OPTIMUM REACTIVE POWER COMPENSATION METHODOLOGY TO MINIMIZE SYSTEM OVERVOLTAGE CONDITIONS

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Degree of Master of Science

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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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Signature of the supervisor:
(Dr. Asanka Rodrigo)

09th February 2017

Abstract

Sri Lankan Power system has experienced power frequency over voltages at steady state conditions predominantly at New Anuradhapura, New Chilaw and Chunnakam Grid Sub Stations. New Anuradhapura being connected to the lengthiest 220kV transmission lines from Kothmale (163km) and New Chilaw being connected to the Lakvijaya Power Station, which accounts to the highest capacity of national generation contribution and Chunnakam having long distance radial connection are the root causes for the issue.

Currently the network overvoltages are mainly monitored at 220kV level due to sensitivity of the protection schemes implemented on the 220kV network equipment. Eg v/f, overvoltage protection, but all network equipments are vulnerable to overvoltage conditions despite their operation voltage level.

In 27th September 2015, the most destructive event in terms of overvoltage occurred in the Sri Lankan power system initiating with tripping of Lakvijaya Gen 03 and ultimately causing a blackout. Post failure studies concluded with stressing out lack of reactive power compensation for overvoltage scenarios in present network topology.

In power system, the reactive power compensation is important for system voltage profile. This is also helpful to power factor improvement and loss reduction.

This study illustrates effectiveness of dynamic stability with integration of variable shunt reactors and static var compensators to the existing network topology, further studies are carried out to assess the effectiveness of disconnecting selected circuits to minimize overvoltage problem.

Dedication

Thank you GOD

I dedicate this thesis to my beloved parents, the two pillars in my life who have guided and motivated me to reach for my best.

To my sister who has been the strength and joy for my whole life.

To my beloved wife, your love made everything possible.

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LIST OF ABBREVIATIONS

Abbreviation	Description
CEB	Ceylon Electricity Board
GSS	Grid Sub Station
LVPS	Lakvijaya Power Station
PSS/E	Power System Simulator for Engineers
SVC	Static Var Compensator
VSR	Variable Shunt Reactor
SCC	System Control Centre
PS	Power Station
BSC	Breaker Switch Capacitor
BB	Bus Bar

Chapter 1

BACKGROUND

1.1 Introduction

Present day power systems are being operated closer to their stability limits due to economic constraints. Maintaining a stable and secure operation of a power system is therefore very important and challenging issue. Power system stability is the field of interest that will govern the reliability of the power system. Power system stability can be further sub categorized in to Voltage Stability, Rotor Angle Stability and Frequency Stability. In recent years, voltage instability has become a major research area in the field of power systems after a number of voltage instability incidents were experienced around the world. Presence of Power Frequency Overvoltage can be classified under voltage stability and its one of the major problem, Sri Lankan power system has experienced over a decade.

The definition of voltage stability as proposed by IEEE task force is as follows:

Voltage stability refer to the ability of power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating point. The system state enters, the voltage instability region when a disturbance or an increase/decrease in load demand or alteration in system state results in an uncontrollable and continuous drop/rise in system voltage [1].

The time frame of interest for voltage stability problems may vary from a few seconds to tens of minutes. Short-term voltage stability involves dynamics of fast acting load components such as induction motors, electronically controlled loads, etc. This type of voltage instability evolves in time frame of several seconds. Long-term voltage stability involves slower acting equipment such as tap-changing transformers, thermostatically controlled loads, and generator current limiters. This type of voltage instability evolves in time frame of several minutes.

1.2 Power frequency over voltages

Power frequency overvoltages are those whose duration are relatively long and may cause serious damages to the installation and to the electrical equipment. Power frequency overvoltages differ from transient and switching overvoltages in that they last for longer durations, typically from a few cycles to a few seconds.

There are many reasons for power frequency overvoltages in power system. The overvoltage causes number of effect in the power system. It may cause insulation failure of the equipment, malfunction of the equipment, damage to electronic components, heating, flashovers, etc...

1.3 Voltage Criteria of Sri Lanka

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

Table 1.1 : 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

1.4 Overvoltage can be caused by Number of Reasons,

Load Rejection

When a transmission line or large inductive load that is fed from a power station is suddenly switched off, the generator will speed up and the bus bar voltage will rise.

Ferranti effect

A long transmission line draws substantial quantity of charging current. If such line is, open circuited or very lightly loaded at the receiving end, the voltage at receiving end may become greater than voltage at sending end. This phenomenon known as Ferranti Effect and is due to the voltage drop across the line inductance (due to charging current) being in phase with the sending end voltages. Therefore both capacitance and inductance is responsible to produce this phenomenon.

The charging current is negligible in short line but significant in medium line and appreciable in long line. Therefore this phenomenon occurs in medium and long lines.

Ground Fault

A single line-to-ground fault will cause the voltages to ground of the healthy phases to rise. In the case of a line-to-ground fault, systems with isolated neutral or grounded through high impedance may develop overvoltages on healthy phases higher than normal line-to-line voltages. Solidly grounded systems will only permit phase-to-ground overvoltages well below the line-to-line value.

1.5 Reactive Power and Voltage Control in Transmission Network

The voltage profile is controlled through the careful balance of reactive power held on the system. Voltage collapse is one of the major limitations in modern transmission systems. The long high voltage transmission lines have an inherent characteristic of self-producing capacitive reactive power along the length of the transmission line. This is due to the distributed nature of the charging current caused by shunt capacitance due to electrostatic field to earth. The amount of reactive power a transmission line provides to the system is related to the line voltage. The greater the voltage, the more capacitive reactive power the line will supply. Higher voltages than rated steady-state voltages also increase the stress levels in the insulation of the network equipment which often leads to reduced life span of the equipment [2].

The system components as well as loads include components of var sources which influence system voltage and system stability. Transmission lines in HV systems (735 kV) may reach 200 Mvar capacitive at a line length of 100 km [3]. Cable connections have even higher var contribution. Without proper reactive power compensation critical system conditions may occur, resulting large voltage deviations and system stability problems in long transmission lines. Most of the power quality problems can be attended or solved with an adequate control of reactive power by using proper shunt and series compensation schemes.

1.6 Methods of Overvoltage Control

The following techniques to control high voltage:

- switching capacitors out-of-service
- switching reactors in-service
- adjust variable reactor tap positions
- adjusting voltage set point of static var compensators (SVC)
- operating synchronous condensers
- changing transformer tap positions
- changing generation excitation
- adjusting generation MW output
- switching transmission facilities in/out of service

The control of voltage levels is achieved by controlling the production, and absorption, of reactive power flow at all levels in the power system. Generating units provide the primary means of voltage control. Additional devices to control over voltages are sinks of reactive power such as shunt reactors or static var compensators (SVC), voltage-regulating transformers such as tap changing transformers or autotransformers and dynamic source such as synchronous motor. Shunt reactors and SVCs provide passive compensation. They are either permanently connected to the power system or switched when necessary. They contribute to voltage control by modifying network characteristics.

It is also important to discuss how these additional devices have been installed by different utilities. According to the paper “Variable Shunt Reactors: Applications and System Aspects” by C. Bengtsson, K. Ryen, O. A. Rui, T. Olsson, Norwegian Transmission System has 8 VSRs in operation, 6 no’s of 420 kV, 90/120-200 Mvar, 2 no’s of 300 kV, 80-150 Mvar. The reason for such high reactive sink requirement is that, in 2004-2010 their voltage was upgraded to 420 kV of a tie-line to Sweden, as a consequence, the capacitive generation from the power lines increased at low power flow. Other consequences were loss of reactive compensation from hydro generators when stopped due to power import. The integration of VSR has been beneficial to less voltage drop/rise when switched (daily switching) and to maintain reactive reserves in SVC and rotating synchronous compensator were secured by tuning of the reactor. The static var compensators are being increasingly applied in electric transmission systems economically to improve the post-disturbance recovery voltages that can lead to system instability. A SVC performs such system improvements and benefits by controlling shunt reactive power sources, both capacitive and inductive, with high-tech power electronic switching devices. As stated in the paper “Reactive power compensation technologies, State of the Art Review” by J. Dixon, L. Moran, J. Rodriguez and R. Domkean, SVC has been used for solving Namibia’s long transmission line’s issues due to unusual resonance. The line’s length of 890 km and there are certain problems mainly with voltage instability and near 50-Hz resonance which already existed in the power system. Several solutions were considered as an answer to the resonance problem including fixed and switched reactors. Finally, they have chosen conventional, proven SVC technology provided by three thyristor controlled reactors (TCRs), a fourth, continuously energized TCR and two identical double-tuned filters. The filters take care of harmonics and supply capacitive reactive power during steady state operation.

Proper analysis is required for integrating Shunt Reactors (SRs) and SVCs in Sri Lankan transmission system with respect to voltage deviation, as SVC’s and SR’s costs are very high. The objective of the study is to analyse the effect of transmission circuit shedding and to analyse the integration of SVC and SR for overvoltage conditions to the Sri Lankan power system for the optimum performance of system over voltage mitigation / voltage stabilization.

1.7 Motivation

Sri Lankan Power system network has experienced Power frequency over voltages at steady state conditions predominantly at New Anuradhapura, New Chilaw and Chunnakam Grid Sub Stations. New Anuradhapura being connected to the lengthiest 220kV transmission lines from Kothmale (163km) and New Chilaw being connected to the Lakvijaya Power Station, which accounts to the highest capacity of national generation contribution and Chunnakam having long distance radial connection are the root causes for this issue.

Apart from that, sudden rejection of loads (due to tripping of transmission circuits), and operation of under frequency load shedding also produces significant overvoltage scenarios in the Sri Lankan power system.

The most severe incident in terms of overvoltage occurred in recent past, initiated with tripping of Lakvijaya Gen. 03, which ultimately resulted a blackout. Although the power system recovered with operation of under frequency load shedding scheme in terms of frequency, system failed to recover voltage stability due to the higher leading reactive power deficit which led to extremely high voltage levels in the power system followed by the over fluxing tripping of 220/132kV coupling transformers at N'Anu, N'Chilaw, Biya Rant and KCCP, AES power stations. A post failure analysis was followed by Manitoba HVDC Research Centre with Public Utilities Commission of Sri Lanka (PUCSL), and as stated in their Final Report: Investigation of Total Failure of the Transmission System (2015_09_27) under conclusions, Sri Lankan power system should assess the integration of fast acting reactive power compensation methodology to attain more effectiveness in dynamic stability [4]. Therefore, detail analysis of a methodology to optimize over voltage scenarios in the power system using new technology has great value for the utilities and thereby to the country.

1.8 Objective of the Study

The objective of this study is to provide the dynamic modeling of the present Sri Lankan power system and to derive optimum solutions in mitigating long-term high voltage collapses. The study is bounded by practical limitations of leading reactive power capability of generators, assessment of transmission lines shedding without compromising system reliability and introducing svc and shunt reactors for providing fast-acting reactive power compensation on high voltage transmission network.

1.9 Outcomes of the study

The research findings will enable followings.

- Maintaining the system voltage at a desired level at steady state operation
- Maintaining stability of system under dynamic conditions with respect to over voltage

1.10 Scope of the work

- PSS/E modeling of Sri Lanka power system
- Validating dynamic properties of the model
- Integration of shunt reactor in various test cases for overvoltage mitigation
- Integration of SVC in various test cases for overvoltage mitigation
- Evaluation of selected transmission line shedding for overvoltage mitigation
- Selection of optimum solution

Chapter 2

SHUNT REACTORS AND STATIC VAR COMPENSATORS

2.1 Shunt Reactors

2.1.1 Introduction to Shunt Reactors

Shunt reactor is the most cost efficient piece of equipment for maintaining voltage stability on the transmission lines. It does this by compensating for the capacitive charging of the high voltage AC-lines and cables, which are the primary generators of reactive power. The reactor can be seen as the voltage control device which is often connected directly to the high voltage lines as in the Figure 2.1.

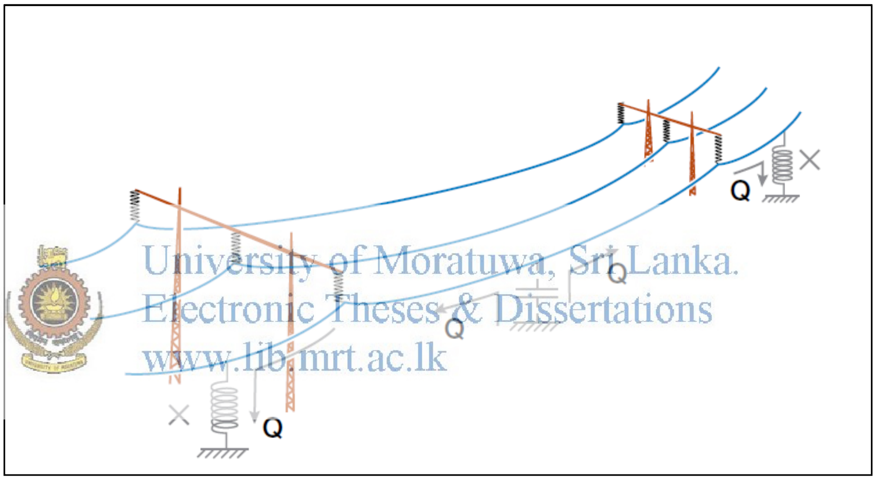


Figure 2.1: The reactor consume the generated reactive power from the line

Source: Voltage stabilization in transmission grids with fixed and variable shunt reactors. ABB Transformers, Tomas Olsson, Syracuse (NY), 6/4/2013

Fixed Shunt Reactors have been traditionally used in transmission and distribution systems for many years. The reason that it is called Fixed Shunt Reactor is that its rated reactive power consumption is approximately constant; in other words, it has a fixed reactance (X_R). The inductive reactive power which is consumed by reactor can be calculated as follows:

$$Q_{IR} = \frac{V^2}{X_R} = X_R \times I^2 = \sqrt{3}V \times I$$

$$X_R = L_R\,\omega$$

Where:

- Q_{IR} is the 3-phase inductive reactive power consumed by the Shunt Reactor in Var
- V is the phase-to-phase voltage at the point the reactor is connected to the network in Volts
- X_R is the total inductive reactance of the Shunt Reactor in Ohms
- L_R is the equivalent inductance of the Shunt Reactor in Henry, and
- I is the flowing current into the Reactor's branch in Amperes

As seen in equation, the consumed reactive power (Q_{IR}) is only a function of the line voltage (V) and is not affected by the load current of the line.

2.1.2 Variable Shunt Reactor (VSR)

Unregulated shunt reactors can only be designed optimal for constant load- and generation-conditions. Contrarily, variable shunt reactors can keep the voltage in the defined voltage band even with big voltage fluctuations. Having the best adaption to the reactive power currently needed, losses are minimized to the maximum. This optimized the transmission capability of the grid as well as the cost effectiveness and thus results in cost savings for the operator of the VSR.

2.1.3 Transformer Type VSR

The main function of VSR is to regulate the consumption of reactive power and in transformer type VSR this is accomplished by connecting/disconnecting electrical turns in the reactor. According to following equations, the reactive power consumption of the VSR (Q_{IR}) is proportional to the square of voltage and inversely proportional to the equivalent inductance of the Reactor (L_R). Considering a constant voltage level, more inductance leads to less current flowing in VSR branch and less reactive power consumption. Following equations show how the reactive power consumed by the reactor is related to the number of electrical turns of the inductive component [5].

$$Q_{IR} \sim \frac{V^2}{L_R}$$

$$L_R = \frac{\mu N^2 A}{X_R}$$

Where:

- **μ** is the magnetic permeability of the core material
- ***l*** is the physical length of the coil inductive component
- A is the cross-sectional area of the coil
- **N** is the number of electrical turns

The inductance of the reactor (L_R) is proportional to the square of the number of electrical turns (N).

$$L_R \sim N^2$$

As a result, the power consumption of the reactor is controlled by the following equation:

$$Q_{IR} \sim \left(\frac{V}{N}\right)^2$$

At maximum reactive power rating the minimum numbers of electrical turns are connected and at minimum reactive power rating the maximum numbers of electrical turns are connected. Thus the minimum reactive power rating is limited by the physical length of the regulating winding and consequently the size of the VSR. This change in number of turns is done by using a tap changer. The same type of tap changer which is already utilized for decades in power transformer applications has been used for VSR. Therefore, it is possible to fine tune the power system voltage level by using VSR. In order to regulate the power in the Variable Shunt Reactor, a separate regulating winding is used. This winding is located outside the main winding around the core limb. The high voltage (HV) inlet to the main winding could either be located as a yoke entrance or as a centre entrance to the winding.

2.1.4 Thyristor Controlled Reactor (TCR)

A thyristor controlled reactor is usually a three-phase assembly, normally connected in a delta arrangement to provide partial cancellation of Harmonics. Often the main TCR reactor is split into two halves, with the thyristor valve connected between the two halves. This protects the vulnerable thyristor valve from damage due to flashovers, lightning strikes etc [6].

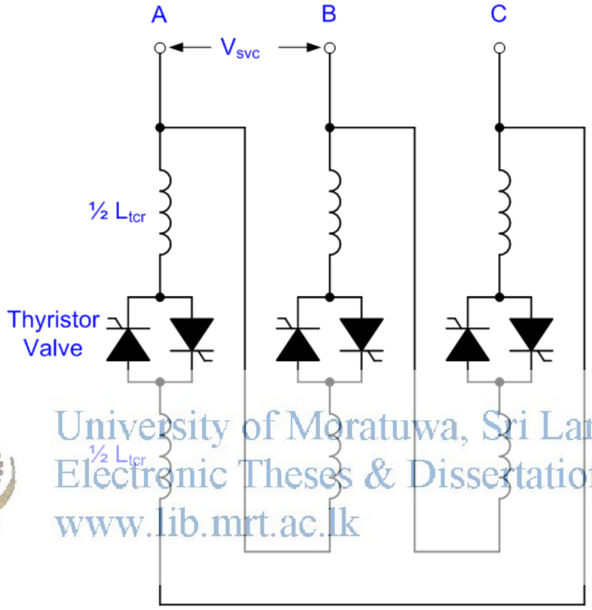


Figure 2.2: Thyristor controlled reactor three-phase assembly

The current in the TCR is varied from maximum (determined by the connection voltage and the inductance of the reactor) to almost zero by varying the "Firing Delay Angle", α. α is defined as the delay angle from the point at which the voltage becomes positive to the point at which the thyristor valve is turned on and current starts to flow.

Maximum current is obtained when α is 90°, at which point the TCR is said to be in "full conduction" and the rms current is given by:

$$I_{tcr-max} = \frac{V_{svc}}{2\pi f L_{tcr}}$$

Where:

- Vsvc is the rms value of the line-to-line bus-bar voltage to which the SVC is connected
- Ltcr is the total TCR inductance per phase

The current lags 90° behind the voltage in accordance with classical AC circuit theory. As α increases above 90°, up to a maximum of 180°, the current decreases and becomes discontinuous and non-sinusoidal. The TCR current, as a function of time, is then given by:

$$\omega t < \pi - \alpha : I(\omega t) = I_{tcr-max}\sqrt{2}[-\cos(\alpha) - \cos(\omega t)]$$

$$\alpha < \omega t < 2\pi - \alpha : I(\omega t) = I_{tcr-max}\sqrt{2}[\cos(\alpha) - \cos(\omega t)]$$

$$\omega t > \pi + \alpha : I(\omega t) = I_{tcr-max}\sqrt{2}[-\cos(\alpha) - \cos(\omega t)]$$

Figure 2:3 Voltage and current waveforms of TCR

2.2 Static Var Compensators

2.2.1 Introduction to SVC

SVC is an electrical device for providing fast-acting reactive power compensation on high voltage transmission networks. It can contribute to improve the voltages profile in the transient state and therefore, in improving the quality performances of the power system. Normally, SVC is a combination of one or more of the following branches:

1. Thyristor Switched Capacitor (TSC)
2. Thyristor Controlled Reactor (TCR)
3. TSC plus TCR
4. Fixed Capacitor (FC) plus TCR

2.2.2 Thyristor Switched Capacitor (TSC)

A TSC branch contains capacitors and current limiting reactors which are switched on and off by thyristor valves. TSC branches can be delta or star connected. In star connection, one valve becomes obsolete and can be left out in one of the three phases [3]. Using the same thyristors in terms of current carrying capability as for a TCR the branch rating will be lower accordingly. Due to transient phenomena at switch-on, TSCs are not continuously controlled but instead are always switched on and off individually as required by the system. Through the precise triggering of thyristor valves, most of the transient phenomena at switch-on can be avoided. TSC branches do not generate harmonic distortions.

2.2.3 Thyristor Controlled Reactor (TCR)

A TCR branch contains reactors which are phase angle controlled by thyristor valves. Three single phase branches are connected in delta to reduce the generation of triplen harmonics in symmetrical operation [3]. TCRs are used to continuously regulate the inductive reactive power from zero to the maximum, depending on the requirements, by means of current. They do not generate transients at the increased firing angles above 90° [3]. However, they do generate harmonic currents that must be absorbed by filters.

2.2.4 TSC plus TCR

TCRs are often used in conjunction with TSCs in order to give reduced power loss at zero var output compared with the losses of a scheme using a fixed capacitor and a larger TCR. When TCR is used with TSC, the steps of TSC can be arranged to switch off at appropriate output levels with minimum losses. As described above, The SVC consisted of inductances and capacitances which may be fast controlled by thyristors. The required capacitive power for the system will be installed in capacitive branches which are fixed connected to the LV bus or switched by thyristor valves. Fixed capacitor branches are typically tuned by series reactors for harmonic filtering purposes [7]. The inductive power is obtained by single phase or three phase reactor combinations which are smoothly controlled by thyristor valves (TCR). The branches are connected to the HV system via a dedicated SVC transformer. The transformer adjusts the system voltage to a level optimized for the thyristor operating capabilities. The thyristor can switch capacitors or inductors in and out of the circuit on per-cycle basis, allowing for very rapid higher control of system voltage.

2.2.5 Basic operation of SVC

The SVC with combination of Fixed Capacitor (FC) plus TCR is used for general analysis. Therefore, control concept of above combination is mainly discussed here. The SVC is a controlled shunt susceptance as defined by control settings that injects reactive power into the system based on the square of its terminal voltage [8]. The control objective of the SVC is to maintain a desired voltage at the high-voltage bus. In the steady-state, the SVC will provide some steady-state voltage control to maintain the voltage in the high-voltage bus at a pre-defined level. If the high voltage bus begins to fall below its set point range, the SVC will inject reactive power into thereby increasing the bus voltage back to its net desired voltage level [8]. If bus voltage increases, the SVC will inject less (or TCR will absorb more) reactive power, and the result will be to achieve the desired bus voltage. Thyristor controlled reactor will absorb the reactive power in this case. If the capacitor is a fixed one, the magnitude of reactive power injected into the system is controlled by the magnitude of reactive power absorbed by the TCR [2].

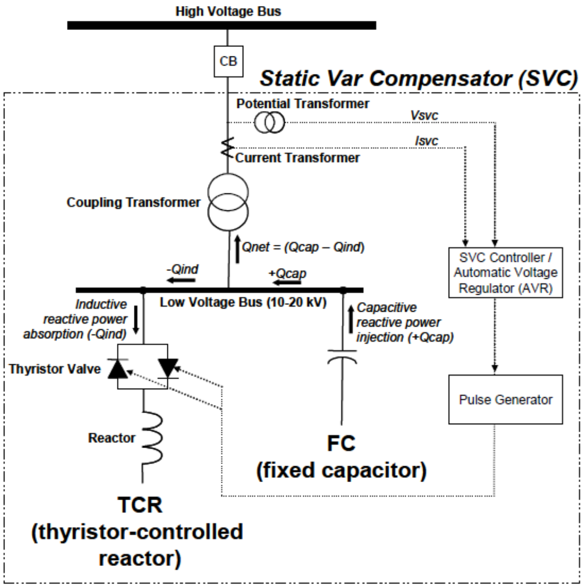


Figure 2.4: Basic arrangement of SVC

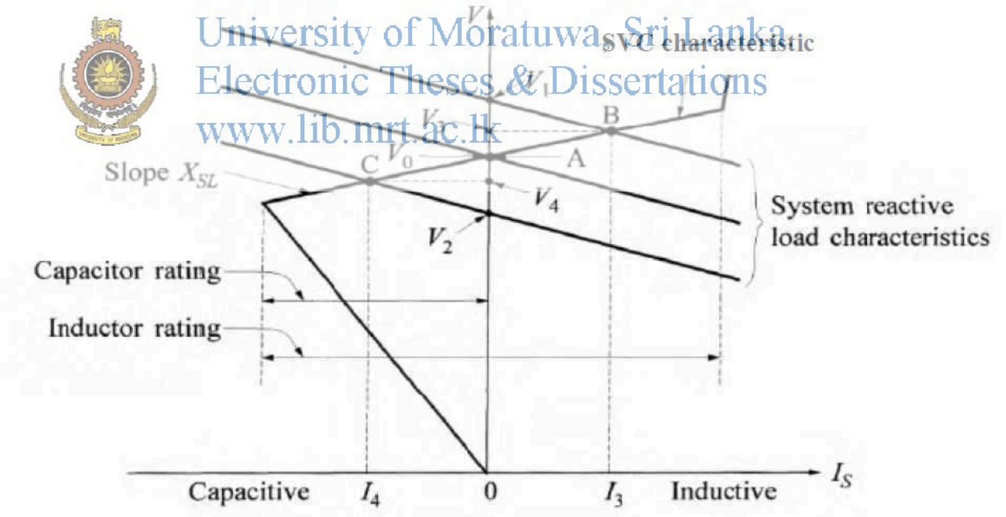


Figure 2.5: Graphical solution of SVC operating point for given system

If the system voltage increases due to decrease in system load level, voltage will increase to V1 without a SVC. But, with SVC, operating point moves to B by absorbing inductive current I3 holding the voltage at V3. Similarly, if the voltage decreases due to increase in system load level SVC will hold the voltage at V4 instead of at V2 without the SVC.

