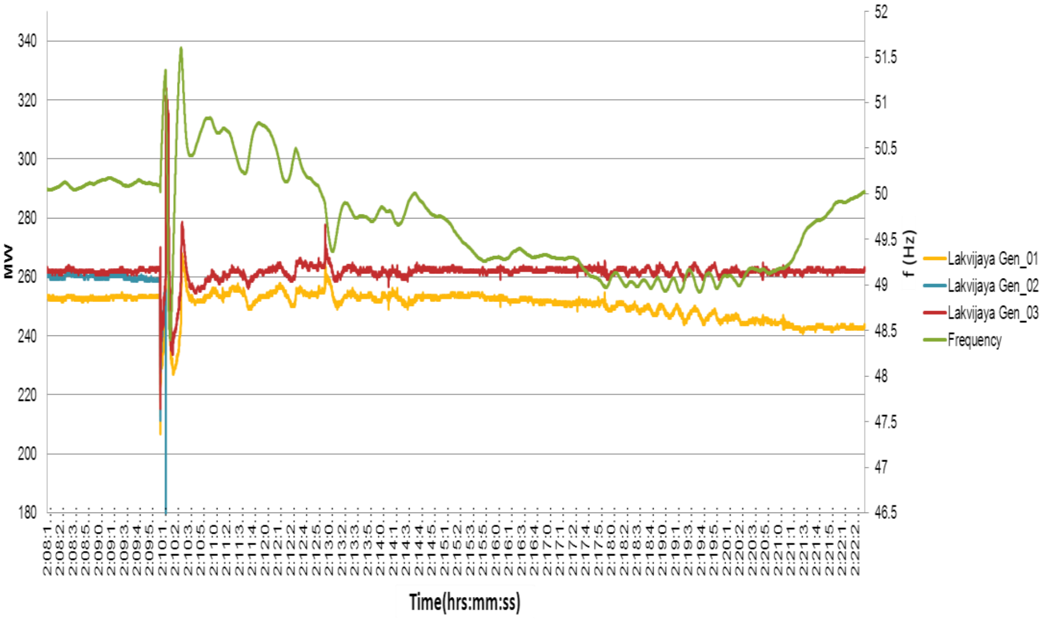


Figure 3.3 Frequency variation at Biyagama 220kV bus and active power variation of LVPS each generator, during the disturbance period

These kind of abnormal syetem responses such as free governor action of genartors, latest trip settings of the transmission and genaration network and generator active power responsing time delay should be critiaclly considered,when it comes to determination of maximum loading capacity of a single geneartor unit.

3.8 Transient over voltage on Sri Lankan transmission network

Even though the UFLS scheme helps the system to recover after a significant generation rejection, the Under Frequency Load Shedding, rejection of loads (GSSs) due to transmission line trips and generator tripping while adsorbing considerable amount of leading reactive power of the system causes over voltages in their post failure scenarios. One such example for this phenomenon is the worst ever of all time overvoltage cascade tripping scenario which occurred on 27th September 2015 which ultimately led to a total system blackout.

The 220kV voltage variation is the most significant when it comes to the electricity transmission level comparing with 132kV. The 220kV voltage variation during the failure period until the total system collapse happened is according to the figure 3.4.

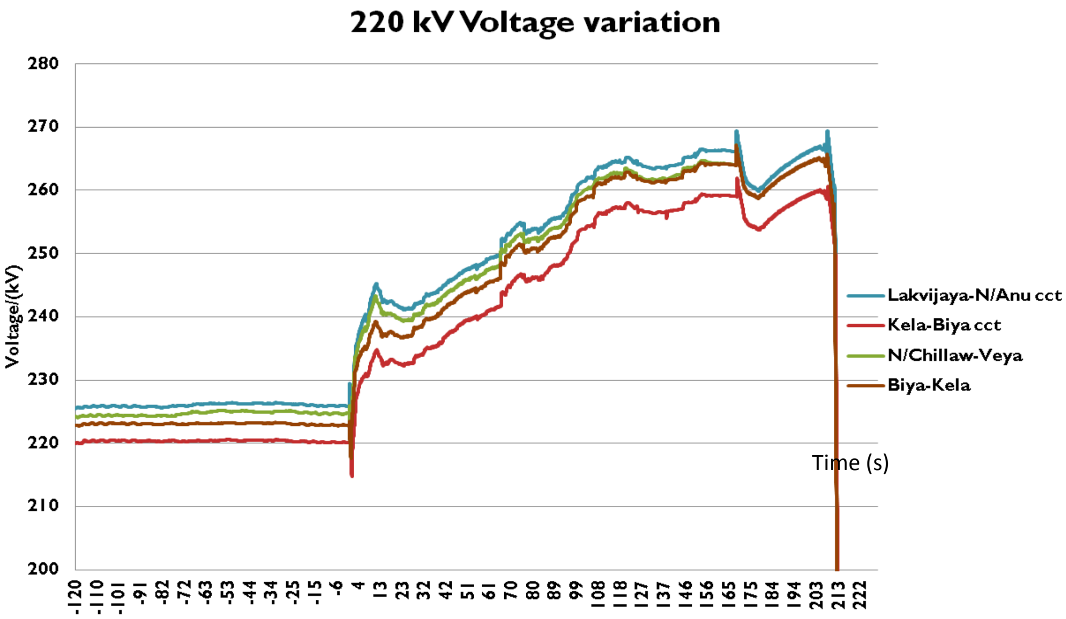


Figure 3.4: Voltage variations at different 220kV busses during the total system failure on 27/09/2016

Chapter 4

OVERVIEW AND PSS/E MODEL VALIDATION

4.1 Overview

4.1.1 Overview of Sri Lankan Power System

At present, Sri Lanka power system has total installed generation capacity of nearly 3800MW including renewable energy sources [1]. Among them, maximum capacity of the single generator unit is 300MW (gross output capacity) at Lakvijaya Coal Power Plant which has the total installed capacity of 900MW. Renewable energy sources include mini hydro plants of 302MW and wind power plant of 124MW which are operated by private power sector [1]. Recorded maximum night peak is 2523MW (on 17.05.2017) and day peak is 2255MW (on 24.04.2017) in the year of 2017[4]. Frequency control operation is done by one particular power station at a time, therefore it operates at lower droop setting (ep1: 1.6% to 2.8%) and other machines operate at higher droop settings on free governor mode (ep2: 4% to 8%). Allowable frequency deviation in Sri Lanka is specified as +/- 1% of the 50Hz in the Grid Code [2] and minimum allowable system spinning reserve is 5% of total system generation. The System Control Centre of CEB adheres to the above accords during carrying out the power system operations.

4.1.2 Overview of PSS/E

The study has been carried out through the simulations of the sophisticated software which is currently used by CEB, Power System Simulator for Engineers software.

The power system model includes the entire 220kV and 132kV transmission network of Sri Lanka. Loads are connected to 33kV buses via 132/33kV distribution transformer and model contains around 200 buses.

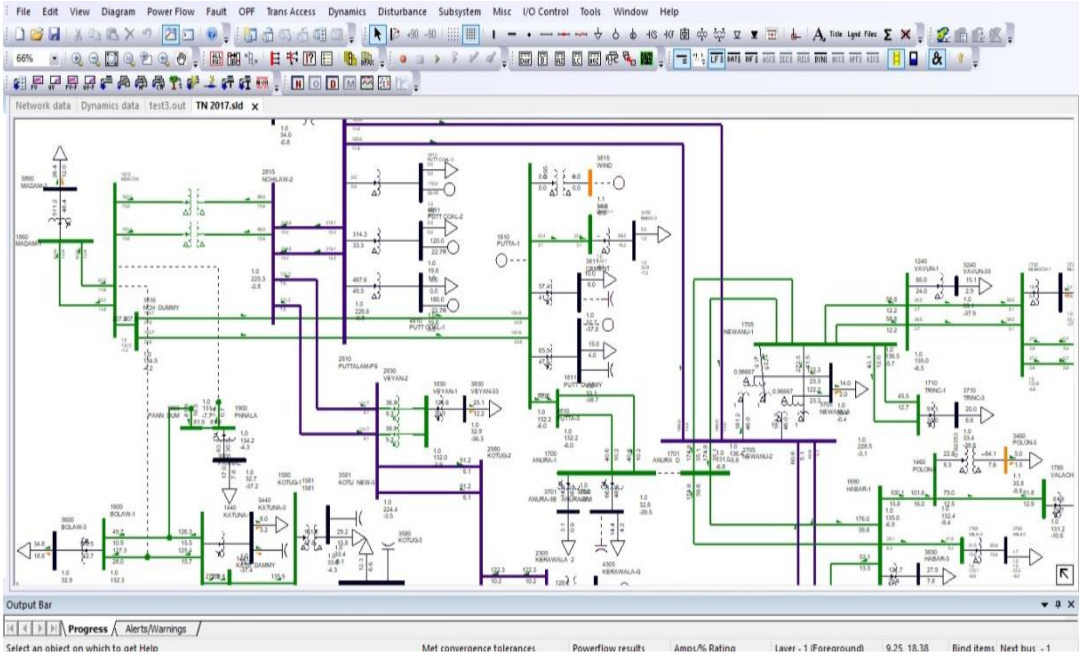


Figure 4.1: PSS/E steady stare power flow interface of Sri Lankan power system

The power system model includes the entire 220kV and 132kV transmission network of Sri Lanka. Loads are connected to 33kV buses via 132/33kV distribution transformer and model contains around 200 buses.

It can be categorized the PSS/E models which are currently used in CEB in to two sections.

1. CEB PSS/E Planning Model
2. CEB PSS/E Dispatching Model

The CEB PSS/E Planning Model is being used by CEB Generation and Transmission Planning branch for their long term power system planning purposes while CEB PSS/E Dispatching Model is being used by CEB System Control Branch for their short term planning and real time operations.

This study considers a combination of both CEB PSS/E Planning Model and CEB PSS/E Dispatching Model with some necessary adjustments.

At the validation of the model, dynamic simulation is carried out by defining following models and the corresponding parameters.

- Synchronous generators (GENROU or GENSAL models)
- Excitation systems (SCRX, EXST1 or IEEET1 models)
- Turbine governors (HYGOV model)
- Transformer OLTC (OLTC1T or OLTC3T model).
- Load reset characteristic model (EXTLAR model)
- Complex load model (CLODAL model)
- Under frequency Load Shedding Model (LDSHBL or DLSHBL model)
- Switched Shunt Dynamic Model (SWSHNT model)

In the PSS/E model, hydro generators are represented by “GENSAL” salient pole machine model. The hydro governors are represented by the model HYGOV. The thermal generators are represented by “GENROU” round-rotor machine model. The wind generators are modeled by the “WT4G1” Wind generator model with power converter.

In the PSS/E model, three different excitation system models were used. The “IEEET1” model represents modified IEEE Type 1 excitation system. ”SEXS” model represents simplified excitation system models and the “SCRX” model represents bus-fed static exciters. The parameters of these excitation systems provide a reasonable response representation for generator exciters.

The parameters of complex load model were defined after monitoring consumer demand at each time of the actual disturbances which have been considered when the validating the model. Model parameters were fine-tuned further in order to correlate with the present Sri Lankan power system.

4.1.3 Steady State and Dynamic State analysis of power system

It can be followed the merit order dispatch sequence according to the corresponding demand, in order to consider the minimization of the power system operational cost. In order to consider the power system stability, it should be performed a thorough analysis through sophisticated software. As mentioned in sub section 4.1.2, PSS/E

(Power System Simulator for Engineers) has been used in order to study the stability responses.

Both steady state analysis and dynamic state analysis have been performed in order to meet the pre-defined objectives, while ensuring the system stability in case of tripping of a single generator.

- Steady state analysis: Analyzes the steady state power flow and voltage for given generation and demand scenario.
- Dynamic study: Analyzes the frequency dynamics, voltage dynamics. Rotor angle variations due to a disturbance (i.e. generator tripping) for a pre-defined state of the power system.

4.1.3.1 Steady state simulation of Sri Lankan power system in PSS/E

The power system model includes the entire 220kV and 132kV transmission network of Sri Lanka (Appendix A). Loads are connected to 33kV buses via 132/33kV distribution transformer and model contains around 200 buses. Before simulating a particular case for the dynamic state, it should be simulated in steady state and the final outcome should converge at a feasible solution which the power system can survive of it’s own. Load flow study should be carried out for generation pattern according to the realistic dispatches. A bus of a specific generator should be defined as a swing bus and the unbalance of active power/reactive power will be taken care of by this particular bus. No modification such as generator selection, etc. (except possible failures of generators, transmission equipments or dynamic parameters, etc.) can be done at dynamic state, once the system runs and converges for the steady state.

4.1.3.2 Dynamic state simulation of Sri Lankan power system in PSS/E

Dynamic data file which includes the generator, turbine /governor, exciter, load, load shedding parameters plays very important role during the dynamic simulation. Conventional frequency and voltage stability analysis uses steady-state tools and static models. The static models usually take on the form of power flow equations with appropriate generator reactive power limits and active power dispatch, together with constant power loads. As the time spectrum of power system dynamic effects is extended beyond several seconds following a set of disturbances, additional effects come into play, such as the tendency of loads to exhibit constant power characteristics through tap changer and/or load control devices.

Properly tuned models would be required to precisely observe the system and to select upon most favorable solution.

The model consists of two types of simulations files such as power flow data file and dynamic model data file. Load flow data file for the particular case used as the initial dynamic data file. Then dynamic behavior of the system was analyzed. System frequency, critical bus voltages, active power variation of generators was recorded.

4.1.3.3 Analyzing Results of Dynamic Simulation

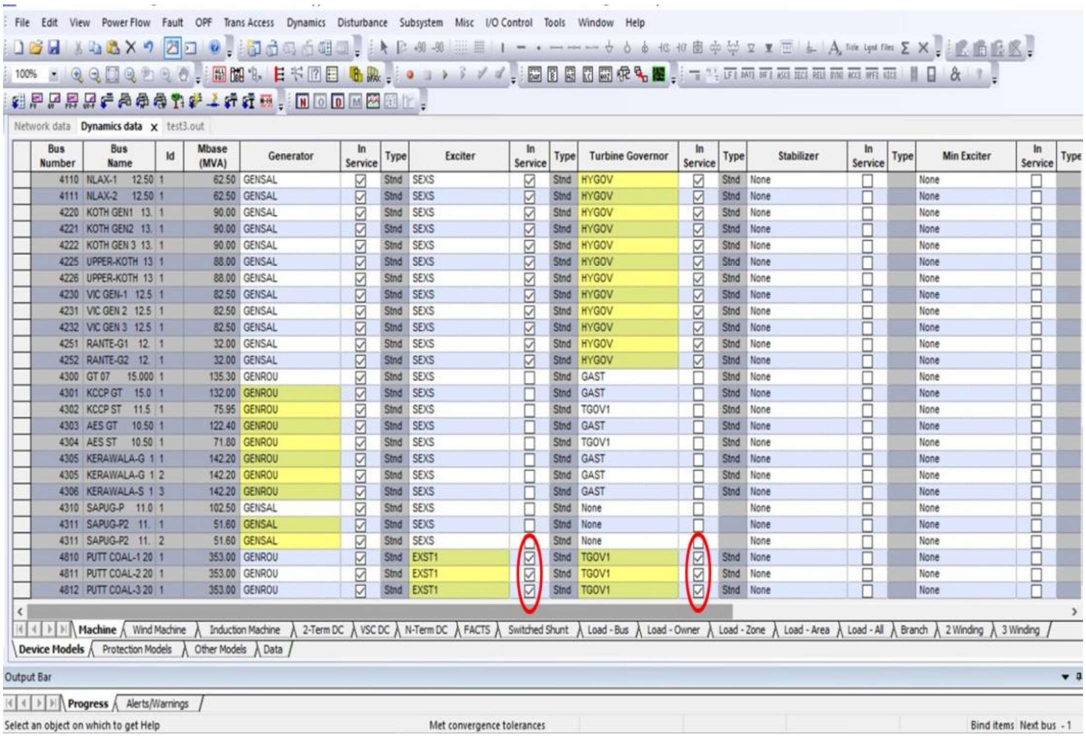
Actual generator tripping scenario was simulated using PSS/E dynamic model and simulated frequency response was compared with actual frequency behavior to validate the dynamic model. The complex load model provides an easy way to investigate the influence of the load model in the dynamic simulation and, in particular, the effect of induction motors in voltage response.

The CLODAL model is added to the original PSS/E dynamic simulation setup and it replaces the original load model which used 100% constant current for real part and 100% constant admittance for reactive part. PSS/E dynamic simulation carried out by switching off the particular generator with a time delay of 5s after the entire power flow converges for a real solution at the steady state power flow simulation. Then, the simulation results were analyzed to observe the system behavior. Main power system dynamics such as frequency profile and 220kV voltage profile behaviors were observed.

4.2 Active power and Reactive power response of LVPS at a disturbance

Sri Lankan power System has experienced significant number of generator tripping incidents (i.e. frequency and Voltage violations). The CEB-System Control Centre has identified the significant amount of active power and reactive power responses of

LVPS at the certain situations. One of such actual incident is a section 3.7.1. Due to this reason, this PSS/E model considers both exciter response (Mvar contribution) and governor response (MW response) of LVPS all three generators beyond the conventional exciter and governor response model which are used in current practice. In order to that, the following modifications have been done to the presently used CEB-PSS/E dispatching model.



Bus Number	Bus Name	Id	Mbase (MVA)	Generator	In Service	Type	Exciter	In Service	Type	Turbine Governor	In Service	Type	Stabilizer	In Service	Type	Min Exciter	In Service	Type
4110	NLAX-1 12.50	1	62.50	GENSAL	☑	Stnd	SEXS	☑	Stnd	HYGOV	☑	Stnd	None	☐		None	☐	
4111	NLAX-2 12.50	1	62.50	GENSAL	☑	Stnd	SEXS	☑	Stnd	HYGOV	☑	Stnd	None	☐		None	☐	
4220	KOTH GEN1 13.	1	90.00	GENSAL	☑	Stnd	SEXS	☑	Stnd	HYGOV	☑	Stnd	None	☐		None	☐	
4221	KOTH GEN2 13.	1	90.00	GENSAL	☑	Stnd	SEXS	☑	Stnd	HYGOV	☑	Stnd	None	☐		None	☐	
4222	KOTH GEN 3 13.	1	90.00	GENSAL	☑	Stnd	SEXS	☑	Stnd	HYGOV	☑	Stnd	None	☐		None	☐	
4225	UPPER-KOTH 13	1	88.00	GENSAL	☑	Stnd	SEXS	☑	Stnd	HYGOV	☑	Stnd	None	☐		None	☐	
4226	UPPER-KOTH 13	1	88.00	GENSAL	☑	Stnd	SEXS	☑	Stnd	HYGOV	☑	Stnd	None	☐		None	☐	
4230	VIC GEN-1 12.5	1	82.50	GENSAL	☑	Stnd	SEXS	☑	Stnd	HYGOV	☑	Stnd	None	☐		None	☐	
4231	VIC GEN 2 12.5	1	82.50	GENSAL	☑	Stnd	SEXS	☑	Stnd	HYGOV	☑	Stnd	None	☐		None	☐	
4232	VIC GEN 3 12.5	1	82.50	GENSAL	☑	Stnd	SEXS	☑	Stnd	HYGOV	☑	Stnd	None	☐		None	☐	
4251	RANTE-G1 12.	1	32.00	GENSAL	☑	Stnd	SEXS	☑	Stnd	HYGOV	☑	Stnd	None	☐		None	☐	
4252	RANTE-G2 12.	1	32.00	GENSAL	☑	Stnd	SEXS	☑	Stnd	HYGOV	☑	Stnd	None	☐		None	☐	
4300	GT 07 15.000	1	135.30	GENROU	☑	Stnd	SEXS	☐	Stnd	GAST	☐	Stnd	None	☐		None	☐	
4301	KCCP GT 15.0	1	132.00	GENROU	☑	Stnd	SEXS	☐	Stnd	GAST	☐	Stnd	None	☐		None	☐	
4302	KCCP ST 11.5	1	75.95	GENROU	☑	Stnd	SEXS	☐	Stnd	TGOV1	☐	Stnd	None	☐		None	☐	
4303	AES GT 10.50	1	122.40	GENROU	☑	Stnd	SEXS	☐	Stnd	GAST	☐	Stnd	None	☐		None	☐	
4304	AES ST 10.50	1	71.80	GENROU	☑	Stnd	SEXS	☐	Stnd	TGOV1	☐	Stnd	None	☐		None	☐	
4305	KERAWALA-G 1	1	142.20	GENROU	☑	Stnd	SEXS	☐	Stnd	GAST	☐	Stnd	None	☐		None	☐	
4305	KERAWALA-G 1	2	142.20	GENROU	☑	Stnd	SEXS	☐	Stnd	GAST	☐	Stnd	None	☐		None	☐	
4306	KERAWALA-S 1	3	142.20	GENROU	☑	Stnd	SEXS	☐	Stnd	GAST	☐	Stnd	None	☐		None	☐	
4310	SAPUG-P 11.0	1	102.50	GENSAL	☑	Stnd	SEXS	☐	Stnd	None	☐		None	☐		None	☐	
4311	SAPUG-P2 11.	1	51.60	GENSAL	☑	Stnd	SEXS	☐	Stnd	None	☐		None	☐		None	☐	
4311	SAPUG-P2 11.	2	51.60	GENSAL	☑	Stnd	SEXS	☐	Stnd	None	☐		None	☐		None	☐	
4810	PUTT COAL-1 20	1	353.00	GENROU	☑	Stnd	EXST1	☑	Stnd	TGOV1	☑	Stnd	None	☐		None	☐	
4811	PUTT COAL-2 20	1	353.00	GENROU	☑	Stnd	EXST1	☑	Stnd	TGOV1	☑	Stnd	None	☐		None	☐	
4812	PUTT COAL-3 20	1	353.00	GENROU	☑	Stnd	EXST1	☑	Stnd	TGOV1	☑	Stnd	None	☐		None	☐	

Select an object on which to get Help
Met convergence tolerances
Bind items Next bus - 1

Figure 4.2: PSS/E interface of generator governor and exciter parameter console

Demarcations with red color in figure 4.2 depict how the each LVPS generator governor parameters and exciter parameters are considered for the study.

4.3 Study Cases

Sri Lankan power system has experienced vast number of different type generator tripping incidents with in different dispatching sceneries and demand scenarios. This study is going to consider two types of distinct generator tripping incidents during different dispatching and demand scenarios and validate the study model. These two selected generator tripping incidents had been occurred after the implementation of new UFLS scheme in 2012 and after all LVPS stages have been implemented. At the time when the two incidents happened the latest transmission network and latest protection trop settings have already been implemented. Therefore, it can be clearly specified here, the two incidents have been selected in such a way that the latest generation and transmission network with all kind of limitations have been taken in to the account of studies.

The actual system frequency behavior and the Voltage behavior have been studied through the data which were obtained from actual DFR data which are referred through CEB - DFR and SCADA records. The two incidents have been ordered according to the dates of occurrence.

4.3.1 Study case 01: The tripping of Kelanithissa Combined Cycle Power plant (KCCP) on 15.04.2016

4.3.1.1 Incident description of study case 01

The failure was initiated with the tripping of KCCP plant on 15.04.2016 at 12:10hrs. The dispatch scenario was hydro maximum and the demand scenario was a very low load condition due to the day after the Sinhala and Tamil New Year festival day. The demand was further at a low conation due to the occurrence of this failure happened just at the day peak valley time. Weather condition was fair and the atmospheric conditions were normal.

System active power generation was 1124MW and the system reactive power generation was 270Mvar prior to the incident occurred. At the failure, the rejected generation was 155MW which was 13.79% from the total generation. The number of operated UFLS scheme stages was 01 and the total shedded 33kV load was 69MW which was 6.14% from the total system generation. The slack generation was catered by the swing generator (Kothmale unit-01), free governor mode activation of the remaining system generators and the involvement of system operator.

The generation status which had been dispatched prior to the failure has depicted in table 4.1.

Table 4.1: Generation status just before initiating the failure-study case 01

Power Station	Unit Number	MW
Old_Laxapana	1	18
Old_Laxapana	2	12
New laxapana	1	25
New laxapana	2	25
Polpitiya	1	32
Polpitiya	2	32
Canyon	1	10
WPS	1	10
Samanalawewa	1	10
Samanalawewa	2	0
Ukuwela	1	20
Ukuwela	2	0
Bowatanna	1	0
Kukule	1	26
Kukule	2	0
Asia Power	1	0
Barge	1	0
Randenigala	1	0
Randenigala	2	0
Puttalam Wind	1	20
Kothmale (Frequency Control)	1	44
Kothmale	2	0
Kothmale	3	0
Upper Kothmale	1	40
Upper Kothmale	2	0
Victoria	1	0
Victoria	2	0
Victoria	3	0
Rantambe	1	0
Rantambe	2	0
KPS GT 7	1	0
KCCP GT	1	105
KCCP ST	1	50
AES GT	1	0
AES ST	1	0
WCP	1	0
SPS A	1	0
SPS B1	1	27
SPS B2	1	18
Lakvijaya	1	200
Lakvijaya	2	200
Lakvijaya	3	200
Total Generation /MW		1124

4.3.1.2 Frequency analysis of the study case 01

The frequency plot of the study frequency variation during the failure duration is illustrated at figure 4.3.

