IMPROVEMENT OF VOLTAGE STABILITY OF A SOLAR PV DOMINATED POWER SYSTEM USING SVC'S- SRI LANKA CASE STUDY

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DECLARATION OF THE CANDIDATE AND SUPERVISORS

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ABSTRACT

According to the Ceylon Electricity Board (CEB), Sri Lanka Long Term Generation Expansion Plan 2020-2039, in the forthcoming years the contribution to meet national energy demand by major hydro sources will become stagnant. However, the development of other renewable energy resources will enhance the renewable energy share to be maintained above 35-40% during next 20-year period.

The increase in solar penetration to the grid can lead to voltage instability problems due to solar ramp rates. Currently solar inverters do not operate in the voltage controlling mode, and they are not capable of producing or absorbing reactive power. Thus, Flexible AC Transmission System (FACTS) devices, such as Static Var Compensators (SVC) are useful to support the reactive power need to sustain voltage stability in the system even under the loss of large generators supplying reactive power in the system.

The behaviour of SVC with the maximum penetration of renewable energy, focusing on solar and wind power generation was studied to size and locate the SVC in the transmission system. The Sri Lankan transmission system of year 2030 base case model simulated in Power System Simulator for Engineers (PSS/E) was used for the study.

The study showed the best location for placement of SVC was Biyagama Grid Substation considering SVC placement at Biyagama, Kotugoda and Pannipitiya Grid Substations (GSS). Furthermore, this study highlights that it is beneficial to consider a further increase of the currently proposed SVC capacity in order to improve the voltage collapse point under increased penetration of renewable sources in the Sri Lankan Power system in year 2030.

DEDICATION

I dedicate this thesis to my ever loving husband for his unconditional love, care and support given at all times to help me achieve this milestone.

To my beloved parents and brother for their continuous motivation and guidance.

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LIST OF ABBREVIATIONS

Abbreviation	Description
CEB	Ceylon Electricity Board
CLODAL	Complex load model
DP	Day Peak
ESAC1A	IEEE Type AC1A Excitation system
ESST1A	IEEE Type ST1A Excitation System
FC	Fixed Capacitor
GAST	Gas turbine governor
GENROU	Round Rotor machine model
GENSAL	Salient pole machine model
GSS	Grid Substations
HYGOV	Hydro turbine governor
Max RE	Maximum Renewable Energy
Min RE	Minimum Renewable Energy
Mvar	Mega volt-amps (reactive)
NP	Night Peak
ORE	Other Renewable Energy
PS	Pumped Storage
PSS/E	Power System Simulator for Engineers
PV	Power-Voltage
QV	Reactive Power-Voltage
SCRX	Bus fed static exciter
SEXS	Simplified Excitation System
SVC	Static Var Compensator
TCR	Thyristor Controlled Reactor
TGOV	Steam turbine governor
TSC	Thyristor Switched Capacitor
UFLS	Under Frequency Load Shedding

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CHAPTER 1

1 Introduction

1.1 Power System Stability

The definition for power system stability may broadly be mentioned as: it is the characteristic of a power system that facilitate it to continually endure a state of stable equilibrium in the instance that normal operating conditions continues to prevail in the power system and also get back to an equilibrium state that is allowable succeeding the event of a disturbance [1]. Power system stability can be categorised into rotor angle stability, frequency stability and voltage stability as given by Figure 1.1 with further divisions based on the size and the time duration of the disturbance.

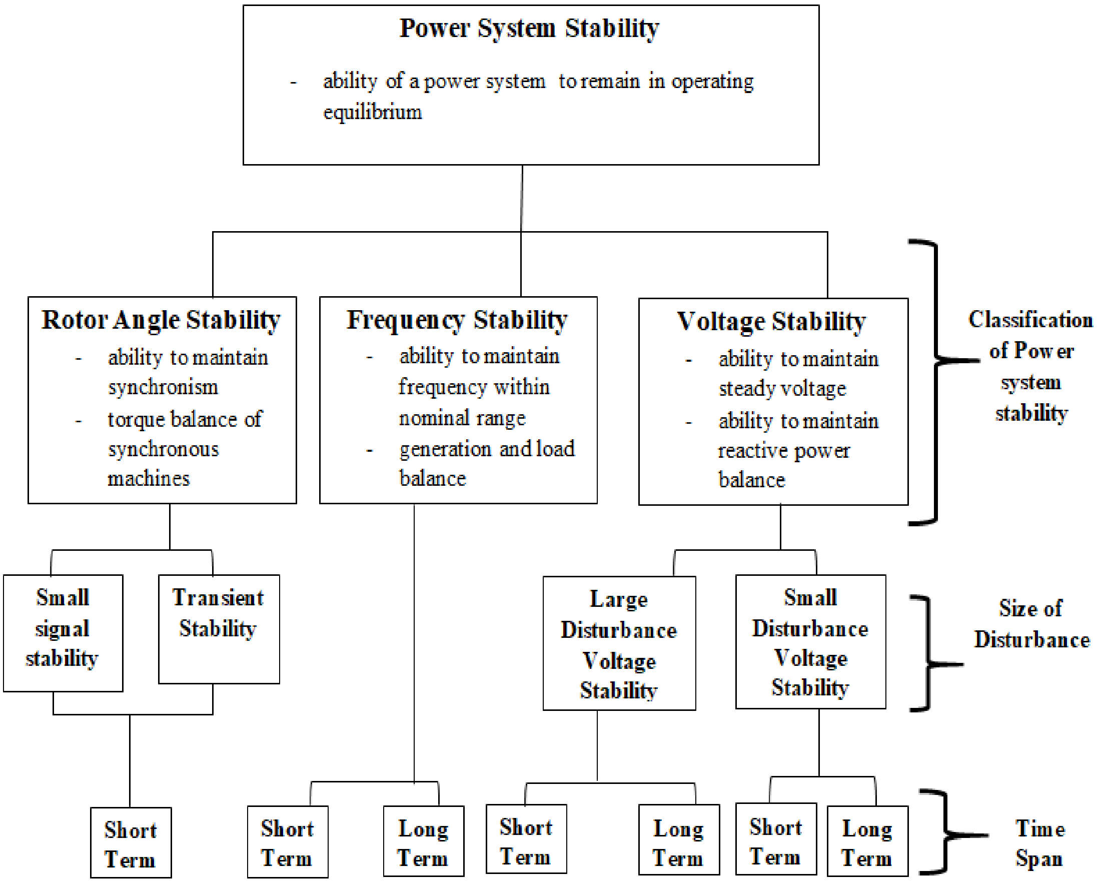


Figure 1.1: Power system stability classification [1]

Rotor angle stability, also commonly known as generator stability is the capability of the interconnected machines observed in a power system to prevail in synchronism when subjected to a disturbance event. This could happen considering a single machine or with a cluster of machines going out of synchronism.

In the steady state, the torque balance of the synchronous machines is maintained and the speed is kept constant. Rotor angle instability is caused by the mismatch in the input and output torque of synchronous generators. This happens when the steady state equilibrium among the mechanical torque input and electromagnetic torque output of the synchronous generators are lost. This results in acceleration and deceleration of the rotors of the synchronous machines. As the power angle relationship is highly non-linear, at some limit the angular separation of the rotors can increase further worsening the situation along with reduced transfer of active power. Furthermore, power system will become instable due to the system been unable to take up the kinetic energy due to difference in speed of rotors and the stability of the system depends on whether there is adequate restoring torque generated by the rotors.

The restoring torque component can be categorized as:

- Synchronizing torque
- Damping torque

The component of synchronizing torque is found in phase alongside the deviation in rotor angle and the damping torque element is found to be in phase with variation of speed.

Insufficient synchronizing torque leads to aperiodic instability and oscillatory instability is due to inadequate damping torque in the power system.

Rotor angle stability is classified as:

- Small signal stability
- Transient stability

Small signal stability is the ability of the power system to maintain synchronism when subjected to small disturbances and can occur due to:

- Increase in the rotor angle because of insufficient synchronizing torque present in a power system.
- Increase in rotor angle oscillations because of insufficient damping torque.

For small signal disturbance analysis, the time period is 10-20 s in the post disturbance situation. For transient stability analysis, the time frame is 3 – 5 s.

1.2 Frequency Stability

Frequency stability of a power system is its ability to sustain steady frequency subjected to a mismatch between generation and load with minimal unintentional reduction in load in restoring the equilibrium. Frequency stability is divided into two categories as short term and long term. Short term frequency instability occurs if the Under frequency Load Shedding was insufficient leading to further reduction in system frequency within a few seconds it could lead to a blackout. Long term frequency instability occurs due to over speed controls of steam turbines and boiler protection controls which are in the range of 10 s to even minutes.

1.3 Voltage Stability

Voltage stability of a power system is affected by how well the generating sources can supply the power requirement of the loads. That is, the real power and reactive power. The ability of a power system to sustain steady voltages after a disturbance is refereed as voltage stability.

In a power system, voltage stability depends on the equilibrium between the generation and the load. Voltage instability is seen from voltage drop or rises at buses after a disturbance and sometimes may lead to progressive drops. The reported latest events of voltage collapse and alike power system instabilities are been readily associated with the imbalances of demand and supply of power [2-4]. The loss of a major load or a sudden tripping of a transmission line can lead to cascading outages.

Voltage stability studies are divided as: Small disturbance voltage stability and Large disturbance voltage stability for the purpose of analysis based on the size of the disturbance [5].

Small disturbance voltage stability is the ability of a power system to sustain steady state voltages subjected to small disturbances such as small load fluctuations in the power system. The period of study is in the range of a few seconds.

Large disturbance voltage stability is the ability of a power system to sustain steady voltages after been subjected to large disturbances such as a system fault and loss of generation. The period of analysis is in the range of few seconds to around 10 minutes.

Voltage instability is mainly driven by the loads. In the post disturbance situation, the system loads tries to get restored in the power system. So, there will be an increase of reactive power consumed by the loads and when the power system stability limit is exceeded it will result in voltage collapse or even widespread blackout [6].

Voltage instability occurs when short or long term disturbances cause an unmanageable and progressive drop in voltage level. The primary cause of voltage collapse is due to the lack of reactive power in the supply network [7].

1.4 Voltage Stability of the Sri Lankan Power System

The Ceylon Electricity Board (CEB) Long Term Transmission Plan 2018-2027 [8], studies have revealed that in peak load condition there are buses with less than specified bus voltage even under steady state operation. In an event of a contingency, this situation further worsens.

By the year 2018, about 495 Mvar (Mega volt-amps (reactive)) of breaker switched capacitor banks, which operate for variation of power factor of the grid load are installed in the system to provide reactive power demand. During night peak, the power factor is around 0.98. Consequently, most capacitor banks would not be operated even though there are severe low voltages in the bus bars. With the drop in voltage, the potential of the capacitor banks in supplying the demand for reactive power will reduce. Therefore, generators have to manage most of the reactive power needs of the system alone.

In light-load condition, due to line charging capacitors, there is excess of reactive power in the system. As there are no reactive power absorption devices, excess amount of reactive power is absorbed generators in the power system.