The TCR provides continuously controllable reactive power in the lagging power-factor range. A fixed-capacitor bank is connected in shunt with the TCR to extend the dynamic controllable range to the leading power-factor domain. The variation in current through the reactor is obtained by phase control of back to back pairs of thyristor connected in series with reactor. The TCR and the coupling transformer are arranged in delta connection to cancel the third harmonics [9]. The fixed-capacitor banks are usually connected in a star configuration and splited into more than one 3-phase group. Each capacitor contains a small tuning inductor that is connected in series and tunes the branch to act as a filter for a specific harmonic order [9]. The capacitor groups are tuned to the 5th & 7th harmonics and to act as a high-pass filter. However, when the net reactive power is small or lagging, large reactive current circulates between the TCR and the capacitors without performing any useful function in the power system. For this reason some capacitors are designed to be switched in groups, so that the capacitive requirement can be adjusted in steps. As an example, SVC arrangement with a switched capacitor shown in Figure 2.6, The TCR controller is provided with a signal representing the capacitor connected and is designed to provide a continuous overall voltage/current characteristic. When the capacitor group is switched on or off, the conduction angle is immediately adjusted along with other reference signals, so that the capacitive reactive power added or subtracted is exactly balanced by an equal change in the inductive reactive power of the TCR. Thereafter, the conduction angle will vary continuously according to the system requirements.

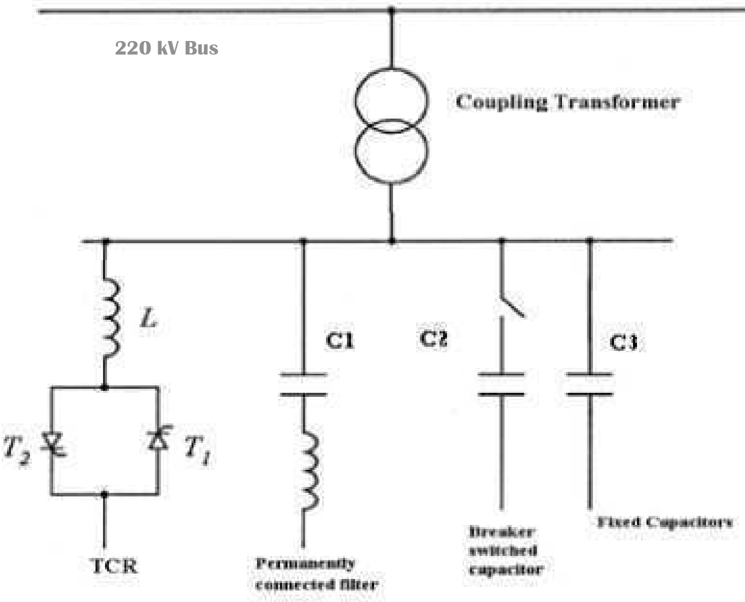


Figure 2.6: SVC arrangement for 220kV BUS

The control objective is to maintain the voltage at 220 kV bus at particular GS in the allowable tolerance margin. If bus voltage increases, the TCR will absorb more reactive power within its controlled limits and the result will be the desired bus voltage at the high voltage bus. Also if the voltage of 220 kV bus begins to fall below 1.00 p.u the SVC will inject reactive power in to the system within its controlled limits increasing the bus voltage back to 1.00 p.u. according to its slope setting.

As mentioned above, SVC injects reactive power (+Q) or removes reactive power (-Q) based on the square of its terminal voltage.

$$Q=BxV2$$

B: Shunt susceptance, V: Terminal voltage of TCR

In this analysis, L and C are components are sized such that Q > 0 is the only operating range. The simplified block diagram for the SVC dynamic model is shown in Figure 2.7. The automatic voltage regulator (AVR) in the form of proportional and integral control, operates on a voltage error signal as computed in the summing block below. $Verror=Vref - V - (Isvc*Xsl)$

There are also measurement lags (Td) and thyristor firing transport lag (T1). The output B of this control block diagram feeds into the pulse generator controller that generates the required thyristor firing signal for the TCR.

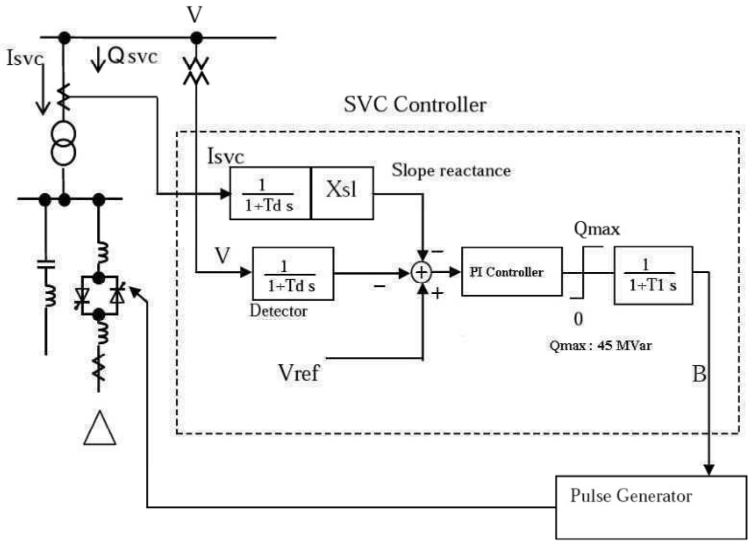


Figure 2.7: SVC control diagram

Chapter 3

Existing Transmission System of Sri Lanka

3.1 Existing Excess Reactive Power Compensation Methodology

Although many studies and measures have been performed to cater the un-served reactive power requirement of Sri Lanka very less priority has been given to excess reactive power problem during steady state low load or transient scenarios. This is mainly due to higher hydro capacity in generation with good leading reactive power capability, which has catered for the above said necessity until recent past. But with rapid increment of demand in the near past due to the weather patterns of very high temperature and economic growth hydro reservoirs are draw downed alarmingly creating a chaos in power sector. Therefore depending on generators for the excess reactive power requirement is not reliable neither it's feasible. Present overvoltage elimination methods other than leading reactive power capability of generators are transmission circuit shedding (double circuits with n-1 criteria) and manual switching off of Breaker Switch Capacitor (BSC).

3.2 Steady State Overvoltage on Sri Lankan Transmission Network

Measurements and registration of voltage values in significant connection points of 220 kV and 132 kV in the power system in Sri Lanka was obtained from Log sheets in System Control Branch, CEB. According to log sheets, voltage values were given half an hourly for time period of one year, from 1st January to 31st December of 2015. For the above period maximum voltage values on buses in substations (SS) presented in Table 3.1, in GSS of 220 kV New Anuradapura, New Chilaw and in GSS of 132 kV Chunnakum , where the maximum overvoltage were recorded. Due to process of recording only half and hourly voltage values, intermediate maximum values cannot be used for the study. Table 3.1 also presents the corrective actions taken by system operator to retain the voltage within the allowable tolerance limit defined by the Grid Code.

Table 3.1: Recorded maximum overvoltage values in 2015.

Date	Time	Substations	Voltage Level	Um	Umm	Switched off Circuits
9-Feb-15	0:00	New Anuradhapura	220	242	240	New Anu. - LVPS cct 01/02
24-Feb-15	0:00	New Anuradhapura	220	242	238	New Anu. - LVPS cct 01/02
25-Feb-15	7:00	New Anuradhapura	220	242	238	New Anu. - LVPS cct 01/02
8-Jul-15	7:00	New Chillaw	220	242	236	LVPS - New Chilaw cct 01/02
9-Jul-15	0:00	New Chillaw	220	242	234	LVPS - New Chilaw cct 01/02
13-Jul-15	0:00	New Chillaw	220	242	234	LVPS - New Chilaw cct 01/02
27-Jan-15	0:00	Chunnakam	132	145	140	Kilinochchi -Chunnakum cct 01/02
2-Feb-15	0:00	Chunnakam	132	145	140	Kilinochchi -Chunnakum cct 01/02
9-Feb-15	0:00	Chunnakam	132	145	140	Kilinochchi -Chunnakum cct 01/02

Um - Highest voltage for single contigency ; Umm - Measured maximum value ofvoltage

Source: Log Sheets 2015- System Control Branch, CEB

Although none of the values in the Table 3.1 has exceeded the tolerance margin of emergency overvoltage criteria, it does not mean the system does not undergo overvoltage scenarios. The table does not provide intermediate values between two consecutive log readings and corrective actions of line shedding has been done for all reading which has led the system to retaining below the margin.

The appearance of overvoltage in metered connection points of the power system happens usually at night and most often during minimal load modes. Overvoltages occur throughout the year, but the most significant ones are in the weekends and holidays when the consumption at its lowest. Figure 3.1, provides a comparison example of appearance of raised 220 kV voltages in New Anuuradhapura with demand of Sri Lanka for specific eight days. If these values are analyzed with maximum voltage values, it can be noticed that the minimum demand is one of the causes of overvoltages.

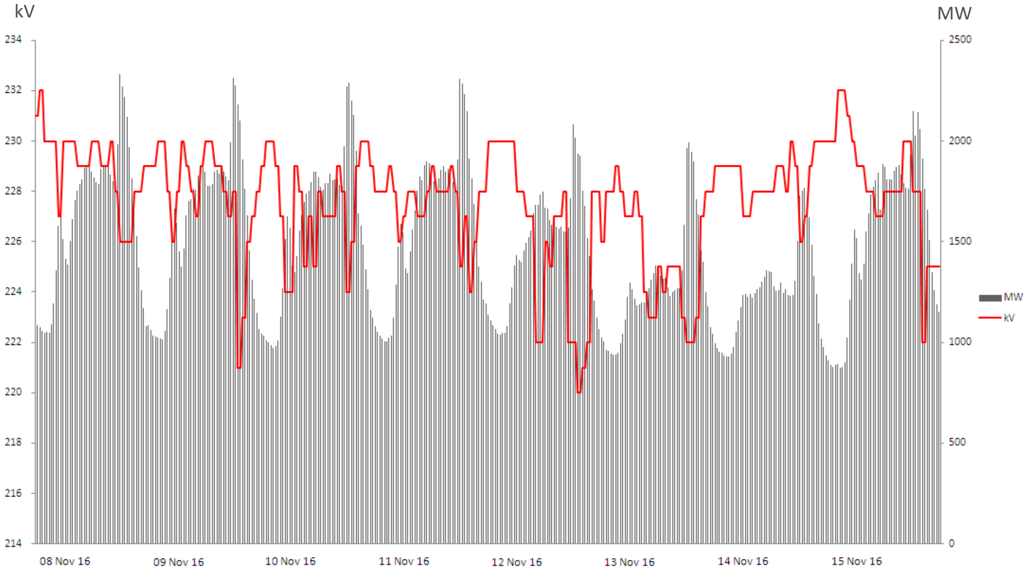


Figure 3.1: Weekly Diagram of voltage change in New Anu. and of consumption in Sri Lanka

Source: Log Sheets 2015/2016 - System Control Branch, CEB

Most of the 220 kV and 132 kV overhead lines, in night operation conditions of Sri Lanka are loaded below normal power transmission capacity (below SIL) which causes the generation of a significant amount of reactive power of charging. The generation of the reactive power of charging, the relatively minor losses of reactive power in the system and the low load of the system with active and reactive power, especially in nonworking days and night hours, cause appearance of overvoltages in Sri Lanka

The voltage profile on 2015_02_09 obtained from the same half and hourly reading presented in Table 3.3, further confirm the lower demand hours(below SIL) which occurs between 22:00 hrs to 04:00 hrs of adjacent days, are the main cause for higher voltage profile at New Anuradapura GSS. The 220kV transmission circuit connecting New Anuradapura GSS from Kothmale PS generate the maximum reactive power (≈20Mvar) as it's the lengthiest (163km) circuit of Sri Lankan transmission network.

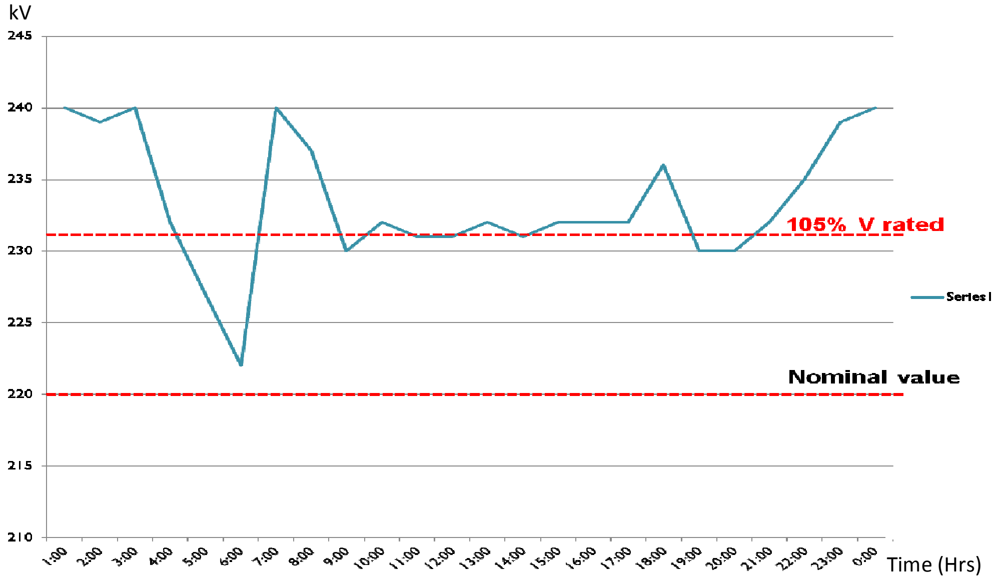


Figure 3.2: New Anu. 220kV voltage variation on 09/02/2015

Source: Log Sheets 2015/2016 - System Control Branch, CEB

The most widely used method for protecting the transmission equipment from continuous high voltages is disconnection of adequate overhead lines, primarily 220 kV networks which is regularly done by system operators. This is due to utilizing additional leading reactive power capability of generators during low demand conditions is difficult as system should cater for its minimum active power generations as well. The other most commonly practiced overvoltage managing technique with change of the ratios of the transformer also disregarded due to both 220kV and 132kV voltage rise simultaneously. Table 3.2 and Table 3.3 presents the disconnection of transmission circuits during the month of January 2016 to maintain the voltage levels at tolerable margin at New Anuradapura and Chunnakum GSSs. There have been 06 breaker operations at Chunnakum GSS and 22 breaker operations at New Anu. only for the month of January which is very significant number to justify the over voltage issue in Sri Lanka.

Table 3.2: Chunnakum GSS transmission line shedding data for Jan 2016

Date	Switched off CCT	Off Time	On Time	kV	A
1/16/2016	Kilinochi 01	0:58	7:00	138	11
1/17/2016	Kilinochi 01	3:54	7:12	136	16
1/23/2016	Kilinochi 01	2:26	7:17	135	16
1/24/2016	Kilinochi 02	22:30	7:16	134	10
1/27/2016	Kilinochi 01	3:39	5:52	137	27
1/31/2016	Kilinochi 02	23:46	7:05	133	32

Table 3.3: New Anu. GSS transmission line shedding data for Jan 2016

Date	Recorded Max kV		Switched off CCT	Off Time	On Time	kV	A	MW	MVAR
	132	220							
11/1/2016	140	231	KOTH 01	2:07	4:54	230	110	40	12
			LVPS 01	2:16	5:20	230	280	90	20
			TRIN 02	2:19	6:02	138	20		
1/13/2016	140	234	LVPS 01	3:37	7:07	228	300	112	20
1/16/2016	140	230	LVPS 01	0:45	6:12	231	300	70	10
			VAVU 01	1:04	6:55	139	60	8	12
			KOTH 01	1:08	5:54	231	20	10	4
			TRIN 02	1:10	6:58	140	20	N/A	N/A
1/17/2016	140	232	TRIN 02	3:17	7:11	138	20	N/A	N/A
			VAVU 01	3:47	7:11	138	70	14	11
			KOTH 01	3:59	7:16	231	116	40	12
1/18/2016	139	232	TRIN 02	0:28	12:05	136	20	N/A	N/A
1/23/2016	140	231	TRIN 02	2:16	7:08	135	20	N/A	N/A
			VAVU 01	2:25	7:09	135	70	14	11
1/24/2016	140	235	TRIN 02	22:18	7:11	137	20	N/A	N/A
			KOTH 01	22:29	7:12	230	50	20	8
			VAVU 01	22:46	7:11	134	65	14	10
1/27/2016	139	232	TRIN 02	3:28	5:40	138	20	N/A	N/A
			KOTH 01	3:29	5:48	230	110	40	15
1/31/2016	139	230	VAVU 02	23:43	7:04	134	65	12	10
			TRIN 02	23:43	7:04	134	20	N/A	N/A
			KOTH 02	23:43	7:04	224	120	40	10

3.3 Transient over Voltage on Sri Lankan Transmission Network

Under frequency load Shedding, rejection of loads (GSSs) due to transmission line tripping and generator tripping while adsorbing considerable amount of leading reactive power of the system causes overvoltages in their post failure scenarios. The worst ever of all time overvoltage cascade tripping scenario was occurred on 27th September 2015 which ultimately led to a system blackout. This blackout pre and post failure conditions are more elaborated under Chapter 4.1.2 Study Case -Total System Failure Occurred On 27th September 2015.

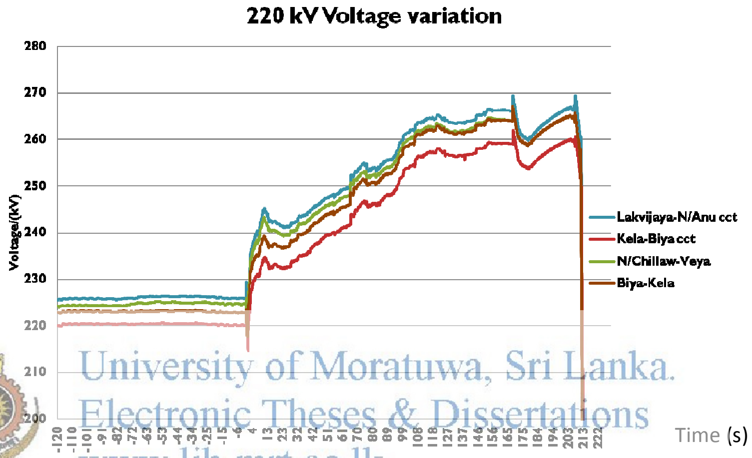


Figure 3.3: 220kV network voltage variations during the failure on 27/09/2016.

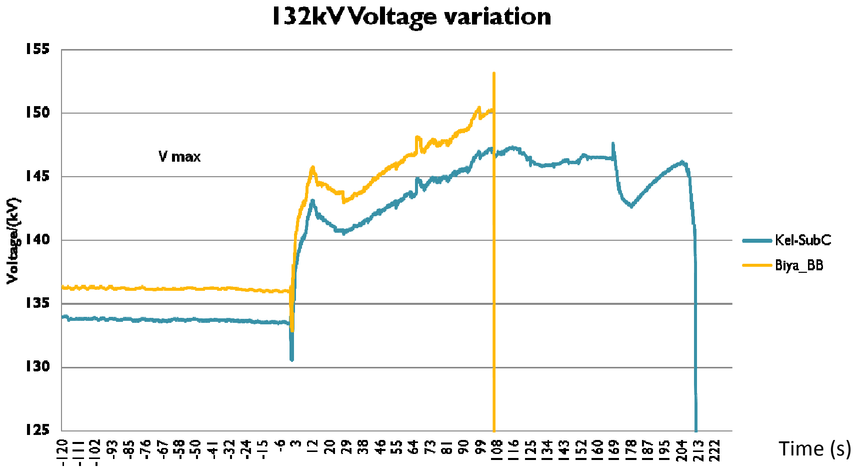


Figure 3.4: 132kV network voltage variations during the failure on 27/09/2016.

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 3800MW including renewable energy sources. Among them maximum capacity of the single generator unit is 300MW at Lakvijaya Coal Power Plant which has total installed capacity of 900MW. Renewable energy sources include mini hydro plants of 302MW and wind power plant of 124MW owned and operated by private power sector. Recorded Night peak is around 2200MW and day peak is around 1900MW. Maximum single unit generation is limited to 30% of total system generation. Frequency control operation is done by one particular power station (hydro) 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 and strictly adhered during the operations. System frequency may rise up to 52Hz or fall to 47.5Hz during severe disturbances. Minimum allowable system spinning reserve is 5% of total system generation.

4.1.2 Study Case -Total System Failure Occurred On 27th September 2015

Sri Lankan power system experienced the most severe case in terms of Voltage Stability on 27th September 2015 at 23:57hrs. The system was delivering about 780MW of active power and 60Mvars of leading reactive power through generation. The failure initiated with the tripping of unit no. 03 of Lakvijaya power plant at 23:53 hrs, which was generating 280MW active power and 28Mvars leading reactive power. The tripping occurred due to the activation of “over flux” relay of unit no. 03 at Lakvijaya power plant. At the time of system failure, the system frequency was controlled by unit no. 02 of Kotmale power plant. The system demand was low and network experienced a little high voltage condition prior to the failure due to the leading reactive power flow in the system. Post failure Voltage of 220kV network was on rising trend and it has even risen up to 265kV - 270kV level just before system collapsed. Voltage on 132kV network also on rising trend and it has risen to maximum value of 157kV.

4.1.3 Sequence of Tripping Of Events

The sequence of incidents that took place during the system failure is summarized as follows.