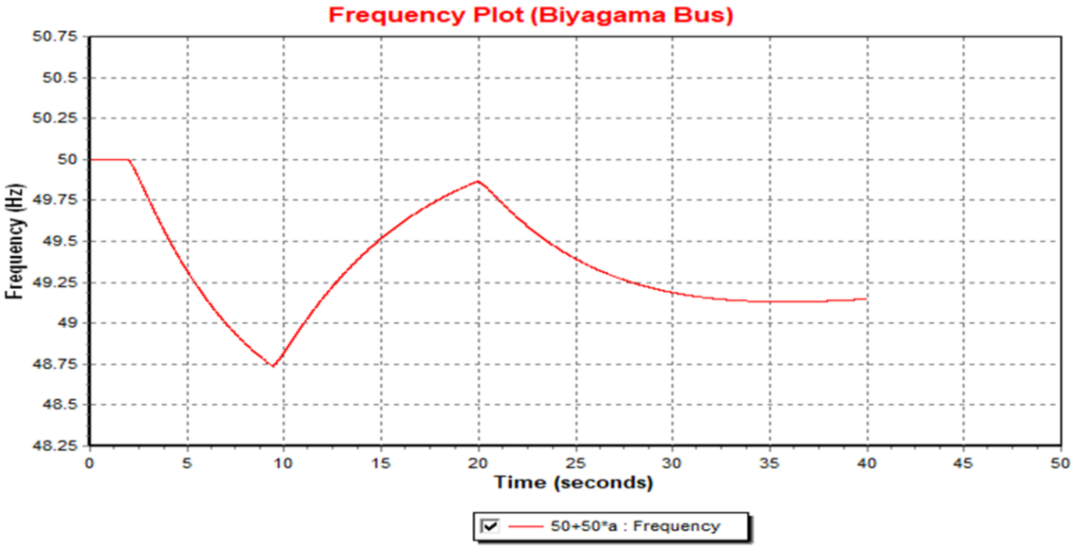


Figure 4.3: Simulation frequency plot of the failure-study case 01 at Biyagama 220kV bus

The frequency plot comparison of the study frequency variation and the actual frequency variation during the failure duration is illustrated at figure 4.4.

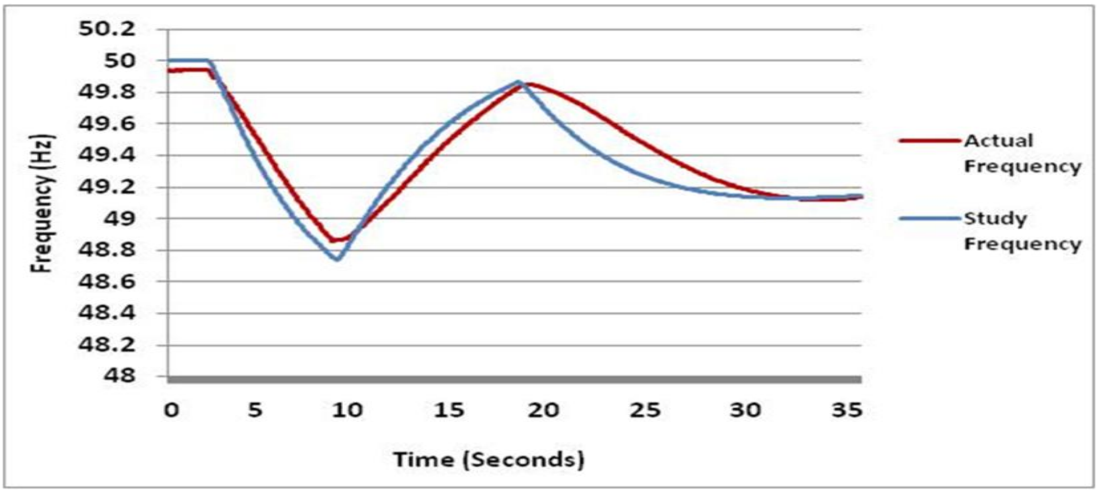


Figure 4.4: Simulation frequency and actual frequency comparison of the failure-study case 01

Figure 4.3 shows the dynamic behavior of system frequency during the power system failure which was coursed by the tripping of KCCP plant. According to the graph, the two frequency collapsing points had been occurred at 5s and 20s due to the tripping of KCCP steam turbine and KCCP gas turbine respectively with the time delay of 15s. A sudden loss of supply or demand will result in frequency deviation from the nominal value. The rate of change in frequency depends on the amount of overload and overall system inertia. As system frequency decreases, the torque of the remaining system generation will tend to increase, the load torque will tend to decrease and the overall effect will be a reduction of rate of frequency decay. If no governor action initiates the damping effect produced by changes in generator and load torques will eventually cause the frequency to stable at lower value than nominal frequency. If free governor machines are responded the rate of change of frequency decay will further reduce and frequency will remain stable at somewhat higher value than previous. In either case frequency will be left at lower value. If available spinning reserve is not adequate to cater the amount of generation loss then frequency will decrease further. Remedial action should be taken to restore the frequency. Any delaying or non-execution of remedial action to restore the frequency, under frequency protection of generators will be activated to avoid the possible damage to the generator. This will lead to cascade tripping and eventually system will be collapsed. Figure 4.1 presents the frequency variation prior and during the failure retrieved from DFR records, as shown in the diagram system reach immediate dynamic stability in terms of frequency just after tripping as stated above.

Comparison of the actual frequency and study frequency profiles are as shown in Figure 4.4. The important consideration was that the model showed the same trends as those recorded following the generator tripping. The frequency variation of the study frequency and the actual frequency is very much similar but not exact up to 100%. This may be basically to not representing the involvement of the system operator at the plot of study frequency variation. In actual case, the remedial actions which had been taken quickly but carefully in order to restore the system by the system operator was very much significant. The other reason can be the unidentified incident such as tripping of embedded generation due to frequency validation which were injecting a significant amount of active power to the system, might have changed the loss of generation percentage and hence the actual frequency behavior. The mismatch of amount of 33kV feeder active power loading and the complex load model with the anticipated values could be other reasons for this frequency plot mismatch. Another major reason for that is the mismatch of study governor parameters with actual governor parameters and the actual active power load flow at the failure time.

4.3.1.3 Voltage analysis of the study case 01

The Voltage plot of the study Voltage variation during the failure duration is illustrated at figure 4.5.

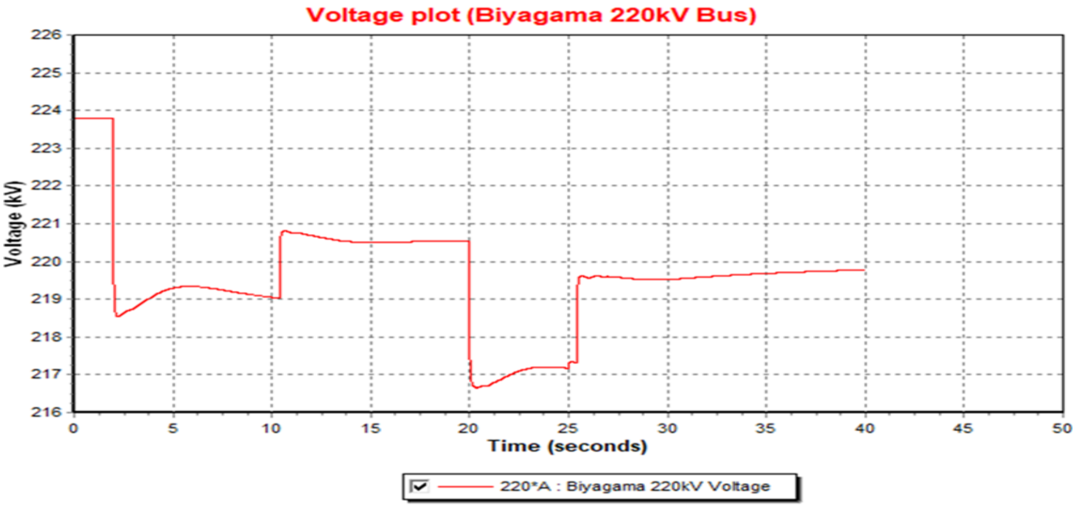


Figure 4.5: Simulation voltage plot of the failure-study case 01 at New Anuradhapura 220kV bus

The voltage plot comparison of the study Voltage variation and the actual Voltage variation during the failure duration is illustrated at figure 4.6.

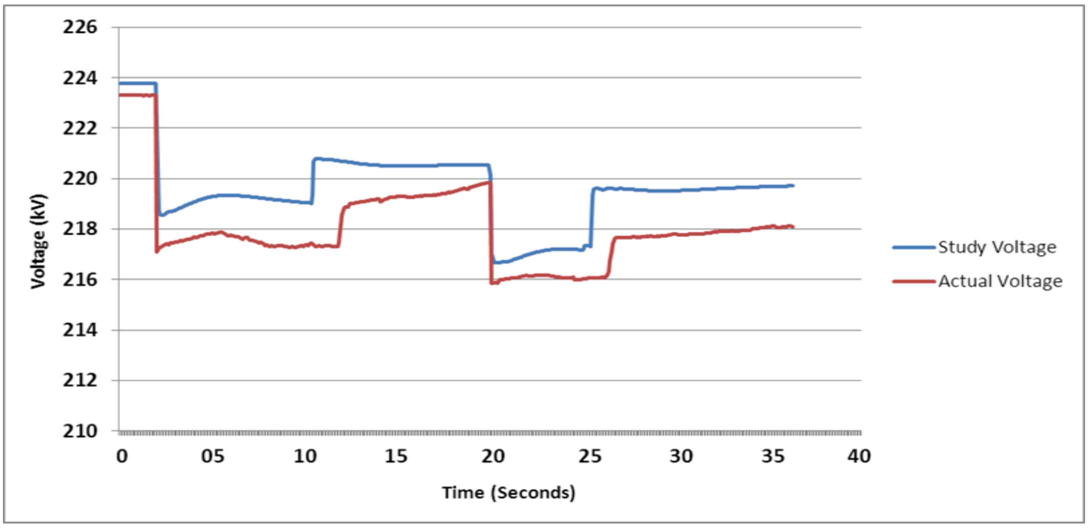


Figure 4.6: Simulation voltage and actual voltage comparison of the failure-study case 01

Just before the generator failure happened, it could be observed that system was under light load condition and most of the generators, running at the time of failure were either producing leading reactive power or zero reactive power. Due to the excess of reactive power, the system was running at little higher voltage. The two Voltage collapsing points had been occurred at 5s and 20s due to the tripping of KCCP steam turbine and KCCP gas turbine respectively with the time delay of 15s.

Comparison of the actual voltage and study voltage profiles are as shown in Figure 4.6. The important consideration was that the model showed the same trends as those recorded following the generator tripping. The voltage variation of the study voltage and the actual voltage is very much similar but not exact up to 100%. This may be basically to not representing the involvement of the system operator at the plot of study voltage variation. In actual case, the remedial actions which had been taken quickly but carefully in order to restore the system by the system operator was very much significant. The other reason can be the unidentified incident such as tripping of embedded generation due to frequency validation which were injecting a significant amount of reactive power to the system, might have changed the system voltage behavior. The mismatch of amount of 33kV feeder reactive power loading and the complex load model with the anticipated values could be other reasons for this voltage plot mismatch. Another major reason for that is the mismatch of study exciter parameters with actual exciter parameters and the actual reactive power load flow at the failure time.

This adjusted PSS/E model will be used to perform further studies to make overall conclusions and recommendation of this research.

4.3.2 Study case 02: The tripping of LVPS unit 01-plant on 06.07.2016

4.3.2.1 Incident description of study case 02

The failure was initiated with the tripping of LVPS unit-01 plant on 06.07.2016 at 02:50hrs. The dispatch scenario was thermal maximum and the demand scenario was a very low load condition at an off peak valley period. Weather condition was fair and the atmospheric conditions were normal.

System active power generation was 1146MW and the system reactive power generation was 349Mvar prior to the incident. At the failure, the rejected generation was 276MW which was 24.08% from the total generation. The number of operated UFLS scheme stages was 03 and the total shedded 33kV load was 250MW which was 21.82% from the total system generation. The slack generation was catered by the swing generator (Kothmale unit-01), free governor mode activation of the remaining system generators and the involvement of system operator.

The generation status which had been dispatched prior to the failure has depicted in table 4.2.

Table 4.2: Generation status just before initiating the failure-study case 02

Power Station	Unit Number	MW
Old_Laxapana	1	5
Old_Laxapana	2	10
New laxapana	1	10
New laxapana	2	10
Polpitiya	1	5
Polpitiya	2	5
Canyon	1	0
WPS	1	0
Samanalawewa	1	0
Samanalawewa	2	0
Ukuwela	1	0
Ukuwela	2	0
Bowatanna	1	0
Kukule	1	0
Kukule	2	0
Asia Power	1	0
Barge	1	30
Randenigala	1	0
Randenigala	2	0
Puttalam Wind	1	10
Kothmale (Frequency Control)	1	54
Kothmale	2	0
Kothmale	3	0
Upper Kothmale	1	0
Upper Kothmale	2	0
Victoria	1	0
Victoria	2	0
Victoria	3	0
Rantambe	1	0
Rantambe	2	0
KPS GT 7	1	0
KCCP GT	1	105
KCCP ST	1	50
AES GT	1	0
AES ST	1	0
WCP	1	0
SPS A	1	0
SPS B1	1	18
SPS B2	1	18
Lakvijaya	1	276
Lakvijaya	2	270
Lakvijaya	3	270
Total Generation /MW		1146

4.3.2.2 Frequency analysis of the study case 02

The frequency plot of the study frequency variation during the failure duration is illustrated at figure 4.7.

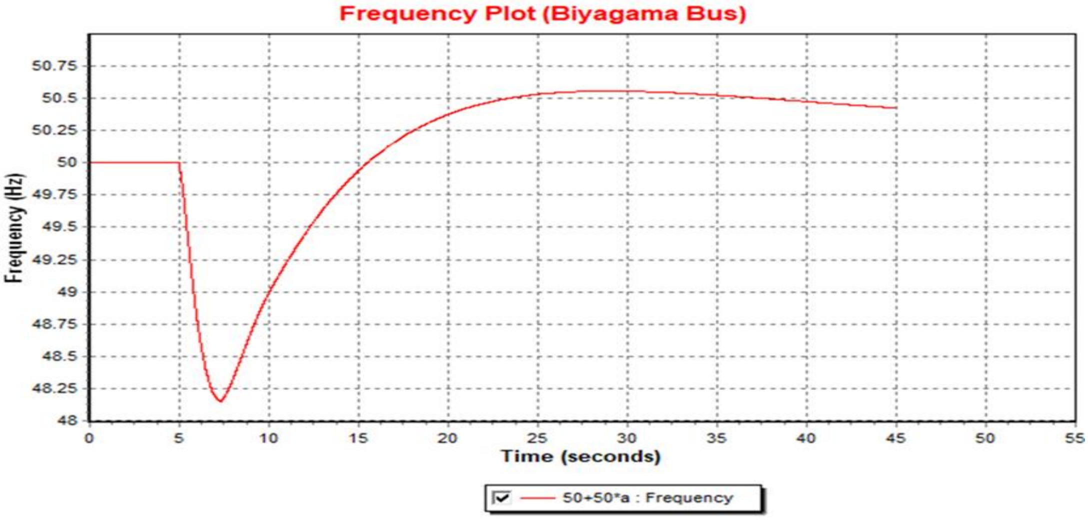


Figure 4.7: Simulation frequency plot of the failure-study case 02 at Biyagama 220kV bus

The frequency plot comparison of the study frequency variation and the actual frequency variation during the failure duration is illustrated at figure 4.8.

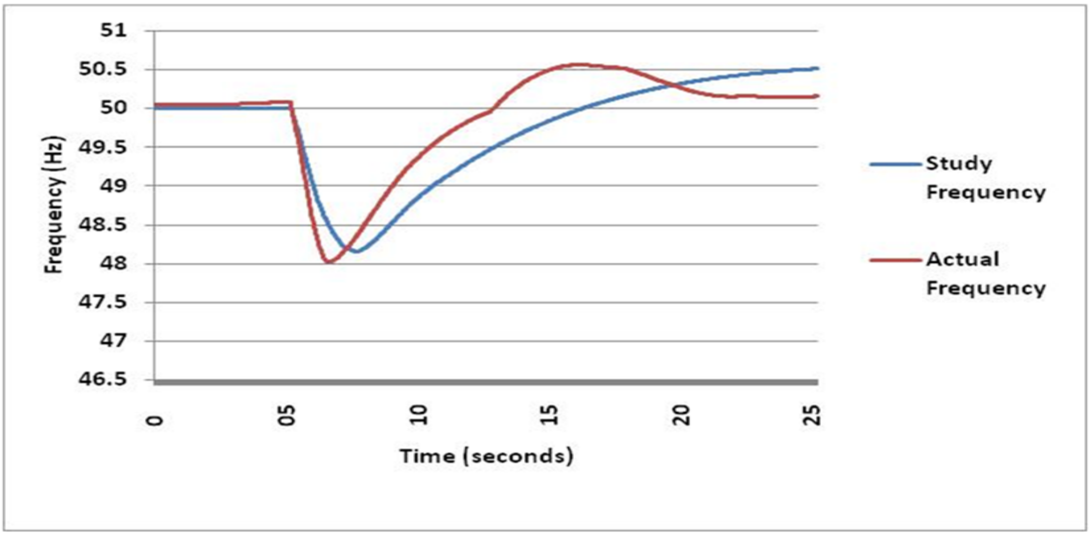


Figure 4.8: Simulation frequency and actual frequency comparison the failure-study case 02 at Biyagama 220kV bus

The power system model includes the entire 220kV and 132kV transmission network of Sri Lanka. Loads are connected to 33kV buses via 132/33kV distribution transformer and model contains around 200 buses. Load flow study carried out for generation pattern as mention in table 4.2 to replicate system condition observed just prior to the generator failure.

Figure 4.7 shows the dynamic behavior of system frequency during the power system failure due to the tripping of LVPS unit-01. According to the graph, after the generator failure happened, the frequency collapsed due to the rejection of such a huge amount of active power generation from the system and the frequency overshoot due to the activation of UFLS scheme was controlled by the remaining governors of the system and the actions which had been taken by the system operator. A sudden loss of supply or demand will result in frequency deviation from the nominal value. The rate of change in frequency depends on the amount of overload and overall system inertia. As system frequency decreases, the torque of the remaining system generation will tend to increase, the load torque will tend to decrease and the overall effect will be a reduction of rate of frequency decay. If no governor action initiates the damping effect produced by changes in generator and load torques will eventually cause the frequency to stable at lower value than nominal frequency. If free governor machines are responded the rate of change of frequency decay will further reduce and frequency will remain stable at somewhat higher value than previous. In either case frequency will be left at lower value. If available spinning reserve is not adequate to cater the amount of generation loss then frequency will decrease further. Remedial action should be taken to restore the frequency. Any delaying or non-execution of remedial action to restore the frequency, under frequency protection of generators will be activated to avoid the possible damage to the generator. This will lead to cascade tripping and eventually system will be collapsed. Figure 4.1 presents the frequency variation prior and during the failure retrieved from DFR records, as shown in the diagram system reach immediate dynamic stability in terms of frequency just after tripping as stated above.

Comparison of the actual frequency and study frequency profiles as shown in Figure 4.8. The important consideration was that the model showed the same trends as those recorded following the generator tripping. The frequency variation of the study frequency and the actual frequency is very much similar but not exact up to 100%. This may be basically to not representing the involvement of the system operator at the plot of study frequency variation. In actual case, the remedial actions which had been taken quickly but carefully in order to restore the system by the system operator was very much significant. The other reason can be the unidentified incident such as tripping of embedded generation due to frequency validation which were injecting a significant amount of active power to the system, might have changed the loss of generation percentage and hence the actual frequency behavior. The mismatch of amount of 33kV feeder active power loading and the complex load model with the anticipated values could be other reasons for this frequency plot mismatch. Another major reason for that, is the mismatch of study governor parameters with actual governor parameters and the actual active power load flow at the failure time.

4.3.2.3 Voltage analysis of the study case 02

The voltage plot of the study Voltage variation during the failure duration is illustrated at figure 4.9.

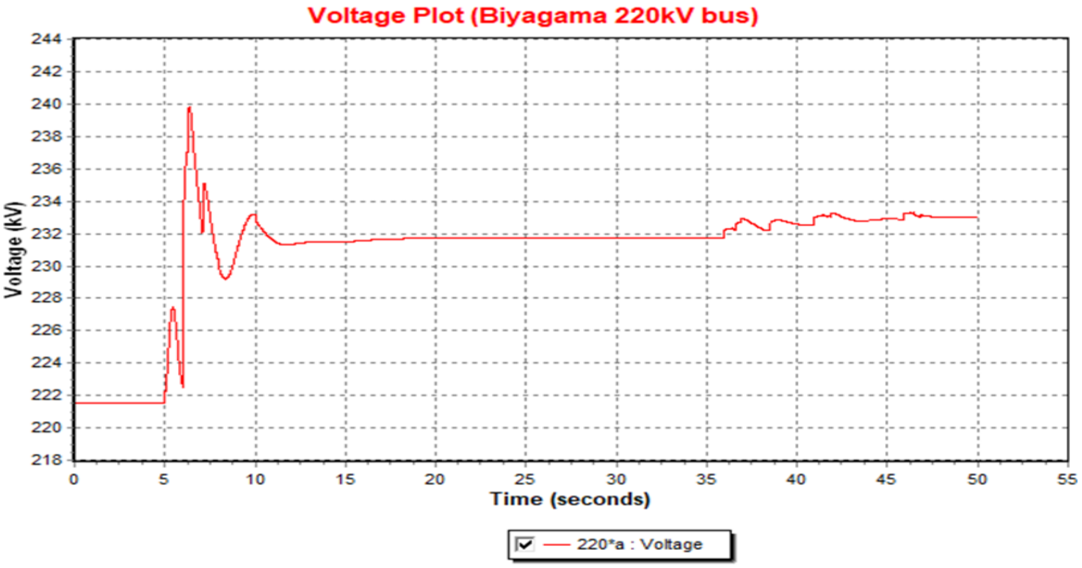


Figure 4.9: Simulation voltage plot of the failure-study case 02 at New Anuradhapura 220kV bus

The Voltage plot comparison of the study voltage variation and the actual Voltage variation during the failure duration is illustrated at figure 4.10.

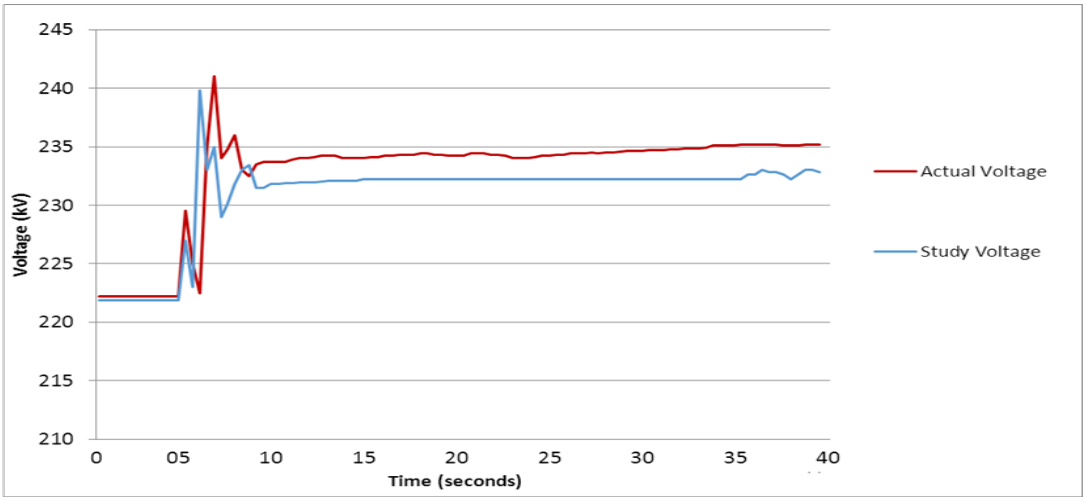


Figure 4.10: Simulation voltage and actual voltage comparison of the failure-study case 02

Just before the generator failure happened, it could be observed that system was under light load condition and most of the generators, running at the time of failure were either producing leading reactive power or zero reactive power. Due to the excess of reactive power, the system was running at little higher voltage. After the generator failure happened, the Voltage roused due to the rejection of such a huge amount of reactive power generation from the system and the voltage overshoot due to the activation of UFLS scheme was controlled by the remaining exciters of the system and the actions which had been taken by the system operator.