It was estimated that about 475 Mvars would be generated by line charging capacitors and about 100 Mvars would be absorbed by the power transformers in the system and around 50 Mvars will be absorbed by line reactance. Thus, part of the reactive power is provided for loads and the balanced is required to be absorbed by the generators running at leading power factor. Thus, system is running at little higher voltage above 1.0 per unit [8].

1.5 Renewable energy integration in Sri Lankan Power system

Natural processes continually restores the most commonly found Renewable energy sources. Renewable Energy systems convert energy found freely in nature to heat or electricity without depleting the source. Energy is found in renewable energy sources such as sunlight, wind, water, sea-waves, geothermal, biomass.

At present, in Sri Lanka the major renewable resources (large hydro) are already been harnessed to almost its maximum economical potential. Due to reduced environmental issues in comparison with energy sources which are based on fossil fuels, Other Renewable Energy (ORE) sources have become a viable option to meet future energy demand in Sri Lanka.

With the rapid growth in electricity demand in Sri Lanka, the portion of renewable energy has also shown significant growth along with the expansion of renewable energy sources that are commonly known as Distributed Renewable Energy sources (DER’s).

The developments of the following renewable energy forms are presently undertaken in Sri Lanka are hydro, wind , solar , biomass and waste energy.

Most of the renewable energy comes either directly or indirectly from sun and wind and can never be exhausted, and therefore they are called renewable. Hydro power and biomass power generation are not intermittent in performance. Wind and Solar Photovoltaic sources are highly intermittent and seasonal in nature. These physical characteristics of the resource make the challenges in grid integration and different power systems have different integration capacities based on resource and system characteristics and economic performances [9].

The Prospective Power Plant Capacity Additions using Renewable Energy Sources that are projected for next 20 year planning period in the long term generation expansion plan 2020-2039 is as given in Table 1.1.

Table 1.1: Projected Future Development of ORE [9]

Year	**Cumulative Mini hydro Capacity (MW)**	**Cumulative Wind capacity (MW)**	**Cumulative Biomass capacity (MW)**	**Cumulative Solar capacity (MW)**	**Cumulative Total ORE capacity (MW)**	**Annual total ORE generation (GWh)**	**Share of ORE from total %**
2020	419	368	49	410	1245	3403	18.4%
2021	439	488	54	470	1450	3970	19.9%
2022	459	558	59	530	1605	4376	20.9%
2023	479	598	64	590	1730	4677	21.2%
2024	499	598	69	650	1815	4863	20.9%
2025	519	638	74	730	1960	5193	21.2%
2026	529	673	79	820	2100	5483	21.3%
2027	539	723	84	910	2255	5819	21.6%
2028	549	763	89	1010	2410	6144	21.8%
2029	559	803	94	1110	2565	6469	21.9%
2030	569	823	99	1210	2700	6738	21.8%
2031	579	883	104	1310	2875	7114	22.0%
2032	589	933	109	1420	3050	7487	22.2%
2033	599	968	114	1530	3210	7801	22.1%
2034	609	1038	119	1650	3415	8244	22.4%
2035	619	1083	124	1770	3595	8613	22.4%
2036	629	1133	129	1880	3770	8985	22.4%
2037	639	1183	134	1990	3945	9357	22.4%
2038	649	1253	139	2100	4140	9786	22.5%
2039	654	1323	144	2210	4330	10198	22.6%

1.6 Demand in Sri Lankan Power System

The average growth rates of electricity demand in Sri Lanka are shown in Table 1.2. In the past fifteen years, the demand has grown at a rate of approximately 5.5% annually while the peak demand showed an annual growth rate of 3.7%. During the last five years, however, the average growth rate of peak demand was 5% and energy demand growth rate was 6.2% annually. The net generation inclusive of rooftop solar photovoltaic installations was 15,305 GWh in the year 2018. However, the reported figure for net generation was 9803 GWh ten years ago. In 2018, a maximum demand of 2616 MW has been recorded which is an increased figure in comparison to the 2523 MW recorded in 2017 and 1868 MW recorded in the last ten years. Table 1.2 shows the "Electricity Demand in Sri Lanka, 2004– 2018".Table 1.3 provides 'Base Load Forecast 2020-2044'. From year 2019 and throughout, the day peak would exceed the night peak [9].

Table 1.2: Demand for electricity in Sri Lanka, 2004– 2018

Year	Demand	Avg. Growth	Trans. & Distribution Losses	Net Generation	Avg. Growth	Load Factor	Peak	Avg. Growth
	(GWh)	(%)	(%)	(GWh)	(%)	(%)	(MW)	(%)
2004	6667	7.4	15.2	7998	5.8	58.4	1563	3.1
2005	7255	8.8	16.7	8709	8.9	56.9	1748	11.8
2006	7832	8.0	15.9	9314	6.9	56.2	1893	8.3
2007	8276	5.7	15.0	9733	4.5	60.3	1842	-2.7
2008	8417	1.7	14.3	9819	0.9	58.3	1922	4.3
2009	8441	0.3	13.9	9803	-0.2	59.9	1868	-2.8
2010	9268	9.8	13.0	10649	8.6	62.2	1955	4.7
2011	10023	8.2	11.7	11353	6.6	59.9	2163	10.6
2012	10474	4.5	10.7	11725	3.3	62.4	2146	-0.8
2013	10624	1.4	10.7	11898	1.5	62.8	2164	0.8
2014	11063	4.1	10.2	12316	3.5	65.3	2152	-0.6
2015	11786	6.5	10.0	13090	6.3	65.4	2283	6.1
2016	12785	8.5	9.6	14148	8.1	65.8	2453	7.4
2017	13431	5.1	8.5	14670	3.7	66.4	2523	2.9
2018	14091	4.9	7.9	15305	4.3	66.8	2616	3.7
Last 5 year		6.2%			5.6%			5.0%
Last 10 year		5.9%			5.1%			3.8%
Last 15 year		5.5%			4.7%			3.7%

Table 1.3:Base demand forecast 2020-2034 [9]

Year	Demand		Loss (net)	Generation (Net value)		Peak Demand
	(GWh)	Rate of growth	(%)	(GWh)	Growth Rate	(MW)
		(%)			(%)	
2020	16914	7.4%	8.78	18542	7.2%	3050
2021	18194	7.6%	8.62	19910	7.4%	3254
2022	19187	5.5%	8.46	20959	5.3%	3403
2023	20233	5.5%	8.30	22065	5.3%	3561
2024	21337	5.5%	8.15	23230	5.3%	3728
2025	22501	5.5%	8.00	24458	5.3%	3903
2026	23667	5.2%	7.90	25696	5.1%	4079
2027	24819	4.9%	7.80	26918	4.8%	4241
2028	26025	4.9%	7.70	28195	4.7%	4444
2029	27279	4.8%	7.60	29522	4.7%	4655
2030	28573	4.7%	7.50	30890	4.6%	4872
2031	29917	4.7%	7.45	32325	4.6%	5101
2032	31279	4.6%	7.40	33778	4.5%	5332
2033	32675	4.5%	7.35	35267	4.4%	5569
2034	34119	4.4%	7.30	36806	4.4%	5814
2035	35607	4.4%	7.25	38390	4.3%	6067
2036	37126	4.3%	7.25	40028	4.3%	6328
2037	38692	4.2%	7.25	41716	4.2%	6597
2038	40298	4.2%	7.25	43448	4.2%	6873
2039	41937	4.1%	7.25	45215	4.1%	7155
2040	43623	4.0%	7.25	47033	4.0%	7445
2041	45368	4.0%	7.25	48914	4.0%	7745
2042	47170	4.0%	7.25	50857	4.0%	8054
2043	49037	4.0%	7.25	52870	4.0%	8376
2044	50978	4.0%	7.25	54963	4.0%	8709
5 Year Average Growth	6.0%			5.8%		5.1%
10 Year Average Growth	5.5%			5.3%		4.8%
20 Year Average Growth	4.9%			4.8%		4.6%
25 Year Average Growth	4.7%			4.6%		4.5%

1.7 Motivation

At present in Sri Lanka, installed capacitor banks, which operate according to the power factor of 33 kV side are used to compensate the reactive power in Grid Substations (GSS). Existing capacitor banks have steps of 5 Mvar, and therefore, providing an intermediate value is not possible. Also, due to power factor correction at low voltage side and by consumers, the power factor lies in the desired range. This results in capacitor banks not operating to maintain voltage by providing reactive power. Therefore, high cost thermal power plants such as, Kelanitissa Power station, Kerawalapitiya Power station and Sapugaskanda Power station needs to be run to provide for the reactive power requirement.

To arrest the issues from capacitor banks, several dynamic compensation devices are available and the most common are: Static Var Compensators (SVC), Synchronous Condensors, Distribution Static Compensators (DSTATCOMS) and Static Synchronous Compensators (STATCOMS).

By the end of year 2018, the capacity of renewable energy in total is 2009 MW which comprises of a major portion of 1399 MW from large Hydro and including 610 MW of Other Renewable Energy (ORE) [9]. Considering the long term scenario in Sri Lanka, the Other Renewable Energy (ORE) is forecasted to be increased from 1245 MW in 2020 to 4330 MW by year 2039. It is further expected that the total capacity of large hydro would increase by 225 MW in the five years at the beginning. However, after the ongoing large hydro projects hits completion, the level of large hydro in the power system of Sri Lanka will remain standstill.

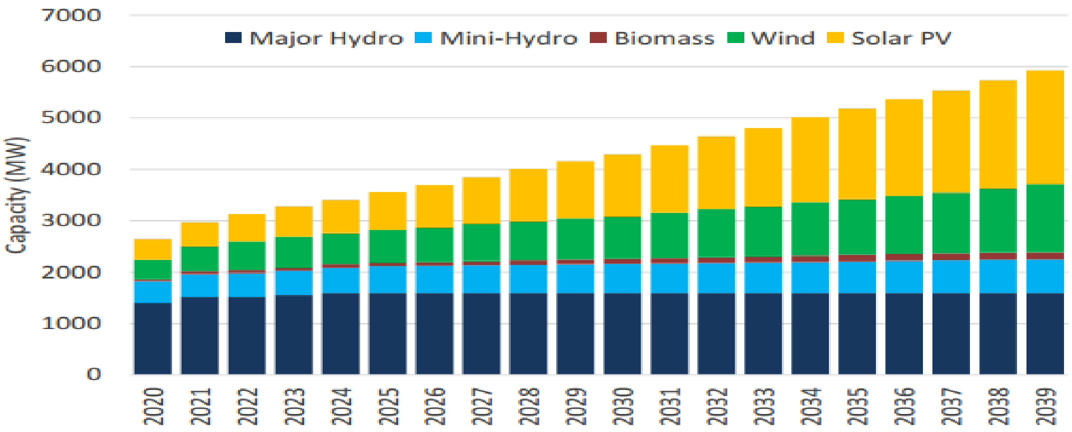


Figure 1.2: Development of Renewable energy capacity in total [9]

In year 2030, Other Renewable Energy (ORE) capacity is expected to rise to 2700MW. It is evident from Figure 1.2 that solar and wind contributes significantly to the ORE capacity increase whereas only a modest advancement is forecasted in Mini-hydro and Biomass energies. Furthermore, after year 2023, the major portion of the other renewables share is mainly by solar power followed by wind power. Other Renewable Energy segment will exceed the major hydro capacity by 2022. In the long term the total ORE capacity is planned to reach 4330 MW by 2039, which comprises 2210 MW of solar and 1323 MW of wind resources.