Table 4.1: Total Failure sequence according to the BEN records and SCADA records

Sequence	Time	Equipment
1	23:53:08	Lakvijaya unit No.03
2	23:54:24	Rantambe coupling T/F
3	23:54:24	New Anuradhapura T/F 01
4	23:54:24	New Anuradhapura T/F 02
5	23:54:26	Kotugoda 132/33 kV T/F 04
6	23:54:54	Biyagama T/F 01
7	23:54:54	Biyagama T/F 02
8	23:55:56	Kothmale Unit 02
9	23:56:33	New Chilaw IBT 01
10	23:56:33	New Chilaw IBT 02
11	23:56:34	KCCP ST
12	23:56:39	KCCP GT

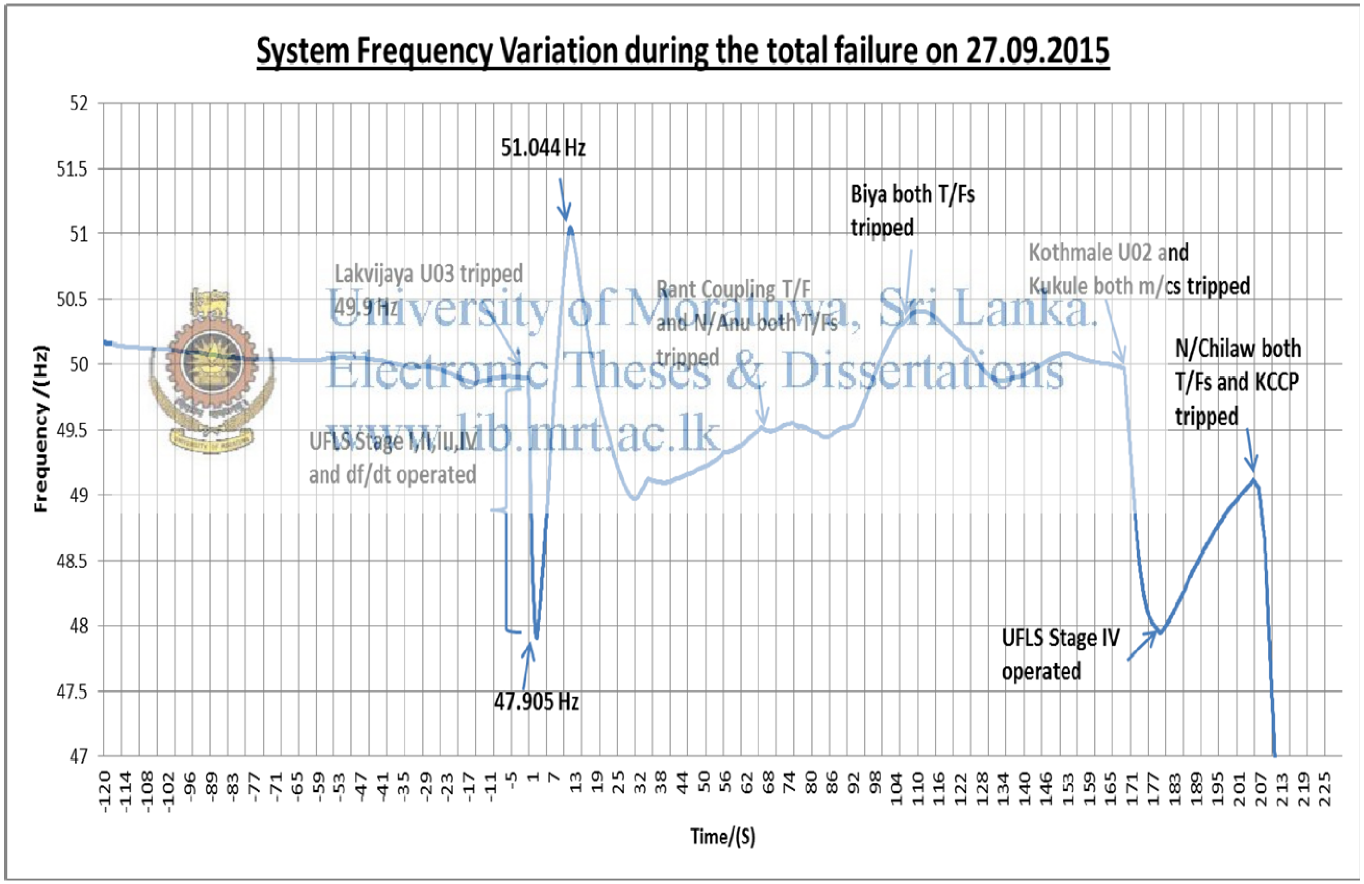
4.1.4 Generation Status before the System Failure

Following generation scenario was dispatched prior to the total system failure.

Table 4.2: Generation pattern used in the study

Power Station	Unit Number	MW
Old_Laxapana	1	7
Old_Laxapana	2	8
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	37
Kukule	2	37
Asia Power	1	0
Barge	1	0
Randenigala	1	0
Randenigala	2	0
Puttalam Wind	1	22
Kothmale	1	32
Kothmale	2	0
Kothmale	3	0
Upper Kothmale	1	15
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	103
KCCP ST	1	56
AES GT	1	103
AES ST	1	56
WCP	1	0
SPS A	1	0
SPS B1	1	0
SPS B2	1	0
Lakvijaya	1	0
Lakvijaya	2	0
Lakvijaya	3	280
Total Generation /MW		786

Figure 4.1: Actual system frequency variation during the failure.



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, but according to the Figure 4.2 and Figure 4.3 system voltage reach beyond tolerance level which result the cascade tripping of 220/132kV coupling transformers.

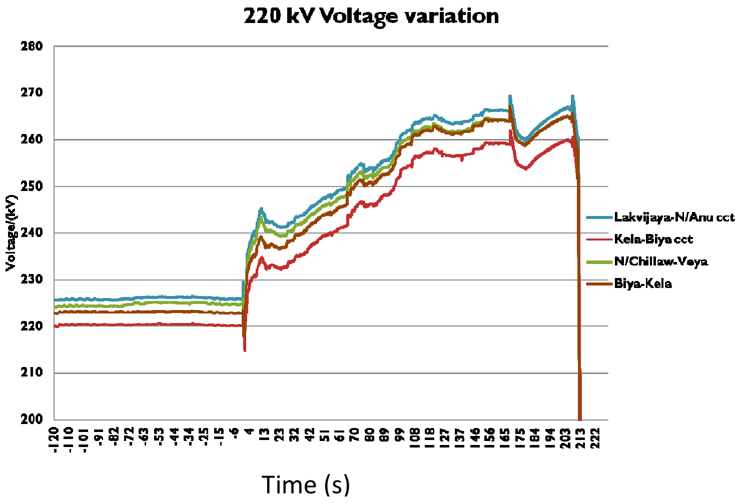


Figure 4.2: 220kV network voltage variations during the failure.

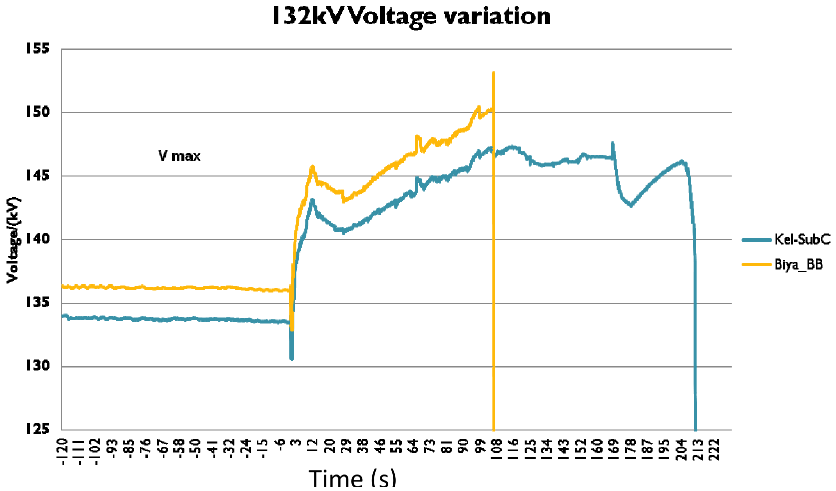


Figure 4.3: 132kV network voltage variations during the failure.

The overvoltage instability can be further justified through the generator reactive power response during the blackout as it reaches for the machine capability margin.

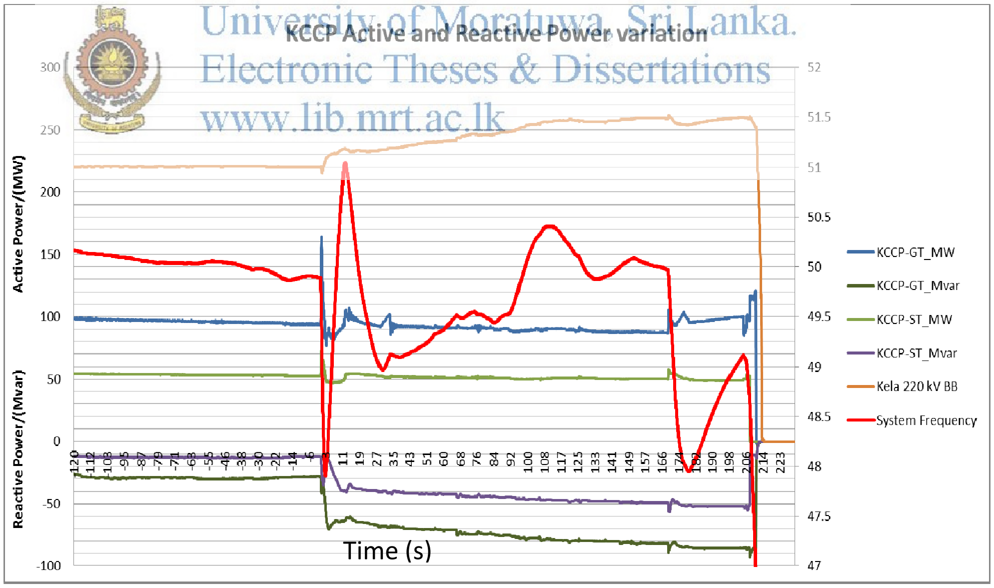


Figure 4.4: Kelanitissa 220kV B/B voltage, system frequency variation, KCCP active power and reactive power variation.

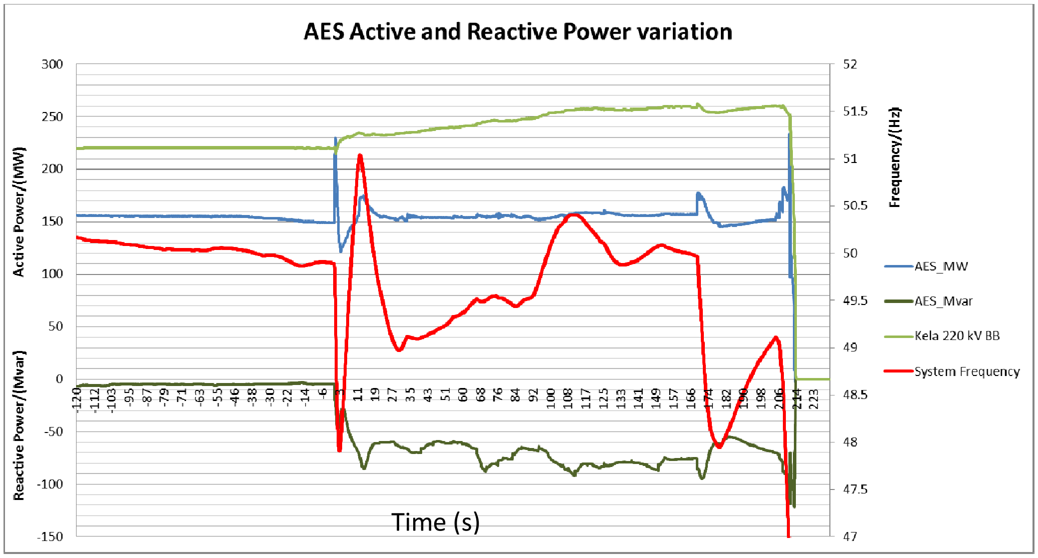


Figure 4.5: Kelanitissa 220kV B/B voltage, system frequency variation, AES active power and reactive power variation.

4.2 Modeling Sri Lankan Power System in PSS®E and Validation

4.2.1 Steady State PSS/E Simulation of Sri Lankan Power System Prior to the Total System Failure.

The power system model includes the entire 220kV and 132kV transmission network of Sri Lanka. Loads are connected to 33 kV buses via 132/33 kV 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 total failure on 27.09.2015. It was 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. Kothmale generator 02 executed frequency controlling just prior to the failure and Kothmale generator bus defined as slack or swing bus.

According to the PSS/E simulation the total amount of reactive power generated in the transmission lines were as follow.

Total reactive power generated in 220kV network = 264Mvars

Total reactive power generated in 132kV network = 247Mvars

4.2.2 Dynamic 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 voltage stability analysis uses steady-state tools and static models, for instance to determine PV curves, from which a “distance to instability” is obtained in terms of load power margin. The static models usually takes 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 three types of simulations files such as power flow data file, dynamic model data file and sequence 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. Kothmale generator bus was considered as the slack bus.

4.3 Analyzing Results of Dynamic Simulation

Actual 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 collapse/voltage recovery.

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. PSSE dynamic simulation carried out by switching off equipment in an order as mentioned in the Table 4.3. Then, the simulation results were analyzed to observe the system behavior. Main power system dynamics such as frequency, 220kV and 132kV voltage profiles, active power and reactive power variation were observed.

Table 4.3: Failure event sequence with PSS/E simulated time

Sequence	Time	Equipment	PSSE simulated time/(S)
1	23:53:08	Lakvijaya unit No.03	2
2	23:54:24	Rantambe coupling T/F	78
3	23:54:24	New Anuradhapura T/F 01	78
4	23:54:24	New Anuradhapura T/F 02	78
5	23:54:26	Kotugoda 132/33 kV T/F 04	80
6	23:54:54	Biyagama T/F 01	108
7	23:54:54	Biyagama T/F 02	108
8	23:55:56	Kothmale Unit 02	170
9	23:56:33	New Chilaw IBT 01	207
10	23:56:33	New Chilaw IBT 02	207
11	23:56:34	KCCP ST	208
12	23:56:39	KCCP GT	213

Figure 4.6 shows the dynamic behavior of system frequency during the total system failure. According to the graph system recovered after tripping of Lakvijaya unit No. 03 with the operation of UFLS scheme up to stage IV. Figure 4.7 and Figure 4.8 reveal the variation of 220kV and 132kV voltage profiles and rising trend of the voltage with time. System voltage started to rise just after the tripping of Lakvijaya unit No. 03 and due to rejection of large amount of loads as a result of operation of UFLS scheme. Then the rise of voltage continues further mainly due to operation of OLTC actions. It is easily seen that the active power and reactive power variation in Figure 4.9 and Figure 4.10 respectively. Kothmale unit 02 functioning as a frequency controlling machine and it tripped at 170s while absorbing maximum reactive power. Finally system collapsed due to the loss of generation and extra high voltage.

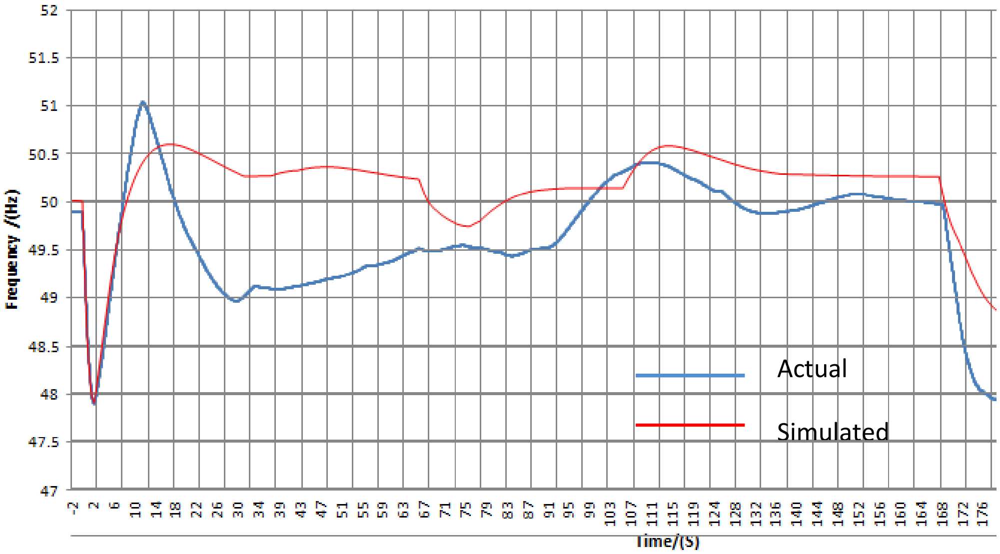


Figure 4.6: Actual and Simulated System Frequency fluctuations during the total system failure

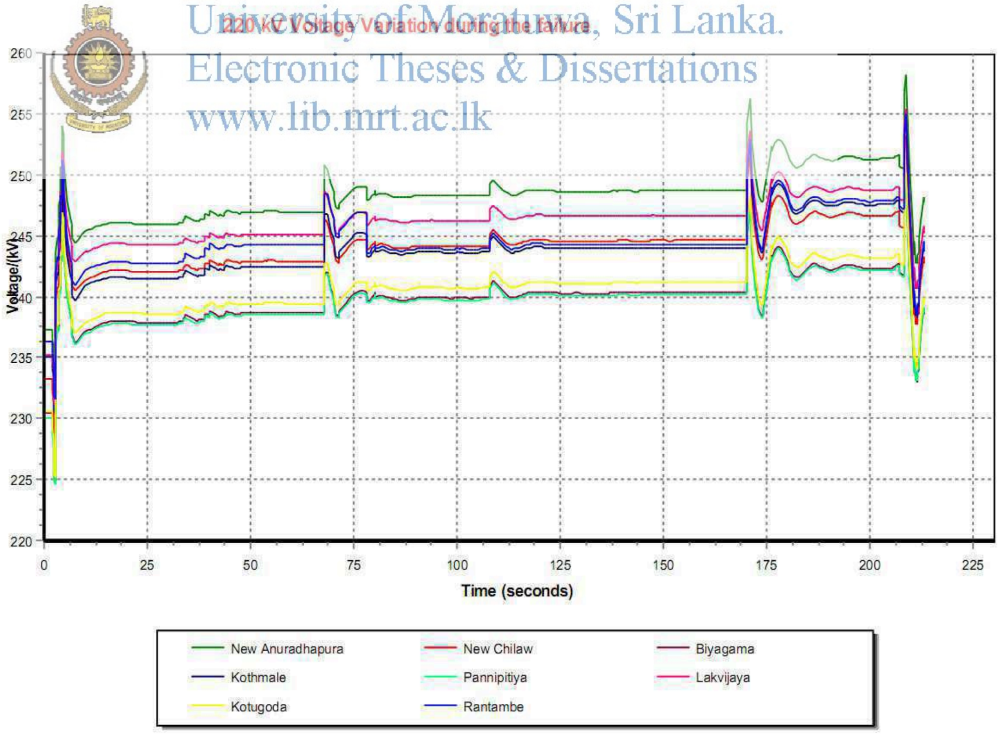


Figure 4.7: Voltage fluctuations of 220 kV System during the total system failure

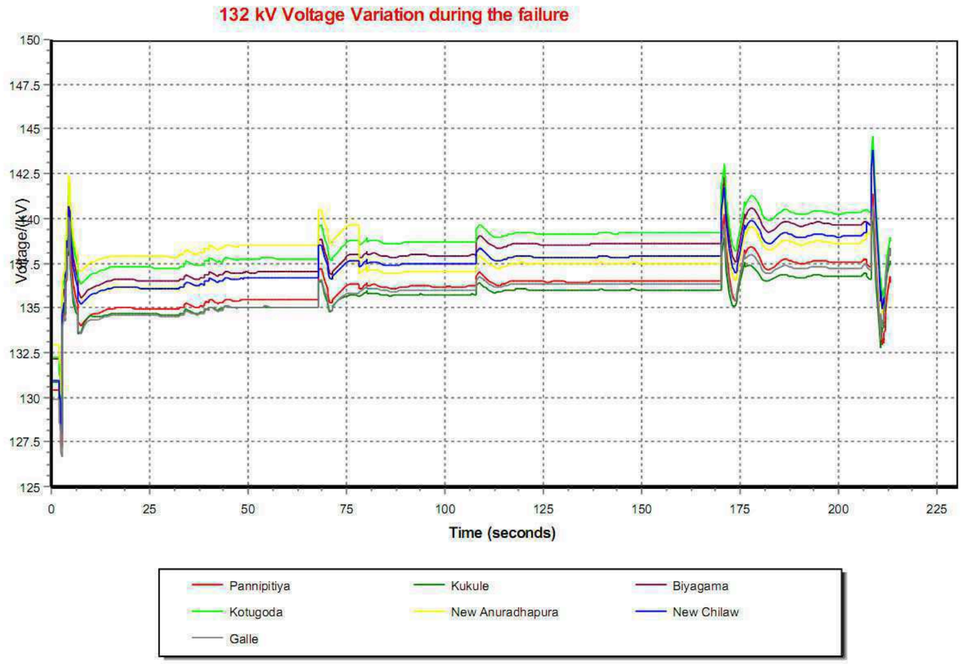


Figure 4.8: Voltage fluctuations of 132 kV System during the total system failure

Figure 4.7 and Figure 4.8 clearly demonstrate that the voltage response trends predicted by the `adjusted model closely follow the field measurements.

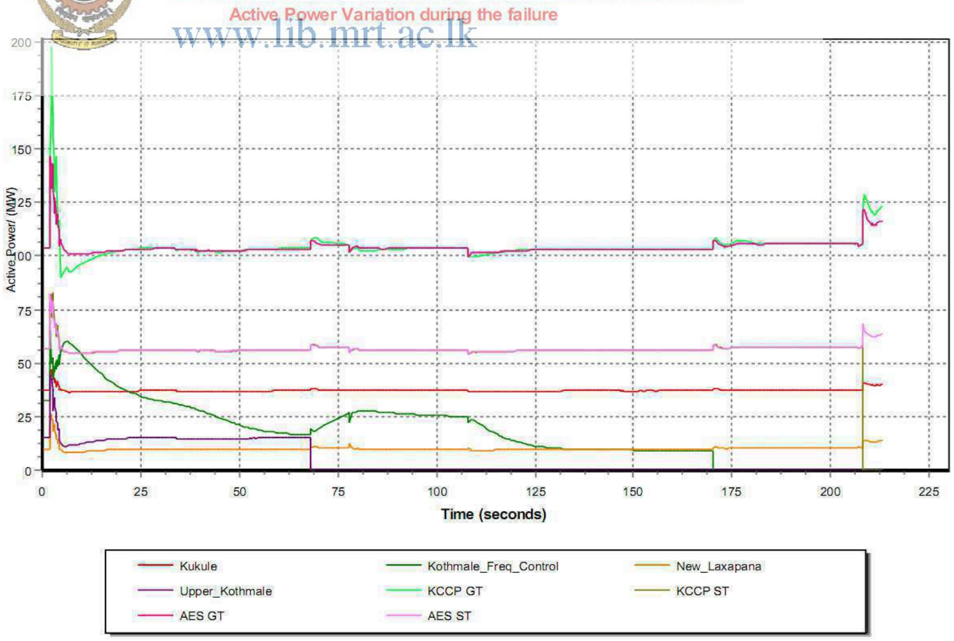


Figure 4.9: Active power variation during the total system failure.

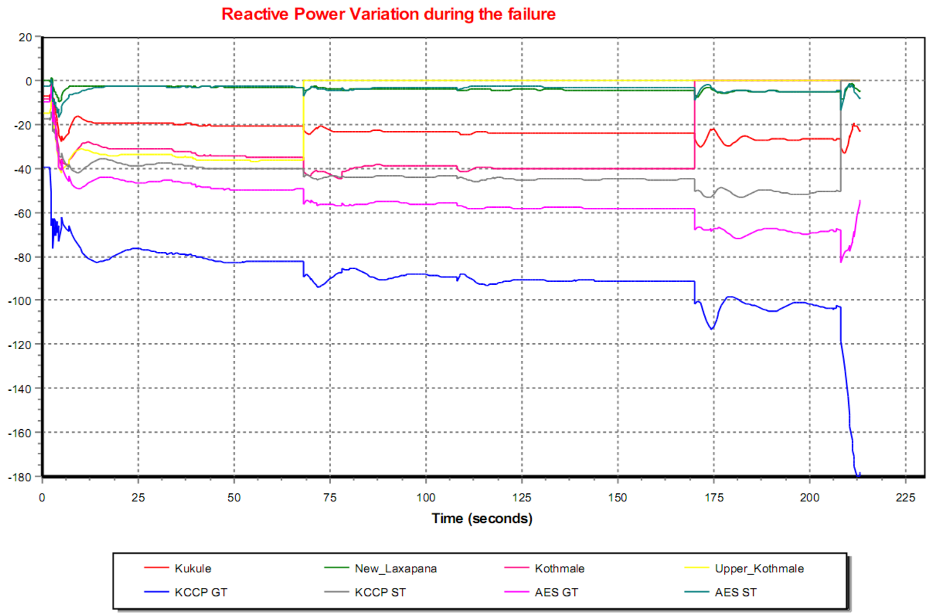


Figure 4.10: Reactive power variation during the total system failure.

The important consideration was that the model showed the same trends as those recorded following the generator tripping. Comparison of the recorded and simulated frequency profiles as shown in Figure 4.6 just prior to the system collapse frequency response of the model follows the actual recorded value closely during the first few seconds. This period is important as it will determine the under frequency load shedding for predicting load shedding.

This 'adjusted' model was used to perform further studies to make overall conclusions and recommendation.

The minor deviations were due to the mismatch of the load model in general and other dynamic parameters not replicating the actual system.

Chapter 5

SIMULATION AND ANALYSIS OF SR/SVC SELECTION

5.1 Methodology

After validating the model with blackout event (Base Case), dynamic simulations are carried out for the same scenario of 27 09 2015 blackout which resulted all time worst voltage hikes in Sri Lankan power system, with integration of shunt reactors (SR), static var compensator (SVC) and disconnection of adequate overhead lines to reach a stable voltage following the tripping of Lakvijaya unit 3 supplying 280 MW.