Comparison of the actual voltage and study voltage profiles as shown in Figure 4.10. The important consideration was that the model showed the same trends as those recorded following the generator tripping. The voltage variation of the study Voltage and the actual voltage is very much similar but not exact up to 100%. This may be basically to not representing the involvement of the system operator at the plot of study voltage variation. In actual case, the remedial actions which had been taken quickly but carefully in order to restore the system by the system operator was very much significant. The other reason can be the unidentified incident such as tripping of embedded generation due to frequency validation, which were injecting a significant amount of reactive power to the system, might have changed the system voltage behavior. The mismatch of amount of 33kV feeder reactive power loading and the complex load model with the anticipated values could be other reasons for this voltage plot mismatch. Another major reason for that is the mismatch of study exciter parameters with actual exciter parameters and the actual reactive power load flow at the failure time.

This adjusted PSS/E model was used to perform further studies to make overall conclusions and recommendation of this study.

Chapter 5

SIMULATION AND ANALYSIS OF GENERATION REJECTION INCIDENTS

5.1 Methodology

After validating the model with separate two kind of tripping cases under separate dispatch scenarios with parameters of present Sri Lankan power system, steady state simulations and dynamic simulations have been carried out for three different dispatch scenarios (i.e. Hydro Maximum, Thermal Maximum, Extreme Thermal Maximum) under light load conditions out of which the power system is highly vulnerable for the collapsing, if a large portion of a generation gets rejected from the system.

According to sub section 3.6.1**,** since LVPS unit 01 is the generator which has highest over frequency trip setting (51.83Hz – 3110r.p.m.) among the entire 03 phases, for the simulations it will be considered the tripping of LVPS unit 01 all the time. Because, if so only it can be determined whether after a considerable amount of generation rejection from the system, the frequency overshoot would rise up until the threshold limit of the generator which has the lowest over frequency trip setting.

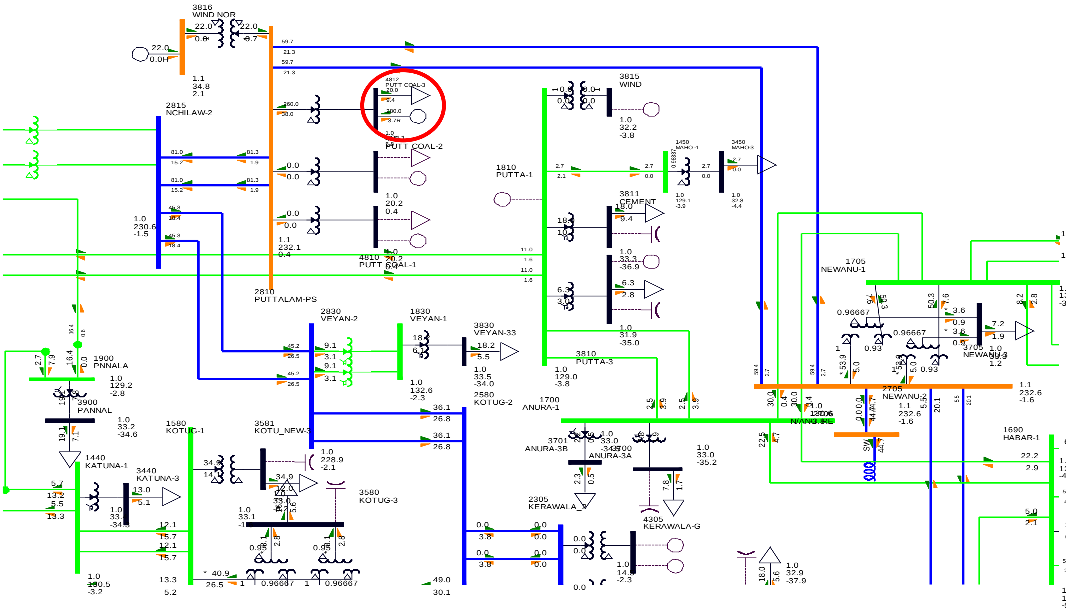


Figure 5.1: Generator tripping simulation of LVPS unit-01 in PSS/E

According to section 2.4, since LVPS single unit generation contribution limited to 19% to 27%, the study will analyze the generation rejection incidents from a single generator with the generation contribution percentage difference of 2% within the above consideration limitation for both frequency and voltage stability. Then the optimum maximum value which can be loaded the cola generation at it’s maximum (i.e. considering the power system operational economy) in such a way that the power system frequency and voltage does not violate the normal operational limits (i.e. considering the power system stability) will be observed through the simulations. Finally, analyzing the observations of the simulations, the maximum range where a single generator unit can be loaded will be determined under each dispatch scenario.

5.2 Case study of Hydro Maximum Scenario

The Hydro maximum scenario mostly occurs in rainy seasons. The significance of hydro maximum scenario is that when it comes to generator dispatching, most of the large thermal generators are replaced by CEB hydro generators and IPP mini hydro generators. In hydro maximum scenario the system demand is also comparatively low considering other dispatch scenarios due to low environmental temperature and high number of 33kV feeder tripping incidents due to rainy and windy atmosphere.

These situations directly lead to weaken the overall system inertia constant (due to low number of high inertia thermal machines with high number of low inertia hydro and mini hydro machines) and as a result it would directly affect to the system frequency stability when a disturbance happens. Also in this case due to the same course, the voltage stability is comparatively poor.

The minimum value of average off peak demand is 800MW [4]. Therefore, the worst case average off peak system demand in maximum hydro scenario has been taken as 800MW for the study simulations. The selected swing generator is Victoria unit 01. LVPS generation percentage is varied according to the following table by adjusting the remaining generation while keeping the total system generation as a constant during the study period. Study cases for generator tripping incidents have been illustrated in table 5.1.

Table 5.1: Study cases for Hydro Maximum Scenario

Case Number	**Contribution percentage of LVPS single generator (%)**	**Corresponding load value of the LVPS single generator (MW)**
1.1	27	216
1.2	25	200
1.3	23	184
1.4	21	168
1.5	19	152

Table 5.2: Sample generator dispatch for the study cases of Hydro Maximum Scenario

Power Station	Unit Number	MW
Old_Laxapana	1	10
Old_Laxapana	2	10
New laxapana	1	20
New laxapana	2	20
Polpitiya	1	25
Polpitiya	2	32
Canyon	1	10
WPS	1	0
Samanalawewa	1	0
Samanalawewa	2	0
Ukuwela	1	0
Ukuwela	2	0
Bowatanna	1	0
Kukule	1	30
Kukule	2	0
Asia Power	1	0
Barge	1	0
Randenigala	1	0
Randenigala	2	0
Puttalam Wind	1	20
Kothmale	1	0
Kothmale	2	0
Kothmale	3	0
Upper Kothmale	1	40
Upper Kothmale	2	0
Victoria (Frequency Control)	1	31
Victoria	2	0
Victoria	3	0
Rantambe	1	0
Rantambe	2	0
KPS GT 7	1	0
KCCP GT	1	0
KCCP ST	1	0
AES GT	1	0
AES ST	1	0
WCP	1	0
SPS A	1	0
SPS B1	1	0
SPS B2	1	0
Lakvijaya	**1**	**184**
Lakvijaya	**2**	**184**
Lakvijaya	**3**	**184**
Total Generation /MW		800

5.2.1 Generator (LVPS unit 01-216MW) tripping of 27% of total system generation

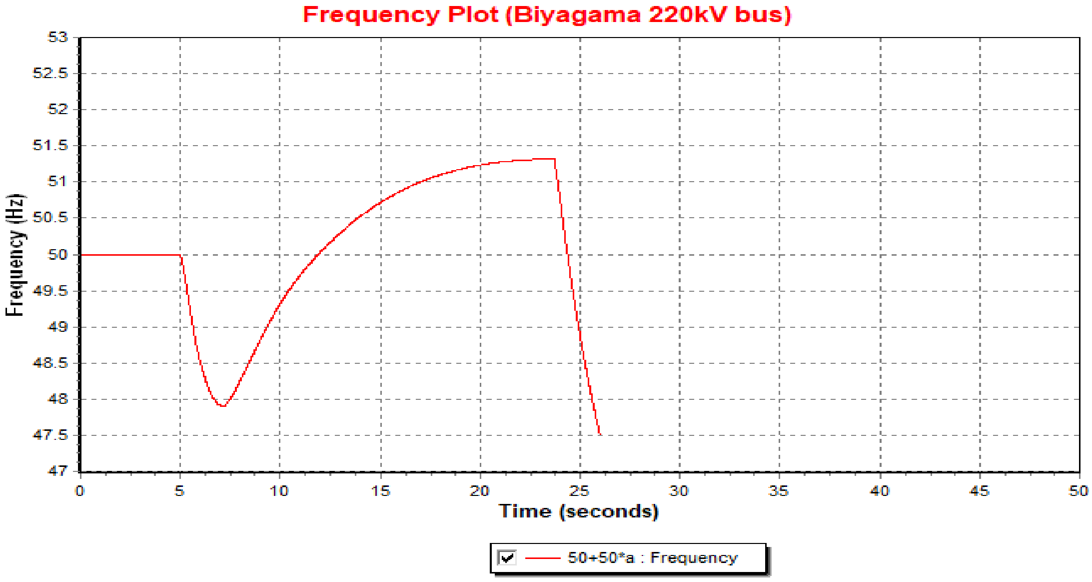


Figure 5.2: Incident 5.2.1-Frequency variation at Biyagama 220kV bus

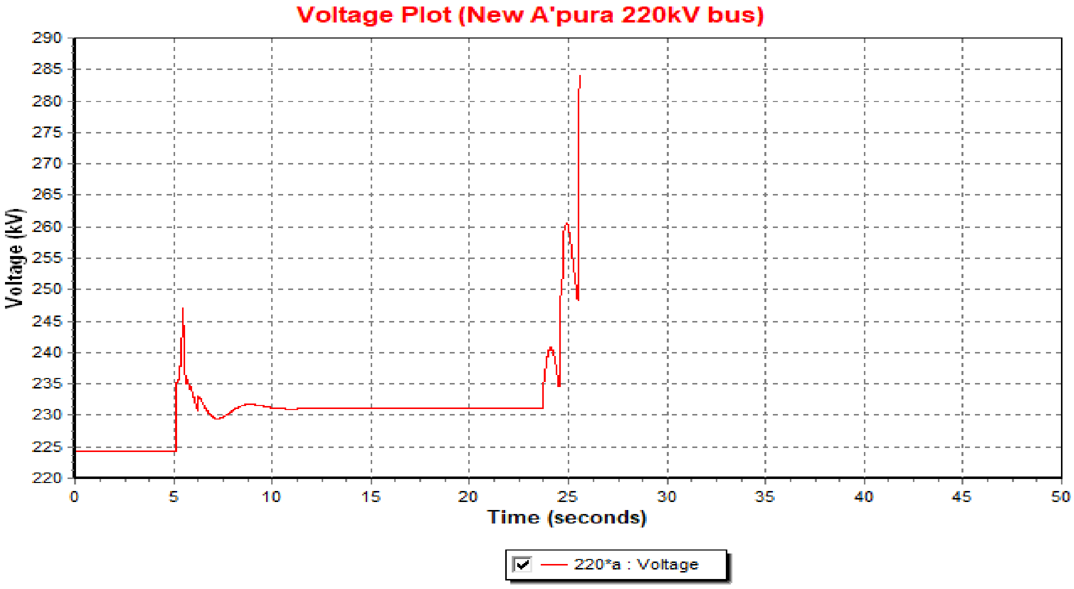


Figure 5.3: Incident 5.2.1-220kV Voltage variation at New Anuradhapura 220kV bus

Figure 5.2 shows the frequency variation of Biyagama 220kV bus when a generator (216MW) tripping of 27% of total system generation (800MW). The observations are as follows.

- Minimum frequency: 47.50Hz
- Maximum frequency: 51.30Hz
- Final stabilizing frequency: Total System Failure
- Frequency normal operational limit violation after final frequency stabilization: YES

In this frequency variation plot there can be clearly observed an under frequency operational limit violation due to the rejection of large generation percentage at 5s from the system. This obvious frequency drop can be normalized by the automatic activation of UFLS scheme. Due to the activation of UFLS scheme (i.e. large rejection of system demand), the frequency overshoot exceeds the desired over frequency normal operational limit and therefor it can be observed an over frequency normal operational limit violation. Furthermore, the frequency overshoot reaches to the over frequency protection trip setting of LVPS gen 02 which is 51.30Hz and hence, the second LVPS generator gets tripped. Due to that incident frequency drastically drops down again until it reaches 47.50Hz which is the under frequency protection trip setting of all generators of the entire national power system. There onwards, this cascade incidents leads the power system in to a total system failure. So, it can be concluded that the frequency behavior at the tripping incident of 27% generation at Hydro Maximum Scenario is infeasible.

Figure 5.3 shows the voltage variation of New Anuradhapura 220kV bus when a generator (216MW) tripping of 27% of total system generation (800MW). The observations are as follows.

- Minimum voltage: 224.31kV
- Maximum voltage: 284.45KV
- Final stabilizing voltage: Total System Failure
- Voltage normal operational limit violation after final voltage stabilization: YES

In this voltage variation plot there is no any under voltage operational limit violation due to the rejection of large generation percentage at 5s from the system. But later on, due to the activation of UFLS scheme (i.e. large rejection of system demand), the voltage overshoot exceeds the desired over voltage normal operational limit and therefor it can be observed an over voltage normal operational limit violation.

After tripping of the second LVPS generator the voltage rise is extremely drastic due to the rejection of such a high Mvar consuming unit at the moment where the system voltage is high due to the operation of UFLS scheme just after the tripping of the first LVPS generator. This voltage overshoot rises beyond 280V at the time when the total system failure is occurred due to the tripping of all generators of the power system. So, it can be concluded that the voltage behavior at the tripping incident of 27% generation at Hydro Maximum Scenario is infeasible.

5.2.2 Generator (LVPS unit 01-200MW) tripping of 25% of total system generation

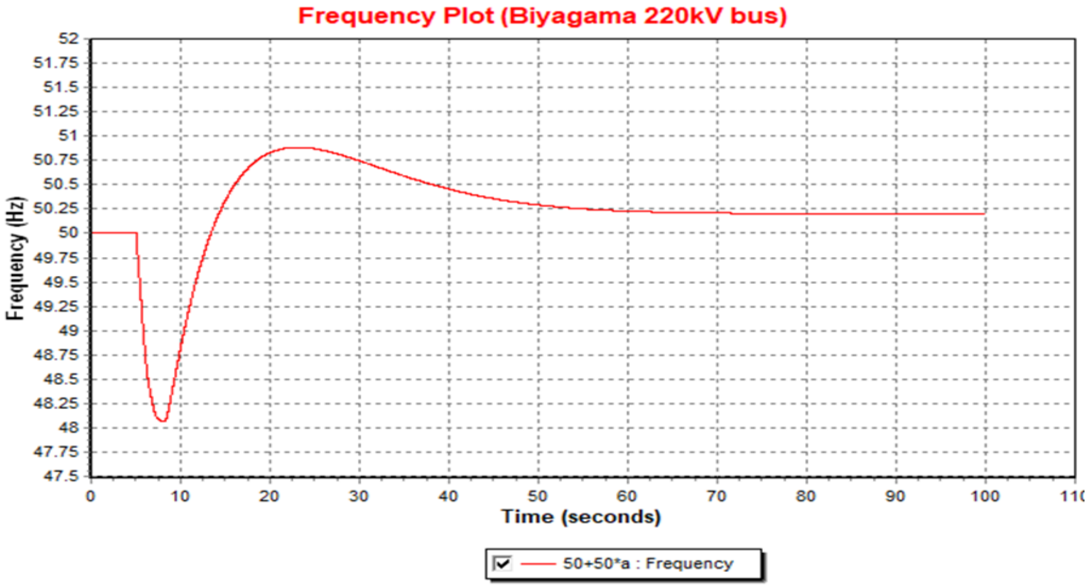


Figure 5.4: Incident 5.2.2-Frequency variation at Biyagama 220kV bus.

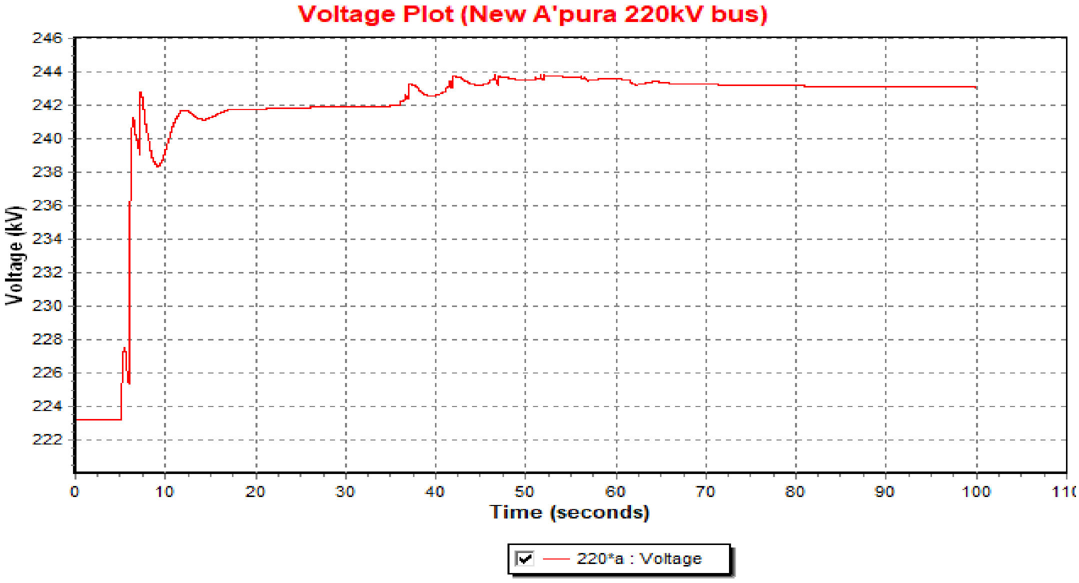


Figure 5.5: Incident 5.2.2-Voltage variation at New Anuradhapura 220kV bus

Figure 5.4 shows the frequency variation of Biyagama 220kV bus when a generator (200MW) tripping of 25% of total system generation (800MW). The observations are as follows.

- Minimum frequency: 48.06Hz
- Maximum frequency: 50.86Hz
- Final stabilizing frequency: 50.19Hz
- Frequency normal operational limit violation after final frequency stabilization: NO

In this frequency variation plot there can be clearly observed an under frequency operational limit violation due to the rejection of large generation percentage from the system after 5s. This obvious frequency drop can be normalized by the automatic activation of UFLS scheme. Due to the activation of UFLS scheme (i.e. large rejection of system demand), the final stabilizing frequency exceeds the desired over frequency normal operational limit and therefor it can be observed an over frequency normal operational limit violation after stabilizing the system. So, it can be concluded that the frequency behavior at the tripping incident of 25% generation at Hydro Maximum Scenario is feasible.

Figure 5.5 shows the voltage variation of New Anuradhapura 220kV bus when a generator (200MW) tripping of 25% of total system generation (800MW). The observations are as follows.

- Minimum voltage: 223.25kV
- Maximum voltage: 243.82kV
- Final stabilizing voltage: 243.20kV
- Voltage normal operational limit violation after final voltage stabilization: YES

In this voltage variation plot there is no any under voltage operational limit violation due to the rejection of large generation percentage from the system at 5s. But later on, due to the activation of UFLS scheme (i.e. large rejection of system demand), the final stabilizing voltage exceeds the desired over voltage normal operational limit and therefor it can be observed an over voltage normal operational limit violation after stabilizing the system. So, it can be concluded that the voltage behavior at the tripping incident of 25% generation at Hydro Maximum Scenario is infeasible.

5.2.3 Generator (LVPS unit 01-184MW) tripping of 23% of total system generation

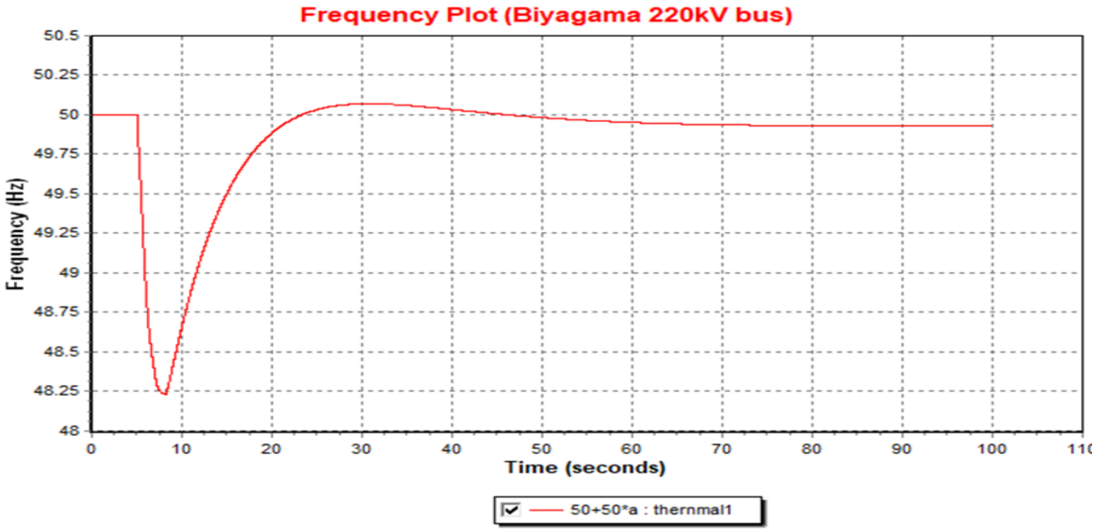


Figure 5.6: Incident 5.2.3-Frequency variation at Biyagama 220kV bus

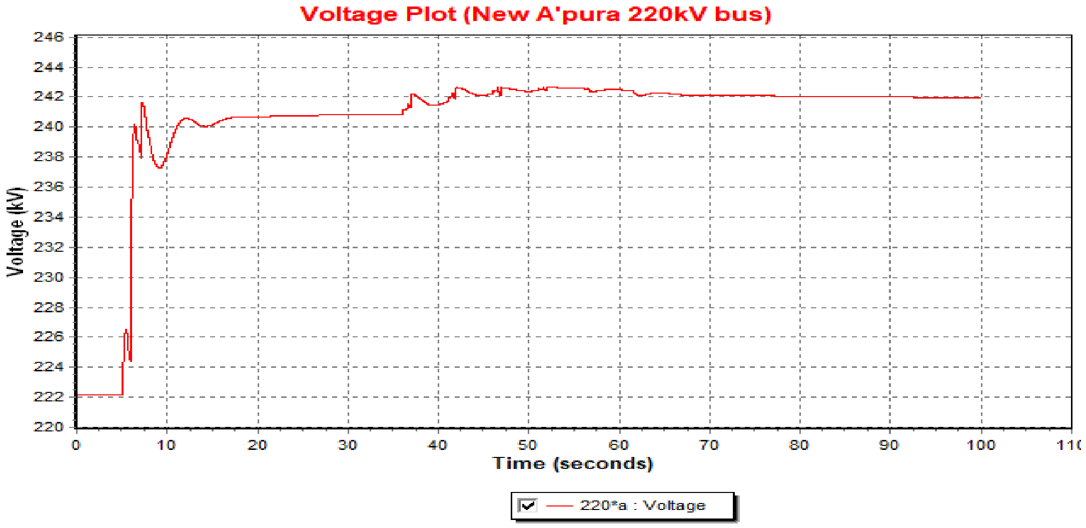


Figure 5.7: Incident 5.2.3-Voltage variation at New Anuradhapura 220kV bus

Figure 5.6 shows the frequency variation of Biyagama 220kV bus when a generator (184MW) tripping of 23% of total system generation (800MW). The observations are as follows.

- Minimum frequency: 48.21Hz
- Maximum frequency: 50.10Hz
- Final stabilizing frequency: 49.91Hz
- Frequency normal operational limit violation after final frequency stabilization: NO

In this frequency variation plot there can be clearly observed an under frequency operational limit violation due to the rejection of large generation percentage from the system at 5s. This obvious frequency drop can be normalized by the automatic activation of UFLS scheme. Due to the activation of UFLS scheme (i.e. large rejection of system demand), the final stabilizing frequency does not exceed the desired over frequency normal operational limit and therefor it cannot be observed an over frequency normal operational limit violation after stabilizing the system. So, it can be concluded that the frequency behavior at the tripping incident of 23% generation at Hydro Maximum Scenario is feasible.

Figure 5.7 shows the voltage variation of New Anuradhapura 220kV bus when a generator (184MW) tripping of 23% of total system generation (800MW). The observations are as follows.