Table 1.4: Summary of the transmission network development 2018- 2027 [8]

Description	**Year 2018**	**Year 2027**
Grid Substations		
132/33 kV (No./Capacity (MVA)	56/4474	85/7064
220/132/33 kV (No./Capacity [MVA])	4/1600/380	4/1600/380
220/132 kV (No./Capacity (MVA)	4/1510	13/5810
220/33 kV (No./Capacity (MVA)	1/75	13/1722
220/22 kV (No./Capacity (MVA)	-	2/320
132/11 kV (No./Capacity (MVA)	5/369	17/1458
Transmission Lines (Route length)		
220 kV, 2 cct. / (km)	582	1641
220 kV, 1 cct. / (km)	20	40
220 kV UG Cable/ (km)	-	63
132 kV, 4 cct. / (km)	4	7
132 kV, 2 cct. / (km)	1845	2600
132 kV, 1 cct. / (km)	415	210
132 kV UG Cable/ (km)	51	80
400 kV (220kV Operation)/(km)	-	100
Reactive Power Sources		
Breaker Switched Capacitors / (Mvar)	485	987
Static Var System / (Mvar)		+100/-50
Reactors / (Mvar)		150
Investment (Billion LKR)		
Committed Investment (Billion LKR)	**Year 2027**	
Transmission Expansions:	45.2	
Power Plant Connections:	1.3	
Fund Required (Billion LKR)		
Transmission Expansions:	68.7	
Power Plant Connections:	65.1	
Total Investment (Billion LKR)	**180.3**	

A summary of the transmission network development from year 2018 to year 2027 is shown by Table 1.4. It shows the reactive power sources expected to be commissioned by the year 2027 [8].

In the Sri Lankan power system, the first Static Var Compensator (SVC) of +100/-50 Mvar capacity as shown by Table 1.4 is expected to commission in the year 2021.

In Sri Lanka, at present, the grid connected solar inverters are not participating in voltage controlling. That is, only active power is transferred to and from the grid and no reactive power is generated or absorbed.

Therefore, studying the SVC behaviour under Maximum and Minimum solar and wind power penetration is useful for the utility to understand the required reactive power management strategies to cope with the increased penetration of renewables in the future power system of Sri Lanka.

In this study, the conventional synchronous generators in the power system of Sri Lanka in the year 2030 which includes both coal power plants and Liquid Natural Gas (LNG) power plants which participate in injection of reactive power to the power system are to be simulated with the proposed solar power plants in year 2030 considering the case of with and without the SVC in operation under Maximum and Minimum Renewable Energy scenarios. Through voltage stability studies the maximum reactive power that needs to be in the power system to avoid voltage collapse is used to determine the optimal capacity and placement of the SVC in the year 2030 Sri Lankan power system.

1.8 Objectives

The main objective of this study is to determine the optimal operating conditions of Static Var Compensator (SVC) for voltage regulation by analysing the voltage stability impacts considering the increased penetration of large scale and distributed solar plants connected to the Sri Lankan Power system.

1.9 Outline of the thesis

This thesis is divided into six chapters. Chapter 1 provides the background and the objectives of the study focusing on the importance of power system stability in the Sri Lankan power system. Furthermore, it highlights the motivation for this study. Chapter 2 consists of a detailed literature survey on voltage stability studies and reactive power compensation devices. Chapter 3 provides a detailed methodology which includes the validation of the simulation model, the initialization of system scenarios and simulation of the Sri Lankan power system in Power System Simulator for Engineers (PSS/E) for year 2030 with and without the Static Var Compensator (SVC) under maximum and minimum renewable energy scenarios. Chapter 4 provides a detailed analysis of the selection of the optimal location and operating condition of the SVC under maximum and minimum renewable energy scenarios. The conclusion and recommendations of the study are found in Chapter 5 followed by the reference list and appendices.

CHAPTER 2

2 Reactive power compensation devices

2.1 Importance of Voltage stability and Reactive power compensation

Voltage stability improvement in a power system is an important consideration in the power system operation when involving a heavily stressed system with a large amount of real and reactive power demand and also under low voltage condition. The electricity demand increases continuously from time to time. This increase should be monitored and observed in the existing electricity transmission network to prevent or control some transmission lines located on the particular paths from becoming overloaded [10]. Due to the overloaded conditions of the transmission lines, the system will have to be driven close to or even beyond their power transfer capacities.

Reactive power is an expression used for the unreal power from inductive loads like motor or capacitive loads, which normally is not so much common. In order to maintain the most advantageous circumstances for a power system from an engineering and economical point of view, it is very important to select and always apply the most advantageous reactive power compensation technology in an electrical power system [11], [12].

If the reactive power needs of a power system are not planned properly, it will lead to voltage instability resulting in voltage collapse. Voltage collapse is a phenomenon where the voltage collapses at one or more busses due to lack of reactive power which is characterized by a decrease in voltage even with an increase in reactive power injection and also due to the voltage drop in connected transmission lines due to large power flows through them [13].

The concept of reactive power compensation embraces a wide and diverse field of both system and customer problems, especially related with power quality issues. This is because most of the power quality problems can be attenuated or solved with sufficient control of reactive power [14]. Reactive power compensation equipment used in transmission systems also improves the stability of the alternating current (a.c.) system by increasing the maximum active power that can be transmitted. It also helps to maintain a substantially flat voltage profile at all levels of power transmission, it improves the performance of High-Voltage Direct Current (HVDC) conversion terminal, increases transmission efficiency, controls steady-state and temporary overvoltages in the power system [15]and can also avoid disastrous blackouts [16].

Considering traditional reactive power compensation equipment, such as fixed or mechanically switched shunt, series capacitors and reactors are used to solve the issues mentioned in [15-16]. Shunt capacitors were first employed in 1914 for power factor correction [17]. The capacitors draws leading current which compensates lagging current been drawn by loads. When loads are fluctuating, reactive power also varies widely, so using fixed shunt capacitors will lead to over or under compensation. For variable reactive power compensation, switched capacitors can be used. But, switching has to be done through mechanical devices such as relays and circuit breakers so they require frequent maintenance and also generate high inrush currents. Also, these conventional devices have the major disadvantage of having slow response and this leads to unreliable operation. The use of Static Var Compensator (SVC) has a distinct advantage over series compensators. A SVC is commonly connected to a particular bus and not directly to a single transmission line so it prevents voltage sag of a bus with multiple lines so the total cost maybe significantly lowered.

A synchronous condenser is a synchronous device that is used to generate reactive power which leads the real power by 90 degrees in phase [18]. It is a piece of equipment that is similar to a synchronous motor, whose shaft is not linked to anything but spins freely without any constraint. The field of the synchronous condenser is regulated by using a voltage regulator to change the grid voltage or to enhance the power factor by controlling the reactive power. The quantity of reactive power from a synchronous condenser can be steadily regulated. However, reactive power from a synchronous condenser can build-up reactive current as the voltage reduces.

Synchronous condensers were once extensively utilized as a means of supplying reactive power compensation before the introduction of power electronic based devices. A number of synchronous condensers were used in electrical power systems beginning in the late 1920’s to the end of late 1970’s. However, synchronous condensers are infrequently used today because they need considerable foundations and a significant quantity of starting and protective gadgets. They also represent a part in short-circuit current, and they cannot be adjusted fast enough to balance speedy load changes. Furthermore, their losses are much higher than those related with static compensators, and the cost is much higher when compared with static compensators [19].

Traditionally, rotating synchronous condensers and fixed or mechanically switched capacitors or inductors have been used for reactive power compensation. However, in recent years, Static Var Compensators (SVC) employing Thyristor-Switched Capacitors (TSC's) and Thyristor-Controlled Reactors (TCR's) to provide or absorb the required reactive power has been developed extensively [19].

2.2 Introduction to Flexible Alternating Current Transmission Systems (FACTS) devices

FACTS (Flexible Alternating Current Transmission systems) are alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and to increase power transfer capability [20].

According to reference [21] , the major advantages of using FACTS are:

- to improve the power lines transmission capabilities to improve power flow control
- static and dynamic stability enhancement
- to maintain secure interconnections between neighbouring utilities

The main disadvantages of using FACTS are:

- very high start-up cost of these devices
- economic requirements.

FACTS devices have the ability to control one or several key parameters in power transmission, such as current, voltage, active and reactive power, frequency or phase angle. In recent decades, due to the increasing demand of electricity in different countries, the need to build new transmission lines, electricity posts and proposals to increase the capacity of transmission lines has greatly increased. But the construction of new electricity transmission lines requires a huge capital investment. As a result, finding effective solutions to reduce the costs for electric companies has been a great challenge. The main objectives of FACTS devices are to increase the useable transmission capacity of lines and to control the power flow over designated transmission routes [22].

There are different types of FACTS devices such as Static Var Compensator (SVC); Thyristor Controlled Series Compensator (TCSC); High Voltage Direct Current back to back (HVDC B2B); Unified Power Flow Controller (UPFC); Static Synchronous Series Compensator (SSSC); Static Synchronous Compensator (STATCOM); and Dynamic Power Flow controller (DPFC) [23,24].

SVC can provide a fast-acting reactive support inside a power system. The SVC can be operated as both inductive and capacitive compensator which can control bus voltage by absorbing or injecting reactive power [25]. Static Var Compensator (SVC) is able to increase the power transmission capability from generators to loads and is widely used due to its low cost and high performance.

2.3 Use of Flexible Alternating Current Transmission Systems (FACTS) devices in renewable energy applications

The emerging use of renewable and Distributed Generation (DG) has accelerated and expanded the role of power electronic devices for efficient electrical utilization and enhanced security and reliability of the electric utility grid [26]. Most of the current Photovoltaic-based inverters don’t have any capabilities for providing any type of reactive power or voltage support. Photovoltaic systems, usually must work at unity power factor and the utility is responsible for reactive power requirements [27].

Recently, FACTS devices and smart control strategies have been gaining a more prominent role in energy generation from renewable sources such as solar, wind, and wave technology [28]. Significant research has been focused on maximizing the energy extraction from renewable energy sources. The results of the implementation of FACTS devices in smart grids with renewable systems are encouraging [29, 30].

2.4 Static Var Compensators

SVC is a shunt FACTS device, used extensively for reactive power compensation purposes. SVC has also been used for power oscillation damping, flicker eliminations in arc furnaces, balancing of load in individual phases, to reduce temporary overvoltage, to damp sub-synchronous oscillations and for improving transient stability margins of the network [31].