New Anu., New Chilaw GSSs, and LVPS which mostly subjected to higher voltage profiles are modeled with shunt reactor whereas Biyagama, Kotugoda, Pannipitiya GSSs are modeled with SVC where mostly unserved reactive power phenomenon is the more general case throughout the day. Finally, the effectiveness of disconnecting adequate overhead lines for overvoltage mitigation is analyzed.

Thereafter each case is further studied with other severe fault condition to assess the performance of SR/SVC.

Table 5.1 Study Scenarios

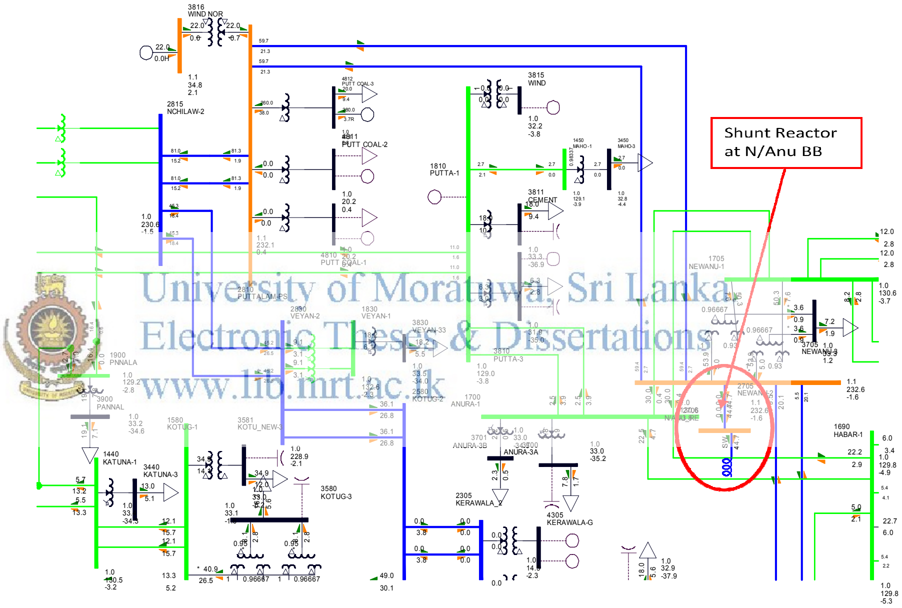
SCENERIO	INTEGRATION	CASES	VALIDATION / OTHER FAULT STUDIES
Over Voltage (Base Case: Blackout 2015/11/27 - LVPS cascade tripping)	**Shunt Reactor**	New Anuradhapura **Test Case A1**	Panp both T/Fs Trip
		LVPS **Test Case B1**	Panp both T/Fs Trip
		New Chilaw **Test Case C1**	Panp both T/Fs Trip
	Static Var Compensator	Biyagama **Test Case A2**	Biya BB Fault in Hydro Max
			Biya BB Fault in Thermal Max
		Kotugoda **Test Case B2**	Biya BB Fault in Hydro Max
			Biya BB Fault in Thermal Max
		Pannipitiya **Test Case C2**	Biya BB Fault in Hydro Max
			Biya BB Fault in Thermal Max
	Tx cct shedding *		

5.2 Integration of Shunt Reactor

The effectiveness of the integration of shunt reactor in the following test cases are modeled and analyzed with base case to determine their performance comparatively.

- Test Case A1 : 100Mvar Shunt Reactor at New Anuradhapura GSS
- Test Case B1 : 100Mvar Shunt Reactor at Lakvijaya PS
- Test Case C1 : 100Mvar Shunt Reactor at New Chilaw GSS

5.2.1 Test Case A1-Installation of 100Mvar reactor at New Anuradhapura



Shunt Reactor at N/Anu BB

Figure 5.1: 100Mvar reactor at New Anu. GSS 220kV BUS.

This test case highlights the transmission network voltage with and without reactor at New Anuradhapura 220kV bus bar and Figure 5.2 and Figure 5.3 illustrate the voltage variation on different bus bar locations. It can be seen that around 10kV voltage reduction of 220kV level and around 5kV voltage reduction of 132kV level can be achieved with the installation of 100Mvar reactor at 220kV bus bar in New Anuradhapura.

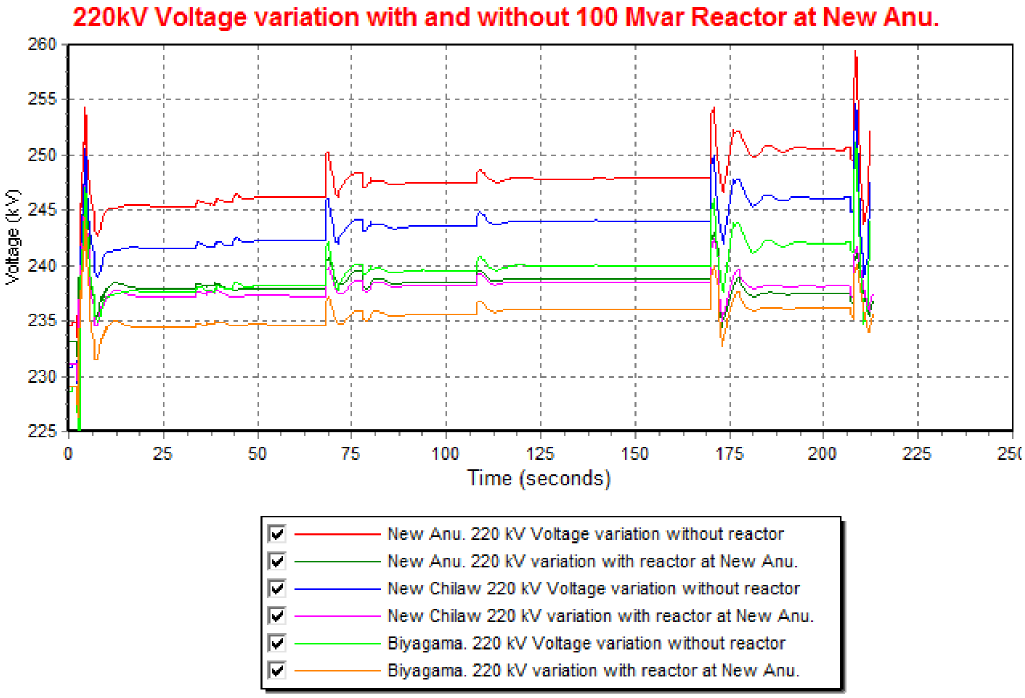


Figure 5.2: 220kV Voltage variation with and without 100Mvar Reactor at New Anu.

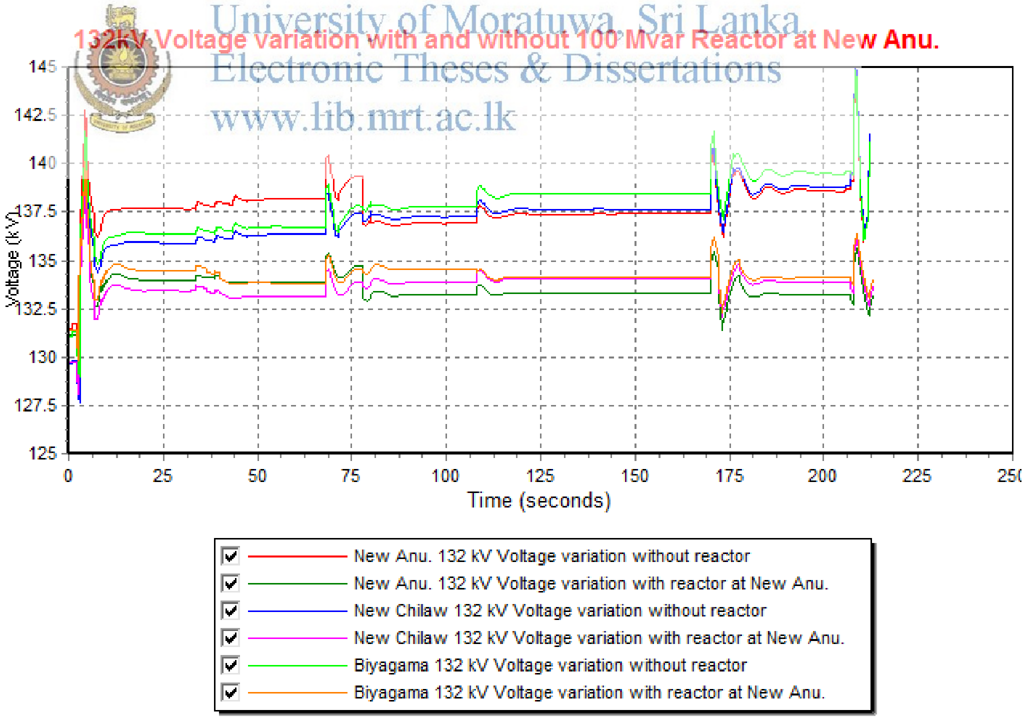


Figure 5.3: 132kV Voltage variation with and without 100Mvar Reactor at New Anu.

Figure 5.4 shows the response of the Frequency controlling machine reactive power variation without reactor and with 100Mvar reactor at New Anuradhapura. Reactive power absorption of Kothmale generator 02 has reduced to 27Mvar from 40Mvar which was its maximum absorption capacity. Hence it’s certain that Kothmale generator will not be tripped with the 100Mvar reactor installation at New Anuradhapura as it will not reach for the under excitation limit.

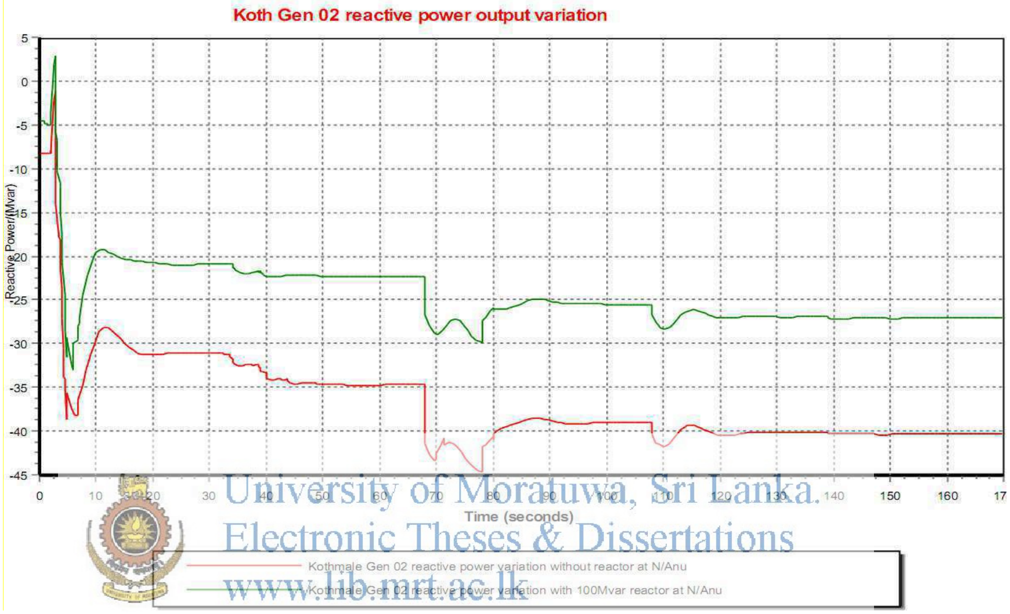


Figure 5.4: Koth Gen 02 reactive power response with and without Reactor at 100Mvar New Anu

Figure 5.5 represents the response of the shunt reactor which was connected to the New Anuradhapura 220 kV bus bar with the 220kV bus bar voltage. According to the graph shunt reactor is on maximum utilization after 170s on the simulation where voltage on particular bus reaches its highest. Figure 5.5 also confirms size of the New Anu. reactive requirement of 100Mvar.

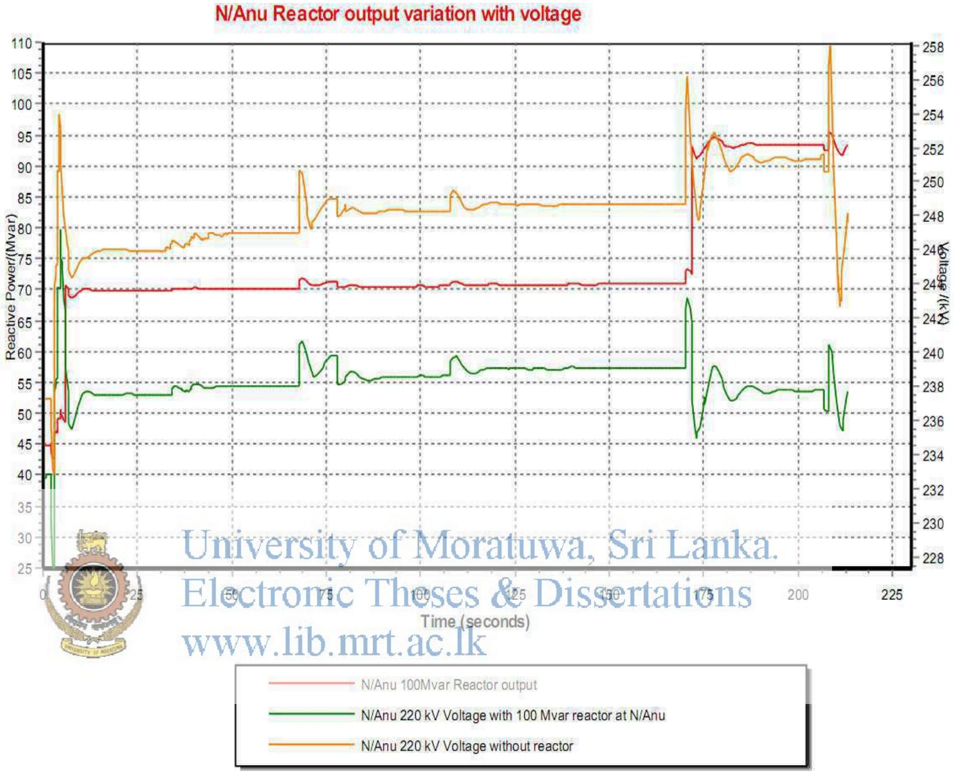


Figure 5.5: 100Mvar New Anu. reactor at output variation.

5.2.2 Test Case B1-Installation of 100Mvar reactor at Lakvijaya PS

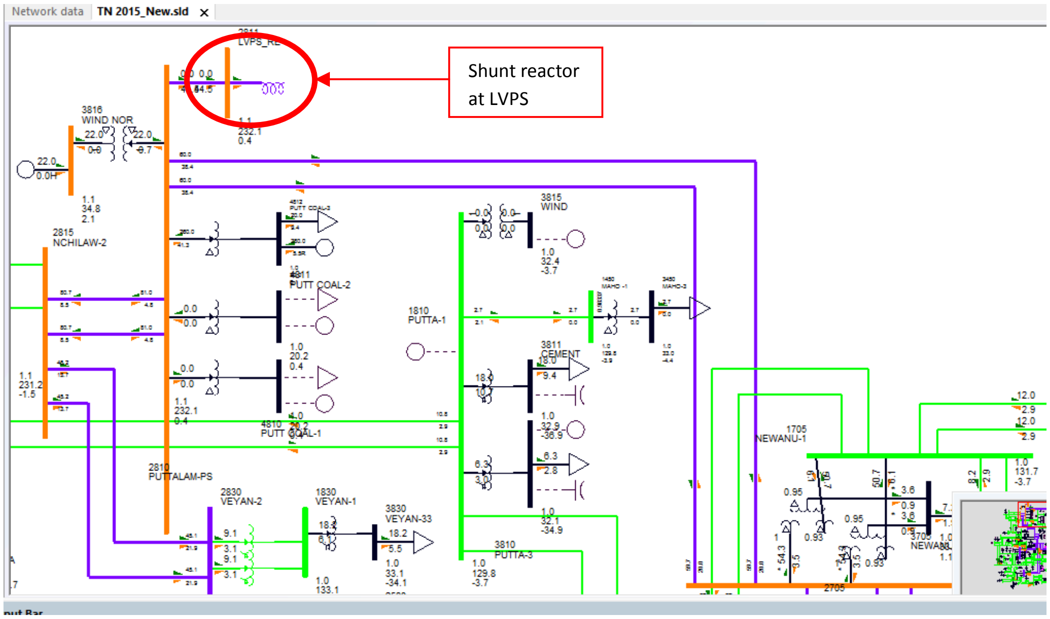


Figure 5.6: 100Mvar reactor at LVPS. 220kV BUS.

This test case highlights the transmission network voltage with and without reactor at Lakvijaya PS 220kV bus bar and Figure 5.7 and Figure 5.8 illustrate the voltage variation on different bus bar locations. It can be seen that around 6kV voltage reduction of 220kV level and around 3kV voltage reduction of 132kV level can be achieved with the installation of 100Mvar reactor at 220kV bus bar in Lakvijaya PS.

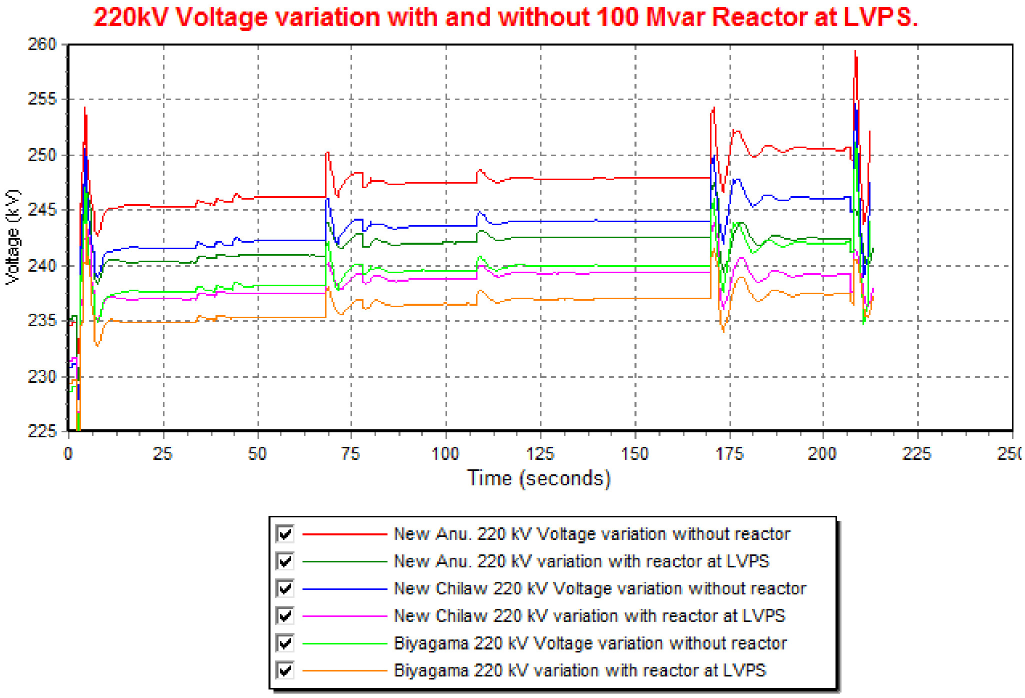


Figure 5.7: 220kV Voltage variation with and without Reactor at 100Mvar LVPS.

Figure 5.8: 132kV Voltage variation with and without Reactor at 100Mvar LVPS

Figure 5.9 shows the response of the Frequency controlling machine reactive power variation without reactor and with 100Mvar reactor at Lakvijaya PS. Reactive power absorption of Kothmale generator 02 has reduced to 29Mvar from 40Mvar which was its' maximum absorption capacity.

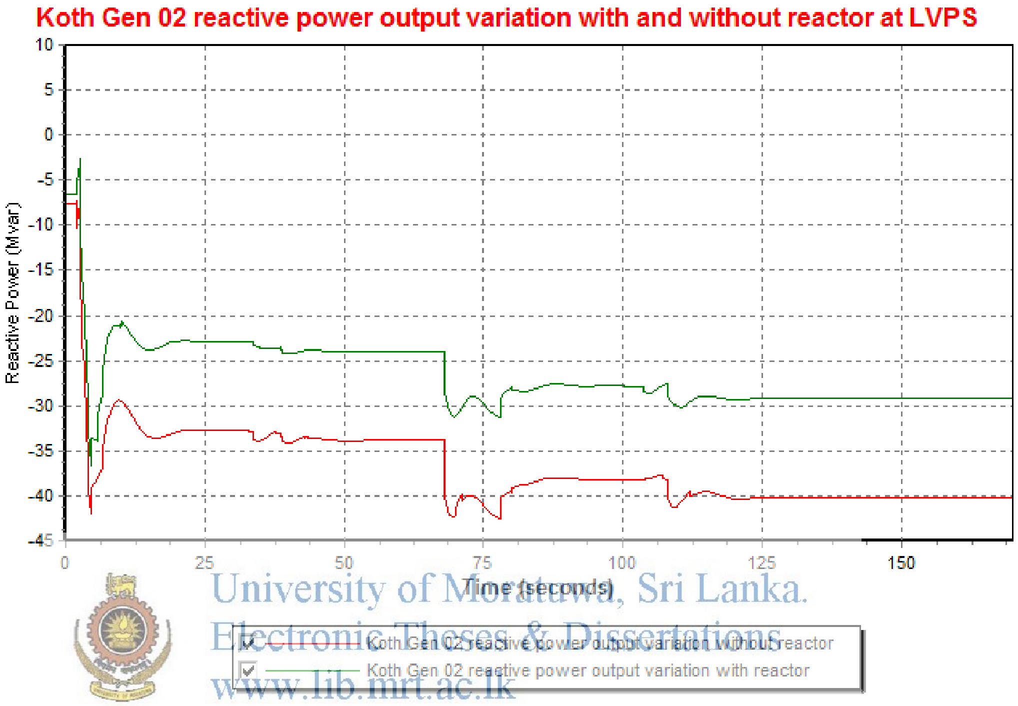


Figure 5.9: Koth Gen 02 reactive power response with and without Reactor at 100Mvar LVPS.

Figure 5.10 represents the response of the shunt reactor which was connected to the Lakvijaya PS 220 kV bus bar with the 220kV bus bar voltage. According to the graph shunt reactor reach for its maximum utilization after 170s on the simulation same as in Test Case A1 where voltage on particular bus reaches its highest.

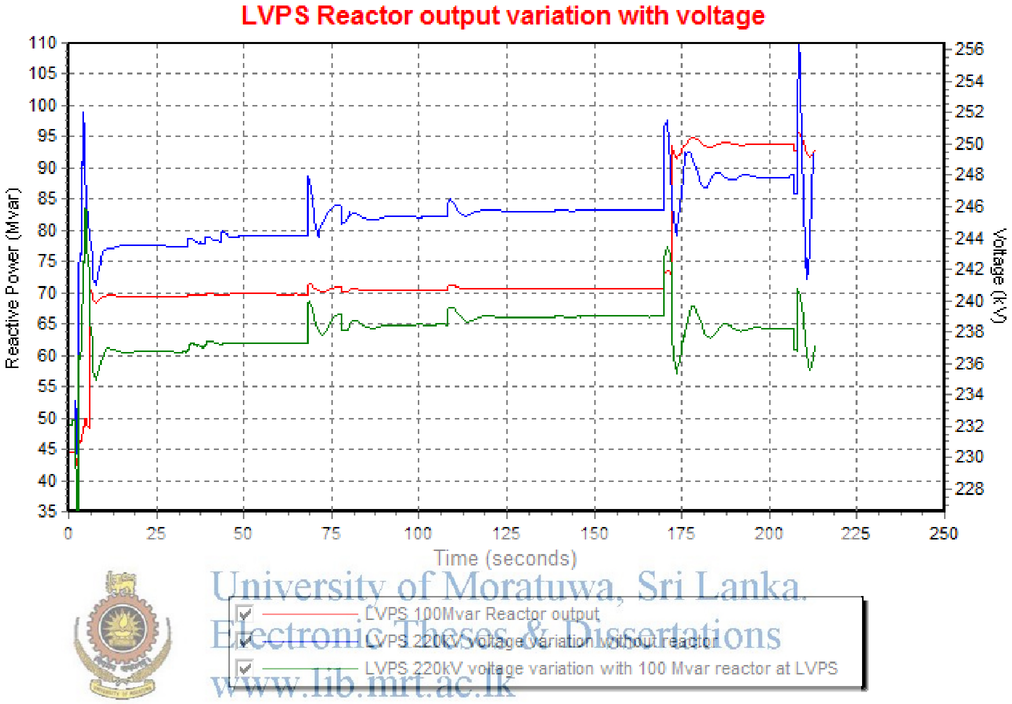
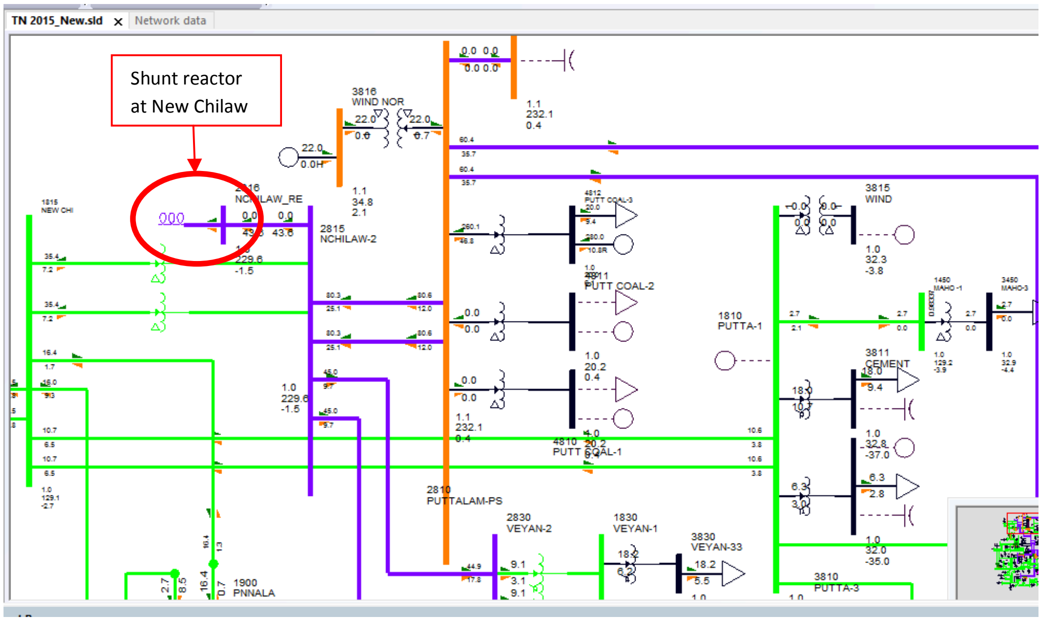


Figure 5.10: 100Mvar New Anu. reactor at output variation.