- Minimum voltage: 222.20kV
- Maximum voltage: 242.74kV
- Final stabilizing voltage: 242.07kV
- Voltage normal operational limit violation after final voltage stabilization: YES

In this voltage variation plot there is no any under voltage operational limit violation due to the rejection of large generation percentage from the system at 5s. But later on, due to the activation of UFLS scheme (i.e. large rejection of system demand), the final stabilizing voltage exceeds the desired over voltage normal operational limit and therefor it can be observed an over voltage normal operational limit violation after stabilizing the system. So, it can be concluded that the voltage behavior at the tripping incident of 23% generation at Hydro Maximum Scenario is infeasible.

5.2.4 Generator (LVPS unit 01-168MW) tripping of 21% of total system generation

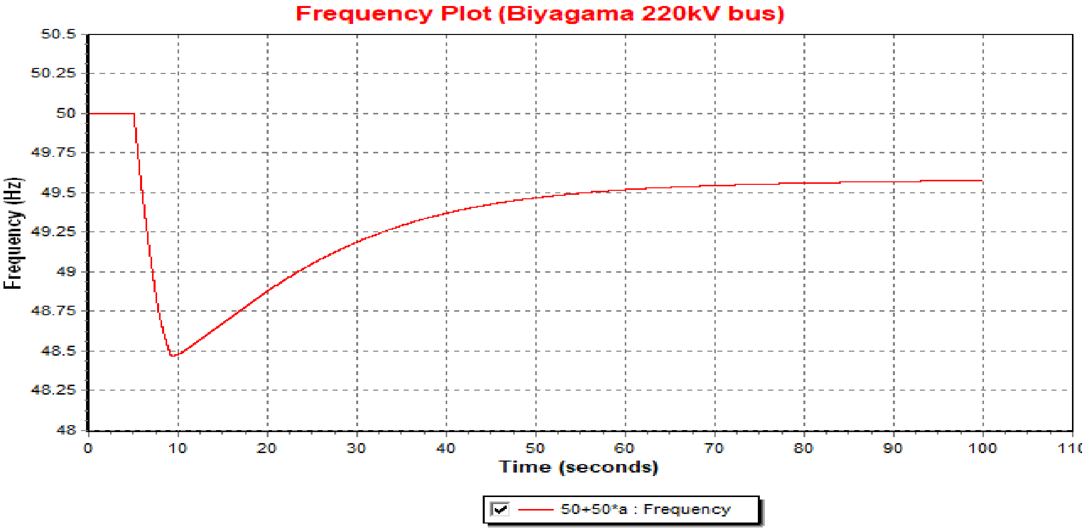


Figure 5.8: Incident 5.2.4-Frequency variation at Biyagama 220kV bus

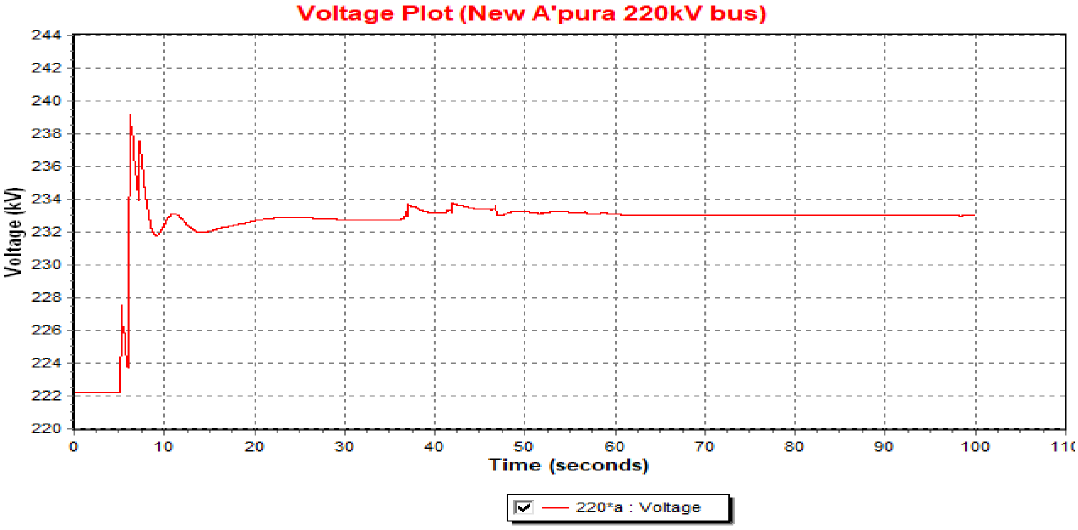


Figure 5.9: Incident 5.2.4-Voltage variation at New Anuradhapura 220kV bus

Figure 5.8 shows the frequency variation of Biyagama 220kV bus when a generator (168MW) tripping of 21% of total system generation (800MW). The observations are as follows.

- Minimum frequency: 48.43Hz
- Maximum frequency: 50.00Hz
- Final stabilizing frequency: 49.58Hz
- Frequency normal operational limit violation after final frequency stabilization: NO

In this frequency variation plot there can be clearly observed an under frequency operational limit violation due to the rejection of large generation percentage from the system at 5s. This obvious frequency drop can be normalized by the automatic activation of UFLS scheme. Due to the activation of UFLS scheme (i.e. large rejection of system demand), the final stabilizing frequency does not exceed the desired frequency normal operational limits and therefor it cannot be observed a frequency normal operational limit violation after stabilizing the system. So, it can be concluded that the frequency behavior at the tripping incident of 21% generation at Hydro Maximum Scenario is feasible.

Figure 5.9 shows the voltage variation of New Anuradhapura 220kV bus when a generator (168MW) tripping of 21% of total system generation (800MW). The observations are as follows.

- Minimum voltage: 222.30kV
- Maximum voltage: 239.45kV
- Final stabilizing voltage: 233.00kV
- Voltage normal operational limit violation after final voltage stabilization: NO

In this voltage variation plot there is no any under voltage operational limit violation due to the rejection of large generation percentage from the system at 5s. Later on, due to the activation of UFLS scheme (i.e. large rejection of system demand), the

final stabilizing voltage does not exceed the desired over voltage normal operational limit and therefor it cannot be observed an over voltage normal operational limit violation after stabilizing the system. So, it can be concluded that the voltage behavior at the tripping incident of 21% generation at Hydro Maximum Scenario is feasible.

5.2.5 Generator (LVPS unit 01-152MW) tripping of 19% of total system generation

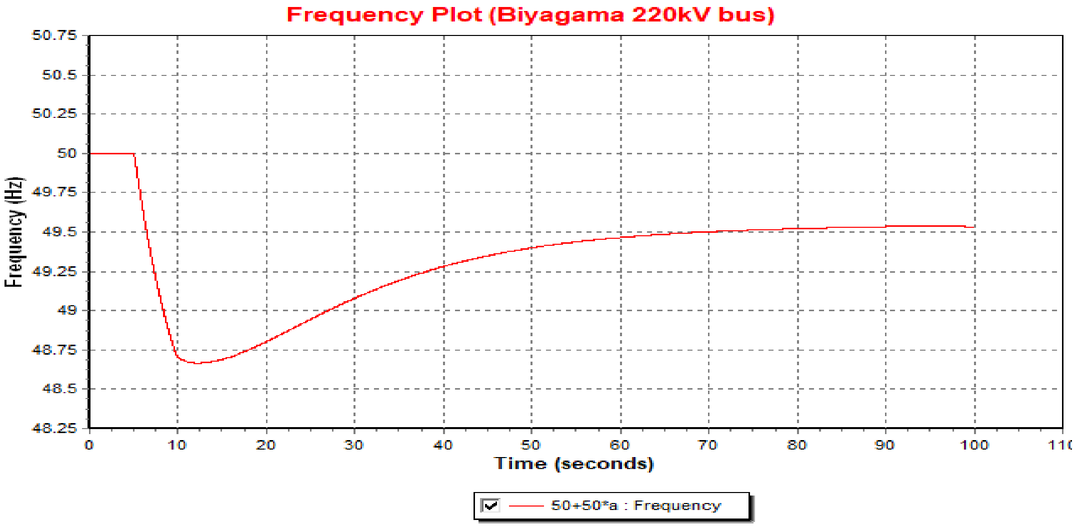


Figure 5.10: Incident 5.2.5-Frequency variation at Biyagama 220kV bus

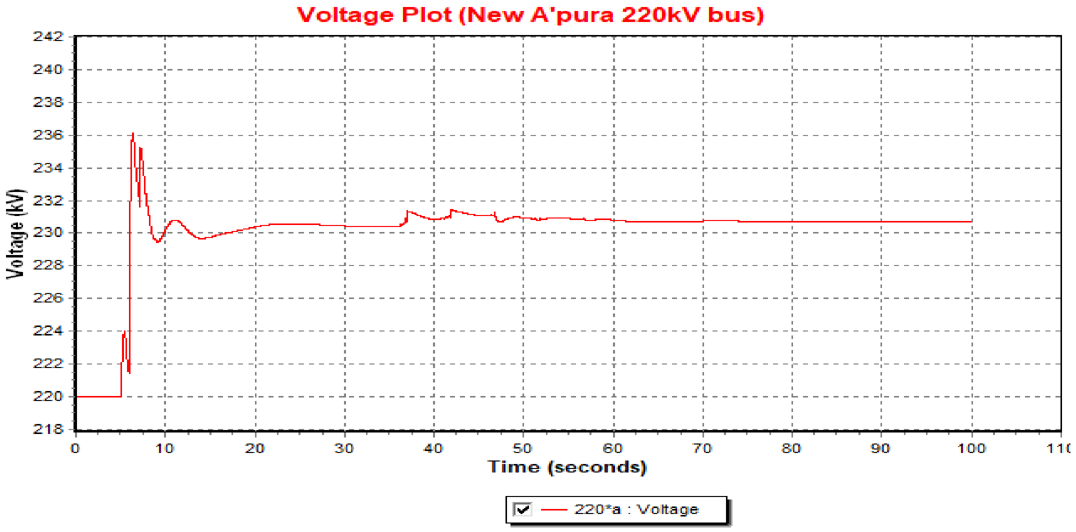


Figure 5.11: Incident 5.2.5-Voltage variation at New Anuradhapura 220kV bus

Figure 5.10 shows the frequency variation of Biyagama 220kV bus when a generator (152MW) tripping of 19% of total system generation (800MW). The observations are as follows.

- Minimum frequency: 48.66Hz
- Maximum frequency: 50.00Hz
- Final stabilizing frequency: 49.53Hz
- Frequency normal operational limit violation after final frequency stabilization: NO

In this frequency variation plot there can be clearly observed an under frequency operational limit violation due to the rejection of large generation percentage from the system at 5s. This obvious frequency drop can be normalized by the automatic activation of UFLS scheme. Due to the activation of UFLS scheme (i.e. large rejection of system demand), the final stabilizing frequency does not exceed the desired frequency normal operational limits and therefor it cannot be observed a frequency normal operational limit violation after stabilizing the system. So, it can be concluded that the frequency behavior at the tripping incident of 19% generation at Hydro Maximum Scenario is feasible.

Figure 5.11 shows the voltage variation of New Anuradhapura 220kV bus when a generator (152MW) tripping of 19% of total system generation (800MW). The observations are as follows.

- Minimum voltage: 220.00kV
- Maximum voltage: 236.10kV
- Final stabilizing voltage: 230.82kV
- Voltage normal operational limit violation after final voltage stabilization: NO

In this voltage variation plot there is no any under voltage operational limit violation due to the rejection of large generation percentage from the system at 5s. Later on, due to the activation of UFLS scheme (i.e. large rejection of system demand), the

final stabilizing voltage does not exceed the desired over voltage normal operational limit and therefor it cannot be observed an over voltage normal operational limit violation after stabilizing the system. So, it can be concluded that the voltage behavior at the tripping incident of 19% generation at Hydro Maximum Scenario is feasible.

5.3 Case study of Thermal Maximum Scenario

The thermal maximum scenario mostly occurs in dry seasons. The significance of thermal maximum scenario is that when it comes to generator dispatching, most of the hydro generators are replaced by CEB thermal generators and IPP thermal generators. In thermal maximum scenario the system demand is also comparatively high at a particular time, considering other dispatch scenarios due to high environmental temperature and high number of 33kV feeder loads due to industrial demand.

These situations directly lead to comparatively strengthen the overall system inertia constant (due to high number of high inertia thermal machines with low number of low inertia hydro and mini hydro machines) and as a result it would directly affect to the system frequency stability when a disturbance happens. Also in this case, due to the same course, the voltage stability is comparatively high.

In this scenario the average minimum value of peak demand is 1000MW [4]. Therefore, the worst case average off peak system demand in maximum thermal scenario has been taken as 1000MW for the study simulations. The selected swing generator is Kothmale unit 01. LVPS generation percentage is varied according to the following table by adjusting the remaining generation while keeping the total system generation as a constant at the study period.

Table 5.3: Study cases for Thermal Maximum Scenario

Case Number	**Contribution percentage of LVPS single generator (%)**	**Corresponding load value of the LVPS single generator (MW)**
1.1	27	270
1.2	25	250
1.3	23	230
1.4	21	210
1.5	19	190

Table 5.4: Sample generation dispatch of the study cases of Thermal Maximum Scenario

Power Station	Unit Number	MW
Old_Laxapana	1	5
Old_Laxapana	2	10
New laxapana	1	10
New laxapana	2	10
Polpitiya	1	5
Polpitiya	2	5
Canyon	1	0
WPS	1	0
Samanalawewa	1	0
Samanalawewa	2	0
Ukuwela	1	0
Ukuwela	2	0
Bowatanna	1	0
Kukule	1	0
Kukule	2	0
Asia Power	1	0
Barge	1	30
Randenigala	1	0
Randenigala	2	0
Puttalam Wind	1	10
Kothmale (Frequency Control)	1	47
Kothmale	2	0
Kothmale	3	0
Upper Kothmale	1	0
Upper Kothmale	2	0
Victoria	1	0
Victoria	2	0
Victoria	3	0
Rantambe	1	0
Rantambe	2	0
KPS GT 7	1	0
KCCP GT	1	100
KCCP ST	1	50
AES GT	1	0
AES ST	1	0
WCP	1	0
SPS A	1	0
SPS B1	1	14
SPS B2	1	14
Lakvijaya	**1**	**230**
Lakvijaya	**2**	**230**
Lakvijaya	**3**	**230**
Total Generation /MW		1000

5.3.1 Generator (LVPS unit 01-270MW) tripping of 27% of total system generation

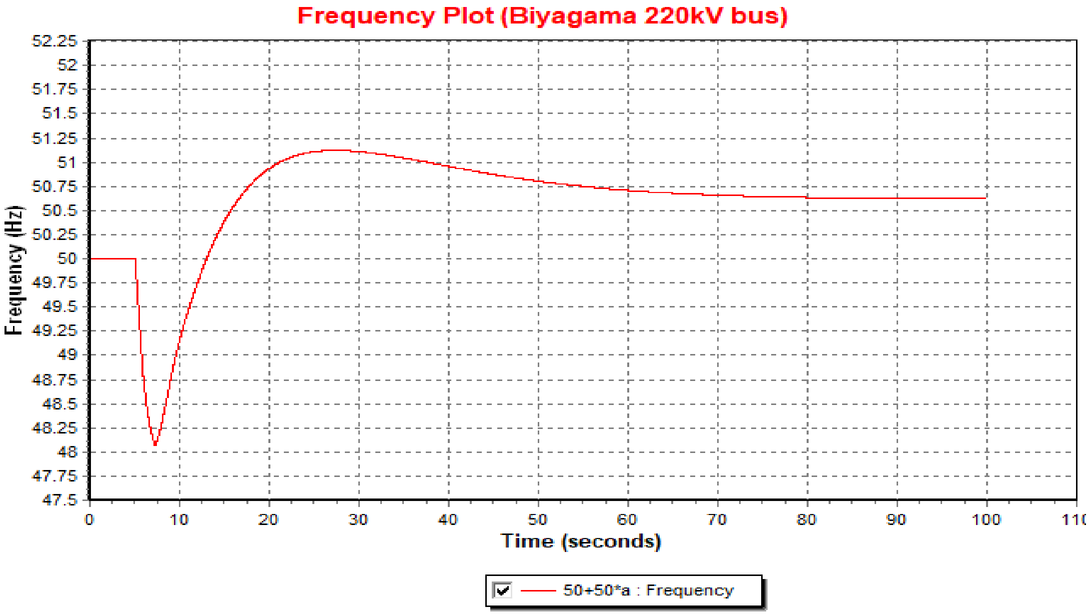


Figure 5.12: Incident 5.3.1-Frequency variation at Biyagama 220kV bus

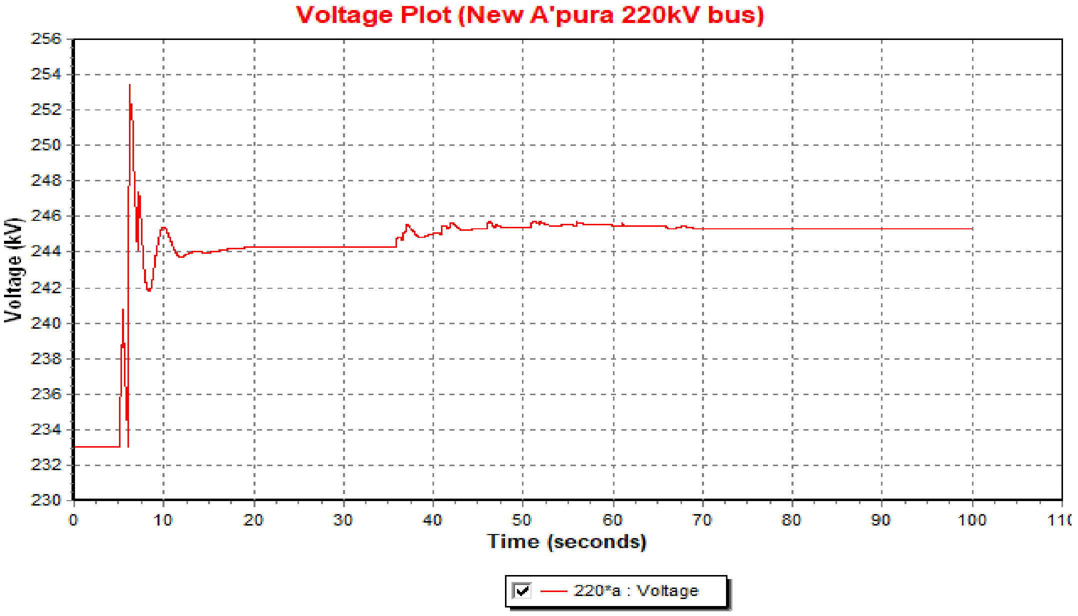


Figure 5.13: Incident 5.3.1-Voltage variation at New Anuradhapura 220kV bus

Figure 5.12 shows the frequency variation of Biyagama 220kV bus when a generator (270MW) tripping of 27% of total system generation (1000MW). The observations are as follows.

- Minimum frequency: 48.03Hz
- Maximum frequency: 51.14Hz
- Final stabilizing frequency: 50.66Hz
- Frequency normal operational limit violation after final frequency stabilization: YES

In this frequency variation plot there can be clearly observed an under frequency operational limit violation due to the rejection of large generation percentage from the system at 5s. This obvious frequency drop can be normalized by the automatic activation of UFLS scheme. Due to the activation of UFLS scheme (i.e. large rejection of system demand), the final stabilizing frequency exceeds the desired over frequency normal operational limit and therefor it can be observed an over frequency normal operational limit violation after stabilizing the system. So, it can be concluded that the frequency behavior at the tripping incident of 27% generation at Thermal Maximum Scenario is infeasible.

Figure 5.13 shows the voltage variation of New Anuradhapura 220kV bus when a generator (270MW) tripping of 27% of total system generation (1000MW). The observations are as follows.

- Minimum voltage: 232.82kV
- Maximum voltage: 253.64kV
- Final stabilizing voltage: 245.20kV
- Voltage normal operational limit violation after final voltage stabilization: YES

In this voltage variation plot there is no any under voltage operational limit violation due to the rejection of large generation percentage from the system at 5s. But later on, due to the activation of UFLS scheme (i.e. large rejection of system demand), the

final stabilizing voltage exceeds the desired over voltage normal operational limit and therefor it can be observed an over voltage normal operational limit violation after stabilizing the system. So, it can be concluded that the voltage behavior at the tripping incident of 27% generation at Thermal Maximum Scenario is infeasible.

5.3.2 Generator (LVPS unit 01-250MW) tripping of 25% of total system generation

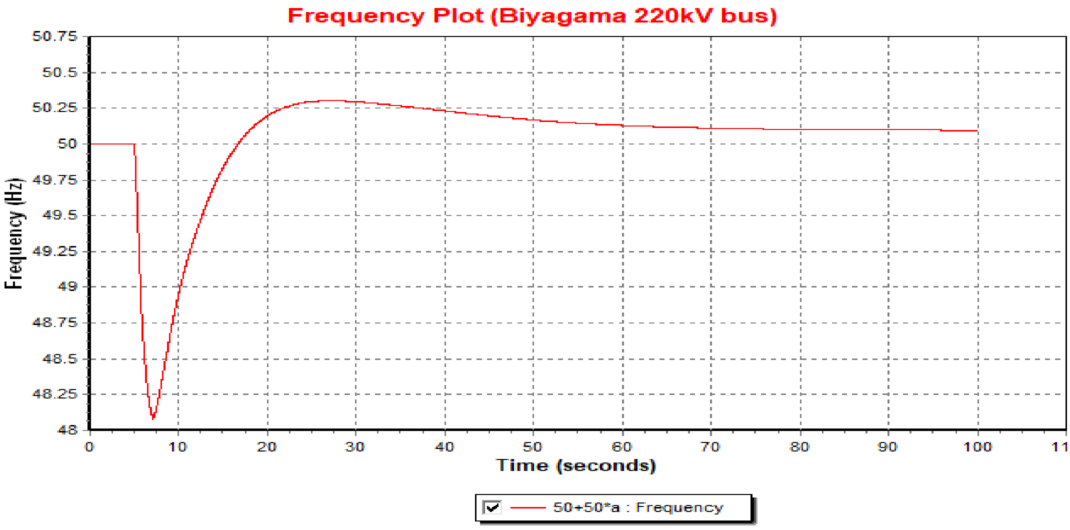


Figure 5.14: Incident 5.3.2-Frequency variation of Bitagama 220kV bus

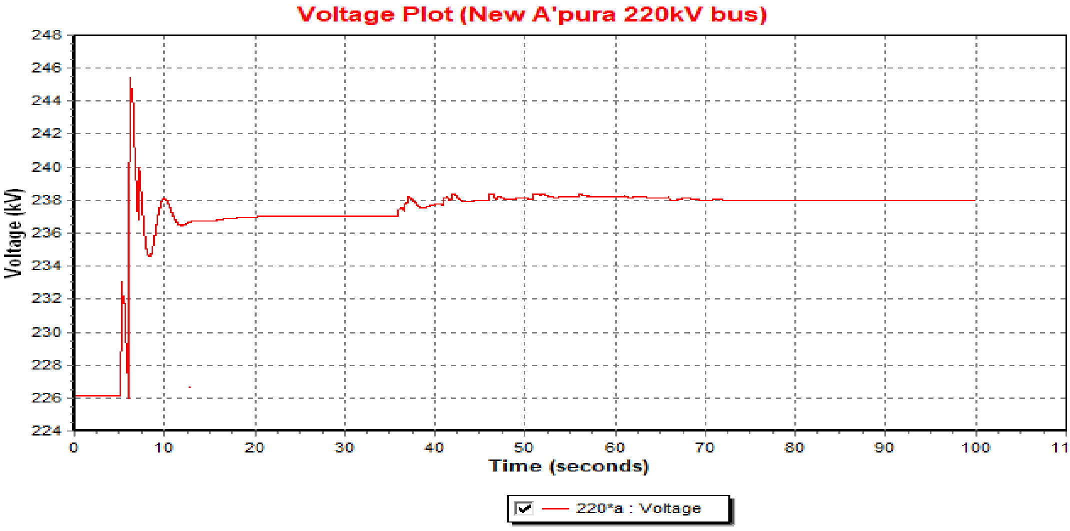


Figure 5.15: Incident 5.3.2-Voltage variation at New Anuradhapura 220kV bus

Figure 5.14 shows the frequency variation of Biyagama 220kV bus when a generator (250MW) tripping of 25% of total system generation (1000MW). The observations are as follows.

- Minimum frequency: 48.09Hz
- Maximum frequency: 50.32Hz
- Final stabilizing frequency: 50.12Hz
- Frequency normal operational limit violation after final frequency stabilization: NO

In this frequency variation plot there can be clearly observed an under frequency operational limit violation due to the rejection of large generation percentage from the system at 5s. This obvious frequency drop can be normalized by the automatic activation of UFLS scheme. Due to the activation of UFLS scheme (i.e. large rejection of system demand), the final stabilizing frequency does not exceed the desired over frequency normal operational limit and therefor it cannot be observed an over frequency normal operational limit violation after stabilizing the system. So, it can be concluded that the frequency behavior at the tripping incident of 25% generation at Thermal Maximum Scenario is feasible.