The primary objective of applying a Static Var Compensator in a power system is to increase the power transmission capability in a given transmission network from the generators to the loads. Since Static Var Compensators cannot generate or absorb real power, the power transmission of the system is affected indirectly by voltage control. That is the reactive output power (capacitive or inductive) of the compensator is varied to control the voltage at given terminals of the transmission network so as to maintain the desired power flow under possible system disturbances and contingencies [32].

In the 1970's, the first generation of FACTS devices, known as Static Var Compensator (SVC)was introduced. A SVC is a shunt-connected absorber capable of exchanging capacitive and inductive power to control specific parameters of the electrical power system [33].

In 1974, the first SVC was installed in Nebraska by General Electric. Upto now, more than 800 SVC's with power ratings ranging from 60 to 600 Mvar have been installed by electrical utilities. ASEA Brown Boveri (ABB) has provided about 55% of the SVC market, with 3% in Asian countries.

Northern States Power Company (NSP) is operating an SVC in the 500 kV power transmission networks of Winnipeg and Minnesota to increase power interchange capability on the existing transmission network [34]. With the SVC in operation, the power transmission capability has been increased to about 200 MW. The option of using a SVC has been preferred over the solution construction a new transmission line.

A total system failure occurred in the Sri Lankan Transmission Licensee's network, the Ceylon Electricity Board (CEB), on the 27th of September 2015 at 23:57. It is reported that the restoration of the power system took more than four hours. This sort of unexpected major failure in the transmission system had a significant negative impact on the continuity of power supply in the country. The installation of dynamic reactive power devices such as SVC as an option to improve the power system dynamic response of the Sri Lankan Power System is recommended [35]A SVC has the ability of continuous and rapid control of reactive power and voltage. SVC's have the ability to enhance different aspects of transmission system performance including:

- control of temporary overvoltages
- prevention of voltage collapse
- enhancement of transient stability
- enhancement of damping of system oscillation.

2.4.1 SVC topologies

The SVC topologies are:

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

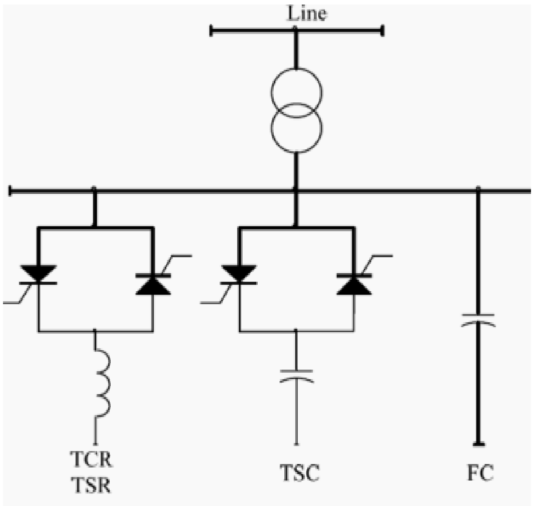


Figure 2.1: SVC combinations

The popular configuration of SVC is a parallel combination of a fixed capacitor (FC) with a Thyristor-Controlled Reactor (TCR) as shown in Figure 2.1. In many SVC installations, a shunt connected fixed capacitance (FC) is used to inject reactive power to the grid as this would provide a cheaper solution. In comparison to TSC, FC topology would not need the expensive thyristor valves for switching and hence requires simpler control equipment [36].

Thyristor-Controlled Reactor (TCR): TCR is defined as a shunt-linked thyristor-controlled inductor whose effective reactance is regulated in a continuous manner by partial conduction regulation of the thyristor valve. A thyristor controlled reactor (TCR) is one of the traditional SVC used in the field of power quality enhancement. It can draw-up sustained reactive power at the primary frequency of the power system network, but it delivers appreciable odd harmonics which could cause many unpleasant consequences, such as; over currents, extra losses, and noises to telecommunication systems [37].

Thyristor-Switched Capacitor (TSC): TSC is defined as a shunt-linked, thyristor-switched capacitor whose effective reactance is differed in a stepwise way by full-conduction or zero-conduction operation of the thyristor valve. It has similar composition and same operational mode as Thyristor Switched Reactor, but the reactor is substituted by a capacitor. The reactance can only be either fully connected or fully disconnected due to the features of capacitor [37].

2.4.2 Basic operation of the Static Var Compensator (SVC)

The Static Var Compensator (SVC) is a device of the Flexible Alternating Current Transmission Systems (FACTS) family which uses power electronics to control power flow on power grids. The SVC regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power system.

When system voltage is low, the SVC generates reactive power (SVC capacitive). When system voltage is high, it absorbs reactive power (SVC inductive). The variation of reactive power is performed by switching of three-phase capacitor banks and inductor banks connected on the secondary side of a coupling transformer. Each capacitor bank is switched on and off by thyristor switches (Thyristor Switched

Capacitor or TSC). Reactors are either switched on-off (Thyristor Switched Reactor or TSR) or phase-controlled (Thyristor Controlled Reactor or TCR). [38]

For three system characteristics, Figure 2.2 shows three values of source voltage. In the normal operating condition, the voltage is at point A (V_0).

Decrease of system Load: Without SVC, when system voltage increases due to a decrease in system load level, V_0 will increase to V_1. To improve the voltage profile, reactive power needs to be absorbed which is done by the SVC. With SVC, by drawing inductive current I_3, the operating point moves to B holding the voltage at V_3.Thus the voltage profile is improved by SVC to V_3 by drawing the current I_4. If there was no SVC then the voltage will be at V_1.

Increase in system load: Without SVC, when system voltage decreases due to an increase in system load level, V_0 will increase to $V_{2.}$ But with the SVC, the voltage will be held at V_4 instead of V_2. In-order to maintain voltage, reactive power has to be supplied, which could be accomplished by using SVC.

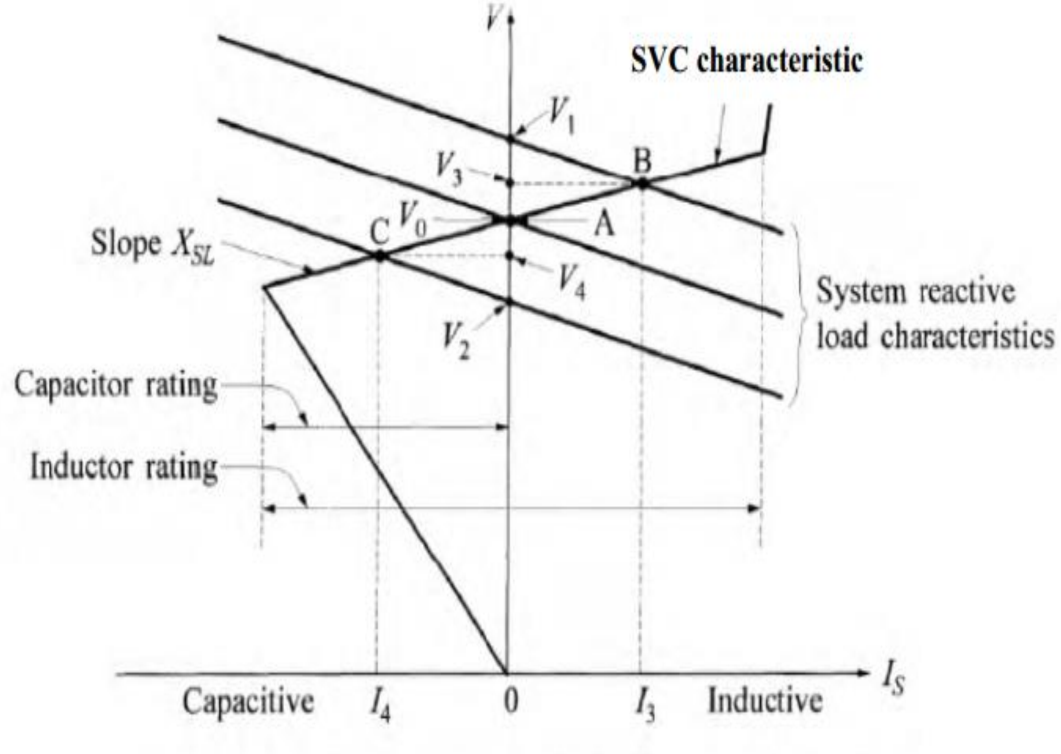


Figure 2.2: Graphical solution of SVC operating point for given system conditions [2]

CHAPTER 3

3 Methodology, Simulation and Analysis

3.1 Modelling of the Components in PSS/E

Steady state analysis and dynamic analysis can be both performed by using the PSS/E software. The dynamic behaviour of all the components in a PSS/E model can be studied during a disturbance and post disturbance conditions. PSS/E comes with hundreds of built-in load models, generation models, tap changers models and reactive compensation models. The models should be selected to simulate as much as possible in detail of the real scenario.

3.2 PSS/E Models used for the study

The following models were used for the study. [1], [40]

- Synchronous generators (GENROU or GENSAL models)
- Excitation systems (ESAC1A, ESST1A,SCRX, SEXS models)
- Turbine governors (HYGOV, TGOV,GAST model)
- Transformer OLTC (OLTC1T or OLTC3T model).
- Complex load model (CLODAL model)
- Under frequency Load Shedding Model (LDSHBL or DLSHBL model)

A generator has two parts, that is, stator and the rotor. The stator consists of the armature winding and the rotor consists of the field winding. The mechanical rotational energy of the rotor is converted into electrical energy of the stator. Generators can be classified into two main types; namely synchronous generators and asynchronous generators.

In this study, the power system is modelled using synchronous generators. The two types are round rotor and salient pole type each having different properties. In thermal plants the round rotor machines are used and it has higher speed of rotation of the rotor whereas salient pole machines are often seen in hydro power plants.

The synchronous generator model used for load flow studies is shown in Figure 3.1.

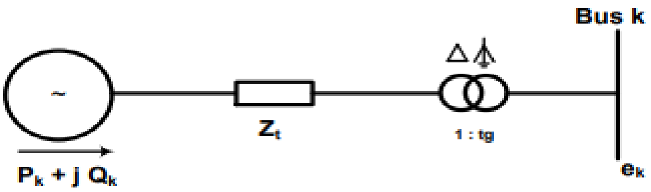


Figure 3.1: Generator model used for load flow studies

It consists of a voltage source behind a step up transformer. The generator parameters are specified in per unit on a MVA base as given in Table 3.1 The transformer input data is given in Table 3.2.

Table 3.1: Machine data for generator

Pgen	Dispatched power / specified output power in MW
Pmax	Maximum active power in MW
Pmin	Minimum active power in MW
Qmax	Maximum reactive power in MVAR
Qmin	Minimum reactive power in MVAR
MVA base	Complex power – machine MVA
Z source	Generator sub-transient unsaturated positive sequence impedance
Z positive	Generator sub-transient saturated positive sequence impedance per unit.
Z negative	Generator sub-transient saturated negative sequence impedance per unit
Z zero	Generator sub-transient saturated zero sequence impedance per unit

Table 3.2: Transformer data

Z_{TR} positive	Transformer positive sequence impedance in p.u. based on 100 MVA
Z_{TR} negative	Transformer negative sequence impedance in p.u. based on 100 MVA
Z_{TR} zero	Transformer zero sequence impedance in p.u. based on 100 MVA
Tap ratio	Transformer tap position
Connection Code	Transformer connection code (Y-Y, Y-delta,….etc.)