5.2.3 Test Case C1-Installation of 100Mvar reactor at New Chilaw GSS



Shunt reactor at New Chilaw

Figure 5.11: 100Mvar reactor at New Chilaw GSS 220kV BUS.

This test case highlights the transmission network voltage with and without reactor at New Chilaw 220kV bus bar and Figure 5.12 and Figure 5.13 illustrate the voltage variation on different bus bar locations. It can be seen that around 5kV voltage reduction of 220kV level and around 2.5kV voltage reduction of 132kV level can be achieved with the installation of 100Mvar reactor at 220kV bus bar in New Chilaw 220kV.

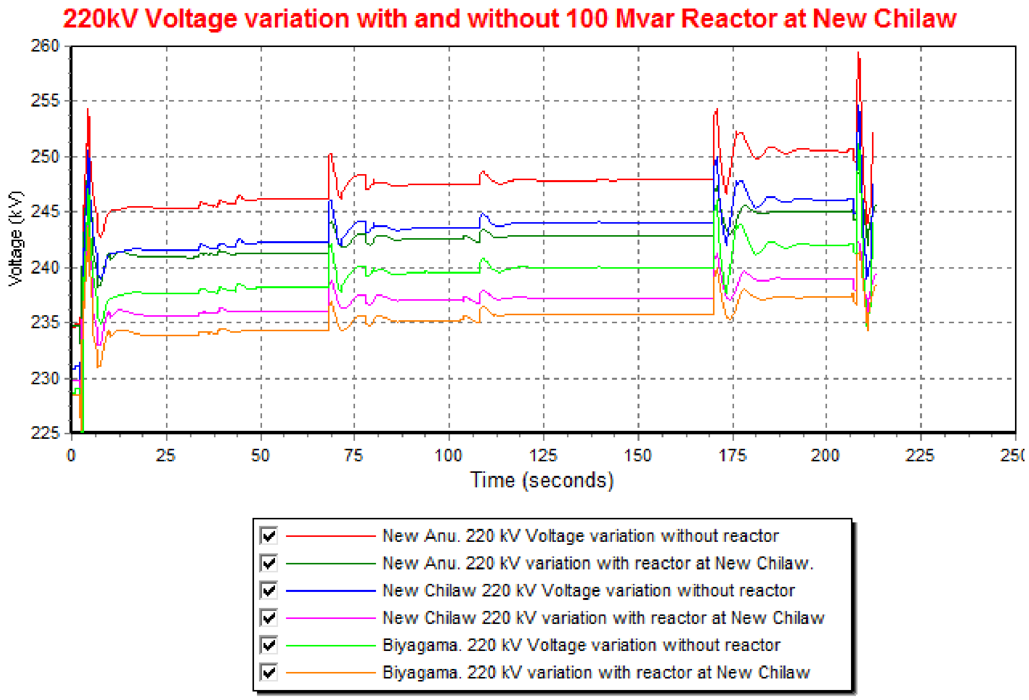


Figure 5.12: 220kV Voltage variation with and without Reactor at 100Mvar New Chilaw.

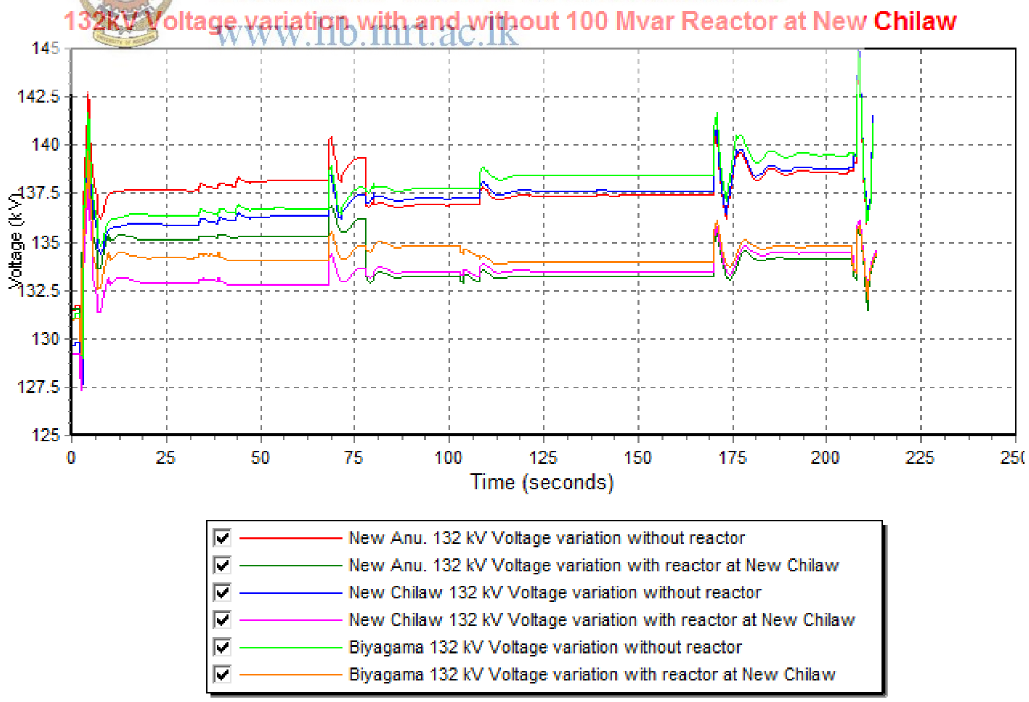


Figure 5.13: 132kV Voltage variation with and without Reactor at 100Mvar New Chilaw.

Figure 5.14 shows the response of the Frequency controlling machine reactive power variation without reactor and with 100Mvar reactor at New Chilaw GSS. Reactive power absorption of Kothmale generator 02 has reduced to 30Mvar from 40Mvar which was its' maximum absorption capacity.

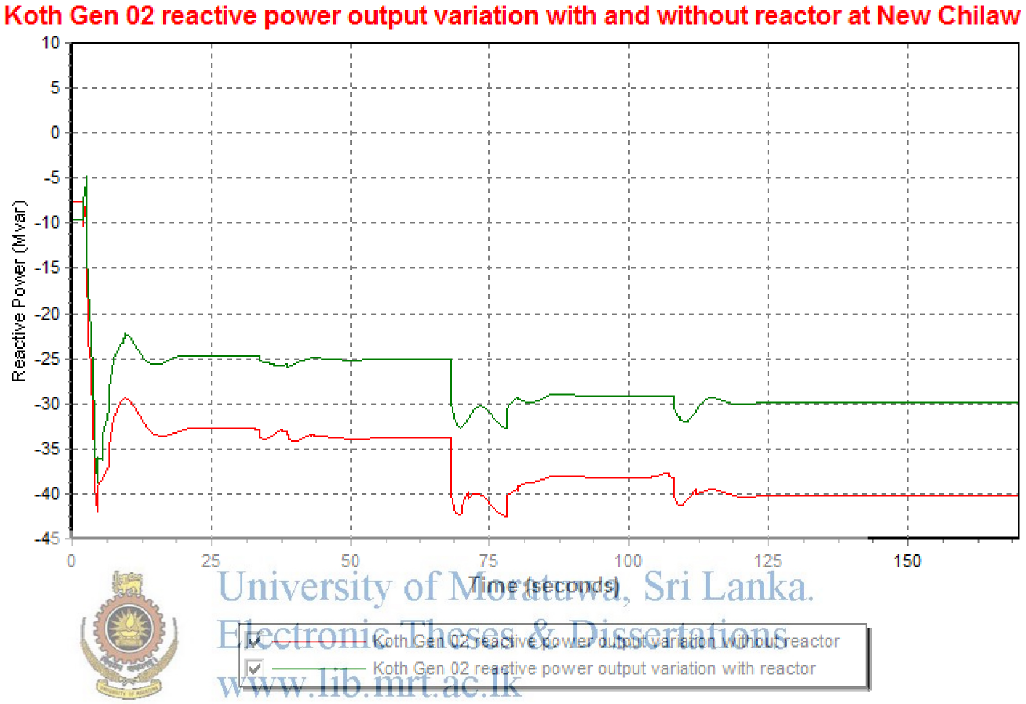


Figure 5.14: Koth Gen 02 reactive power response with and without Reactor at 100Mvar New Chilaw.

Figure 5.15 represents the response of the shunt reactor which was connected to the New Chilaw 220 kV bus bar with the 220kV bus bar voltage. According to the graph shunt reactor retains at -70Mvar as the New Chilaw BB voltage is comparatively lower than both other cases.

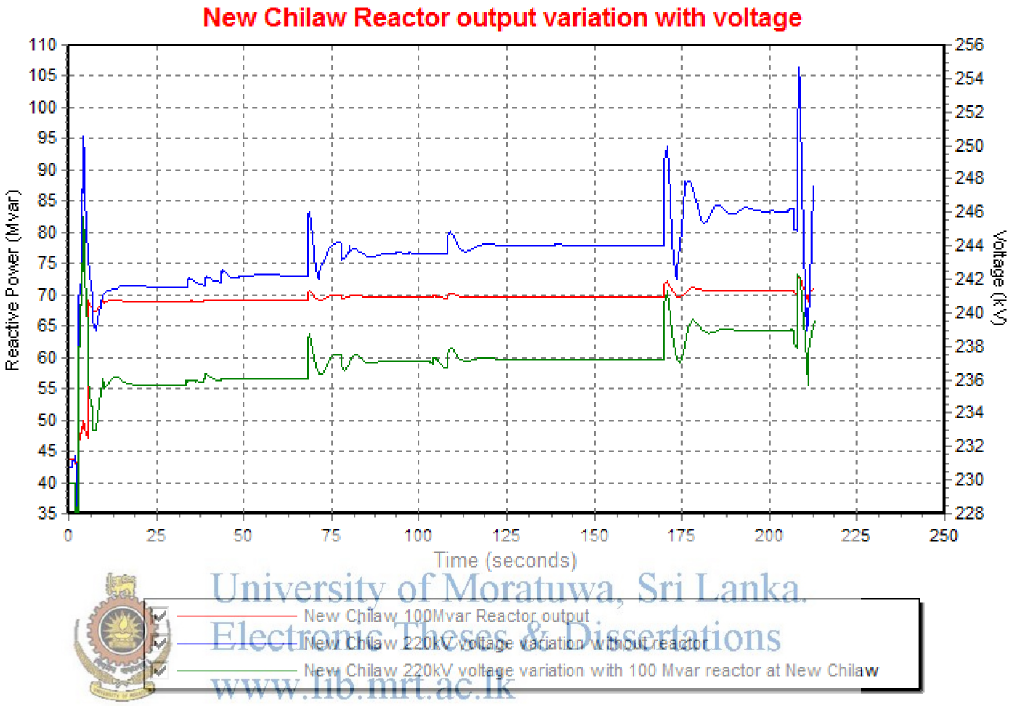


Figure 5.15: 100Mvar New Chilaw reactor at output variation.

5.2.4 Shunt Reactor Integration Summery

Shunt reactors are effective means of controlling steady state voltage, as well as improving the system dynamic response. The effectiveness of shunt reactor additions for above tests cases are comparatively illustrated in this section.

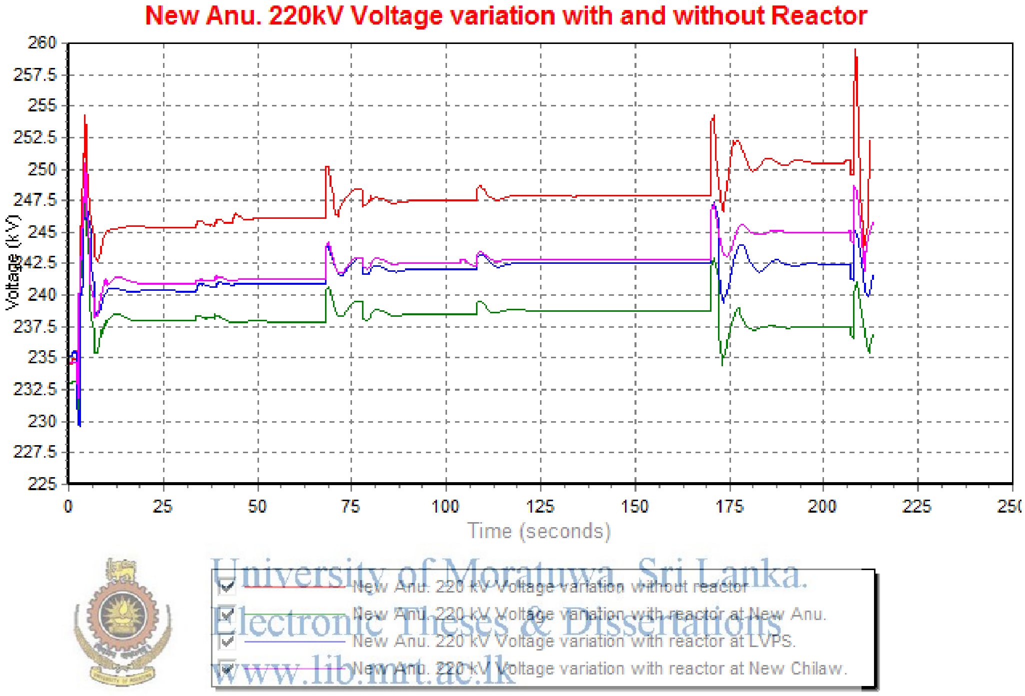


Figure 5.16: New Anuradhapura 220kV variation with and without reactor for all test cases

As shown in Figure 5.16 maximum voltage reduction is achieved in 220kV level is with the reactor at New Anu.(Test case A1), in which values are well below in compliance with Grid Code 1.1p.u (242kV) overvoltage tolerance margin. Test Case B1 shows marginal reduction of overvoltage as its maximum reaches the 1.1p.u O/V tolerance margin. Test Case C1 has to be definitely ruled out as New Chilaw bus voltage is comparatively lower to New Anu. and LVPS BBs. A reactor installed at New Chilaw cannot contribute much with utilization its maximum capacity, therefor voltage levels at other BBs reaches beyond tolerance margin even with reactor at New Chilaw GSS 220kV BB.

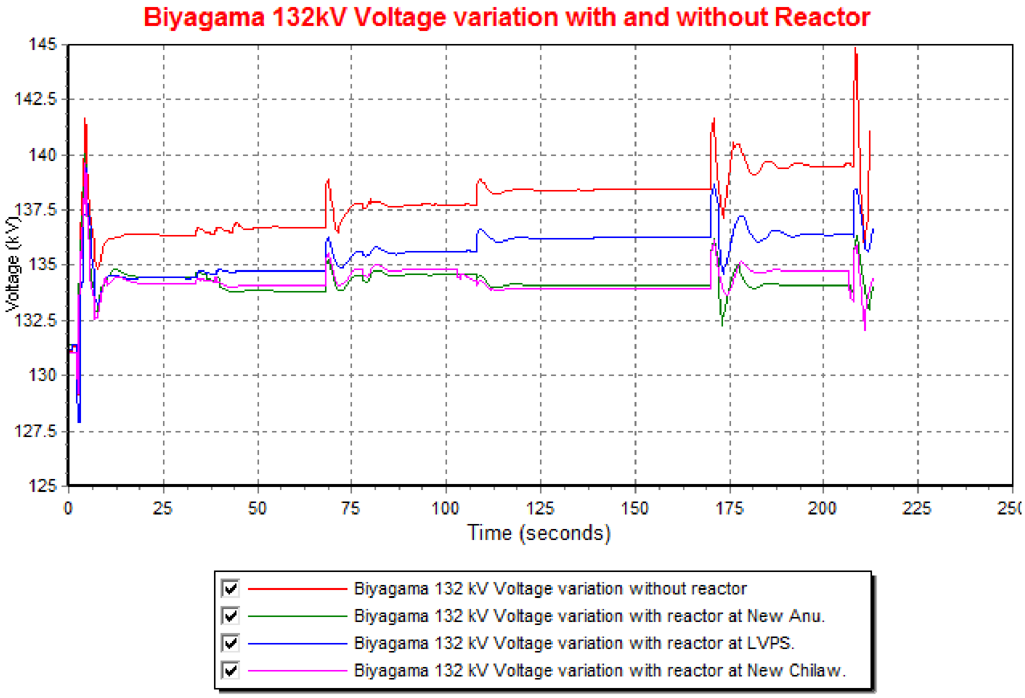


Figure 5.17: Biyagama 132kV variation without and with reactor for all test cases

In 132kV level also maximum reduction of voltage is achived with integrating reactor at New Anu 220kv Bus. All test cases shows no advorse violations of Grid Code maximum voltage criteria, although integrating reactor at New Chilaw shows less 132kV voltage reduction compared to other test cases.

Figure 5.18 confirms maximim spinnin(reserve) capapcity of reactive power in the system can be achived with the reactor integration at New Anu. than of both LVPS and New Chilaw as frequency controlling Kothmale Gen 02 reaches for the lowest loaded for reactive power in Test Case A1.

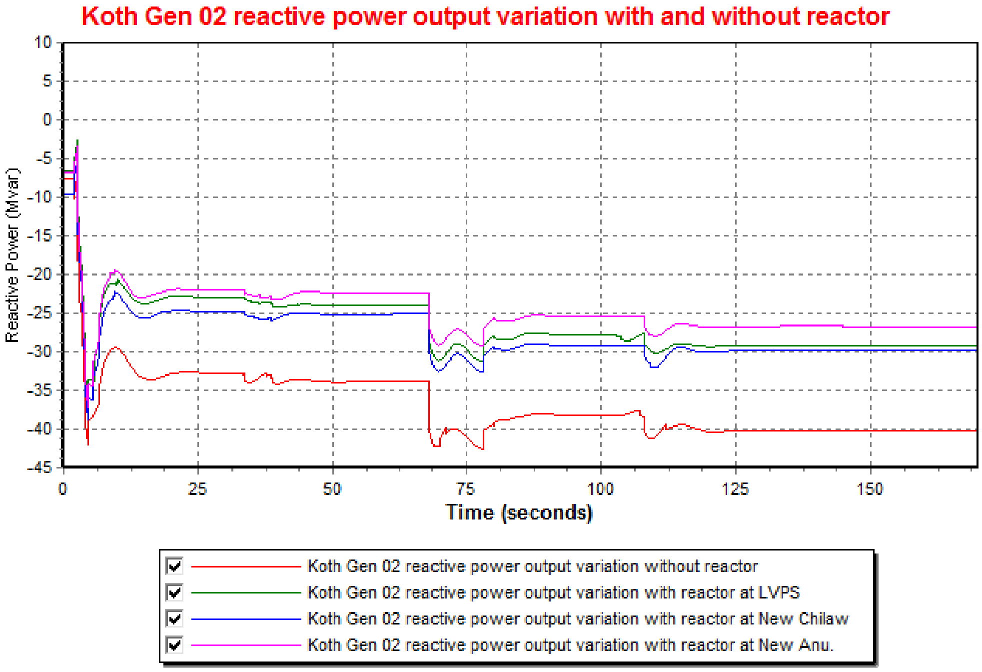


Figure 5.18: Kothmale Gen 02 reactive power response without and with reactor for all test cases

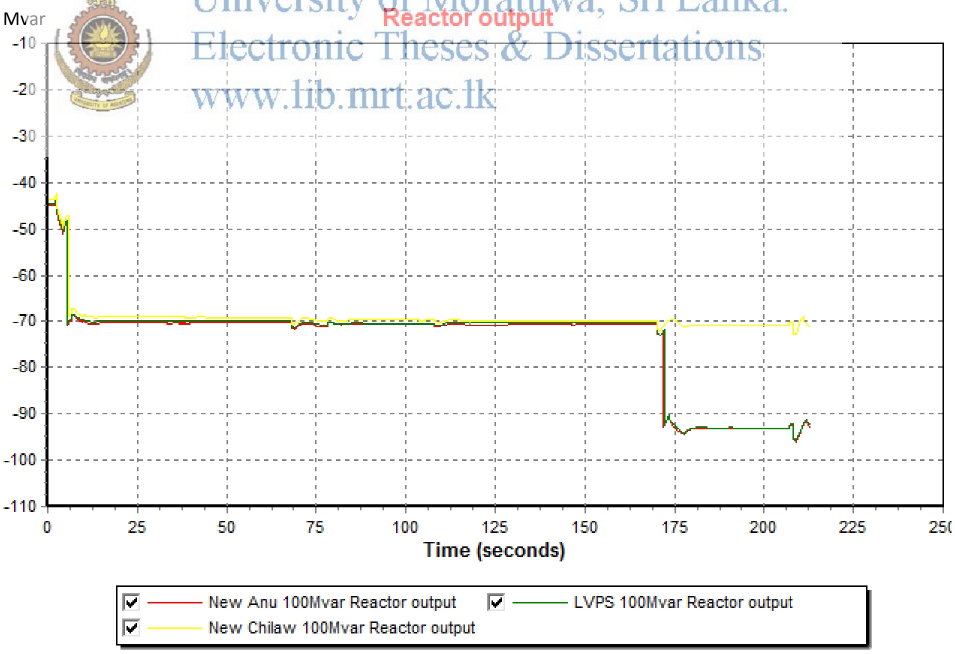


Figure 5.19: Reactor response for all test cases

Table 5.02: Shunt Reactor integration summery table

Test Case	Max. reached 220kV	Max. reached 132kV	Min. Leading Mvar of frequency control m/c	Max. reactor output
Base Case	251	139	-40	*
Reactor at New Anu.	**238**	**133**	**-27**	**-90**
Reactor at LVPS	243	135	-29	-90
Reactor at New Chilaw	245	137	-30	-70

Voltage Criteria	Normal(kV)	Emergency(kV)
220kV Max. Voltage Tolerance	231	242
132kV Max. Voltage Tolerance	139	145

As illustrated in Table 05:02 from all the test cases Test Case A1 shows more pronounced outcome for Sri Lankan power system as it gives lowest trend values for 132kV and 220kV voltage levels for the simulated results. Further frequency controlling Kothmale Gen. 02 is least loaded for leading reactive requirement in the Test Case A1. Therefore, integrating a reactor in the New Anu. GSS is the most favorable solution for Sri Lankan power system.

5.2.5 Validation of 100 Mvar Reactor at New Anu. GSS

Following fault case and procedures were followed as the worst-case scenario of load rejection to perform further analysis of New Anu. 100 Mvar integration.

Fault Study: Tripping of Pannipitiya 220/132 kV both Transformers (35×2 MW)

The tripping of T/Fs or circuits in Pannaipitiya GSS is one of the most frequently occurring event, which results severe system overvoltages. To analyze the shunt reactor integration effectiveness for worst case scenario other than the blackout case, Pannipitiya 220/132kV both transformers are tripped for an off peak low load condition rejecting 35×2MW and the system behavior is observed at various bus bar locations. This being the worst-case scenario due to highest load rejection, it is assumed to be optimum for all other cases which are less severe.