Figure 5.15 shows the voltage variation of New Anuradhapura 220kV bus when a generator (250MW) tripping of 25% of total system generation (1000MW). The observations are as follows.

- Minimum voltage: 226.20kV
- Maximum voltage: 245.42kV
- Final stabilizing voltage: 238.00kV
- Voltage normal operational limit violation after final voltage stabilization: NO

In this voltage variation plot there is no any under voltage operational limit violation due to the rejection of large generation percentage from the system at 5s. But later on, due to the activation of UFLS scheme (i.e. large rejection of system demand), the

final stabilizing voltage does not exceed the desired over voltage normal operational limit and therefor it cannot be observed an over voltage normal operational limit violation after stabilizing the system. So, it can be concluded that the voltage behavior at the tripping incident of 25% generation at Thermal Maximum Scenario is feasible.

5.3.3 Generator (LVPS unit 01-230MW) tripping of 23% of total system generation

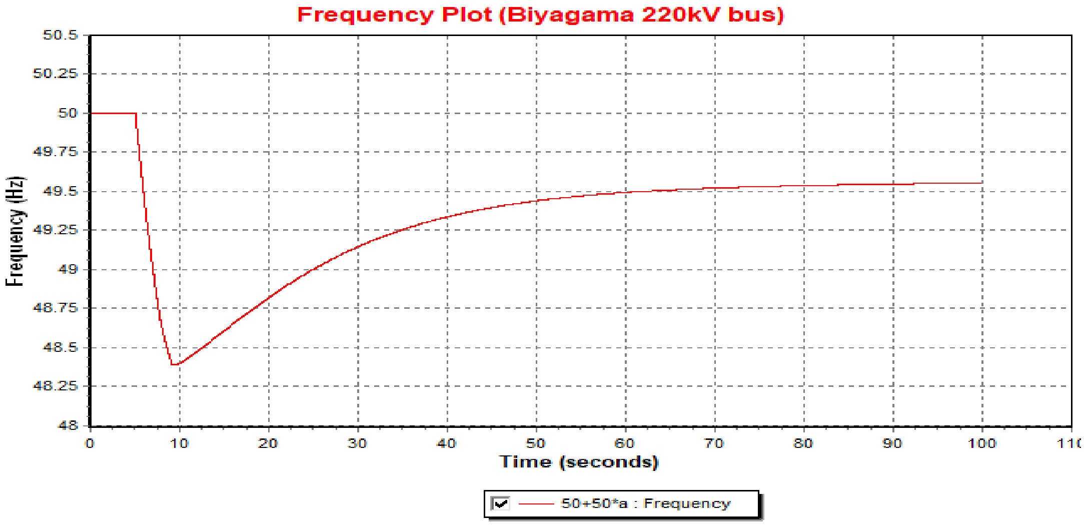


Figure 5.16: Incident 5.3.3-Frequency variation of Biyagama 220kV bus

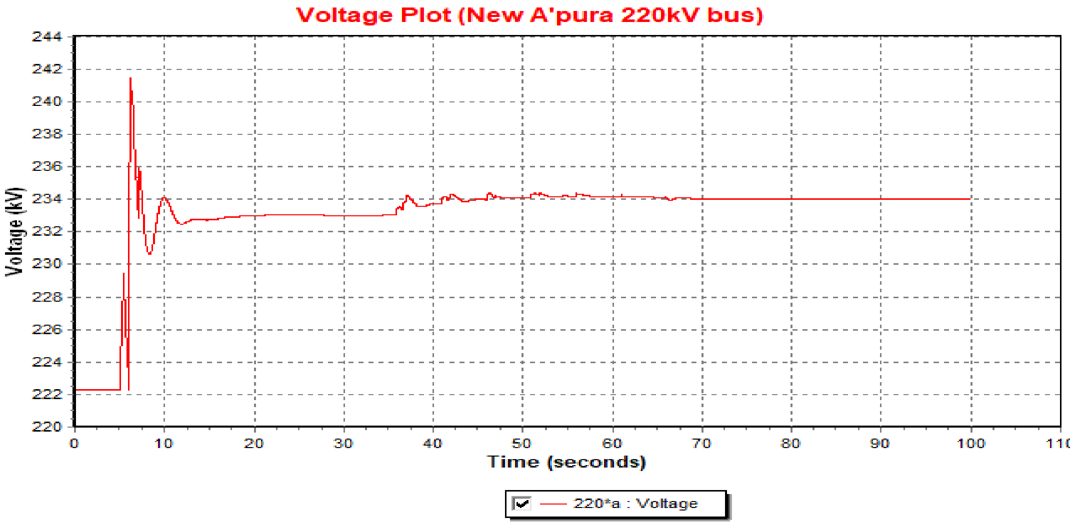


Figure 5.17: Incident 5.3.3-Voltage variation at New Anuradhapura 220kV bus

Figure 5.16 shows the frequency variation of Biyagama 220kV bus when a generator (230MW) tripping of 23% of total system generation (1000MW). The observations are as follows.

- Minimum frequency: 48.41Hz
- Maximum frequency: 50.00Hz
- Final stabilizing frequency: 49.54Hz
- Frequency normal operational limit violation after final frequency stabilization: NO

In this frequency variation plot there can be clearly observed an under frequency operational limit violation due to the rejection of large generation percentage from the system at 5s. This obvious frequency drop can be normalized by the automatic activation of UFLS scheme. Due to the activation of UFLS scheme (i.e. large rejection of system demand), the final stabilizing frequency does not exceed the desired frequency normal operational limits and therefor it cannot be observed a frequency normal operational limit violation after stabilizing the system. So, it can be concluded that the frequency behavior at the tripping incident of 23% generation at Thermal Maximum Scenario is feasible.

Figure 5.17 shows the voltage variation of New Anuradhapura 220kV bus when a generator (230MW) tripping of 23% of total system generation (1000MW). The observations are as follows.

- Minimum voltage: 222.38kV
- Maximum voltage: 241.34kV
- Final stabilizing voltage: 334.00kV
- Voltage normal operational limit violation after final voltage stabilization: NO

In this voltage variation plot there is no any under voltage operational limit violation due to the rejection of large generation percentage from the system at 5s. Later on, due to the activation of UFLS scheme (i.e. large rejection of system demand), the

final stabilizing voltage does not exceed the desired over voltage normal operational limit and therefor it cannot be observed an over voltage normal operational limit violation after stabilizing the system. So, it can be concluded that the voltage behavior at the tripping incident of 23% generation at Thermal Maximum Scenario is feasible.

5.3.4 Generator (LVPS unit 01-210MW) tripping of 21% of total system generation

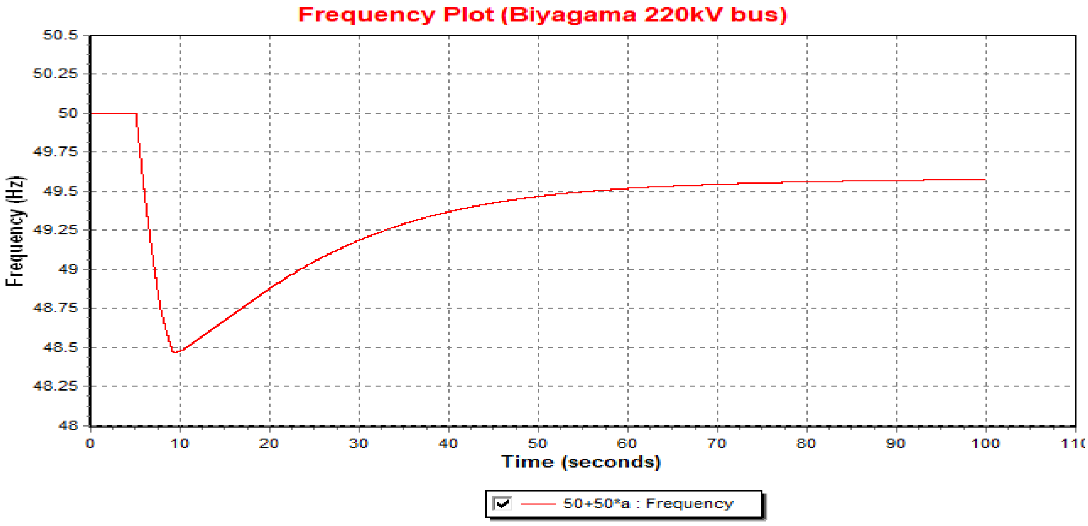


Figure 5.18: Incident 5.3.4-Frequency variation at New Biyagama 220kV bus

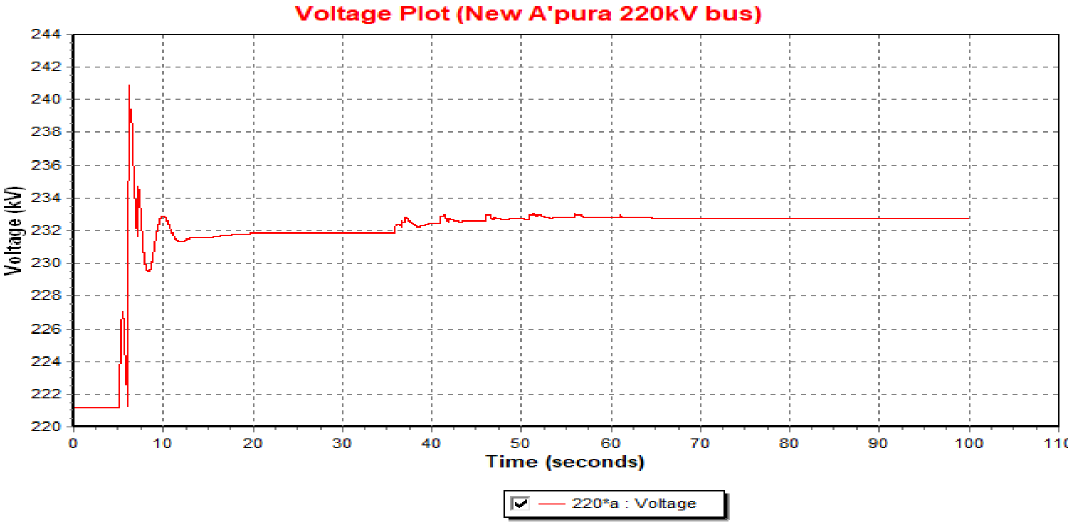


Figure 5.19: Incident 5.3.4-Voltage variation at New Anuradhapura 220kV bus

Figure 5.18 shows the frequency variation of Biyagama 220kV bus when a generator (210MW) tripping of 21% of total system generation (1000MW). The observations are as follows.

- Minimum frequency: 48.45Hz
- Maximum frequency: 50.00Hz
- Final stabilizing frequency: 49.58Hz
- Frequency normal operational limit violation after final frequency stabilization: NO

In this frequency variation plot there can be clearly observed an under frequency operational limit violation due to the rejection of large generation percentage from the system at 5s. This obvious frequency drop can be normalized by the automatic activation of UFLS scheme. Due to the activation of UFLS scheme (i.e. large rejection of system demand), the final stabilizing frequency does not exceed the desired frequency normal operational limit and therefor it cannot be observed a frequency normal operational limit violation after stabilizing the system. So, it can be concluded that the frequency behavior at the tripping incident of 21% generation at Thermal Maximum Scenario is feasible.

Figure 5.19 shows the voltage variation of New Anuradhapura 220kV bus when a generator (210MW) tripping of 21% of total system generation (1000MW). The observations are as follows.

- Minimum voltage: 221.18kV
- Maximum voltage: 240.98kV
- Final stabilizing voltage: 232.88kV
- Voltage normal operational limit violation after final voltage stabilization: NO

In this voltage variation plot there is no any under voltage operational limit violation due to the rejection of large generation percentage from the system at 5s. But later on, due to the activation of UFLS scheme (i.e. large rejection of system demand), the

final stabilizing voltage does not exceed the desired over voltage normal operational limit and therefor it cannot be observed an over voltage normal operational limit violation after stabilizing the system. So, it can be concluded that the voltage behavior at the tripping incident of 21% generation at Thermal Maximum Scenario is feasible.

5.3.5 Generator (LVPS unit 01-190MW) tripping of 19% of total system generation

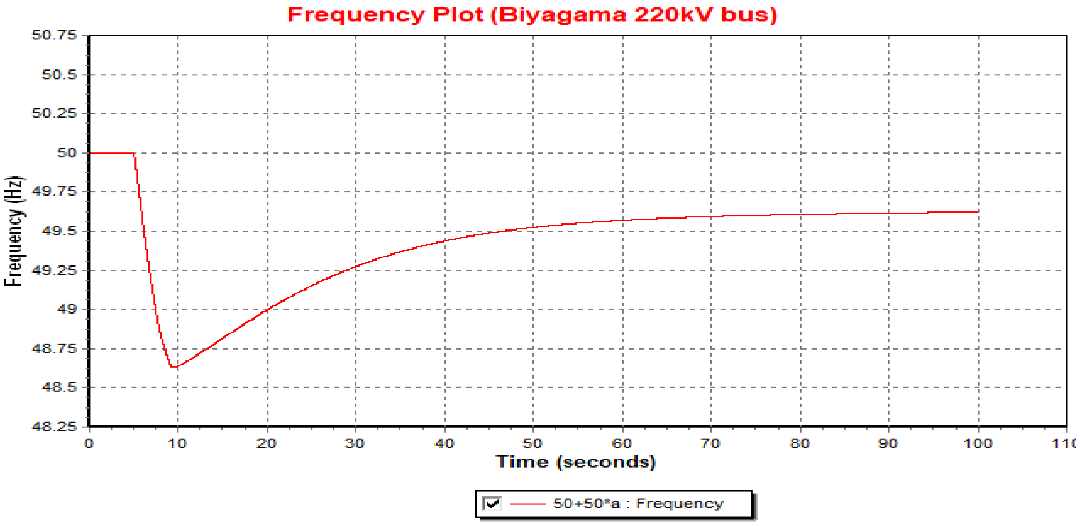


Figure 5.20: Incident 5.3.5-Frequency variation at Biyagama 220kV bus

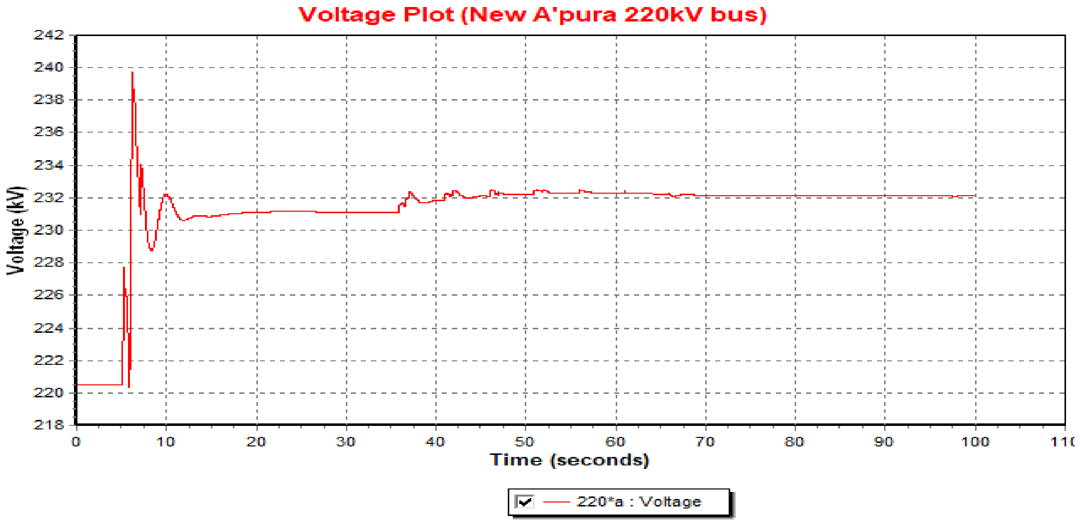


Figure 5.21: Incident 5.3.5-Voltage variation at New Anuradhapura 220kV bus

Figure 5.20 shows the frequency variation of Biyagama 220kV bus when a generator (190MW) tripping of 19% of total system generation (1000MW). The observations are as follows.

- Minimum frequency: 48.63Hz
- Maximum frequency: 50.00Hz
- Final stabilizing frequency: 49.67Hz
- Frequency normal operational limit violation after final frequency stabilization: NO

In this frequency variation plot there can be clearly observed an under frequency operational limit violation due to the rejection of large generation percentage from the system at 5s. This obvious frequency drop can be normalized by the automatic activation of UFLS scheme. Due to the activation of UFLS scheme (i.e. large rejection of system demand), the final stabilizing frequency does not exceed the desired frequency normal operational limit and therefor it cannot be observed a frequency normal operational limit violation after stabilizing the system. So, it can be concluded that the frequency behavior at the tripping incident of 19% generation at Thermal Maximum Scenario is feasible.

Figure 5.21 shows the voltage variation of New Anuradhapura 220kV bus when a generator (190MW) tripping of 19% of total system generation (1000MW). The observations are as follows.

- Minimum voltage: 220.45kV
- Maximum voltage: 239.62kV
- Final stabilizing voltage: 232.21kV
- Voltage normal operational limit violation after final voltage stabilization: NO

In this voltage variation plot there is no any under voltage operational limit violation due to the rejection of large generation percentage from the system at 5s. But later on, due to the activation of UFLS scheme (i.e. large rejection of system demand), the

final stabilizing voltage does not exceed the desired over voltage normal operational limit and therefor it cannot be observed an over voltage normal operational limit violation after stabilizing the system. So, it can be concluded that the voltage behavior at the tripping incident of 19% generation at Thermal Maximum Scenario is feasible.

5.4 Case study of Extreme Thermal Maximum Scenario

The extreme thermal maximum scenario mostly occurs in severely dry seasons. The significance of extreme thermal maximum scenario is that when it comes to generator dispatch, most of the hydro generators are replaced by CEB thermal generators and IPP thermal generators. In extreme thermal maximum scenario, the system demand is also comparatively higher, considering other dispatch scenarios due to high environmental temperature and higher number of 33kV feeder loads.

These situations directly lead to comparatively strengthen the overall system inertia constant. The most significant feature in this case is, here the swing generator is not an ordinary hydro generator but a GT (i.e. in order to minimize the hydro generation further more).as a result it would directly affect to the system frequency stability when a disturbance happens. Also in this case, due to the same course, the voltage stability is comparatively high.

In this scenario the average minimum value of peak demand is 1000MW. So, in this case, the worst case average off peak system demand has been taken as 1000MW for the study simulations [4]. The selected swing generator is KCCP GT. LVPS generation percentage is varied according to the table 5.5 by adjusting the remaining generation while keeping the total system generation as a constant at the study period.

Table 5.5: Study Cases for Extreme Thermal Maximum Scenario

Case Number	**Contribution percentage of LVPS single generator (%)**	**Corresponding load value of the LVPS single generator (MW)**
1.1	27	270
1.2	25	250
1.3	23	230
1.4	21	210
1.5	19	190

Table 5.6: Sample generation dispatch for the study case of Extreme Thermal Maximum Scenario

Power Station	Unit Number	MW
Old_Laxapana	1	0
Old_Laxapana	2	10
New laxapana	1	0
New laxapana	2	10
Polpitiya	1	0
Polpitiya	2	5
Canyon	1	0
WPS	1	0
Samanalawewa	1	0
Samanalawewa	2	0
Ukuwela	1	0
Ukuwela	2	0
Bowatanna	1	0
Kukule	1	0
Kukule	2	0
Asia Power	1	0
Barge	1	30
Randenigala	1	0
Randenigala	2	0
Puttalam Wind	1	10
Kothmale	1	0
Kothmale	2	0
Kothmale	3	0
Upper Kothmale	1	0
Upper Kothmale	2	0
Victoria	1	0
Victoria	2	0
Victoria	3	0
Rantambe	1	0
Rantambe	2	0
KPS GT 7	1	0
KCCP GT (Frequency Control)	1	86
KCCP ST	1	0
AES GT	1	0
AES ST	1	0
WCP	1	120
SPS A	1	11
SPS B1	1	14
SPS B2	1	14
Lakvijaya	**1**	**230**
Lakvijaya	**2**	**230**
Lakvijaya	**3**	**230**
Total Generation /MW		1000

5.4.1 Generator (LVPS unit 01-270MW) tripping of 27% of total system generation

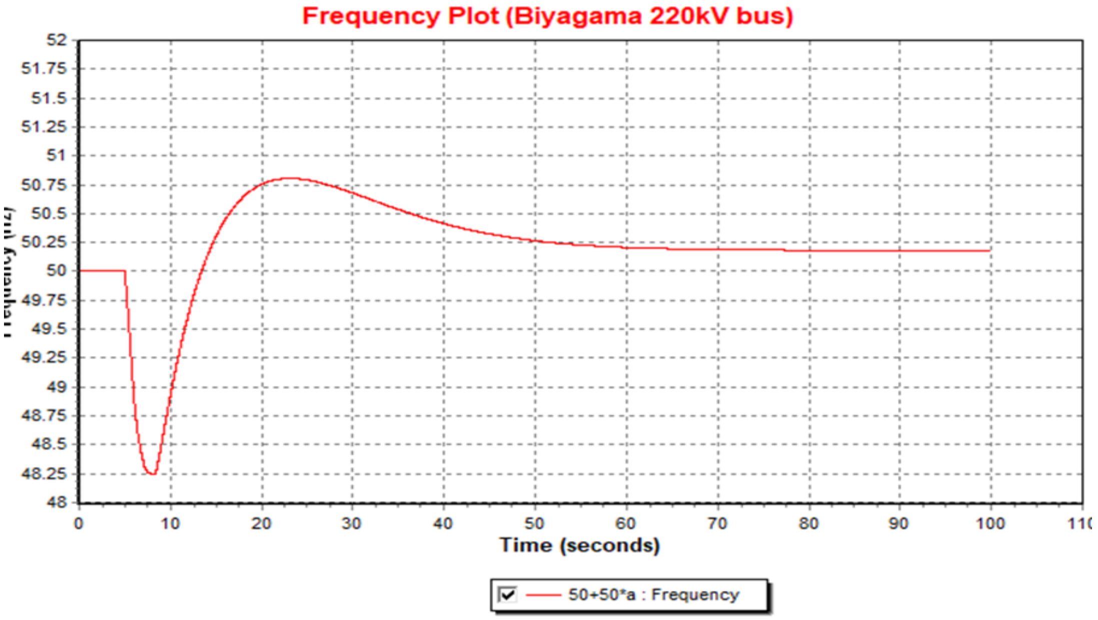


Figure 5.22: Incident 5.4.1-Frequency variation at Biyagama 220kV bus

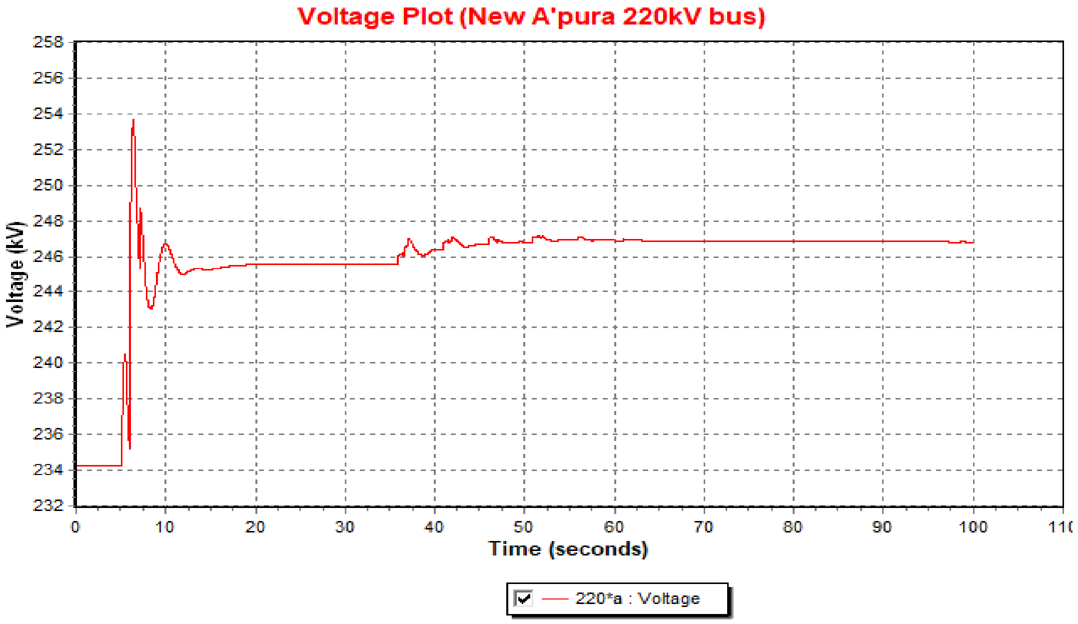


Figure 5.23: Incident 5.4.1-Voltage variation at New Anuradhapura 220kV bus

Figure 5.22 shows the frequency variation of Biyagama 220kV bus when a generator (270MW) tripping of 27% of total system generation (1000MW). The observations are as follows.