For dynamic simulation in PSS/E, the generator has to be converted into a Norton equivalent circuit as shown by Figure 3.2.

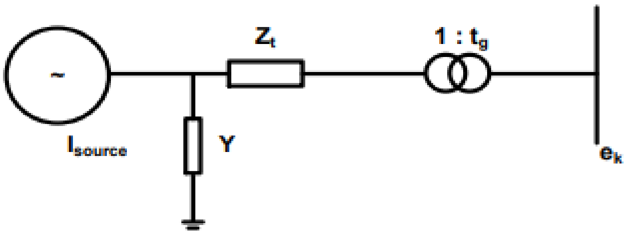


Figure 3.2: Generator model used for dynamic simulation

The current source is represented by “I source” and it is the Norton equivalent current. “Y” is the Norton equivalent admittance and “Y=1/source”. The unsaturated sub- transient reactance is represented by the Z source. δ is the phase angle of the Norton equivalent current. Z_t is the step up transformer impedance and t_g is its tap ratio.

Table 3.3: PSS/E GENROU and GENSAL parameters

T’do	d-axis transient time constant (s)
T”do	d-axis subtransient time constant (s)
T’qo	q-axis transient time constant (s)
T”qo	q-axis subtransient time constant (s)
H	Inertia constant (s)
D	Damping factor (pu)
Xd	d-axis synchronous reactance (pu)
Xq	q-axis synchronous reactance (pu)
X’d	d-axis transient reactance (pu)
X’q	q-axis transient reactance (pu)
X”d = X”q	d- & q-axis sub transient reactance (pu)
X1	Stator leakage reactance (pu)
S(1.0)	Saturation factor at 1 pu flux
S(2.0)	Saturation factor at 1.2 pu flux

.

The thermal generators are normally round rotor type synchronous generators. In PSS/E, the round rotor type generators are denoted by “GENROU” as shown by Figure 3.3 hence it was used to represent thermal generators. The hydro generators are generally salient pole type machines. In PSS/E, the salient pole machines are represented by model “GENSAL” as shown in Figure 3.4 and hence used to represent the hydro generators in the study.

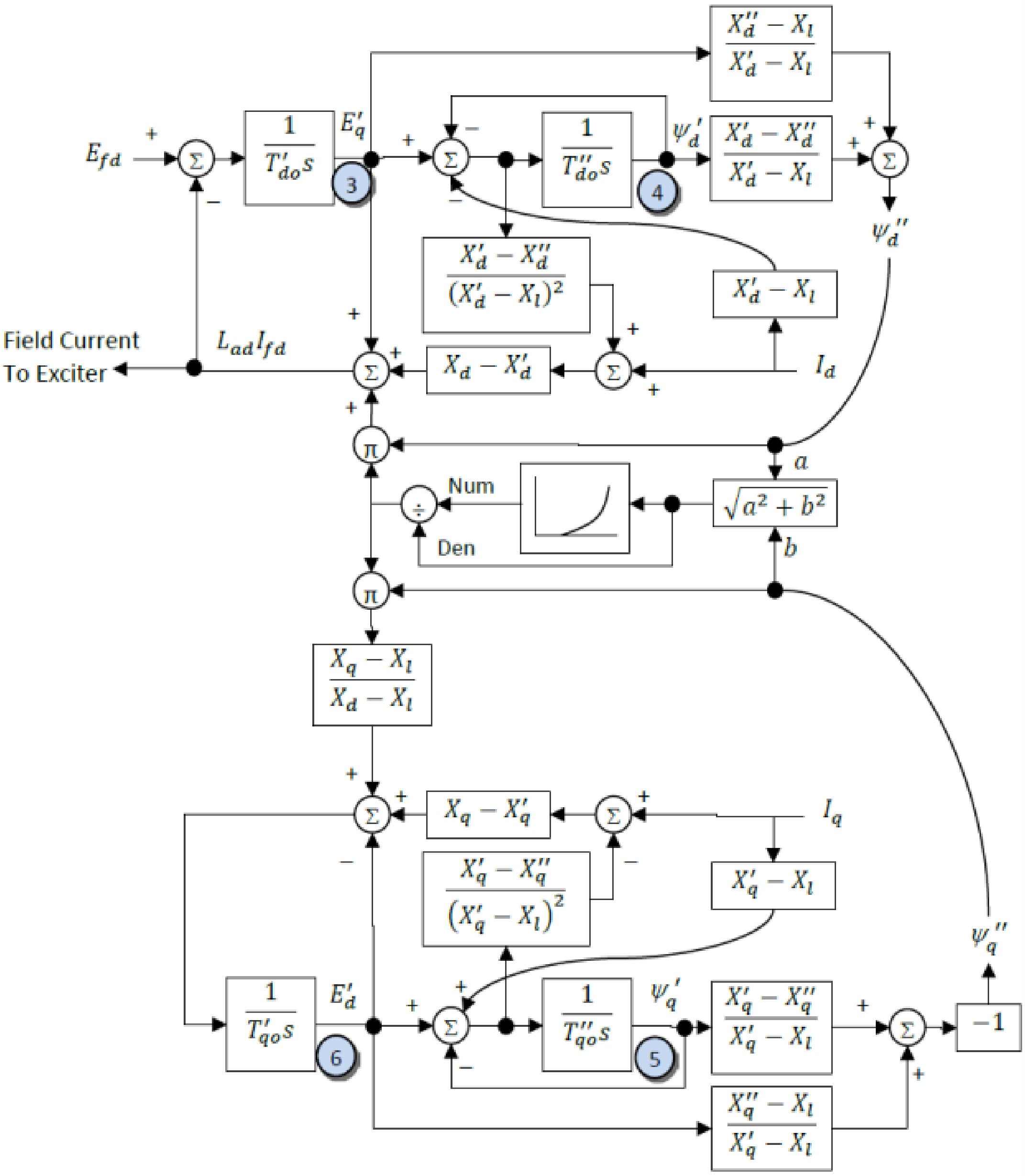


Figure 3.3: PSS/E GENROU- Round rotor generator model

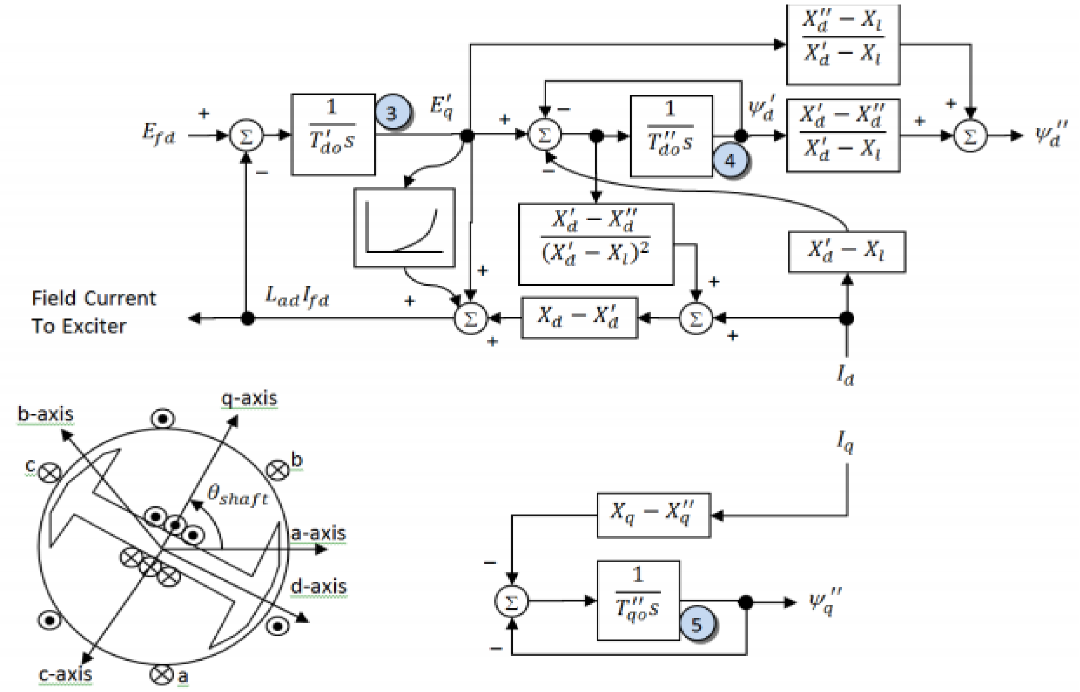


Figure 3.4: PSS/E GENROU- Salient pole generator model

A turbine governor performs the function of speed/load control to schedule real power output. In PSS/E, the model “HYGOV” as shown in Figure 3.5 represents the hydro turbine governors which model the penstock with unrestricted head race and tail race, but no surge tank. The speed/ load control function provides a feedback speed error to control the gate position. The parameters of the HYGOV model are provided in Table 3.4.

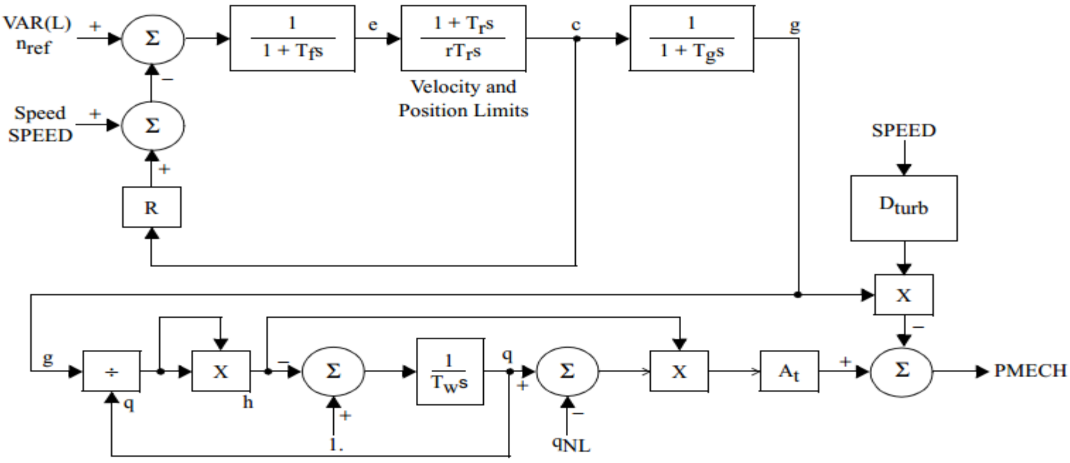


Figure 3.5: PSS/E HYGOV- Hydro Turbine-Governor model

Table 3.4: PSS/E HYGOV parameters

Parameters
R :Permanent droop
r: Temporary droop
T_r : Governor time constant
T_f :Filter time constant
T_g: Servo time constant
$\pm V_{ELM}$:Gate velocity limit
G_{MAX} : Maximum gate limit
G_{MIN}: Minimum gate limit
T_W(>0) : Water time constant
A_t :Turbine gain
D_{turb} :Turbine damping
q_{NL} :No-load flow

The model “GAST” in Figure 3.6 is the gas turbine-governor system which “represents the principal dynamic characteristics of industrial gas turbines driving generators connected to electric power systems.” The GAST model parameters are shown in Table3.5. The input signal to the GAST governor is the rotor speed.