This test case highlights the transmission network voltage with and without reactor at New Anu 220kV bus bar and Figure 5.20 and Figure 5.21 illustrate the voltage variation on different bus bar locations. It can be seen that around 7.5kV voltage reduction of 220kV level and around 2.5kV voltage reduction of 132kV level can be achieved with the installation of 100Mvar reactor at 220kV bus bar in New Anu. 220kV, these are just representative, as all the other bus bars of 220kV and 132 kV of are also recovered to the normal level of voltage i.e. below 1.05 PU, in compliance with Grid code.

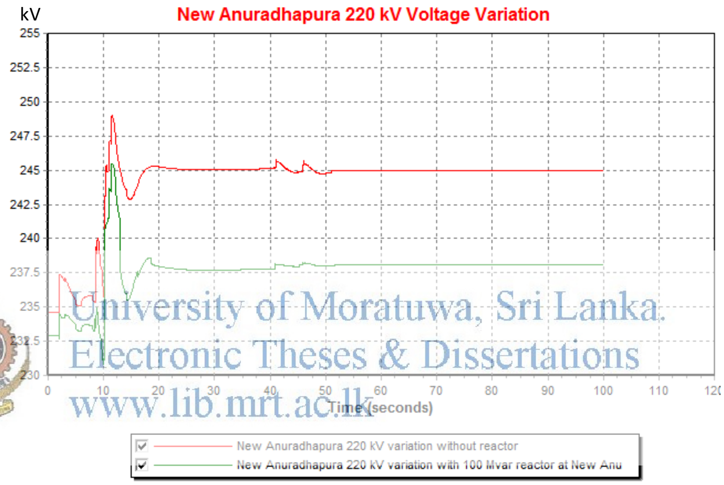


Figure 5.20: New Anu. 220kV variation for Pannipitiya both T/F fault

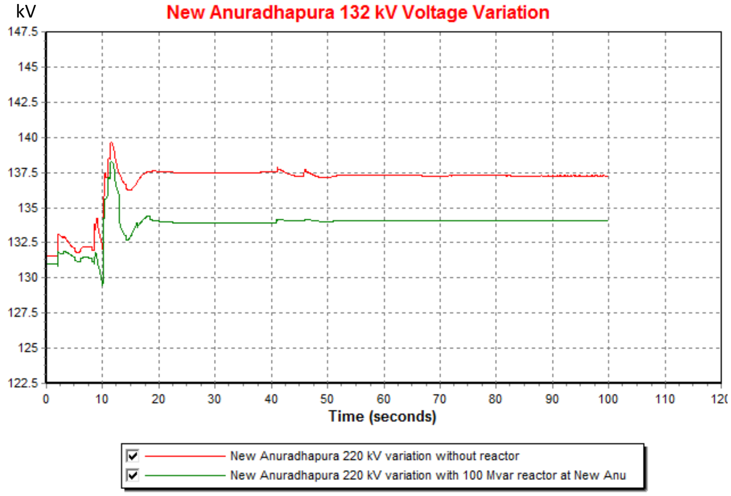


Figure 5.21: New Anu. 132kV variation for Pannipitiya both T/F fault

Figure 5.22 shows the response of the Frequency controlling machine reactive power variation without reactor and with 100Mvar reactor at New Anu GSS. Reactive power absorption of Kothmale generator 02 has reduced from 10Mvar with integration of 100Mvar shunt reactor at New Anu. GSS.

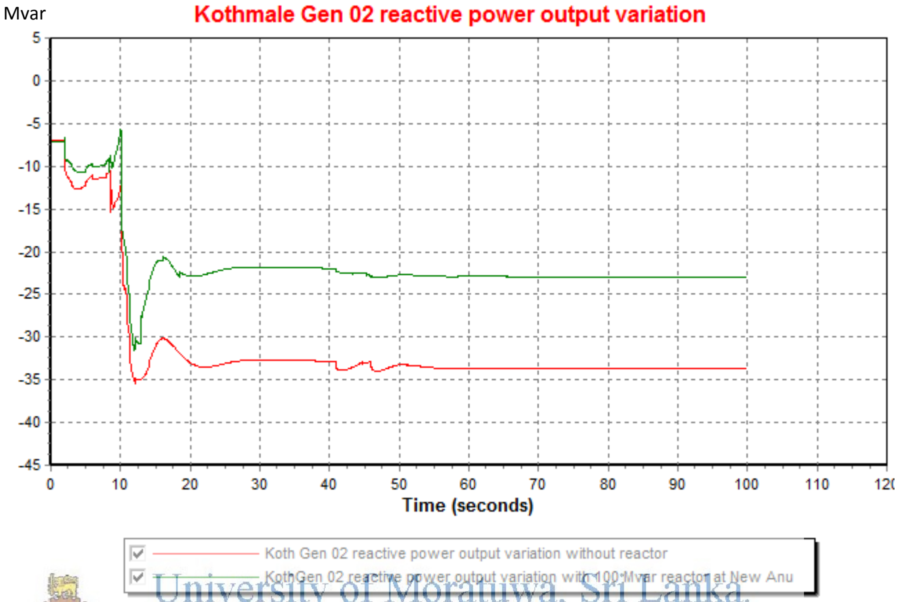


Figure 5.22: Koth Gen 02 reactive power response for Pannipitiya both T/F fault

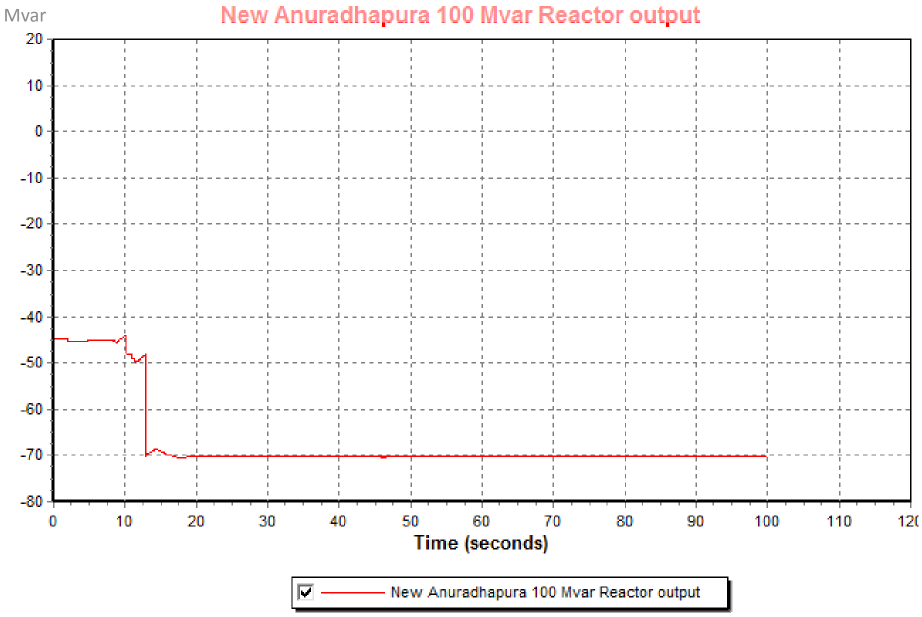


Figure 5.23: New Anu. 100Mvar reactor response for Pannipitiya both T/F fault

5.3 Integration of SVC

The integration of different sizes of SVCs and their performance were considered at the 220 kV level at Biyagama, Kotugoda and Pannipitiya GSSs. The optimum size of SVC was found to be as shown in bellow test cases. The effectiveness with the integration of SVC in the following test cases, are modeled and analyzed with validation case to determine their performance comparatively. SVC capacity for leading reactive power was attained through rigorous studies, benchmarking 1.1 pu maximum tolerance overvoltage for the fault scenario complying with the Grid Code.

- Test Case A2 : +100/-225 Mvar SVC at Biyagama GSS
- Test Case B2 : +100/-175 Mvar SVC at Kotugoda GSS
- Test Case C2 : +100/-175 Mvar SVC at Pannipitiya GSS

5.3.1 Test Case A2-Installation of +100/-225 Mvar SVC at Biyagama GSS

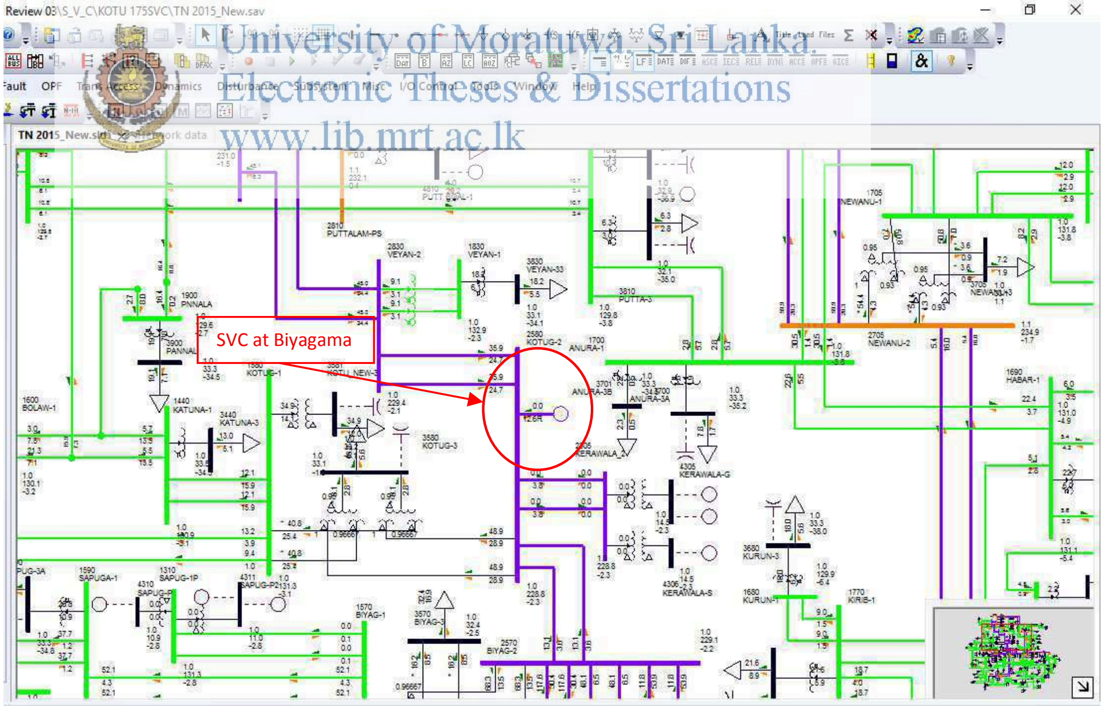


Figure 5.24: +100/-225 Mvar SVC at Biyagama 220kV bus.

This test case highlights the transmission network voltage with +100/-225 Mvar SVC at Biyagama GSS 220kV bus bar and Figure 5.25 and Figure 5.26 illustrate the voltage variation on different bus bar locations. It can be seen that more controlled voltage variation below 242kV(1.1p.u) in 220kV voltage level and below 146kV (1.1 p.u) voltage in 132kV level could be achieved with the installation of +100/-225 Mvar SVC at 220kV bus bar at Biyagama GSS.

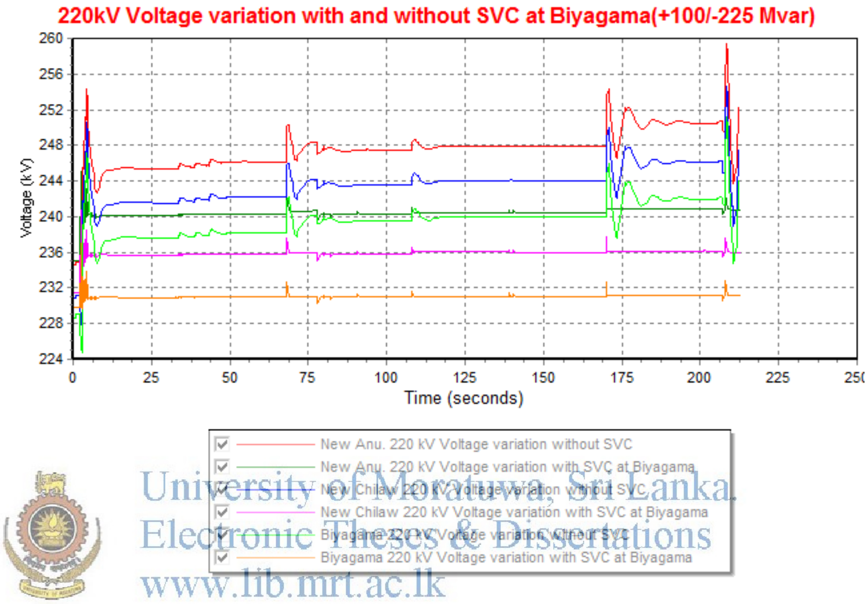


Figure 5.25: 220kV variation with +100/-225 Mvar SVC at Biyagama

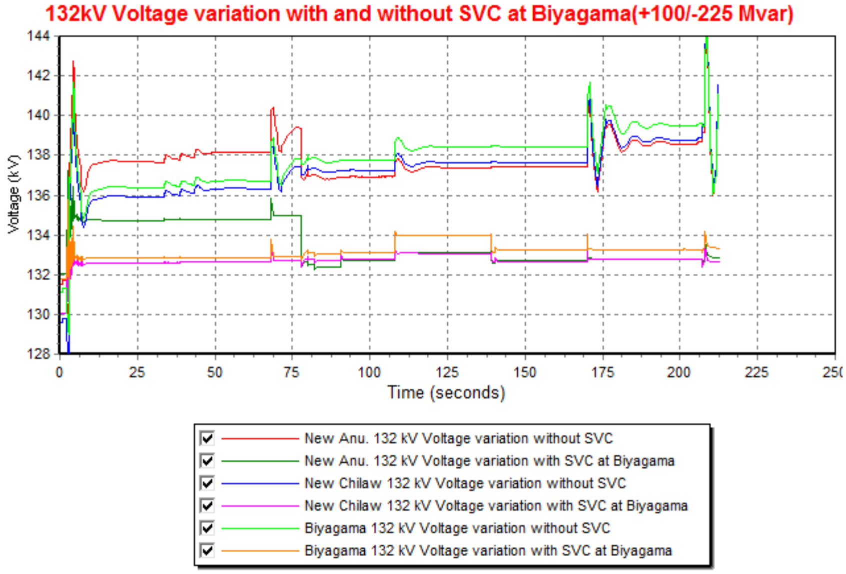


Figure 5.26: 132kV variation with +100/-225 Mvar SVC at Biyagama

Figure 5.27 shows the response of the Frequency controlling machine reactive power variation without svc and with +100/-225 Mvar SVC at Biyagama GSS. Reactive power absorption of Kothmale generator 02 has reduced to 17Mvar from 40Mvar which was its' maximum absorption capacity. Hence the reactive power spinning margin of the system is increased and it is assured that Kothmale generator will not be tripped with the +100/-225Mvar SVC installation at Biyagama GSS.

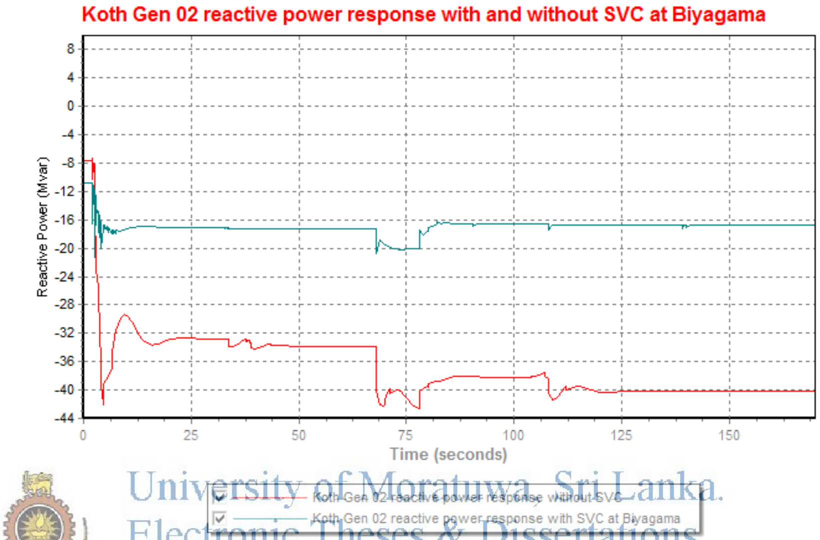


Figure 5.27: Koth Gen 02 reactive power response with and without SVC at Biyagama.

Figure 5.28 represents the response of the SVC which was connected to the Biyagama 220kV bus bar with the 220kV bus bar voltage. According to the graph SVC reaches maximum utilization after 170s on the simulation where voltage on particular bus reaches its highest.

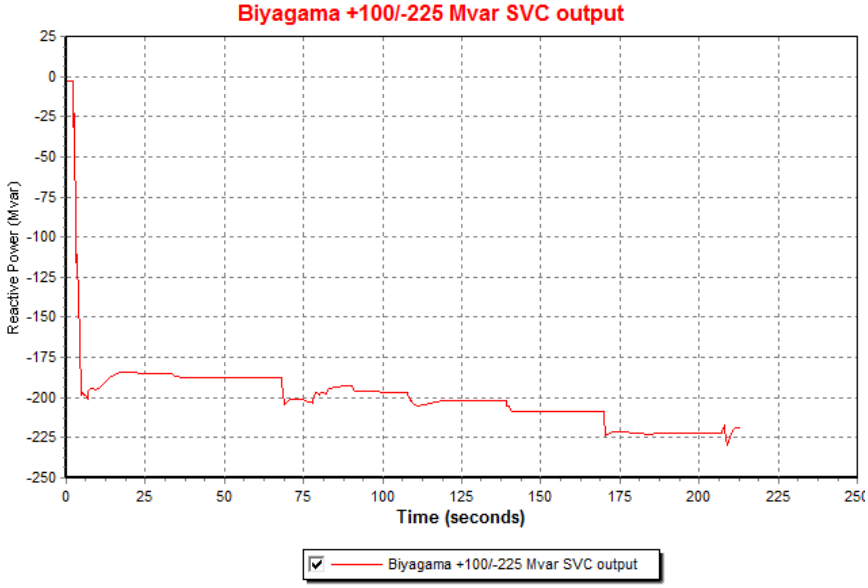


Figure 5.28: +100/-225 Mvar SVC at Biyagama, output variation.

5.3.2 Test Case B2-Installation of +100/-175 Mvar SVC at Kotugoda GSS

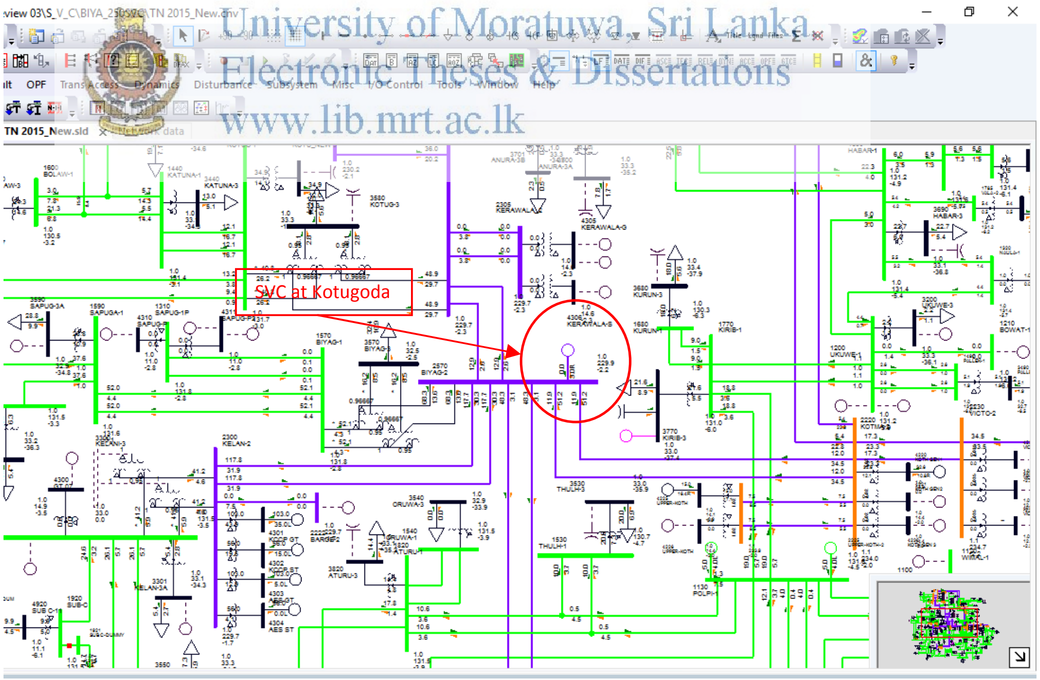


Figure 5.29: +100/-175 Mvar SVC at Kotugoda 220kV bus.

This test case highlights the transmission network voltage with +100/-175 Mvar SVC at Kotugoda GSS 220kV bus bar and Figure 5.30, and Figure 5.31 illustrate the voltage variation on different bus bar locations. It can be seen that more controlled voltage variation below 242kV(1.1p.u) in 220kV voltage level and below 146kV (1.1 p.u) voltage in 132kV level same as in Test Case A2, could be achieved with the installation of +100/-175 Mvar SVC at 220kV bus bar at Kotugoda GSS.

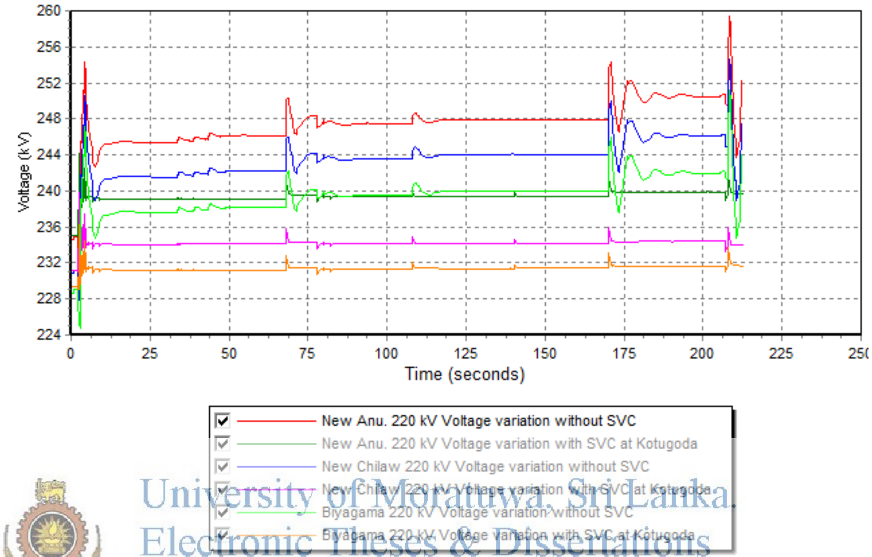


Figure 5.30: 220kV variation with +100/-175 Mvar SVC at Kotugoda.

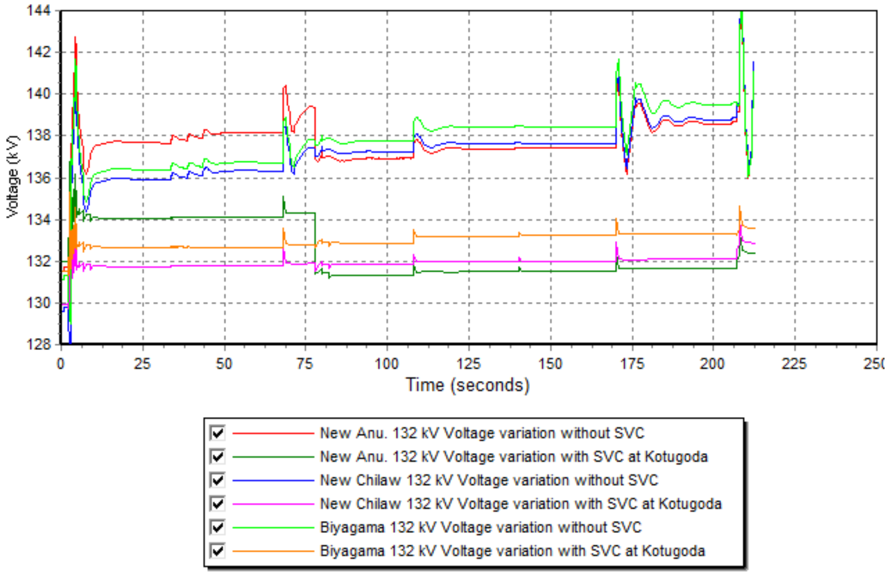


Figure 5.31: 132kV variation with +100/-175 Mvar SVC at Kotugoda.