- Minimum frequency: 48.24Hz
- Maximum frequency: 50.79Hz
- Final stabilizing frequency: 50.19Hz
- Frequency normal operational limit violation after final frequency stabilization: NO

In this frequency variation plot there can be clearly observed an under frequency operational limit violation due to the rejection of large generation percentage from the system at 5s. This obvious frequency drop can be normalized by the automatic activation of UFLS scheme. Due to the activation of UFLS scheme (i.e. large rejection of system demand), the final stabilizing frequency does not exceed the desired over frequency normal operational limit and therefor it cannot be observed an over frequency normal operational limit violation after stabilizing the system. So, it can be concluded that the frequency behavior at the tripping incident of 27% generation at Extreme Thermal Maximum Scenario is feasible.

Figure 5.23 shows the voltage variation of New Anuradhapura 220kV bus when a generator (270MW) tripping of 27% of total system generation (1000MW). The observations are as follows.

- Minimum voltage: 234.36kV
- Maximum voltage: 253.81kV
- Final stabilizing voltage: 246.78kV
- Voltage normal operational limit violation after final voltage stabilization: YES

In this voltage variation plot there is no any under voltage operational limit violation due to the rejection of large generation percentage from the system at 5s. But later on, due to the activation of UFLS scheme (i.e. large rejection of system demand), the

final stabilizing voltage exceeds the desired over voltage normal operational limit and therefor it cannot be observed an over voltage normal operational limit violation after stabilizing the system. So, it can be concluded that the voltage behavior at the tripping incident of 27% generation at Extreme Thermal Maximum Scenario is infeasible.

5.4.2 Generator (LVPS unit 01-250MW) tripping of 25% of total system generation

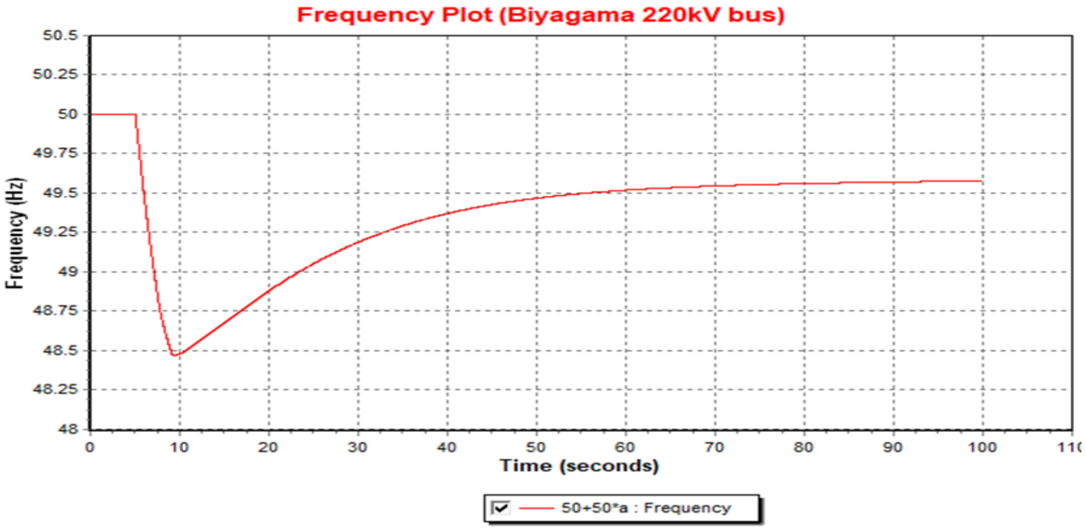


Figure 5.24: Incident 5.4.2-Frequency variation at biyagama 220kV bus

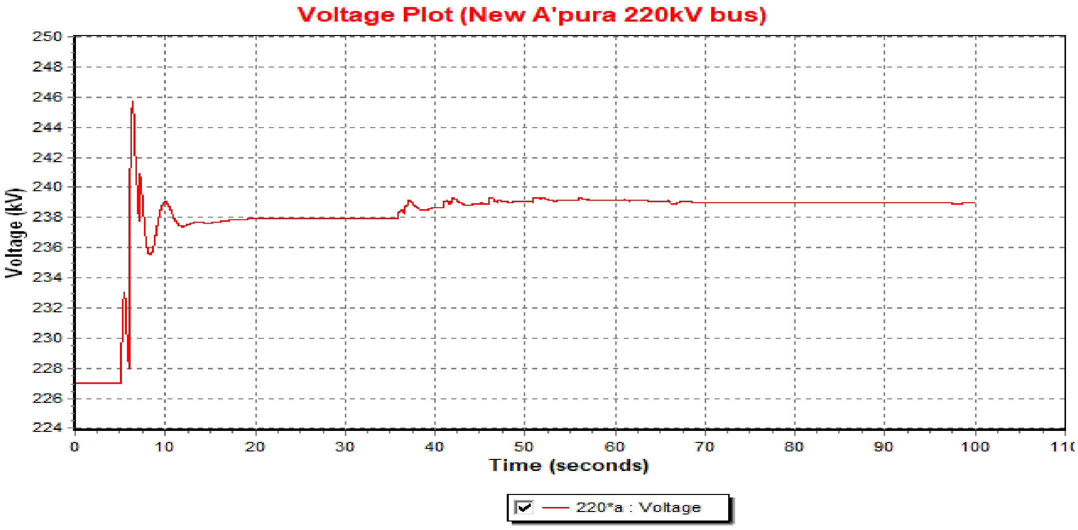


Figure 5.25: Incident 5.4.2-Voltage variation at New Anuradhapura 220kV bus

Figure 5.24 shows the frequency variation of Biyagama 220kV bus when a generator (250MW) tripping of 25% of total system generation (1000MW). The observations are as follows.

- Minimum frequency: 48.44Hz
- Maximum frequency: 50.00Hz
- Final stabilizing frequency: 49.59Hz
- Frequency normal operational limit violation after final frequency stabilization: NO

In this frequency variation plot there can be clearly observed an under frequency operational limit violation due to the rejection of large generation percentage from the system at 5s. This obvious frequency drop can be normalized by the automatic activation of UFLS scheme. Due to the activation of UFLS scheme (i.e. large rejection of system demand), the final stabilizing frequency does not exceed the desired frequency normal operational limit and therefor it cannot be observed a frequency normal operational limit violation after stabilizing the system. So, it can be concluded that the frequency behavior at the tripping incident of 25% generation at Extreme Thermal Maximum Scenario is feasible.

Figure 5.25 shows the voltage variation of New Anuradhapura 220kV bus when a generator (250MW) tripping of 25% of total system generation (1000MW). The observations are as follows.

- Minimum voltage: 227.19kV
- Maximum voltage: 245.86kV
- Final stabilizing voltage: 238.92kV
- Voltage normal operational limit violation after final voltage stabilization: NO

In this voltage variation plot there is no any under voltage operational limit violation due to the rejection of large generation percentage from the system at 5s. But later on, due to the activation of UFLS scheme (i.e. large rejection of system demand), the

final stabilizing voltage does not exceed the desired over voltage normal operational limit and therefor it cannot be observed an over voltage normal operational limit violation after stabilizing the system. So, it can be concluded that the voltage behavior at the tripping incident of 25% generation at Extreme Thermal Maximum Scenario is feasible.

5.4.3 Generator (LVPS unit 01-230MW) tripping of 23% of total system generation

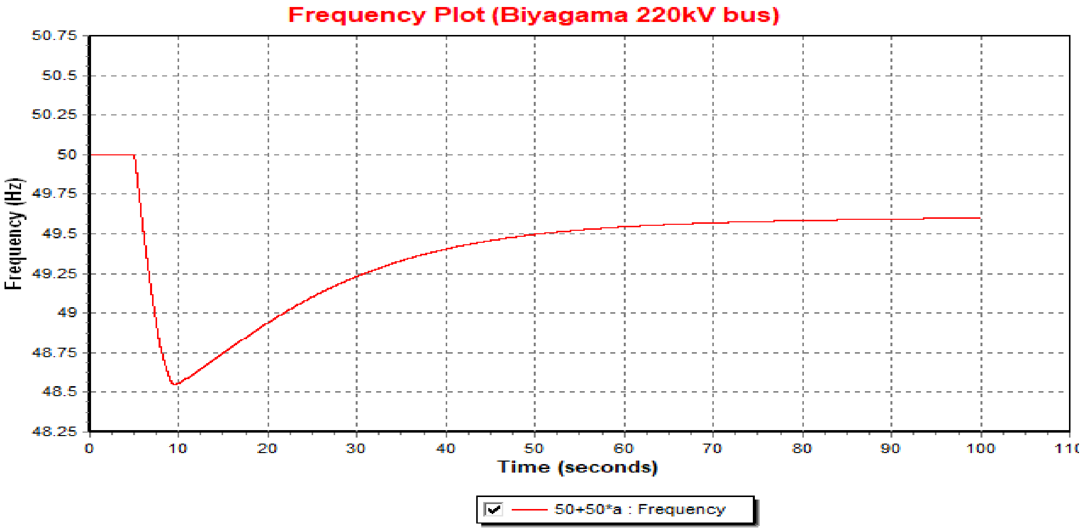


Figure 5.26: Incident 5.4.3-Frequency variation at Biyagama 220kV bus

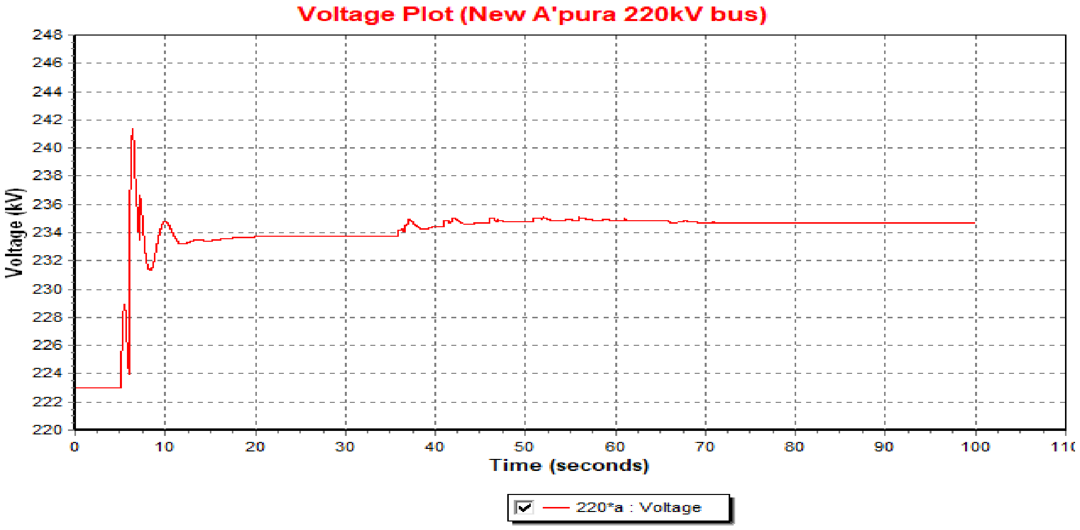


Figure 5.27: Incident 5.4.3-Voltage variation at New Anuradhapura 220kV bus

Figure 5.26 shows the frequency variation of Biyagama 220kV bus when a generator (230MW) tripping of 23% of total system generation (1000MW). The observations are as follows.

- Minimum frequency: 48.53Hz
- Maximum frequency: 50.00Hz
- Final stabilizing frequency: 49.65Hz
- Frequency normal operational limit violation after final frequency stabilization: NO

In this frequency variation plot there can be clearly observed an under frequency operational limit violation due to the rejection of large generation percentage from the system at 5s. This obvious frequency drop can be normalized by the automatic activation of UFLS scheme. Due to the activation of UFLS scheme (i.e. large rejection of system demand), the final stabilizing frequency does not exceed the desired frequency normal operational limit and therefor it cannot be observed a frequency normal operational limit violation after stabilizing the system. So, it can be concluded that the frequency behavior at the tripping incident of 23% generation at Extreme Thermal Maximum Scenario is feasible.

Figure 5.27 shows the voltage variation of New Anuradhapura 220kV bus when a generator (230MW) tripping of 23% of total system generation (1000MW). The observations are as follows.

- Minimum voltage: 222.98kV
- Maximum voltage: 241.44kV
- Final stabilizing voltage: 234.88kV
- Voltage normal operational limit violation after final voltage stabilization: NO

In this voltage variation plot there is no any under voltage operational limit violation due to the rejection of large generation percentage from the system at 5s. Later on, due to the activation of UFLS scheme (i.e. large rejection of system demand), the

final stabilizing voltage does not exceed the desired over voltage normal operational limit and therefor it cannot be observed an over voltage normal operational limit violation after stabilizing the system. So, it can be concluded that the voltage behavior at the tripping incident of 23% generation at Extreme Thermal Maximum Scenario is feasible.

5.4.4 Generator (LVPS unit 01-210MW) tripping of 21% of total system generation

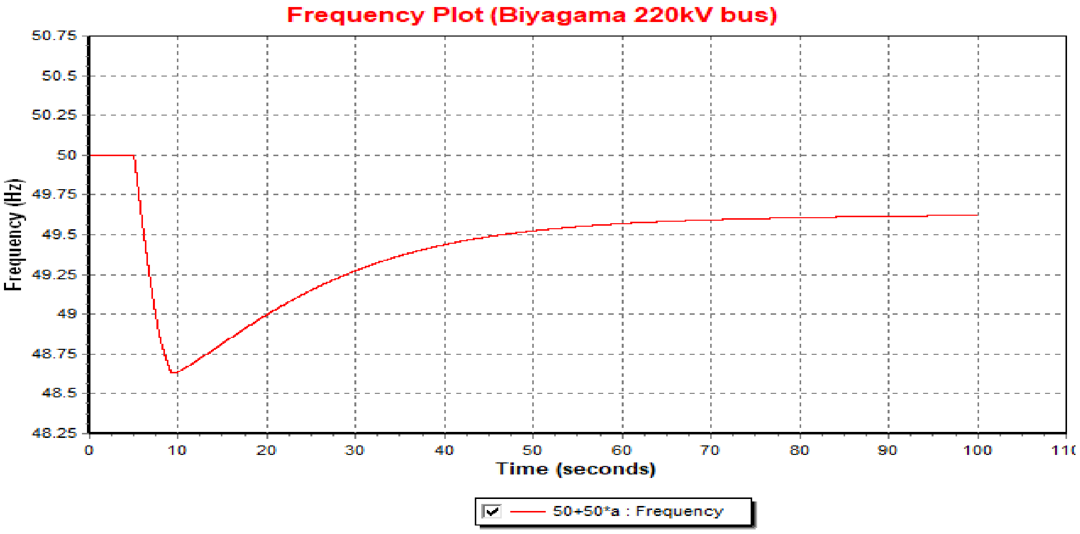


Figure 5.28: Incident 5.4.4-Frequency variation at Biyagama 220kV bus

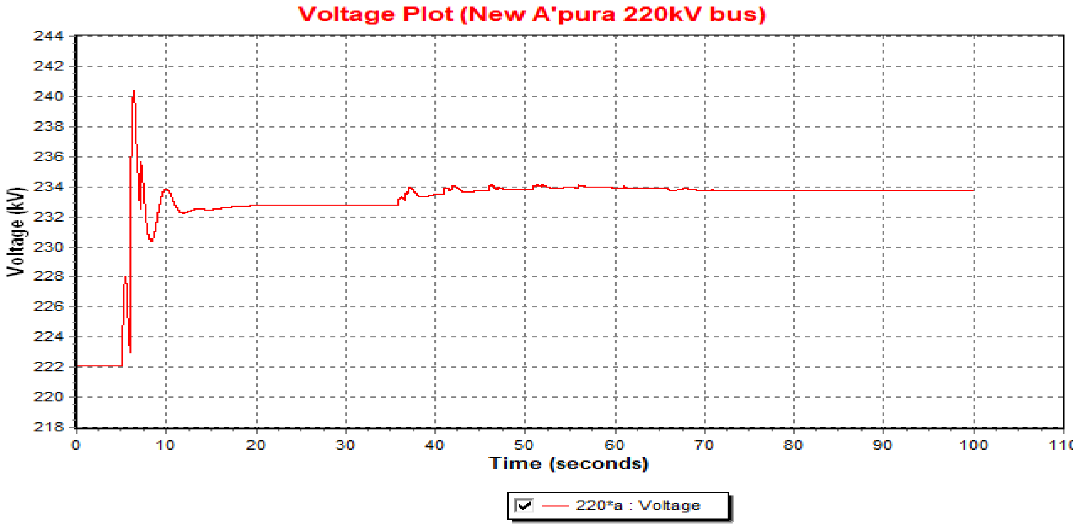


Figure 5.29: Incident 5.4.4-Voltage variation at New Anuradhapura 220kV bus

Figure 5.28 shows the frequency variation of Biyagama 220kV bus when a generator (210MW) tripping of 21% of total system generation (1000MW). The observations are as follows.

- Minimum frequency: 48.62Hz
- Maximum frequency: 50.00Hz
- Final stabilizing frequency: 49.66Hz
- Frequency normal operational limit violation after final frequency stabilization: NO

In this frequency variation plot there can be clearly observed an under frequency operational limit violation due to the rejection of large generation percentage from the system at 5s. This obvious frequency drop can be normalized by the automatic activation of UFLS scheme. Due to the activation of UFLS scheme (i.e. large rejection of system demand), the final stabilizing frequency does not exceed the desired frequency normal operational limit and therefor it cannot be observed a frequency normal operational limit violation after stabilizing the system. So, it can be concluded that the frequency behavior at the tripping incident of 21% generation at Extreme Thermal Maximum Scenario is feasible.

Figure 5.29 shows the voltage variation of New Anuradhapura 220kV bus when a generator (210MW) tripping of 21% of total system generation (1000MW). The observations are as follows.

- Minimum voltage: 222.14kV
- Maximum voltage: 240.42kV
- Final stabilizing voltage: 233.75kV
- Voltage normal operational limit violation after final voltage stabilization: NO

In this voltage variation plot there is no any under voltage operational limit violation due to the rejection of large generation percentage from the system at 5s. Later on, due to the activation of UFLS scheme (i.e. large rejection of system demand), the

final stabilizing voltage does not exceed the desired over voltage normal operational limit and therefor it cannot be observed an over voltage normal operational limit violation after stabilizing the system. So, it can be concluded that the voltage behavior at the tripping incident of 21% generation at Extreme Thermal Maximum Scenario is feasible.

5.4.5 Generator (LVPS unit 01-190MW) tripping of 19% of total system generation

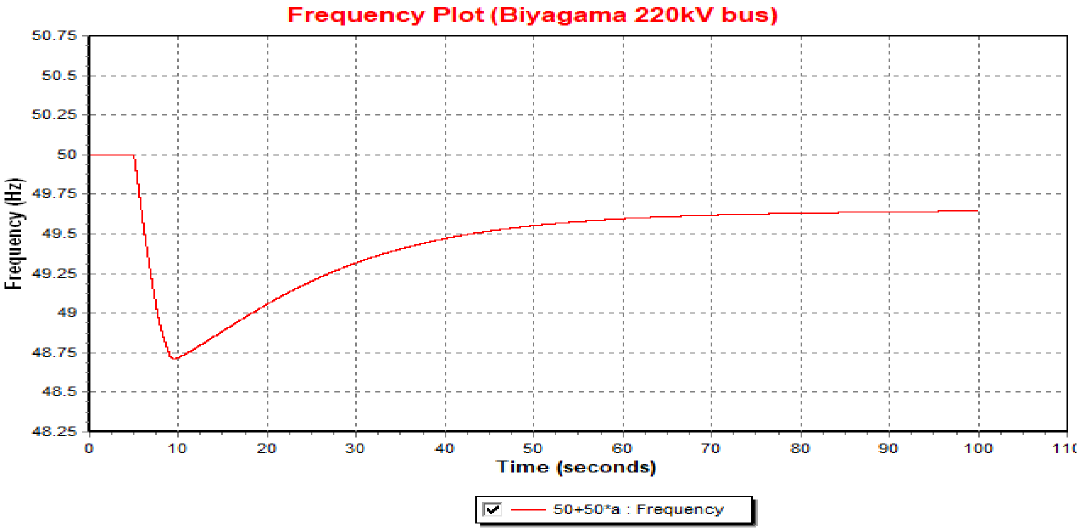


Figure 5.30: Incident 5.4.5-Frequency variation at Biyagama 220kV bus

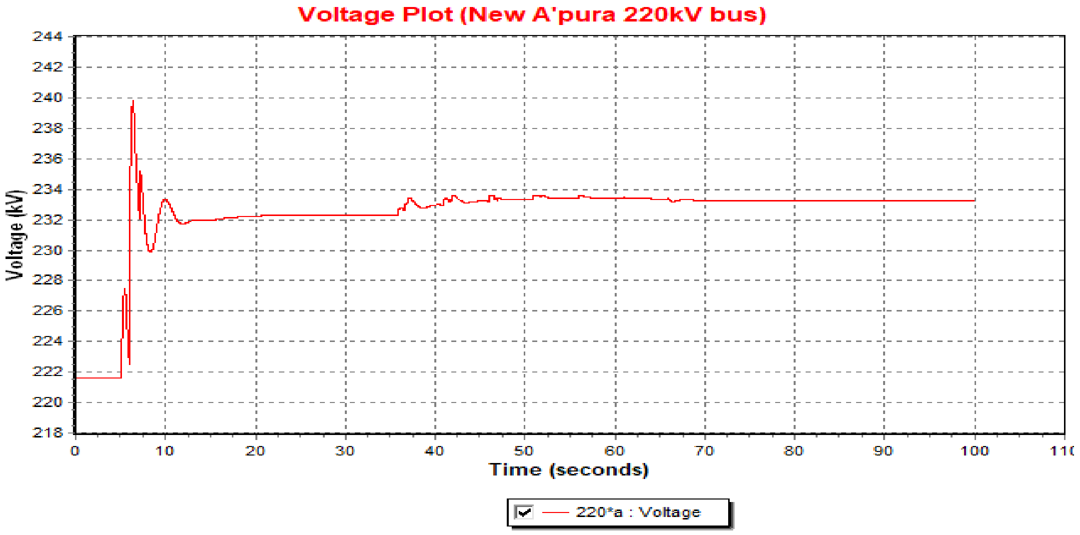


Figure 5.31: Incident 5.4.5-Voltage variation at New Anuradhapura 220kV bus

Figure 5.30 shows the frequency variation of Biyagama 220kV bus when a generator (190MW) tripping of 19% of total system generation (1000MW). The observations are as follows.

- Minimum frequency: 48.72Hz
- Maximum frequency: 50.00Hz
- Final stabilizing frequency: 49.69Hz
- Frequency normal operational limit violation after final frequency stabilization: NO

In this frequency variation plot there can be clearly observed an under frequency operational limit violation due to the rejection of large generation percentage from the system at 5s. This obvious frequency drop can be normalized by the automatic activation of UFLS scheme. Due to the activation of UFLS scheme (i.e. large rejection of system demand), the final stabilizing frequency does not exceed the desired frequency normal operational limit and therefor it cannot be observed a frequency normal operational limit violation after stabilizing the system. So, it can be concluded that the frequency behavior at the tripping incident of 19% generation at Extreme Thermal Maximum Scenario is feasible.

Figure 5.31 shows the voltage variation of New Anuradhapura 220kV bus when a generator (190MW) tripping of 19% of total system generation (1000MW). The observations are as follows.

- Minimum voltage: 221.52kV
- Maximum voltage: 239.90kV
- Final stabilizing voltage: 233.42kV
- Voltage normal operational limit violation after final voltage stabilization: NO

In this voltage variation plot there is no any under voltage operational limit violation due to the rejection of large generation percentage from the system at 5s. Later on, due to the activation of UFLS scheme (i.e. large rejection of system demand), the

final stabilizing voltage does not exceed the desired over voltage normal operational limit and therefor it cannot be observed an over voltage normal operational limit violation after stabilizing the system. So, it can be concluded that the voltage behavior at the tripping incident of 19% generation at Extreme Thermal Maximum Scenario is feasible.

Chapter 6

OBSERVATIONS AND DISCUSSION

6.1 Observations and Discussion summary

The important observations and the discussion of the case studies under Off Peak demand scenario can be summarized according to the three major dispatch scenarios. Under each dispatch scenario, the frequency final stabilizing point variations and voltage final stabilizing point variations will be discussed according to each generation rejection percentage. Under each dispatch scenario, whenever there is found a cross over point of generation rejection percentage regarding frequency stability and voltage stability which has not been analyzed at chapter 5, that point will be again analyzed for both frequency stability and voltage stability in order to obtain a proper conclusion.

6.1.1 Observation of complete case study of Hydro Maximum Scenario

Under Hydro Maximum Scenario case study, the generation rejection percentages in between 19% to 27% (i.e. 19%, 21%, 23%, 25%, 27%) have been critically analyzed for both frequency stability and voltage stability. The summery of the case study results will be discussed as follows.