Table 3.5:PSS/E GAST parameters

Parameters
T_1: governor time constant
T_2: combustion chamber time constant
T_3: load limit time constant (exhaust gas measurement time)
K_T: load limit feedback gain
R: droop; reciprocal of the proportional gain
D_{turb}: speed damping coefficient of gas turbine rotor
V_{MAX}: operational control high limit on fuel valve opening
V_{MIN}: low output control limit on fuel valve opening

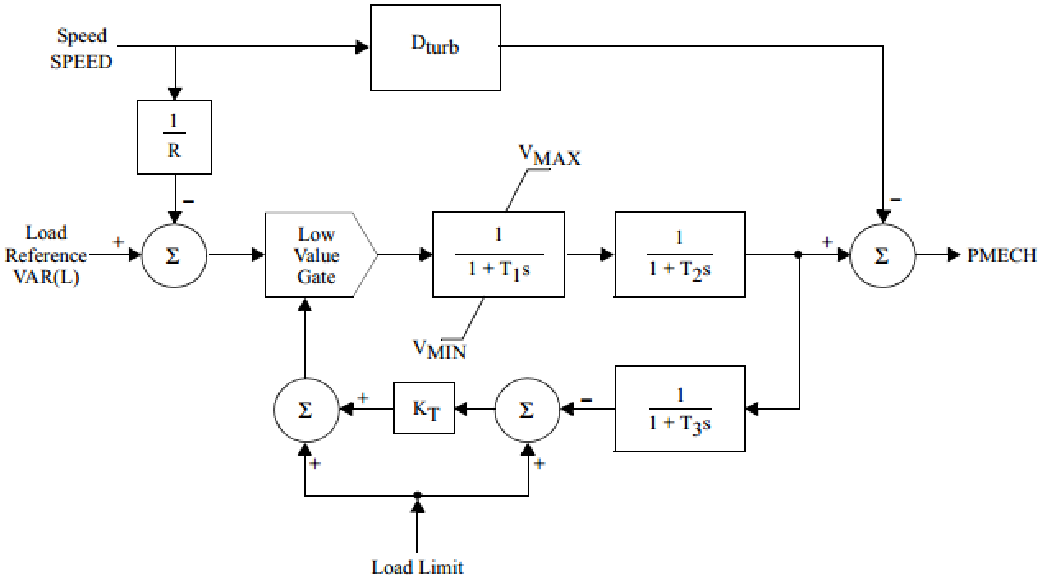


Figure 3.6: PSS/E GAST- Gas turbine governor model

The steam-turbine governor (TGOV) used is given in Figure 3.7 and the parameters are listed in Table 3.6. The Governor action, re-heater time constant, and the ratio of high-pressure turbine are recognized in this model.

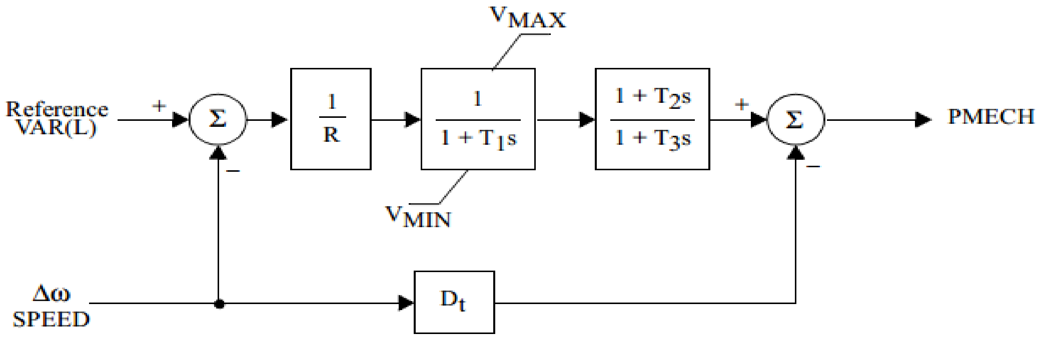


Figure 3.7: PSS/E TGOV- Steam Turbine-Governor model

Table 3.6: PSS/E TGOV parameters

Parameters
T_1: governor time constant
T_2/T_3: high pressure fraction
T_3: reheater time constant.
D_t: speed damping coefficient of steam turbine rotor
V_{MAX}: operational control high limit on fuel valve opening
V_{MIN}: low output control limit on fuel valve opening

Synchronous machines depend on excitation control which is based on voltage feedback to schedule reactive power output. The excitation systems that were used in this study are “ESAC1A”, “ESST1A”, “SCRX”, “SEXS”. The “ESAC1A” is the IEEE Type AC1A Excitation system as shown in Figure 3.8. It is a field controlled alternator excitation system with non-controlled rectifiers that is brushless excitation system. A lower limit of zero is applied on the exciter voltage output. A pilot exciter gives the exciter field.

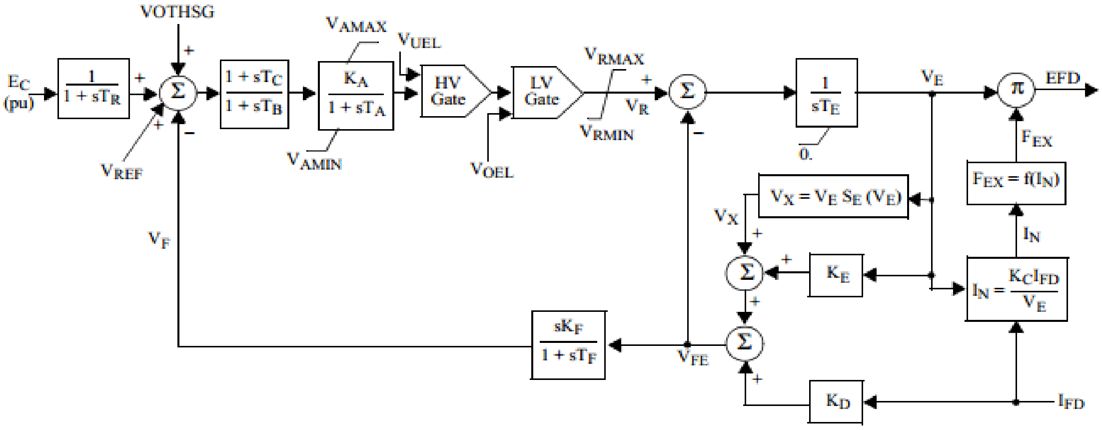


Figure 3.8: PSS/E ESAC1A- IEEE Type AC1A Excitation System

“ESST1A” is the IEEE Type ST1A Excitation System as shown in Figure 3.9. A potential source controlled rectifier system is represented by the ST1A rectifier exciter system. A transformer supplies the excitation power from the generator.

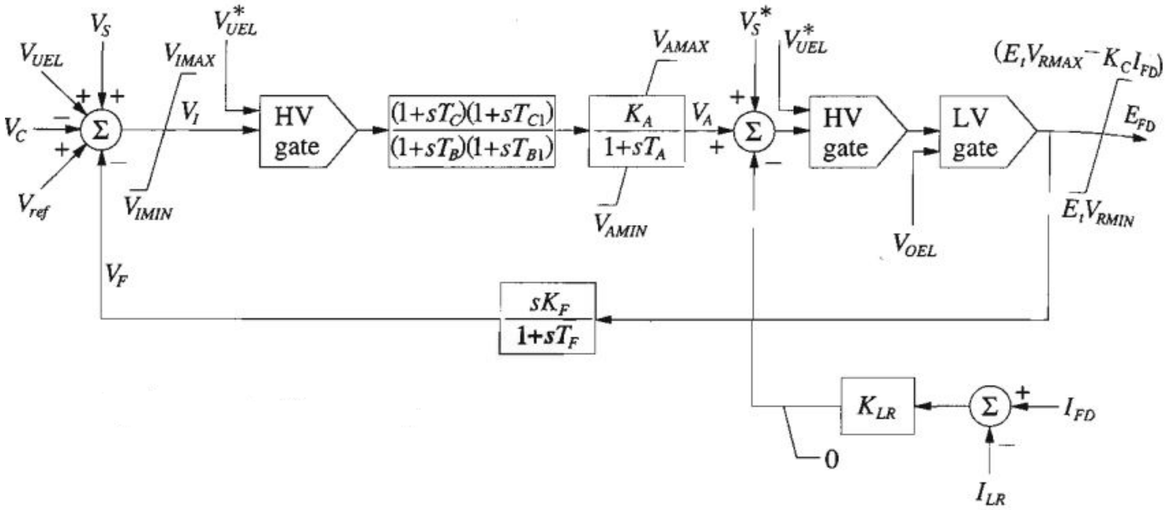


Figure 3.9: PSS/E ESST1A- IEEE Type ST1A Excitation System

Modern generators are equipped with static exciters, and these are most commonly bus-fed, meaning they are powered by the generator terminal voltage so the output will be lower during the fault period. The corresponding PSS/E “SCRX” model shown in Figure 3.10 represents bus-fed fed static exciters.

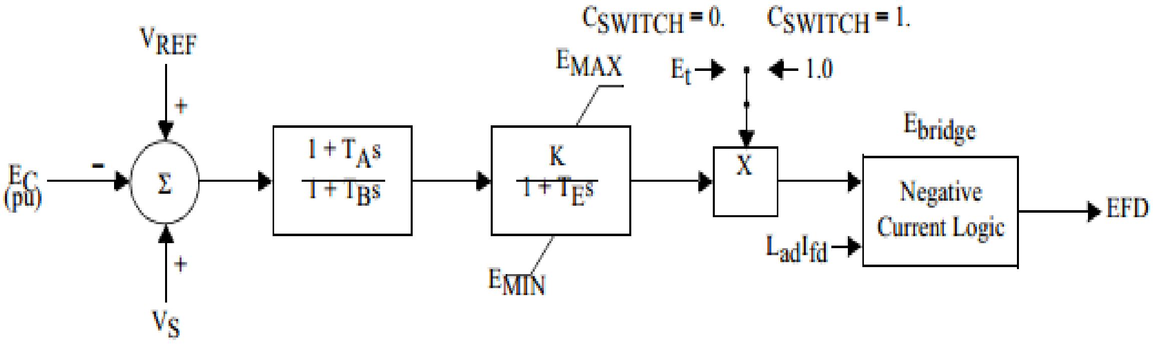


Figure 3.10: PSS/E SCRX- Bus fed static exciter

“SEXS” model is the Simplified Excitation System model as shown by Figure 3.11. Excitation time constant T_E, gain K, over-excitation limit E_{max} set by generator field winding thermal constraint, and under-excitation limit E_{min} set by the stability constraint or the stator core end-region heating limit. The compensator provides a transient gain reduction of T_A/T_B, which allows satisfactory performance on the full frequency spectrum.