Figure 5.32 shows the response of the Frequency controlling machine reactive power variation without svc and with +100/-175 Mvar SVC at Kotugoda GSS. Reactive power absorption of Kothmale generator 02 has reduced to 16Mvar from 40Mvar which was its' maximum absorption capacity. Hence as the reactive power spinning margin increased it is assured that Kothmale generator will not be tripped with the +100/-175Mvar SVC installation at Kotugoda GSS.

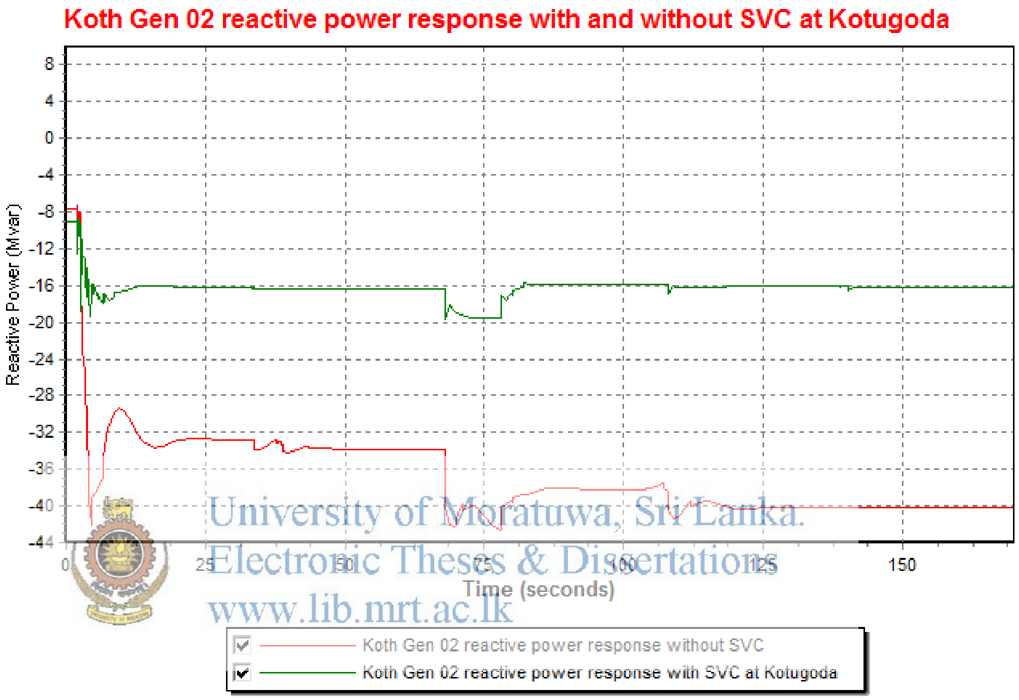


Figure 5.32: Koth Gen 02 reactive power response with and without SVC at Kotugoda.

Figure 5.33 represents the response of the SVC which was connected to the Kotugoda 220kV bus bar with the 220kV bus bar voltage. According to the graph SVC is on maximum utilization after 170s on the simulation where voltage on particular bus reaches its highest.

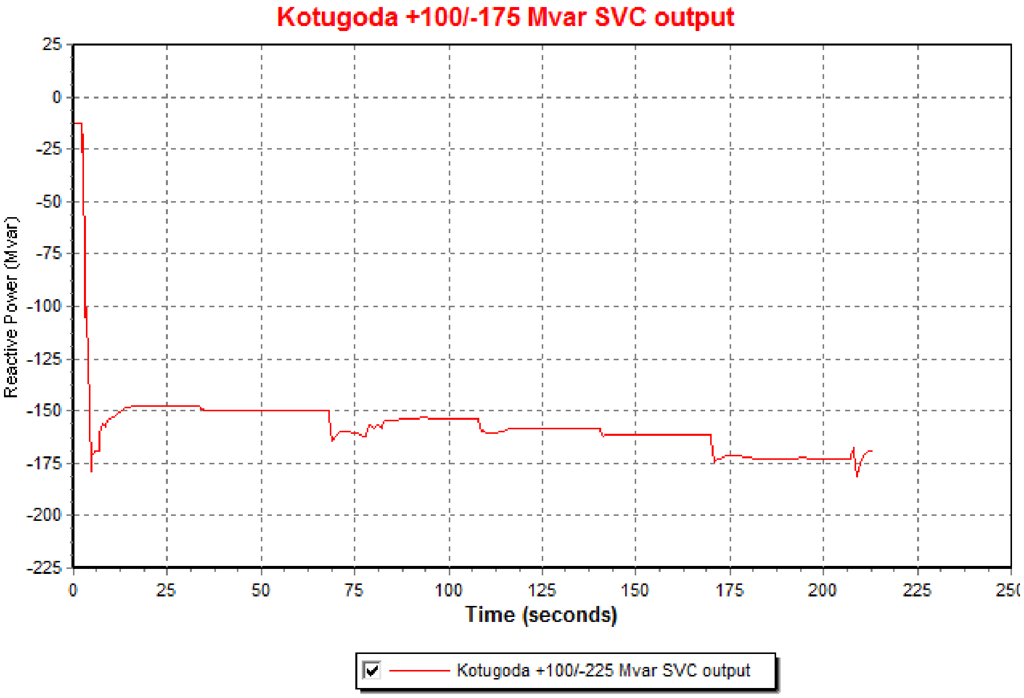


Figure 5.33: +100/-175 Mvar SVC at Kotugoda, output variation.

5.3.3 Test Case C2-Installation of +100/-175 Mvar SVC at Pannipitiya GSS

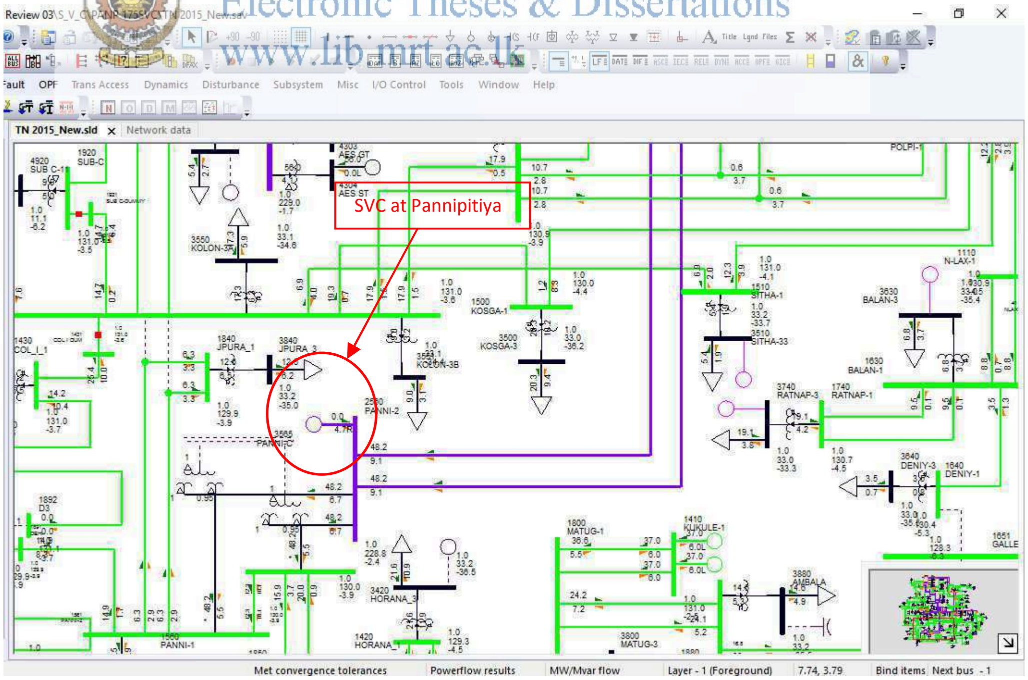


Figure 5.34: +100/-225 Mvar SVC at Pannipitiya 220kV bus.

This test case highlights the transmission network voltage with +100/-175 Mvar SVC at Pannipitiya GSS 220kV bus bar and Figure 5.35, and Figure 5.36 illustrate the voltage variation on different bus bar locations. It can be seen that more controlled voltage variation below 242kV(1.1p.u) in 220kV voltage level and below 146kV (1.1 p.u) voltage in 132kV level same as in Test Case A2/B2, can be achieved with the installation of +100/-175 Mvar SVC at 220kV bus bar at Pannipitiya GSS.

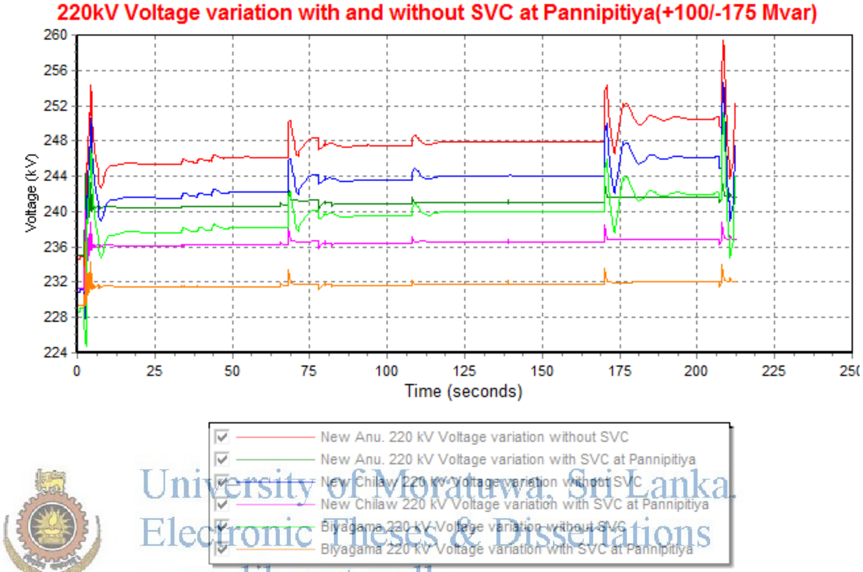


Figure 5.35: 220kV variation with +100/-175 Mvar SVC at Pannipitiya.

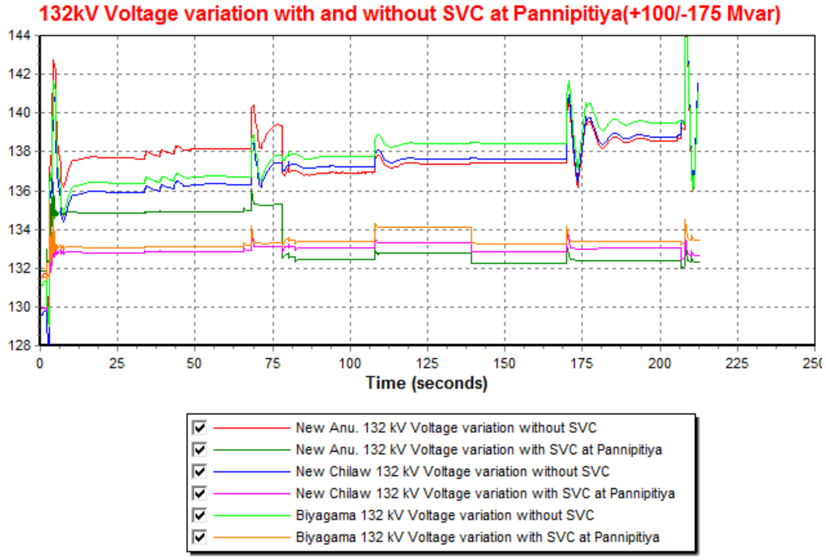


Figure 5.36: 132kV variation with +100/-175 Mvar SVC at Pannipitiya.

Figure 5.37 shows the response of the Frequency controlling machine reactive power variation without svc and with +100/-175 Mvar SVC at Pannipitiya GSS. Reactive power absorption of Kothmale generator 02 has reduced to 18Mvar from 40Mvar which was its' maximum absorption capacity. Hence as the reactive power spinning margin increased and it is assured that Kothmale generator will not be tripped with the +100/-175Mvar SVC installation at Pannipitiya GSS.

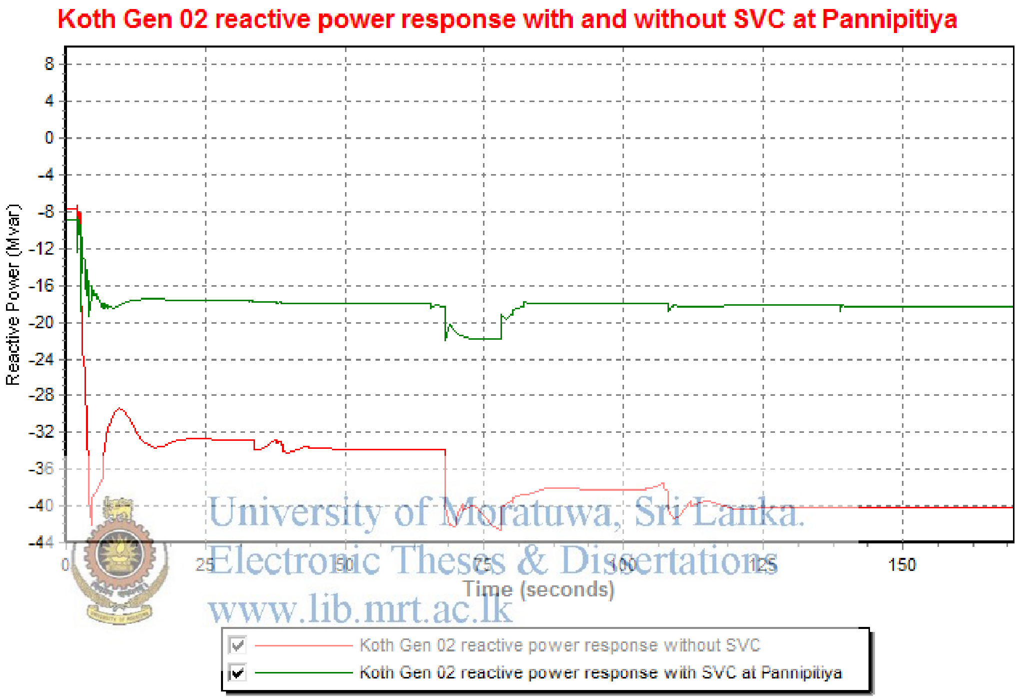


Figure 5.37: Koth Gen 02 reactive power response with and without SVC at Pannipitiya.

Figure 5.38 represents the response of the shunt SVC which was connected to the Pannipitiya 220kV bus bar with the 220kV bus bar voltage. According to the graph SVC is on maximum utilization after 170s on the simulation where voltage on particular bus reaches its highest.

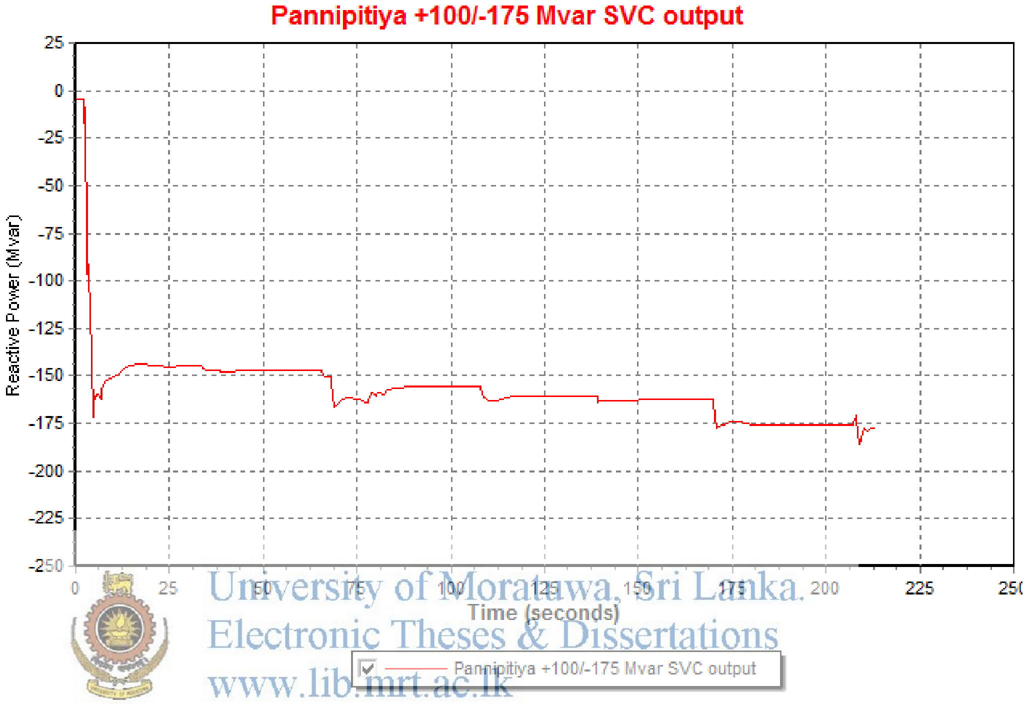


Figure 5.38: +100/-175 Mvar SVC at Pannipitiya, output variation.

5.3.4 SVC Integration Summery

The effectiveness of SVC integration for Sri Lankan power system for above tests cases are comparatively illustrated in this section by carrying out the stability studies using the dynamic load models. The results indicated that the installation of an SVC of correct sizes and appropriate locations would be a remedy to overcome overvoltage instability.

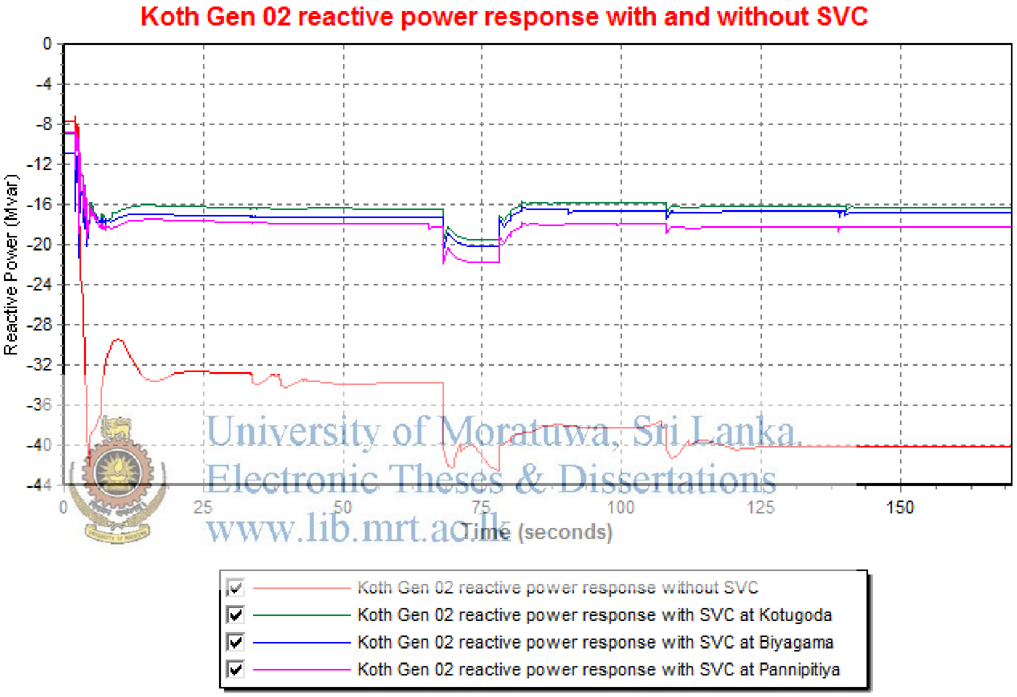


Figure 5.39: Kothmale Gen 02 reactive power response without and with SVC for all test cases

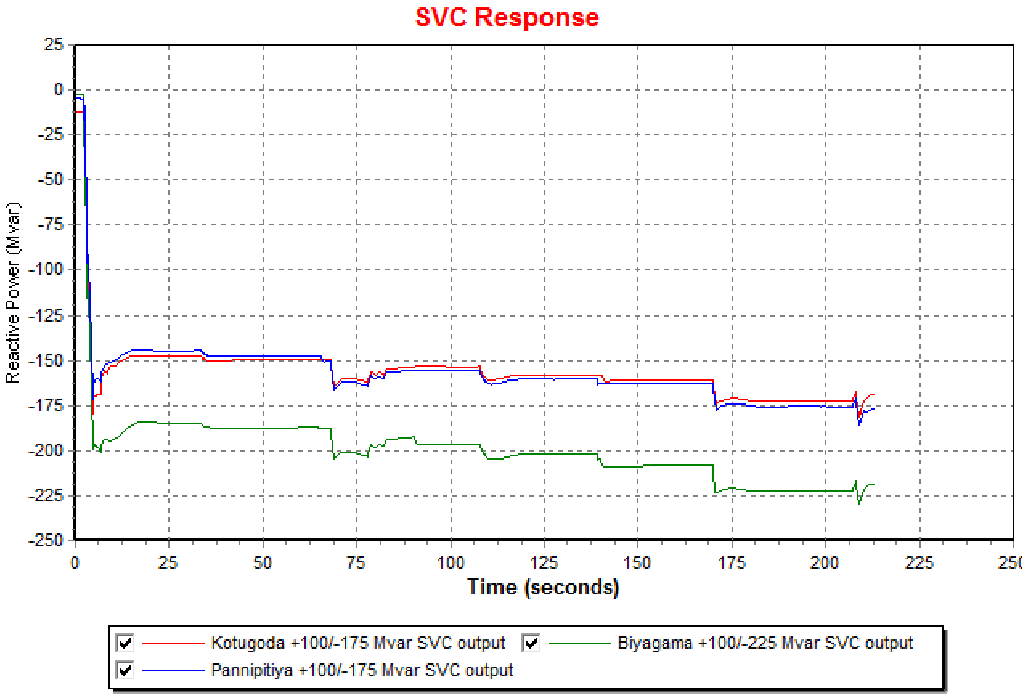


Figure 5.40: SVC response for all test cases

Although more controlled voltage profile is achieved with integration of SVC for all test cases , Test case A_2 is infeasible compared with others as its inductive part is very high comparatively. Therefor Test case A2 is infeasible compared to other test cases.

Though both SVC integration cases for Kotu, Panp perform with equal characteristics, integrating SVC at Kotugoda 220kV bus shows more favorable outputs in voltage reduction and Kothmale reactive power reserve. Panp is in a radial end of the network topology.

Hence, it’s more economical and reliable to have a SVC at Kotugoda GSS.

5.3.5 Validation of +100/-175 Mvar SVC at Kotugoda GSS

Following fault case and procedures were followed as the worst case scenario to perform further analysis of +100/-175 Mvar SVC at Kotugoda GSS.

a) Bus bar fault at Biyagama 220kV bus bar.

b) The fault cleared in 5 cycles (100ms).

c) Trip Biyagama - Kothmale one circuit and ran the simulation for 10 second.

The Biyagama – Kothmale line was selected after performing several simulations and found to be the highest impact on the system with the tripping. This being the worst-case scenario due to highest loading on these circuits, is assumed to be optimum for all other cases which are less severe.

- ❖ Test Case B2.1 : SVC at Kotugoda GSS with Hydro Max. Gen. condition
- ❖ Test Case B2.2 : SVC at Kotugoda GSS with Thermal Max. Gene. Condition

Test Case B2.1, SVC at Biyagama GSS with Hydro Max. Generation condition

(Generation scenario with hydro gen. 74% of total)

The voltages were monitored at 220 kV bus at Biyagama GSS. The plotted results shown in Figure 5.41 indicate the voltage recorded at 220kV bus with and without SVC. The plotted results shown in Figure 5.35 indicate the voltage recorded at Biya GSS without SVC 220 kV bus bars as 0.83 p.u, which is very low voltage leading to voltage-collapse situation, caused by motor stalling due to deficiency of reactive power support. The plotted results with the SVC at Kotugoda GSS shown in Figure 5.35 indicate the recovery of voltages of 220 kV voltages at Biyagama GSS. These are just representative, as all the other bus bars of 220kV and 132 kV of are also recovered to the normal level of voltage i.e. above 0.95 p.u, in compliance with Grid code.