6.1.1.1 Observations of Hydro Maximum Scenario case study-Frequency analysis

The summary of the final frequency stabilizing behavior in each five numbers of study case under Hydro Maximum Scenario is as follows.

- Decreasing the LVPS loading percentage directly affects for smoothening the frequency stabilization after the system recovery.
- In the cases of 27%, the final stabilizing frequency is above the frequency upper operational limit.
- In the cases of 25%, 23%, 21% and 19%, the final stabilizing frequencies are within the desired frequency operational limits.

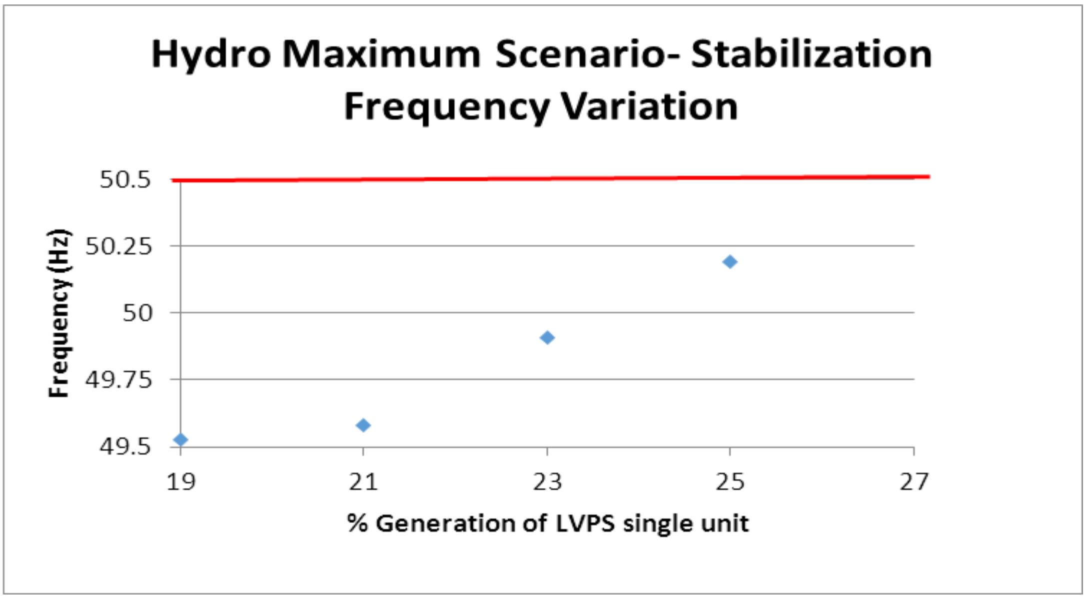


Figure 6.1: Summary of the final stabilization frequency value variation in Hydro Maximum Scenario

- According to the final stabilizing frequency points, considering the frequency stability only, the maximum possible loading capacity of a single generator at Hydro Maximum Scenario is up to 25%.

6.1.1.2 Observations of the Hydro Maximum Scenario case study-Voltage analysis

The summary of the final voltage stabilizing behavior in each five number of study cases under Hydro Maximum Scenario is as follows.

- Decreasing the LVPS loading percentage directly affects for smoothening the voltage stabilization after the system recovery.
- In the cases of 27%, 25% and 23%, the final stabilizing voltages are above the voltage upper operational limit.
- Cases of 21% and 19%, the final stabilizing voltages are within the desired voltage operational limits.

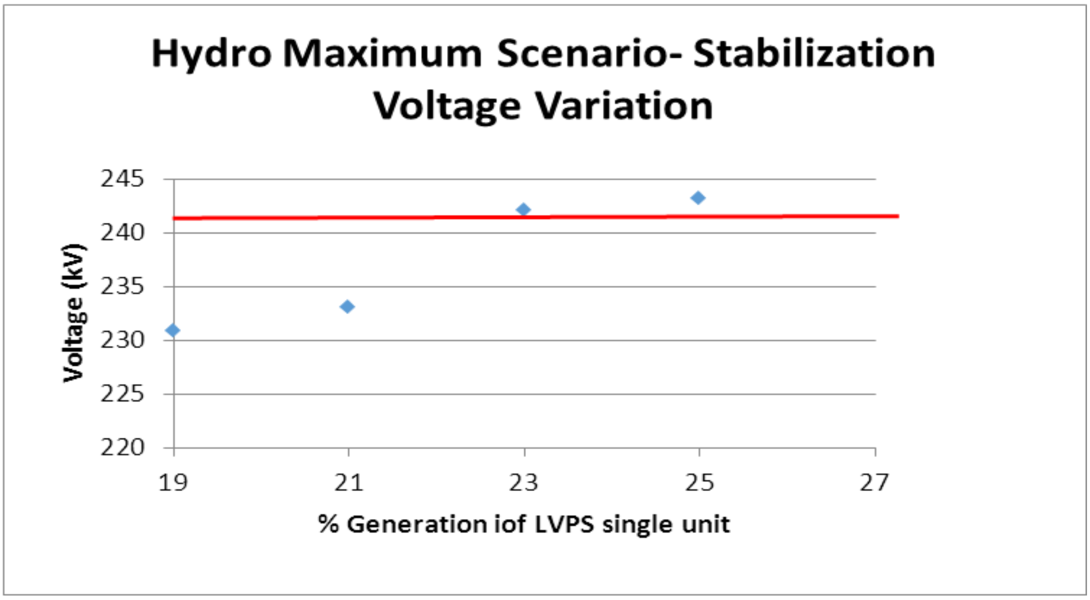


Figure 6.2: Summary of the final stabilization voltage value variation in Hydro Maximum Scenario

- According to the final stabilizing voltage points, considering the voltage stability only, the maximum possible loading capacity of a single generator at Hydro Maximum Scenario is up to 21%.

Referring to the section 6.1.1, considering the frequency stability only, the maximum possible loading capacity of a single generator is up to 25%. Considering the voltage stability only, the maximum possible loading capacity of a single generator is up to 21%. Hence, considering both frequency and voltage stability, the maximum possible loading capacity of a single generator for Hydro Maximum Scenario is up to 21%.

According to the section 2.4, this study has been conducted within the generation percentage range of 19% to 27% and for equal spaced 05 numbers of cases (i.e. 19%, 21%, 23%, 25%, 27%). Since the frequency stability is not violated up to 25%(i.e. all the cases from 19% to 25% can be accepted) and the voltage stability is not violated up to 21%(i.e. all the cases from 19% to 21% can be accepted), the cross over point of the generation rejection percentages of frequency stability and voltage stability will be observed at 22%.

6.1.1.3 Generator (LVPS unit 01-176MW) tripping of 22% of total system generation at Hydro Maximum Scenario

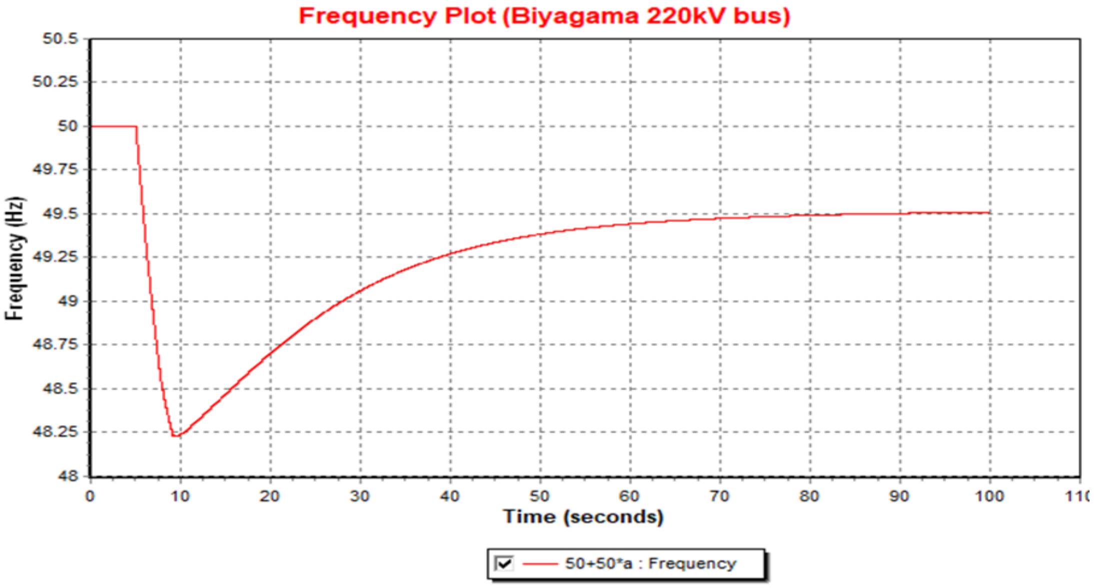


Figure 6.3: 6.1.1.3 incident-Frequency variation at Biyagama 220kV bus due to the generator (LVPS unit 01-176MW) tripping of 22% of total system generation

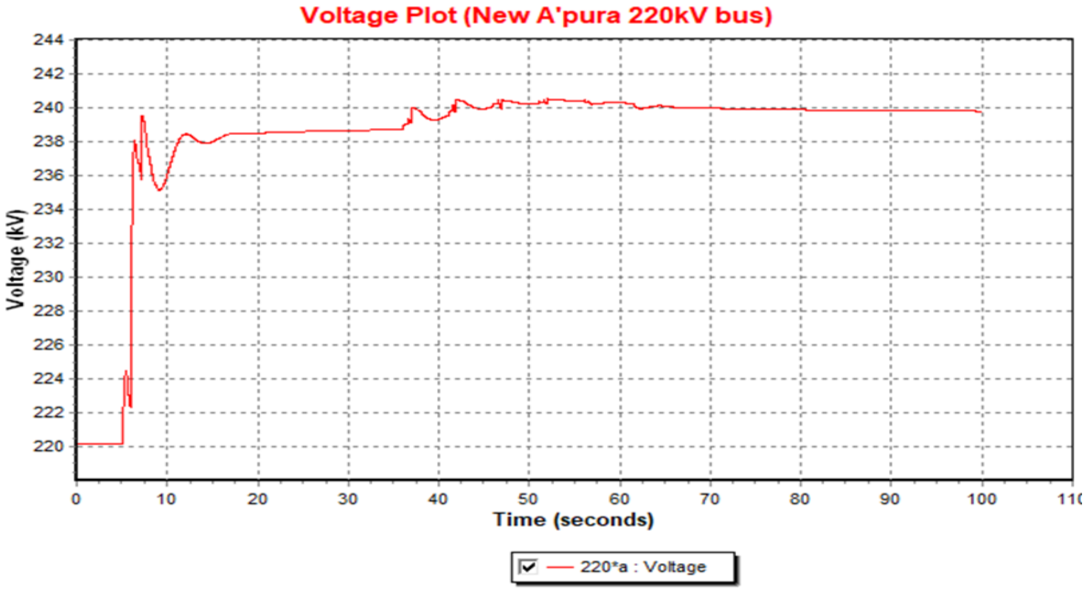


Figure 6.4: 6.1.1.3 incident-Voltage variation at New Anuradhapura 220kV bus due to the generator (LVPS unit 01-176MW) tripping of 22% of total system generation

Figure 6.3 shows the frequency variation of Biyagama 220kV bus when a generator (176MW) tripping of 22% of total system generation (800MW). The observations are as follows.

- Minimum frequency: 48.23Hz
- Maximum frequency: 50.00Hz
- Stabilizing frequency: 49.52Hz
- Frequency normal operational limit violation after final frequency stabilization: NO

In this frequency variation plot there can be clearly observed an under frequency operational limit violation due to the rejection of large generation percentage from the system at 5s. This obvious frequency drop can be normalized by the automatic activation of UFLS scheme. Due to the activation of UFLS scheme (i.e. large rejection of system demand), the final stabilizing frequency does not exceed the desired frequency normal operational limit and therefor it cannot be observed a frequency normal operational limit violation after stabilizing the system. So, it can be concluded that the frequency behavior at the tripping incident of 22% generation at Hydro Maximum Scenario is feasible.

Figure 6.4 shows the voltage variation of New Anuradhapura 220kV bus when a generator (176MW) tripping of 22% of total system generation (1000MW). The observations are as follows.

- Minimum voltage: 220.20kV
- Maximum voltage: 240.82kV
- Stabilizing voltage: 239.96kV
- Voltage normal operational limit violation after final voltage stabilization: NO

In this voltage variation plot there is no any under voltage operational limit violation due to the rejection of large generation percentage from the system at 5s. Later on, due to the activation of UFLS scheme (i.e. large rejection of system demand), the final stabilizing voltage does not exceed the desired over voltage normal operational limit and therefor it cannot be observed an over voltage normal operational limit violation after stabilizing the system. So, it can be concluded that the voltage behavior at the tripping incident of 22% generation at Hydro Maximum Scenario is feasible.

6.1.2 Discussion of complete case study of Hydro Maximum Scenario

Referring to the results which gave been obtained from the sub sections of 6.1.1.1, 6.1.1.2 and 6.1.1.3, considering both frequency and voltage operational limits, the maximum possible loading capacity of a single generator for Hydro Maximum Scenario is up to 22%.

6.1.3 Observation of complete case study of Thermal Maximum Scenario

Under Thermal Maximum Scenario case study, the generation rejection percentages in between 19% to 27% (i.e. 19%, 21%, 23%, 25%, 27%) have been critically analyzed for both frequency stability and voltage stability. The summery of the case study results are as follows.

6.1.3.1 Observations of Thermal Maximum Scenario case study-Frequency analysis

The summary of the final frequency stabilizing behavior in each five study cases under Thermal Maximum Scenario is as follows.

- Decreasing the LVPS loading percentage directly affects for smoothening the frequency stabilization after the system recovery.
- In the case of 27%, the final stabilizing frequency is above the frequency upper operational limit.
- In the cases of 25%,23%,21% and 19%, the final stabilizing frequencies are within the desired frequency operational limits.

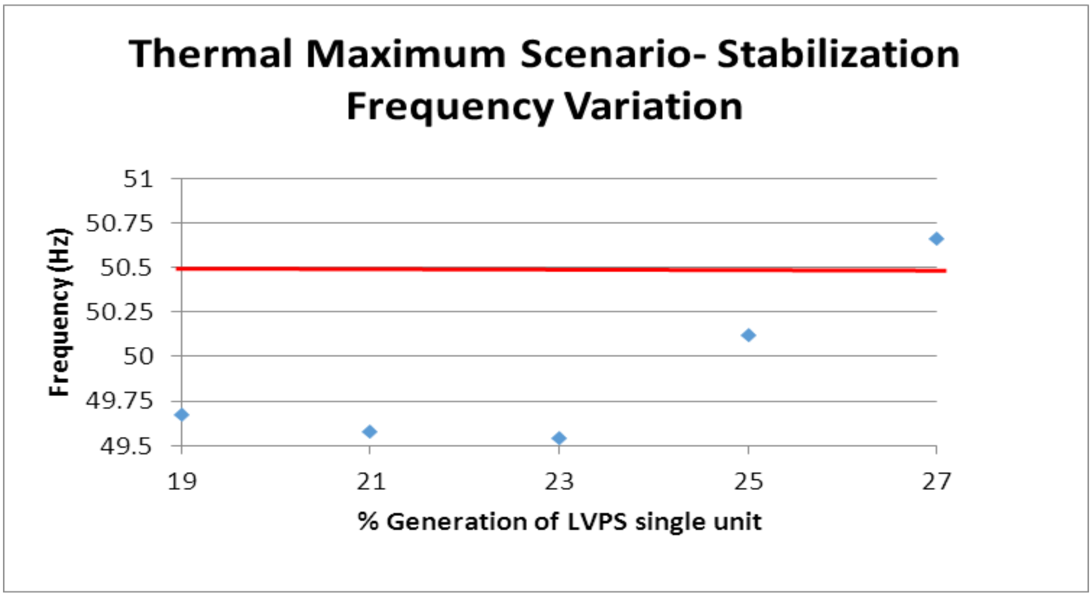


Figure 6.5: Summary of the final stabilization frequency value variation in Thermal Maximum Scenario

- According to the final stabilizing frequency points, considering the frequency stability only, the maximum possible loading capacity of a single generator at Hydro Maximum Scenario is up to 25%.

6.1.3.2 Observations of Extreme Thermal Maximum Scenario case study- Frequency analysis

The summary of the final voltage stabilizing behavior in each five study cases under Thermal Maximum Scenario is as follows.

- Decreasing the LVPS loading percentage directly affects for smoothening the voltage stabilization after the system recovery.
- In the case of 27%, final stabilizing voltage is above the voltage upper operational limit.
- Cases of 25%,23%,21% and 19%, the final stabilizing voltages are within the desired voltage operational limits.

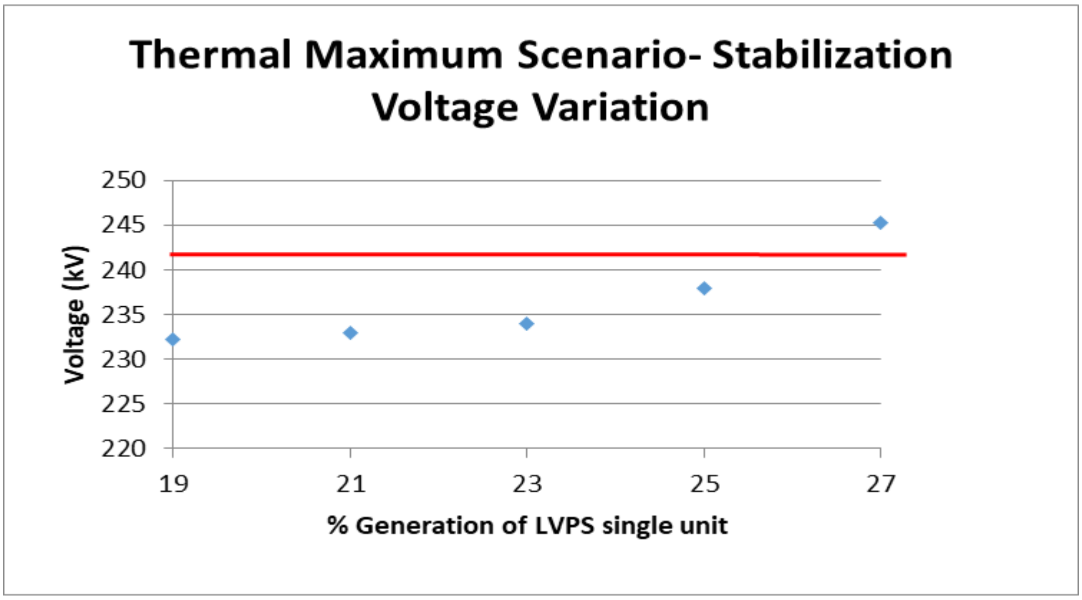


Figure 6.6: Summary of the final stabilization voltage value variation in Thermal Maximum Scenario

- According to the final stabilizing voltage points, considering the voltage stability only, the maximum possible loading capacity of a single generator at Thermal Maximum Scenario is up to 25%.

Referring to section 6.1.2, considering the frequency stability only, the maximum possible loading capacity of a single generator is up to 25%. Considering the voltage stability only, the maximum possible loading capacity of a single generator is up to 25%. Hence, considering both frequency and voltage stability, the maximum possible loading capacity of a single generator for Hydro Maximum Scenario is up to 25%.

According to the section 2.4, this study has been conducted within the generation percentage range of 19% to 27% and for equal spaced 05 numbers of cases (i.e. 19%, 21%, 23%, 25%, 27%).Since the frequency stability is not violated up to 25%(i.e. all the cases from 19% to 25% can be accepted) and the voltage stability is not violated up to 25%(i.e. all the cases from 19% to 25% can be accepted), the cross over point of the generation rejection percentages of frequency stability and voltage stability will be observed at 26%.

6.1.3.3 Generator (LVPS unit 01-260MW) tripping of 26% of total system generation at Thermal Maximum Scenario

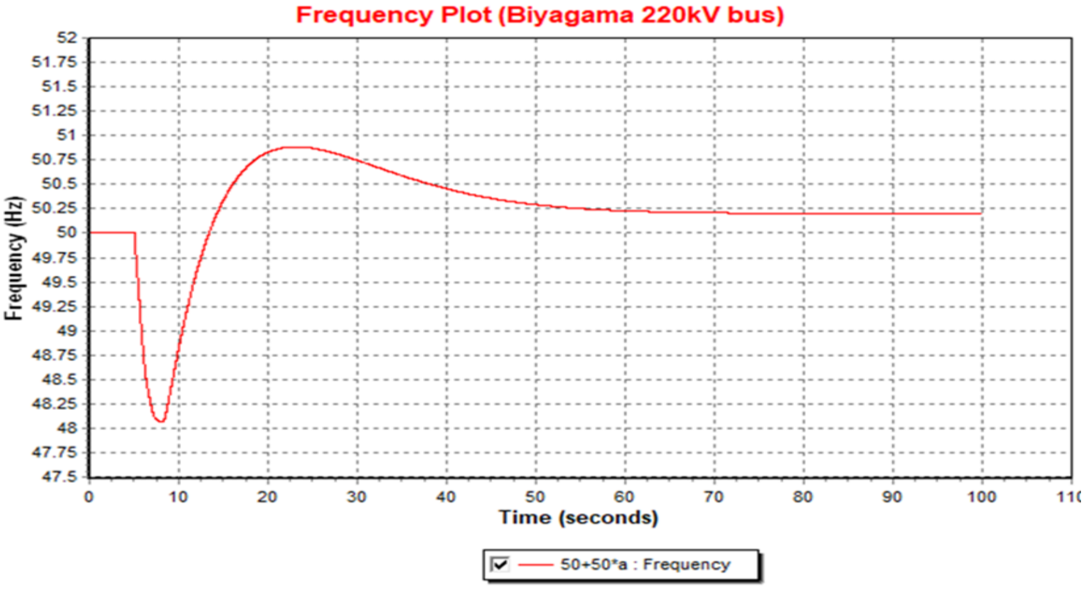


Figure 6.7: 6.1.3.3 incident- Frequency variation at Biyagama 220kV bus due to the generator (LVPS unit 01-260MW) tripping of 26% of total system generation

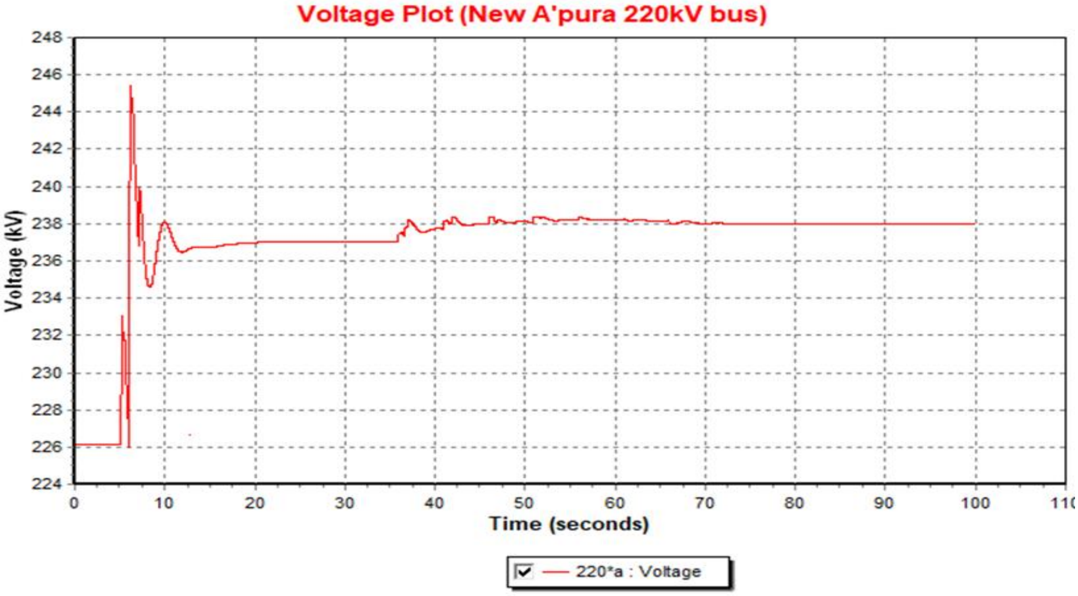


Figure 6.8: 6.1.3.3 incident- Voltage variation at New Anuradhapura 220kV bus due to the generator (LVPS unit 01-260MW) tripping of 26% of total system generation

Figure 6.7 shows the frequency variation of Biyagama 220kV bus when a generator (260MW) tripping of 26% of total system generation (1000MW). The observations are as follows.

- Minimum frequency: 48.06Hz
- Maximum frequency: 50.86Hz
- Stabilizing frequency: 49.19Hz
- Frequency normal operational limit violation after final frequency stabilization: NO

In this frequency variation plot there can be clearly observed an under frequency operational limit violation due to the rejection of large generation percentage from the system at 5s. This obvious frequency drop can be normalized by the automatic activation of UFLS scheme. Due to the activation of UFLS scheme (i.e. large rejection of system demand), the final stabilizing frequency does not exceed the desired over frequency normal operational limit and therefor it cannot be observed an over frequency normal operational limit violation after stabilizing the system. So, it can be concluded that the frequency behavior at the tripping incident of 26% generation at Thermal Maximum Scenario is feasible.