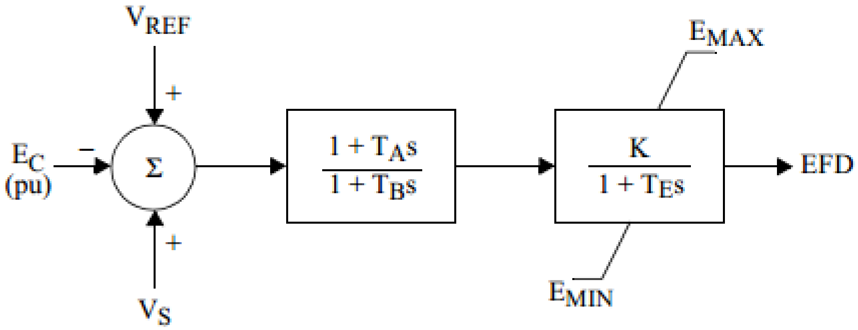


Figure 3.11: PSS/E SEXS- Simplified Excitation System model

The Complex load model (CLODAL model) is used along with ZIP load model (Constant power/current/admittance) for this study as shown by Table 3.7. The dynamics of saturated transformers, discharge lighting and induction motors (large and small) are not represented by the ZIP load model as the ZIP model assumes a static correlation between power of the load and bus voltage so CLODAL model is used.

Table 3.7: Load model [8]

Load Type	**Load Category (%)**		
	Industrial Loads	**Commercial Loads**	**Domestic Loads**
Large motor	5	1	0
Small motor	25	30	10
Transformer exciting current	1	1	1
Discharge lighting	10	10	20
Constant power	30	30	30
Constant Current & Impedance Load	29	28	39
Total	100	100	100

3.3 Analysis of CEB Sri Lankan transmission network model

The proposed CEB Sri Lankan transmission network model of year 2030 was analyzed in PSS/E software to study the performance of SVC in the future transmission network. The year 2030 transmission system which was modelled and simulated in PSS/E is attached in Appendix 1.

3.4 Steady state analysis

Initially, the network model was studied under steady state condition to observe the performance of the year 2030 transmission network.

The simulation model of the power system was initialized. Load flow analysis using Newton-Raphson method was used for the steady state analysis.

From steady state analysis, considering the steady state voltages of the 220 kV buses the weakest bus of the system was identified.

3.5 Contingency analysis

Contingency studies were done to determine the capability of the transmission network to deliver power from generating stations to load centres without violating the operating limits of equipment during the loss of continuity of supply or widespread failure.

The performance of the transmission system under two contingency situations was taken into consideration. The contingency levels analysed were n-1 contingency and n-2 contingency and is as follows:

- n-1: the outage of any one element of the transmission system at a time was observed

- n-2:outage of any two elements of the transmission system at a time was observed

3.6 Voltage criteria

The voltage criterion is defined as the allowable voltage deviation at any live bus bar of the network under normal operating conditions and during a contingency condition. The allowable voltage variation limits for the transmission level voltages of 220 kV and 132 kV are given in Table 3.8.

Table 3.8: Allowable voltage variations at 220 kV and 132 kV

Bus bar voltage	**Allowable voltage variation (%)**	
	Normal operating condition	**Single contingency condition**
220 kV	±5%	±10%
132 kV	±10%	±10%

3.7 Under Frequency Load Shedding scheme of Sri Lanka

Table 3.9: Under frequency Load shedding scheme of CEB as of December 2014[39]

Stage	**Load Shedding Criteria**	**Load shed per Stage**	**Reconnection Criteria**	**Reconnecting Load**
I	48.75 Hz + 100 ms	7.50%		
II	48.50 Hz + 500 ms	7.50%		
III	48.25 Hz + 500 ms	11%	51 Hz + 500 ms AND df/dt> 0.2 Hz/s	2%
IV	48.00 Hz + 500 ms	11%	51 Hz + 500 ms AND df/dt> 0.2 Hz/s	2%
V	47.5 Hz instantaneous	5.50%		
	47.5 Hz instantaneous OR 49 Hz AND df/dt < -0.85 Hz/s +100ms	4.50%		
df/dt	49 Hz AND df/dt < -0.85 Hz/s +100ms	13.5% and 4.5% embedded in V		
Total	df/dt	18% (4.5% embedded with V)		
	Frequency only	42.50%		

The Under Frequency Load shedding (UFLS) scheme of CEB implemented as of December 2014 and currently used for system studies are shown by Table 3.9. The normal limits of frequency are between 49.5 Hz and 50.5 Hz. The nominal frequency in Sri Lanka is 50 Hz. The load shedding scheme is activated by the value of (df/dt), which is the rate of change of the frequency.

In stage I, when the df/dt is lower than 0.85 Hz/s and the frequency is lower than 48.75 Hz for duration of 100 ms, 7.5 % of the total load is shed. The second stage of load shedding happens if there is no rise in the frequency after stage 1 load has shed. In Stage II, if the frequency is further dropped to 48.5 Hz, and if the frequency stays below for a period of 500 ms there will be a further 7.5 % of the total load shedded. An additional 11 % of the total load is shed in stage III and stage IV at the frequencies of 48.25 Hz and 48 Hz respectively following that the frequency remains for more than 500 ms without building up. In the Stage V of the load shedding scheme, 10% of the total load will be shed instantaneously at a frequency of 47.5 Hz. The total load shed will be now 47 %. The df/dt further increases in the event of a disturbance, that is, maybe the loss of a large generator.

In the case of a contingency situation, with reference to the existing load shedding scheme, 18 % of the total load will be shed if the rate of change of frequency is -0.85 Hz/s and the frequency drops to a value of 49 Hz [39].

3.8 Generation and Loading scenarios

The generation and load mix considered for the purpose of this study is given in Table 3.10.

The CEB transmission planning division considers the generation and loading scenarios given in Table 3.11 for system studies.

Table 3.10: Generation Mix considered for the study

Scenario	**Load**	**Generation Mix**					
		Wind	**Mini-Hydro**	**Bio-Mass**	**Solar**	**Major Hydro**	**Thermal**
Minimum Renewable Energy Night Peak (Min RE NP)	Night Peak	0%	10%	20%	0%	Minimum	Maximum
Minimum Renewable Energy Day Peak (Min RE DP)	Day Peak	0%	10%	20%	10%	Minimum	Maximum
Maximum Renewable Energy Day Peak (Max RE DP)	Day Peak	100%	100%	100%	100%	Maximum	Balance

Table 3.11: Generation and load mix

Scenario	**Load**	**Generation Mix**					
		Wind	**Mini-Hydro**	**Bio-Mass**	**Solar**	**Major Hydro**	**Thermal**
Thermal Maximum Night Peak (TMNP)	Night Peak	50%	20%	100%	0%	Balance	Maximum
Thermal Maximum Day Peak (TMDP)	Day Peak	50%	20%	100%	100%	Balance	Maximum
Hydro Maximum Night Peak (HMNP)	Night Peak	100%	100%	60%	0%	Max	Balance
Thermal Maximum Day Peak HMDP	Day Peak	100%	100%	60%	50%	Max	Balance
Thermal Maximum Off Peak (TMOP)	Off Peak	50%	20%	0%	0%	Partial	Partial
Hydro Maximum Off Peak (HMOP)	Off Peak	100%	100%	0%	0%	Partial	Partial
Minimum Renewable Rnergy Night peak (Min RE NP)	Night Peak	0%	10%	20%	0%	Minimum	Maximum
Minimum Renewable Energy Day peak (Min RE DP)	Day Peak	0%	10%	20%	10%	Minimum	Maximum
Maximum Renewable Energy Day peak (Max RE DP)	Day Peak	100%	100%	100%	100%	Maximum	Balance

The total generation considering the total thermal, major hydro, solar, wind, biomass, mini-hydro in the day peak and night peak which was used for the simulation scenarios are given by Table 3.12.

Table 3.12: Total generation for each of the selected study scenarios

Maximum Renewable Energy Day Peak (Max RE DP)-Year 2030		**Minimum Renewable Energy Day Peak (Min RE DP)-Year 2030**	**Minimum Renewable Energy Night Peak (Min RE NP)-Year 2030**
Source of energy	**Total generation (MW)**	**Total generation (MW)**	**Total generation (MW)**
Thermal	601	3909	3725
Major hydro	2046	707	914
Wind	980	0	0
Dendro	94	89	19
Solar	1019	0	0
Mini hydro	579	559	56
Total	**5319**	**4791**	**4714**

3.9 Proposed Simulation Scenarios

In this study, the SVC capacity and the location were selected considering the voltage stability limits of selected Grid Substations (GSS) based on the maximum solar penetration to the Sri Lankan power system in year 2030.

Therefore, to determine optimal location of the SVC and its capacity, the three simulation study scenarios consisting of Minimum Renewable energy (Min RE) and Maximum Renewable energy (Max RE) were only considered for this study. That is, high solar and wind condition compared with low solar and wind condition.

The detailed power system studies were performed under the two generation scenarios: Maximum Renewable Energy (Max RE), Minimum Renewable Energy (Min RE) and the two loading conditions; Day Peak (DP) (11.00 hours), Night Peak (NP) (19.30 hours) as shown through the block diagram illustrated by Figure 3.12. In order to analyse the behaviour of integrating a SVC along with large scale solar integration the Day Peak and Night Peak was only selected. Because in the off peak, there is no solar power although wind power is present.