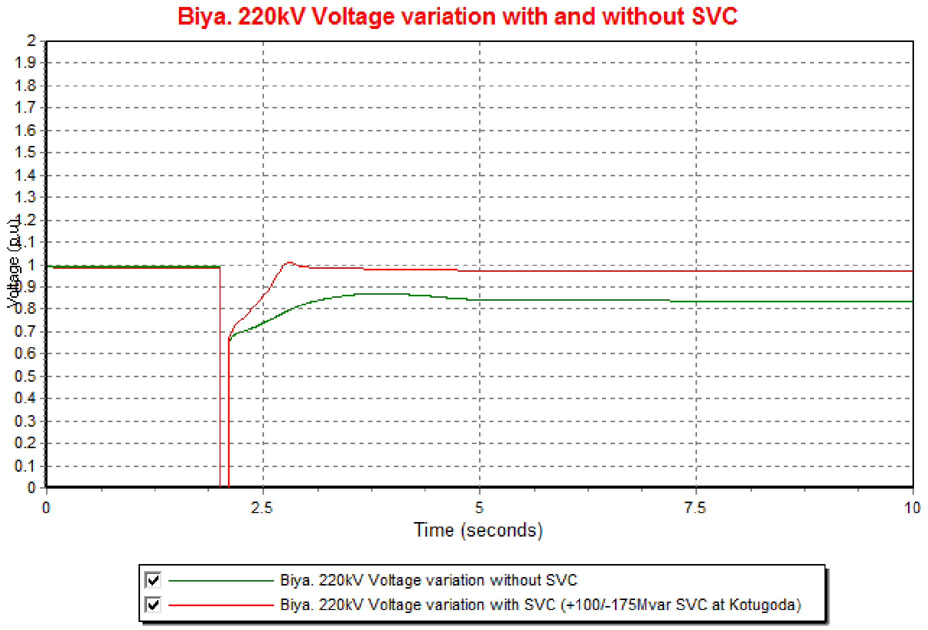


Figure 5.41: Biya 220kV(p.u) for BB fault at Biya – Hydro max.

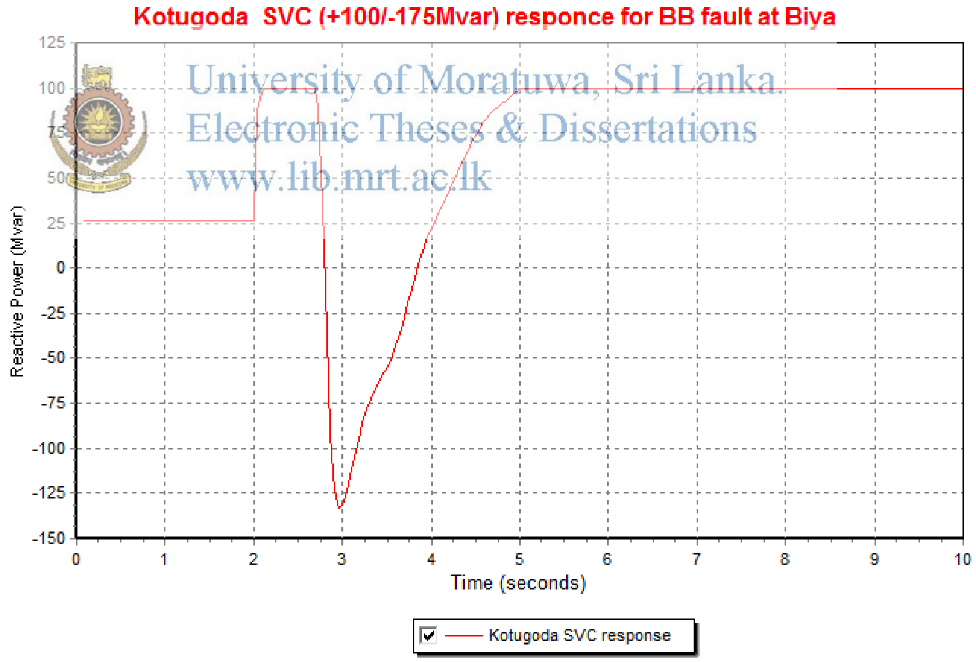


Figure 5.42: Kotugoda SVC response for BB fault at Biya – Hydro max.

Test Case B2.2, SVC at Biyagama GSS with Thermal Max. Generation Condition

(Generation scenario is modeled with thermal gen. 76% of total)

The voltages were monitored at 220 kV bus at Biyagama GSS. The plotted results shown in Figure 5.43 indicate the voltage recorded at 220kV bus with and without SVC. The plotted results shown in Figure 5.35 indicate the voltage recorded at Biya GSS without SVC 220 kV bus bars as 0.84 p.u, which is very low voltage leading to voltage-collapse situation, caused by motor stalling due to deficiency of reactive power support. The plotted results with the SVC at Kotugoda GSS are shown in Figure 5.35 indicates the recovery of voltages of 220 kV voltages at Biyagama GSS. These are just representative, as all the other bus bars of 220kV and 132 kV of are also recovered to the normal level of voltage i.e. above 0.95 p.u, in compliance with Grid code.

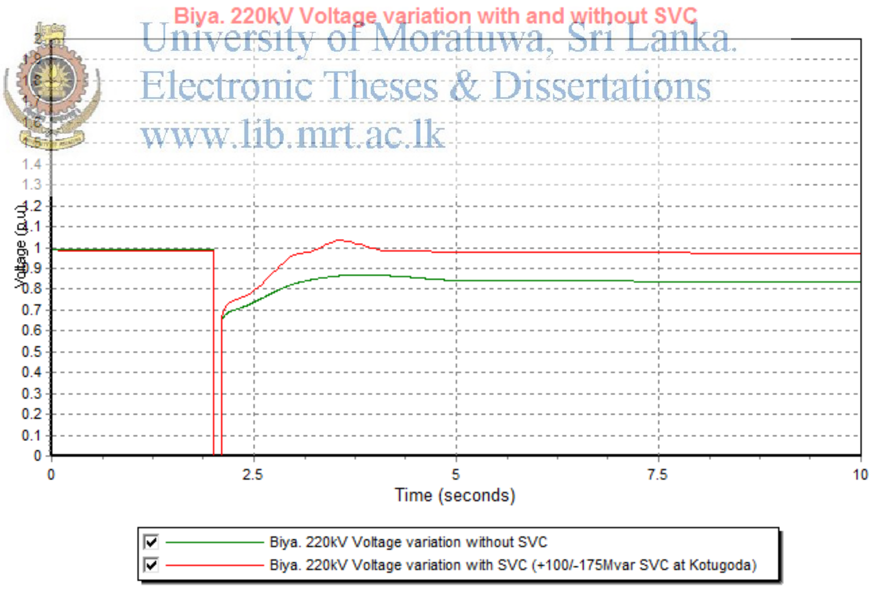


Figure 5.43: Biya 220kV(p.u) for BB fault at Biya – Thermal max.

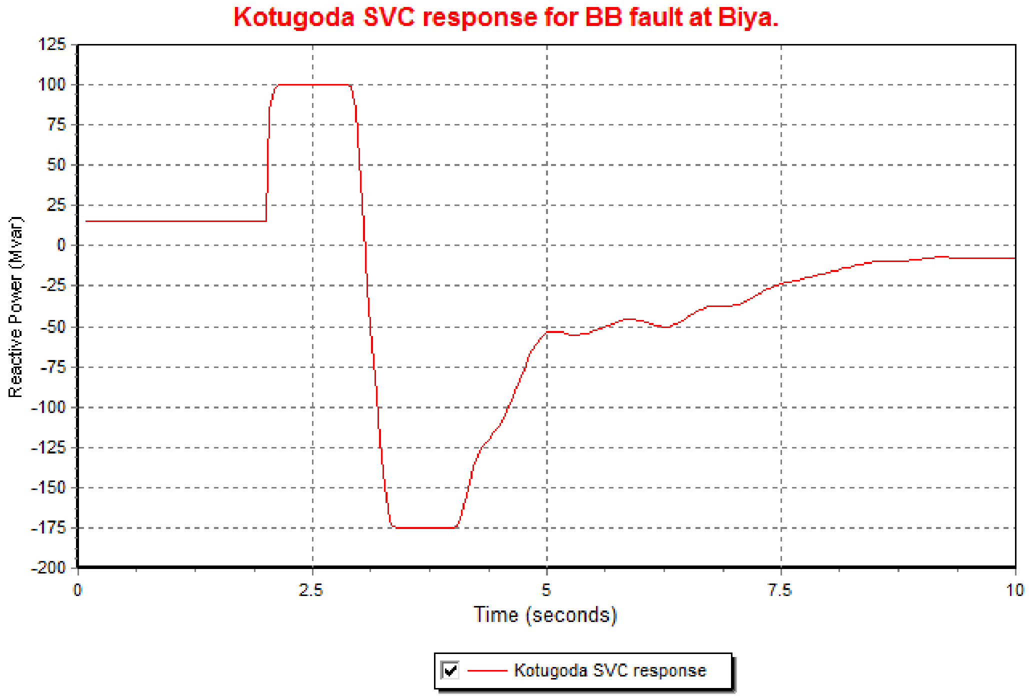


Figure 5.44: Kotugoda SVC response for BB fault at Biya – Thermal max.

5.4 Taking selected transmission lines out of service

As an interim measure, the steady state voltage during low load periods can be improved by taking selected transmission lines out of service during low load periods (although not recommended as a permanent solution, as this action impacts overall system reliability). If system voltages get too high, it may be difficult (if not impossible) to remove a line from service due to the voltage rise experienced at the open end of the circuit being removed from service. Corrective actions have a maximum effect only when they are accomplished prior to experiencing the problem.

During high voltage conditions, opening an HV circuit has a positive effect in reducing system voltages for two reasons:

- it increases losses on the rest of the HV system
- it eliminates the capacitive charging of the line

The performance of taking selected transmission lines out of service is analyzed with validation case to determine their performance comparatively. Circuit for shedding are chose with double circuits with n-1 criteria which accounts to higher capacitive reactive power under lightly loaded scenarios.

Suggested HV circuits to be studied are:

Koth –New Anu. cct 01
New Anu – LVPS cct 01
New Anu. – Vavu cct 01
Vavu –Kili cct 01
Kili – Chunnakum cct 01
New Anu. – Trinco cct 01

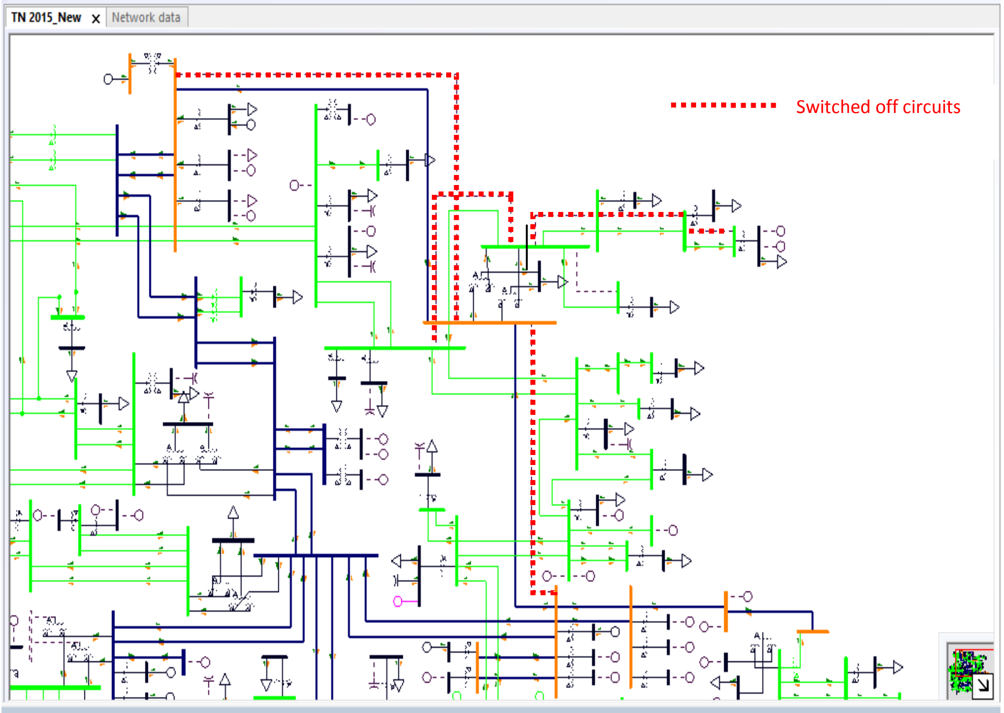


Figure 5.45: Out of service transmission lines

Figure 5.46 and Figure 5.47 illustrate the voltage variation at New Anuradapura GSS 220kV bus bar. It can be seen that around 5kV voltage reduction of 220kV level and around 1.5kV voltage reduction of 132kV level can be achieved with selected transmission lines out of service. Although significant level of voltage reduction is achieved through this, yet the sustained voltage lies above 242kV or the tolerance margin.

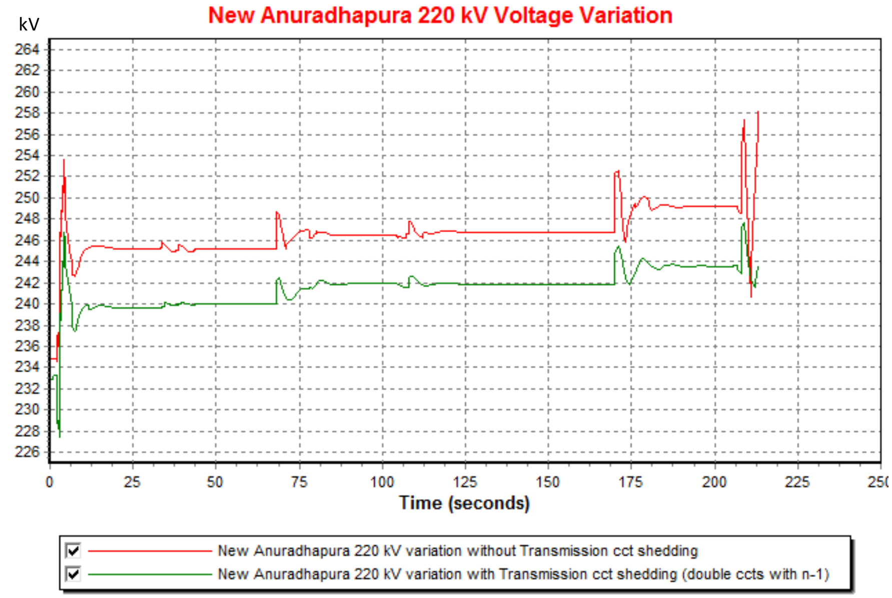


Figure 5.46: New Anu. 220kV variation with and without out of service transmission lines

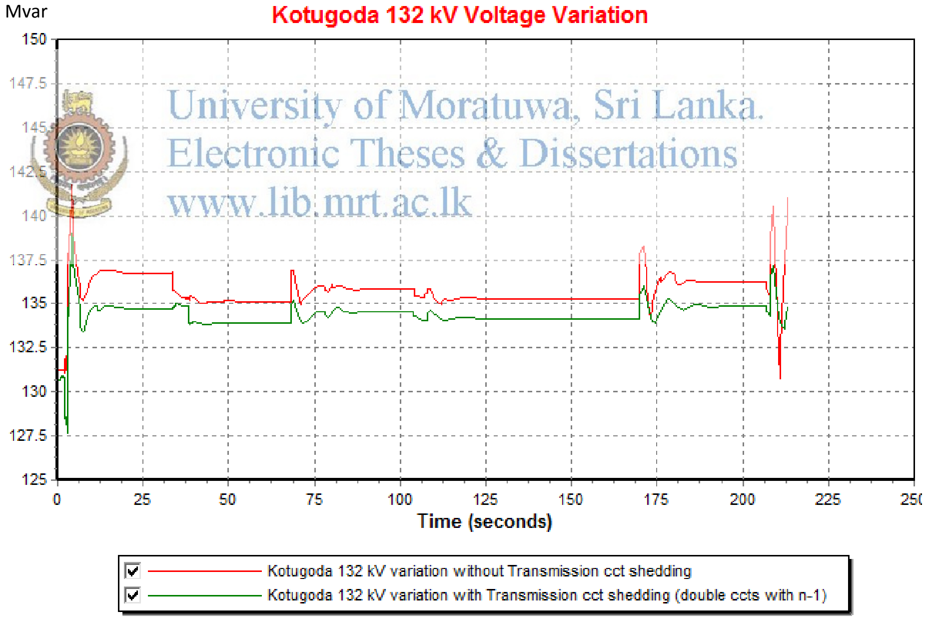


Figure 5.47: New Anu. 220kV variation with and without out of service transmission lines

Figure 5.48 shows the response of the Frequency controlling machine reactive power variation without reactor and with selected transmission lines out of service. Reactive power absorption of Kothmale generator 02 has reduced to 23Mvar from 40Mvar which was its' maximum absorption capacity.

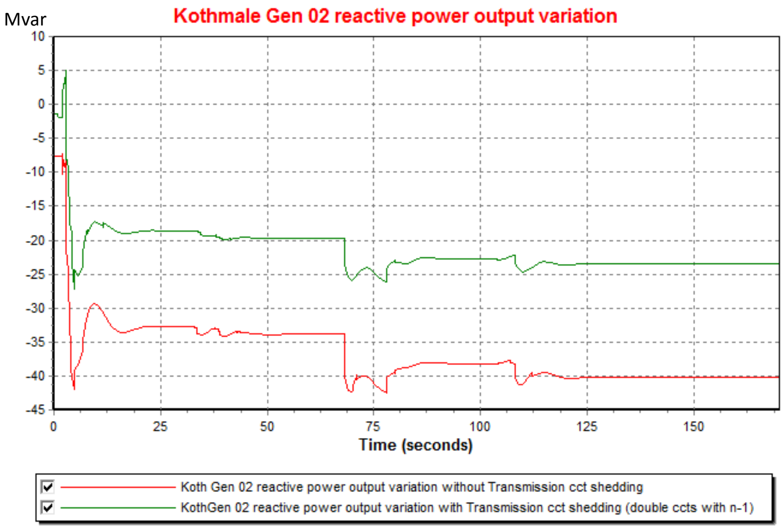


Figure 5.48: Koth Gen 02 reactive power response with and without out of service transmission lines

5.5 Overall Analysis

Table 5.3 illustrates the obtained results for best cases for integration of shunt reactor (New Anu. 100Mvar), SVC (Kotugoda +100/-175Mvar) and Selective transmission line shedding. The results suggest that maximum 220kV reduction of power system could be achieved with integration of reactor of 100Mvar at New Anu. GSS.

Table 5.3 Summery Table

Test Case	Max. reached 220kV	Max. reached 132kV	Min. Leading Mvar of frequency control m/c	Max. Reactor /SVC output
Base case	251.0	139.0	-40	*
Reactor at New Anu.	238.0	133.0	-27	-90
SVC at Kotugoda	240.0	135.5	-16	-175
Switching off selected Tx cct	243.5	138.0	-23	*

Voltage Criteria	Normal(kV)	Emergency(kV)
220kV Max. Voltage Tolerance	231	242
132kV Max. Voltage Tolerance	139	145

Note: In financial terms also having installation of SVC cost more than ten times than for a shunt reator of similar capacity. And very importantly due to Sri Lankan power system does not have any fast acing mechanism for reactive compensation; installation of SVC should strictly concentrated giving priority to unserverd reactive requirement load centers than giving benefit to overvoltage compensation.

5.6 Steady State Analysis for recommended solution of integration 100Mvar Reactor at New Anu.

Table 5.4 illustrates the steady state voltage reduction obtained having the reactor at New Anu. at 40Mvar initially.

Table 5.4 Steady State Voltages of with and without New Anu. 100Mvar reactor

Bus Voltage(kV)	Location	Bus Voltage without SR (kV)	Bus Voltage with SR at 40Mvar (kV)	% reduction
132	New Lax.	131.27	130.650	**0.47**
132	Kolonnawa	131.21	130.320	**0.68**
132	Pannipitiya	130.03	129.200	**0.64**
132	Biyagama	131.56	130.620	**0.72**
132	Kotugoda	131.50	130.550	**0.73**
132	New Galle	128.57	127.880	**0.54**
132	New Anu.	131.91	129.710	**1.70**
220	Kelanitissa	229.28	227.700	**0.69**
220	Biyagama	229.45	227.690	**0.77**
220	Kotugoda	229.29	227.130	**0.95**
220	New Anu.	234.96	229.950	**2.18**
220	LVPS	232.10	227.920	**1.83**
220	New Chilaw	231.24	227.780	**1.52**

Table 5.5 Steady State generator reactive power responce with and without New Anu. 100Mvar reactor

Power Station	Q Gen (Mvar) without SR	Q Gen (Mvar) with SR at 40Mvar
LAX-1	-3.00	-3.00
LAX-1	-2.00	-2.00
POLPI-1	4.00	4.00
POLPI-1	4.00	4.00
KUKULE-1	-6.00	-6.00
KUKULE-1	-6.00	-6.00
NLAX-1	-3.20	-0.17
NLAX-2	-3.20	-0.17
KOTH GEN1	-9.35	-1.88
UPPER-KOTH	-15.24	-9.23
KCCP GT	-35.00	-14.31
KCCP ST	-15.00	-14.31
AES GT	-5.00	-5.00
AES ST	0.00	0.00
PUTT COAL-3	-51.23	-52.35
Total	**-146.22**	**-106.41**

Chapter 6

DISCUSSION and CONCLUSION

6.1 Discussion

The blackout which happened on 27th September 2015 was the key motive for the study. It was the worst ever scenario in terms of voltage stability that led the entire system to collapse initiating with LVPS gen 03 tripping. Post failure studies carried out by Manitoba HVDC Research Centre in co-operation with Public Utility Commission of Sri Lanka, stated in their final report the importance of overvoltage mitigating mechanism to Sri Lankan power system. Further the report also highlighted that the steady state voltage tolerance margin should be practiced, at or below 105% from the rated voltage.

The prolonged power frequency overvoltage has caused number of issues including excess operation of transformer tap changer, unnecessary breaker operation caused due to selective transmission circuit shedding and most importantly unserved energy caused by failures involved. As none of the above factors are straightforward it's not easy to economically justify the importance of overvoltage mitigating mechanism.

This study illustrates a comprehensive analysis of integration of shunt reactor and svc to Sri Lankan power system to mitigate overvoltage scenarios. The location for the integration of svcs and shunt reactors, in the high voltage network are identified with considering the voltage profile and their reactive power requirement of GSSs. The capacities of the shunt reactor or the svc are identified by performing rigorous analysis with PSS/E to comply with Grid Code and recommendations of Manitoba HVDC Research Centre report (Investigation of Total Failure of the Transmission System).

The methodology for the selection of shunt reactor and svc capacity to adhere the system with solutions in mitigating long-term high voltage collapse and the blackout (27/09/2015) event list is considered for the simulation analysis. Further studies also carried out with the selective integrations to validate the test cases with aid of literature review resources.

6.2 Conclusion

At low loads especially during off peak hours, the voltage increases along the transmission line such as Kothmale-New Anuradhapura, Lakvijaya-New Anuradhapura and generate around 80 Mvars. NCRE generations is also another vital aspect of the growing part of the energy mix which causes unpredictable fluctuations in power and thereby voltage.

Voltage unbalance of the system is a main reason for the most of the power quality issues. The voltage profile must remain within +/-5 % of the rated value for better and efficient operation of various electrical equipments (as per IEC 60364-5-52). A power system is expected to operate under widely varying conditions and the quality of the supply should be maintained under all conditions maintaining voltage magnitude and the system frequency.

The main objective of the study is to provide the dynamic modeling for the present Sri Lankan power system and to seek optimum solutions in mitigating long-term high voltage collapses.

Many researches have gone into developing new technologies over the past few years to gain improvement in Power Quality from the existing power systems in the world. As a result of this, high speed thyristors are employed for switching in or out transmission components such as capacitors and reactors for desirable performance of the system replacing the existing slow acting mechanical controls. Today, the world has come to the third generation of reactive power compensation. Converter based self commutated devices such as STATCOM, UPFC, IPFC.. etc. are being used by utilities in the world to ensure the reliable power system while maintaining the power quality. SVC can be considered as second generation of reactive power compensation which use thyristor based technologies. Mechanically switched capacitors and reactors are belonged to the first generation of reactive power compensation.

In this context, methods of improving voltage stability are outlined and it has been proven by the results, which obtained from the analysis carried out using the dynamic PSS/E simulations.

Studies carried out with various integrations (with respect to size and locations) of SVCs and shunt reactors, suggest that the most feasible and reliable means of voltage stability in terms of overvoltage collapse can be achieved through installing a shunt reactor at New Anuradhapura 220kV bus.

Although more controlled and better dynamic response could be achieved with integration of a SVC to Kotugoda 220kV bus, to cater for the desired performance with system stability in mitigating long-term high voltage collapses its capacity and thereby its cost is very high in comparison with shunt reactor at New Anuradhapura.

Further only as an interim measure taking selected transmission lines out of service during low load periods (although not recommended as a permanent solution, as this action impacts overall system reliability) can also be employed.

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