Figure 6.8 shows the voltage variation of New Anuradhapura 220kV bus when a generator (260MW) tripping of 26% of total system generation (1000MW). The observations are as follows.

- Minimum voltage: 220.20kV
- Maximum voltage: 240.82kV
- Stabilizing voltage: 239.96kV
- Voltage normal operational limit violation after final voltage stabilization: NO

In this voltage variation plot there is no any under voltage operational limit violation due to the rejection of large generation percentage from the system at 5s. Later on, due to the activation of UFLS scheme (i.e. large rejection of system demand), the

final stabilizing voltage does not exceed the desired over voltage normal operational limit and therefor it cannot be observed an over voltage normal operational limit violation after stabilizing the system. So, it can be concluded that the voltage behavior at the tripping incident of 26% generation at Thermal Maximum Scenario is feasible.

6.1.4 Discussion of case study of Thermal Maximum Scenario

Referring to the results which have been obtained from 6.1.3.1, 6.1.3.2 and 6.1.3.3, considering both frequency and voltage operational limits, the maximum possible loading capacity of a single generator for Thermal Maximum Scenario is up to 26%.

6.1.5 Observation of complete case study of Extreme Thermal Maximum Scenario

Under Extreme Thermal Maximum Scenario cases study the generation rejection percentages in between 19% to 27% (i.e. 19%, 21%, 23%, 25%, 27%) have been critically analyzed for both frequency stability and voltage stability. The summery of the case study results are as follows.

6.1.5.1 Observations of Extreme Thermal Maximum Scenario case study-Frequency analysis

The summary of the final frequency stabilizing behavior in each five study cases under Extreme Thermal Maximum Scenario is as follows.

- Decreasing the LVPS loading percentage directly affects for smoothening the frequency stabilization after the system recovery.
- In all the cases (i.e. 27%,25%,23%,21% and 19%, the final stabilizing frequencies are within the desired frequency operational limits.

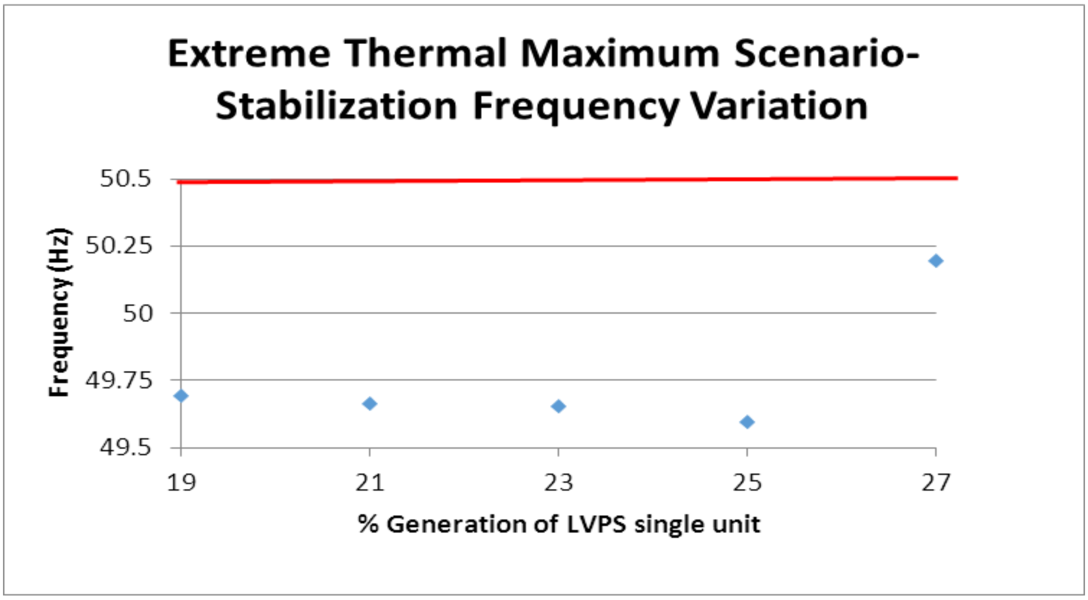


Figure 6.9: Summary of the final stabilization frequency value variation in Extreme Thermal Maximum Scenario

- According to the final stabilizing frequency points, considering the frequency stability only, the maximum possible loading capacity of a single generator at Extreme Thermal Maximum Scenario is up to 27%.

6.1.5.2 Observations of Extreme Thermal Maximum Scenario case study-Frequency analysis

The summary of the final voltage stabilizing behavior in each five study cases under Extreme Thermal Maximum Scenario is as follows.

- Decreasing the LVPS loading percentage directly affects for smoothening the voltage stabilization after the system recovery.
- In the case of 27%, the final stabilizing voltage is above the voltage upper operational limit.
- Cases of 25%,23%,21% and 19%, the final stabilizing voltages are within the desired voltage operational limits.

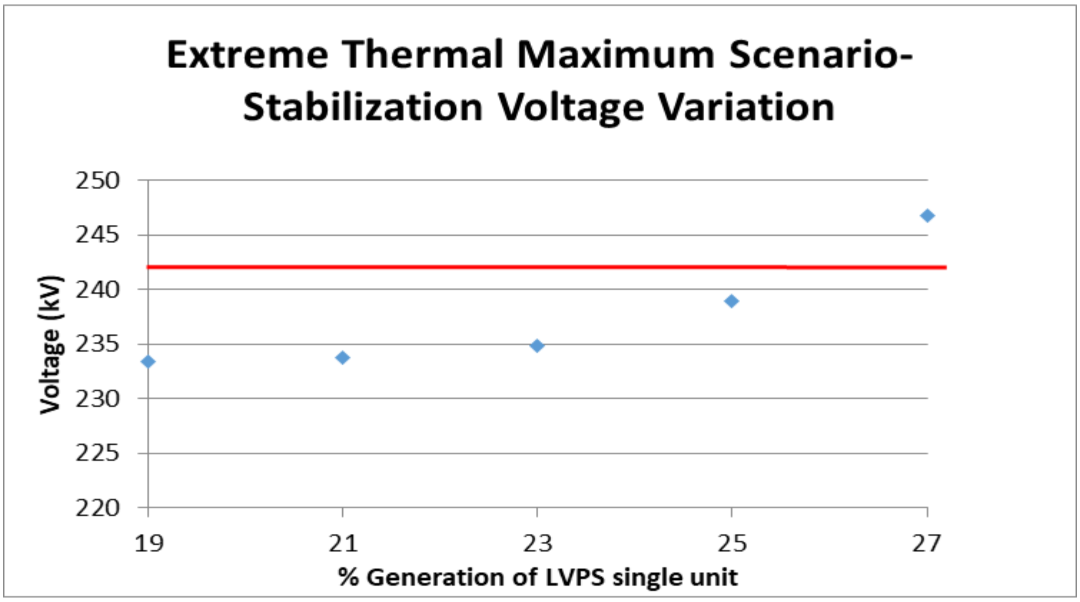


Figure 6.10: Summary of the final stabilization voltage value variation in Extreme Thermal Maximum Scenario

- According to the final stabilizing voltage points, considering the voltage stability only, the maximum possible loading capacity of a single generator at Hydro Maximum Scenario is up to 25%.

Referring to section 6.1.5, considering the frequency stability only, the maximum possible loading capacity of a single generator is up to 27%. Considering the voltage stability only, the maximum possible loading capacity of a single generator is up to 25%. Hence, considering both frequency and voltage stability, the maximum possible loading capacity of a single generator for Extreme Thermal Maximum Scenario is up to 25%.

According to the section 2.4, this study has been conducted within the generation percentage range of 19% to 27% and for equal spaced 05 numbers of cases (i.e. 19%, 21%, 23%, 25%, 27%).Since the frequency stability is not violated up to 27%(i.e. all the cases from 19% to 27% can be accepted) and the voltage stability is not violated up to 25%(i.e. all the cases from 19% to 25% can be accepted), the cross over point of the generation rejection percentages of frequency stability and voltage stability will be observed at 26%.

6.1.5.3 Generator (LVPS unit 01-260MW) tripping of 26% of total system generation at Extreme Thermal Maximum Scenario

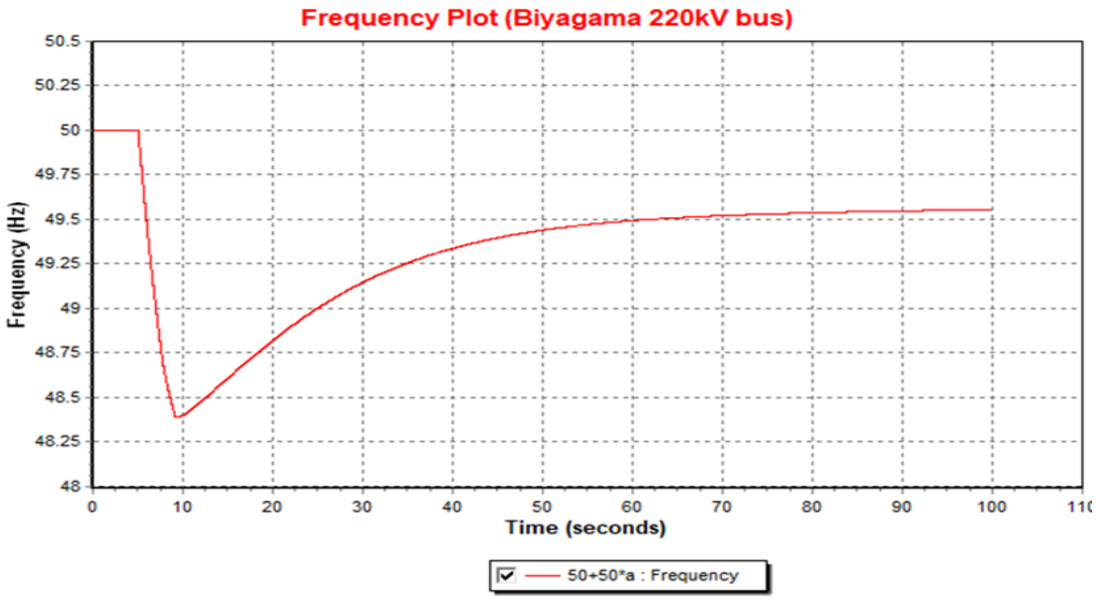


Figure 6.11: 6.1.5.3 incident- Frequency variation at Biyagama 220kV bus due to the generator (LVPS unit 01-260MW) tripping of 26% of total system generation

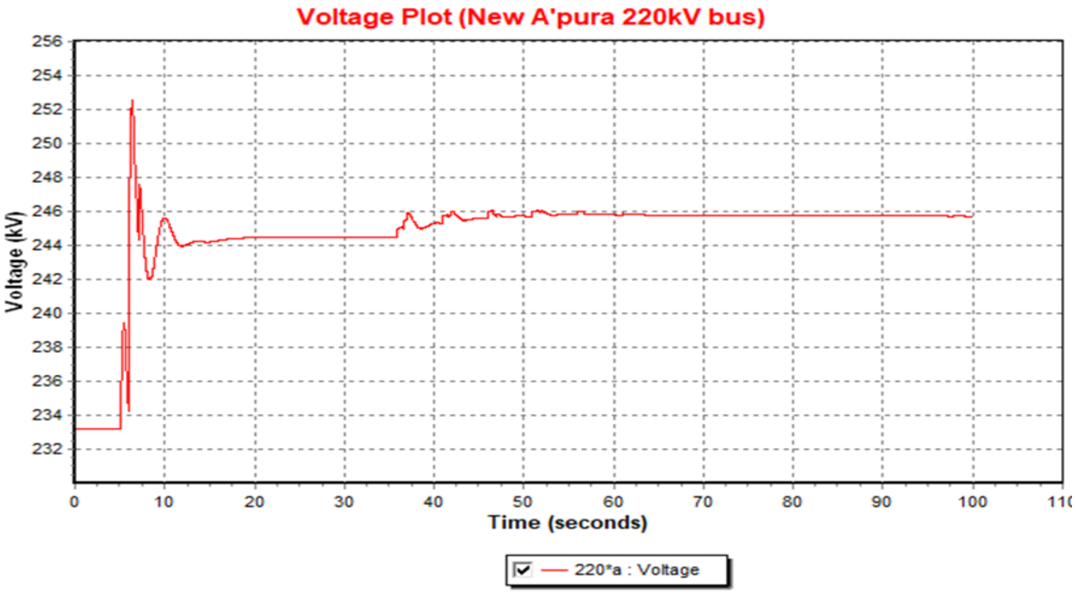


Figure 6.12: 6.1.5.3 incident-Voltage variation at New Anuradhapura 220kV bus due to the generator (LVPS unit 01-260MW) tripping of 26% of total system generation

Figure 6.9 shows the frequency variation of Biyagama 220kV bus when a generator (260MW) tripping of 26% of total system generation (1000MW). The observations are as follows.

- Minimum frequency: 48.37Hz
- Maximum frequency: 50.00Hz
- Stabilizing frequency: 49.56Hz
- Frequency normal operational limit violation after final frequency stabilization: NO

In this frequency variation plot there can be clearly observed an under frequency operational limit violation due to the rejection of large generation percentage from the system at 5s. This obvious frequency drop can be normalized by the automatic activation of UFLS scheme. Due to the activation of UFLS scheme (i.e. large rejection of system demand), the final stabilizing frequency does not exceed the desired frequency normal operational limit and therefor it cannot be observed a frequency normal operational limit violation after stabilizing the system. So, it can be concluded that the frequency behavior at the tripping incident of 26% generation at Extreme Thermal Maximum Scenario is feasible.

Figure 6.8 shows the voltage variation of New Anuradhapura 220kV bus when a generator (260MW) tripping of 26% of total system generation (1000MW). The observations are as follows.

- Minimum voltage: 233.21kV
- Maximum voltage: 252.81kV
- Stabilizing voltage: 245.96kV
- Voltage normal operational limit violation after final voltage stabilization: YES

In this voltage variation plot there is no any under voltage operational limit violation due to the rejection of large generation percentage from the system at 5s. Later on, due to the activation of UFLS scheme (i.e. large rejection of system demand), the

final stabilizing voltage exceeds the desired over voltage normal operational limit and therefor it can be observed an over voltage normal operational limit violation after stabilizing the system. So, it can be concluded that the voltage behavior at the tripping incident of 26% generation at Extreme Thermal Maximum Scenario is infeasible.

6.1.6 Discussion of case study of Extreme Thermal Maximum Scenario

Referring to the results which have been obtained from 6.1.5.1, 6.1.5.2 and 6.1.5.3, considering both frequency and voltage operational limits, the maximum possible loading capacity of a single generator for Thermal Maximum Scenario is up to 25% in Extreme Thermal Maximum Scenario.

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

This study has been conducted considering the actual system parameters and data (dispatch scenarios, dispatch schedules, latest protection trip settings, actual failure incidents, etc.) and the actual dynamic response of the system. Real time failure Digital Fault Records (DFRs) and the generation dispatch data have been obtained from Transmission Protection branch and System Control Centre branch of CEB, for the study purpose.

The summary of the simulation studies can be illustrated clearly in a table according to table 7.1.

Table 7.1: Summary of the simulation case studies

Dispatching Scenario	Generator tripping % out of total generation (%)	Frequency Stability				Voltage Stability				Overall acceptance for both Frequency and Voltage
		Maximum Frequency Reached (Hz)	Minimum Frequency Reached (Hz)	Final Stabilization Frequency (Hz)	Acceptance for Frequency Stability	Maximum Voltagey Reached (kV)	Minimum Voltagey Reached (kV)	Final Stabilization Voltage (kV)	Acceptance for Frequency Stability	
Hydro Maximum	27	51.30	47.50	BLACK OUT	BLACK OUT	284.90	178.84	BLACKOUT	BLACK OUT	NO
	25	50.86	48.06	50.19	YES	243.82	223.25	243.20	NO	NO
	23	50.10	48.21	49.91	YES	242.74	222.20	242.07	NO	NO
	21	50.00	48.43	49.64	YES	239.45	222.30	233.00	YES	YES
	19	50.00	48.66	49.53	YES	236.10	220.00	230.82	YES	YES
Thermal Maximum	27	51.14	48.03	50.66	NO	253.64	232.82	245.20	NO	NO
	25	50.32	48.09	50.12	YES	245.42	226.20	238.00	YES	YES
	23	50.00	48.41	49.54	YES	241.34	222.38	234.00	YES	YES
	21	50.00	48.45	49.58	YES	240.98	222.18	232.88	YES	YES
	19	50.00	48.63	49.67	YES	239.62	220.45	232.21	YES	YES
Extreme Thermal Maximum	27	50.79	48.24	50.19	YES	253.81	234.36	246.78	NO	NO
	25	50.00	48.44	49.59	YES	245.86	227.19	238.92	YES	YES
	23	50.00	48.53	49.65	YES	241.44	222.98	234.88	YES	YES
	21	50.00	48.62	49.66	YES	240.42	222.14	233.75	YES	YES
	19	50.00	48.72	49.69	YES	239.90	221.52	233.42	YES	YES

- In addition to that, under Hydro Maximum Scenario, the case of generator tripping of 22% was analyzed and the results were acceptable for both frequency stability and voltage stability, hence the overall stability as well.
- In addition to that, under Thermal Maximum Scenario, the case of generator tripping of 26% was analyzed and the results were acceptable for both frequency stability and voltage stability, hence the overall stability as well.
- In addition to that, under Extreme Thermal Maximum Scenario, the case of generator tripping of 26% was analyzed and the results were not acceptable for voltage stability, hence the overall stability as well.

Considering the summery of the above simulation case studies, the summary of the complete case study can be illustrated clearly in a table according to table 7.2.

Table 7.2: Summary of the complete case study

Dispatching Scenario	Generator tripping % out of total generation (%)	Frequency Stability				Voltage Stability				Overall acceptance for both Frequency and Voltage
		Maximum Frequency Reached (Hz)	Minimum Frequency Reached (Hz)	Final Stabilization Frequency (Hz)	Acceptance for Frequency Stability	Maximum Voltage Reached (kV)	Minimum Voltage Reached (kV)	Final Stabilization Voltage (kV)	Acceptance for Frequency Stability	
Hydro Maximum	27	51.30	47.50	BLACK OUT	BLACK OUT	284.90	178.84	BLACKOUT	BLACK OUT	NO
	25	50.86	48.06	50.19	YES	243.82	223.25	243.20	NO	NO
	23	50.10	48.21	49.91	YES	242.74	222.20	242.07	NO	NO
	22	50.00	48.23	49.52	YES	240.82	220.20	239.96	YES	YES
	21	50.00	48.43	49.64	YES	239.45	222.30	233.00	YES	YES
	19	50.00	48.66	49.53	YES	236.10	220.00	230.82	YES	YES
Thermal Maximum	27	51.14	48.03	50.66	NO	253.64	232.82	245.20	NO	NO
	26	50.86	48.06	50.19	YES	240.82	220.20	239.96	YES	YES
	25	50.32	48.09	50.12	YES	245.42	226.20	238.00	YES	YES
	23	50.00	48.41	49.54	YES	241.34	222.38	234.00	YES	YES
	21	50.00	48.45	49.58	YES	240.98	222.18	232.88	YES	YES
	19	50.00	48.63	49.67	YES	239.62	220.45	232.21	YES	YES
Extreme Thermal Maximum	27	50.79	48.24	50.19	YES	253.81	234.36	246.78	NO	NO
	26	50.00	48.37	49.54	YES	252.81	233.21	245.96	NO	NO
	25	50.00	48.44	49.59	YES	245.86	227.19	238.92	YES	YES
	23	50.00	48.53	49.65	YES	241.44	222.98	234.88	YES	YES
	21	50.00	48.62	49.66	YES	240.42	222.14	233.75	YES	YES
	19	50.00	48.72	49.69	YES	239.90	221.52	233.42	YES	YES

The summary of the complete case study can be illustrated in a graph according to figure 7.1.

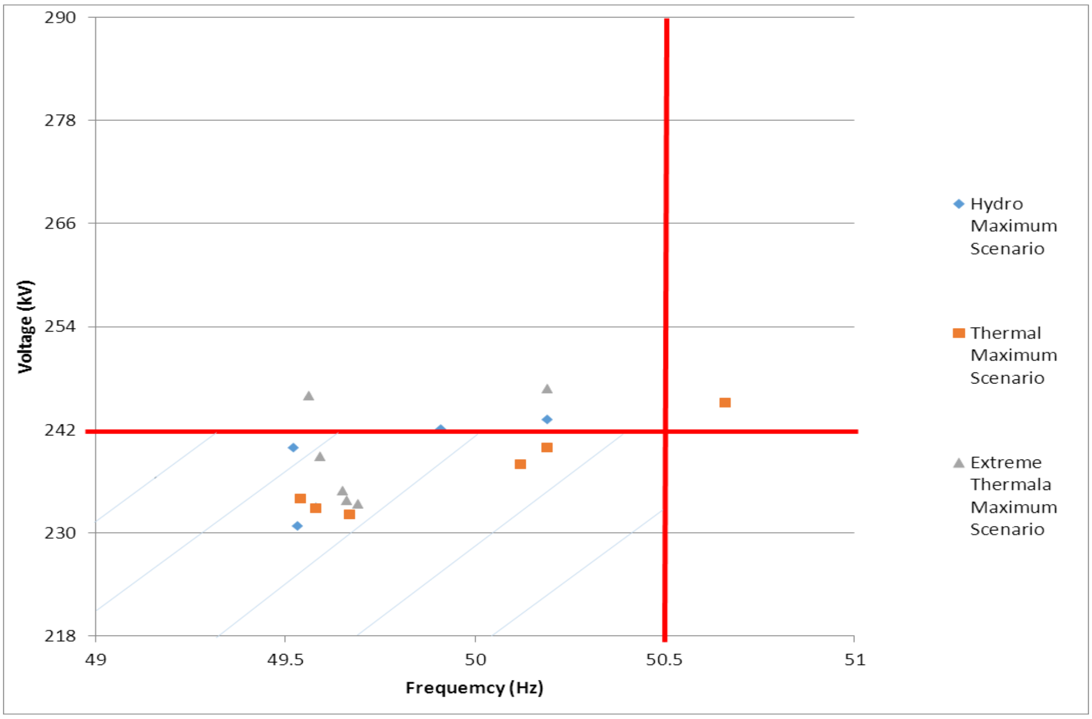


Figure 7.1: Summary of the complete case study

An optimum solution range at each generation dispatch scenario has been derived through the study. Since there are three major dispatch scenarios according to the table 7.1 and table 7.2, the optimum solution range for maximum loading capacity of a single generator unit can be concluded as follows.

1. Considering both frequency and voltage stability, the maximum possible loading capacity of a single generator for Hydro Maximum Scenario is up to 22%.
2. Considering both frequency and voltage stability, the maximum possible loading capacity of a single generator for Thermal Maximum Scenario is up to 26%.
3. Considering both frequency and voltage stability, the maximum possible loading capacity of a single generator for Extreme Thermal Maximum Scenario is up to 25%.

7.2 Recommendations

It should be emphasized that, during some rare and abnormal system conditions (extreme weather conditions, extreme load behaviors, etc), the actual power system behavior is comparatively complex up to certain extent considering the normal system responses. In those cases, the steady state frequency and voltage rises are so much abnormal and uncontrollable. Therefore, this study has been conducted considering the operational limit violation of normal system operation stability (i.e. steady state) at the final frequency and voltage stabilization, instead of the operational limit violation of emergency operation stability (i.e. dynamic state) throughout the emergency response duration, in order to plan the failure incidents for the worst cases and omit the uncaptured incidents.

Even though as the conclusion, it has been obtained three distinct answers for the maximum loading capacity of a single generator respective to each generation dispatch scenario, it can be decided whether the power system should be operated with above distinct values at each dispatch scenario or whether to operate the power system at a single common value for maximum loading capacity of a single generator unit.

Operating the system with different values (i.e. results obtained through the above studies under each dispatch scenario) is the recommendation of the author, since that method would utilize the low cost coal generation of LVPS, at it’s maximum feasible values (i.e. minimizing the operational cost) throughout all the demand scenarios at each dispatch scenario, without compromising the power system stability and reliability.

Since these results totally depend on the present power system parameters and the prevailing UFLS scheme, most of the demand side modifications such as 33kV load transferring and rearranging the priority feeders, should not be frequently conducted in large scale, assuming that the aging and natural degrading of system parameters (ex: Governor response time, Exciter response time, Transformers tap changing time, feeder relay operating time, etc.) are negligible.

Further, it should be noted that the conclusions of this research have complete validity corresponding to the present national power system of Sri Lanka up to the date when the author has published this thesis. The conclusions have provision to be deviated from the research findings with the adaptations of future system modifications, which will be implemented considering the power system dynamic characteristics.

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Appendix A: The map of Sri Lankan Transmission System in 2016