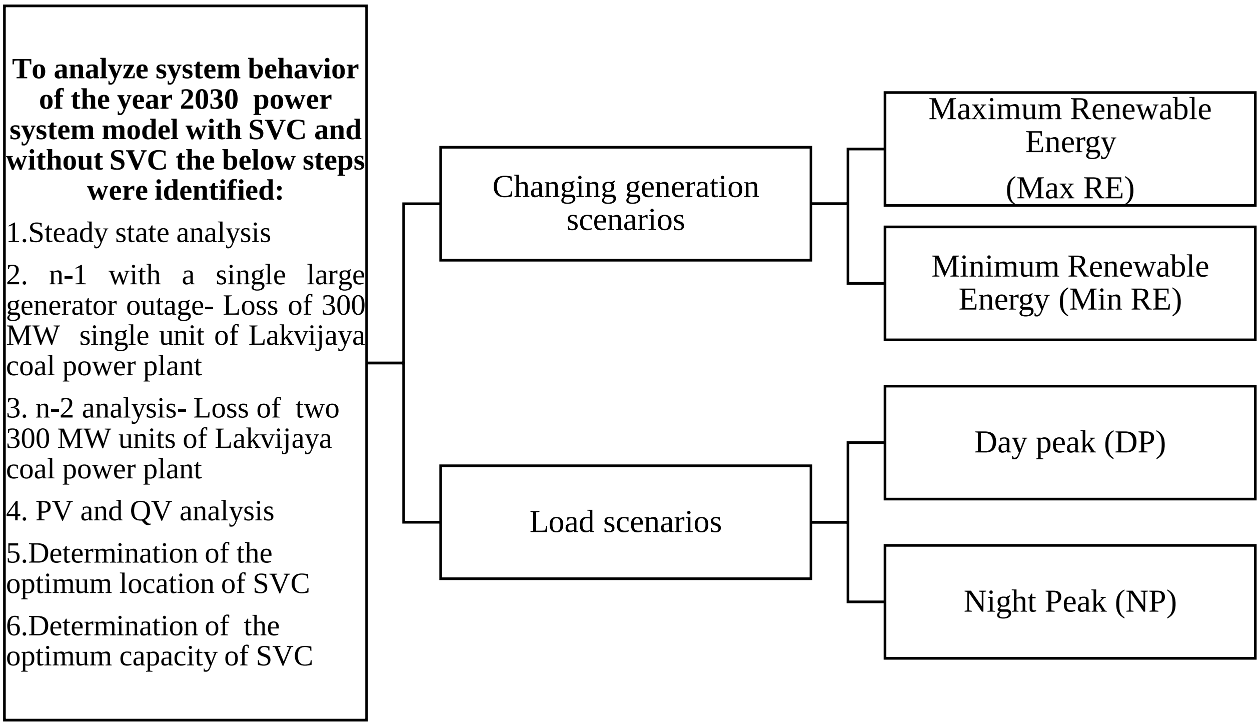


Figure 3.12: Generation and Loading scenarios considered for the study

3.10 Verification of the Simulation model

The tripping of one thermal unit of West Coast Power (WCP) Private Limited on 17.07.2019 was simulated in PSS/E on the 2019 transmission network of Sri Lanka. The frequency controlling machine was unit 1 of the Kotmale power station.

The data which was available at the time the tripping event happened was used for the verification of the power system is given in Table 3.13. The pre-fault generation and demand data that has been fed into the simulation system is given by Table 3.14.

Table 3.13: Pre-fault data of frequency controlling machine

Frequency controlling Machine	**Generated Power (MW)**	**Maximum Power output (MW)**
Kotmale power station **Generator unit 2**	55	67

Table 3.14: Pre-fault generation and demand data

Pre fault data	**Power in MW**
Generation	2337
Demand	1949

PSS/E results showed similar behavior with small deviations in comparison to the actual behavior of the frequency response drawn using the BEN 6000 Digital Fault Recorder data installed at 220 kV Kelanitissa Grid Substation.

The actual variation vs PSS/E variation of the system frequency during the failure of West Coast Power (WCP) on 17.07.19 is shown by Figure 3.13. The graph shows the frequency response plotted against the time duration.

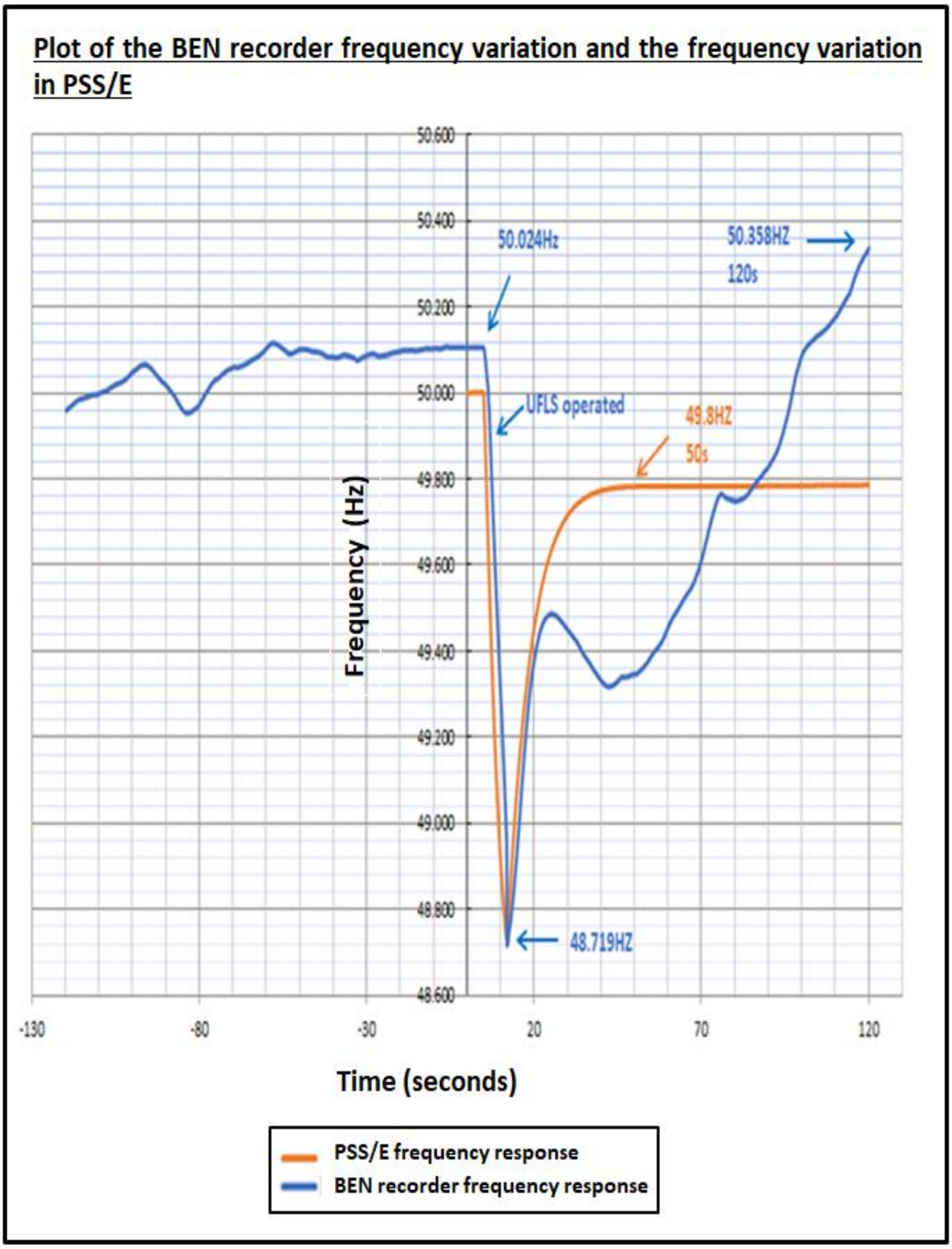


Figure 3.13: Plot of the Actual Frequency Variation vs Frequency variation in PSS/E

The year 2030 power system was built using the 2019 power system with additions on Generation and Transmission as per the Long Term Generation Plan 2018-2030.

3.11 SVC settings

The ratings of the proposed SVC by Ceylon Electricity Board (CEB) to be installed at Biyagama Grid Substation (GSS) ranges from -50 Mvar (inductive) to +100 Mvar (capacitive) at a voltage level of 220 kV (1.0 p.u.) and system frequency of 50 Hz.

The proposed SVC which is expected to be commissioned at the Biyagama GSS, is set to work in the dynamic operation , meaning that, there is no operation in the steady state despite there were small voltage variations. The reason for having this setting was that the SVC will be able to operate in its full range during a contingency event. Therefore, the SVC scheduled voltage was set to be the same as bus voltage to restrict its operation in steady state.

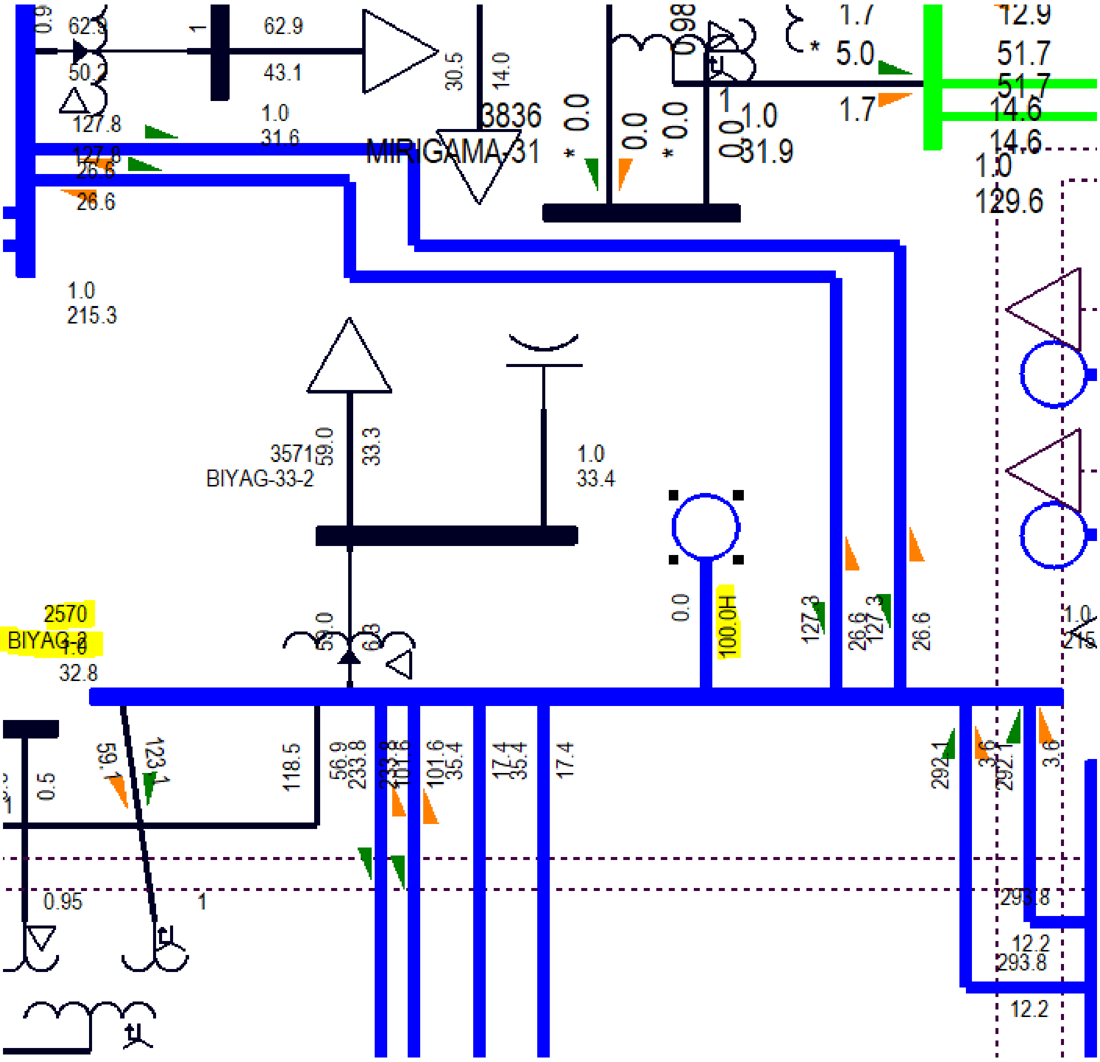
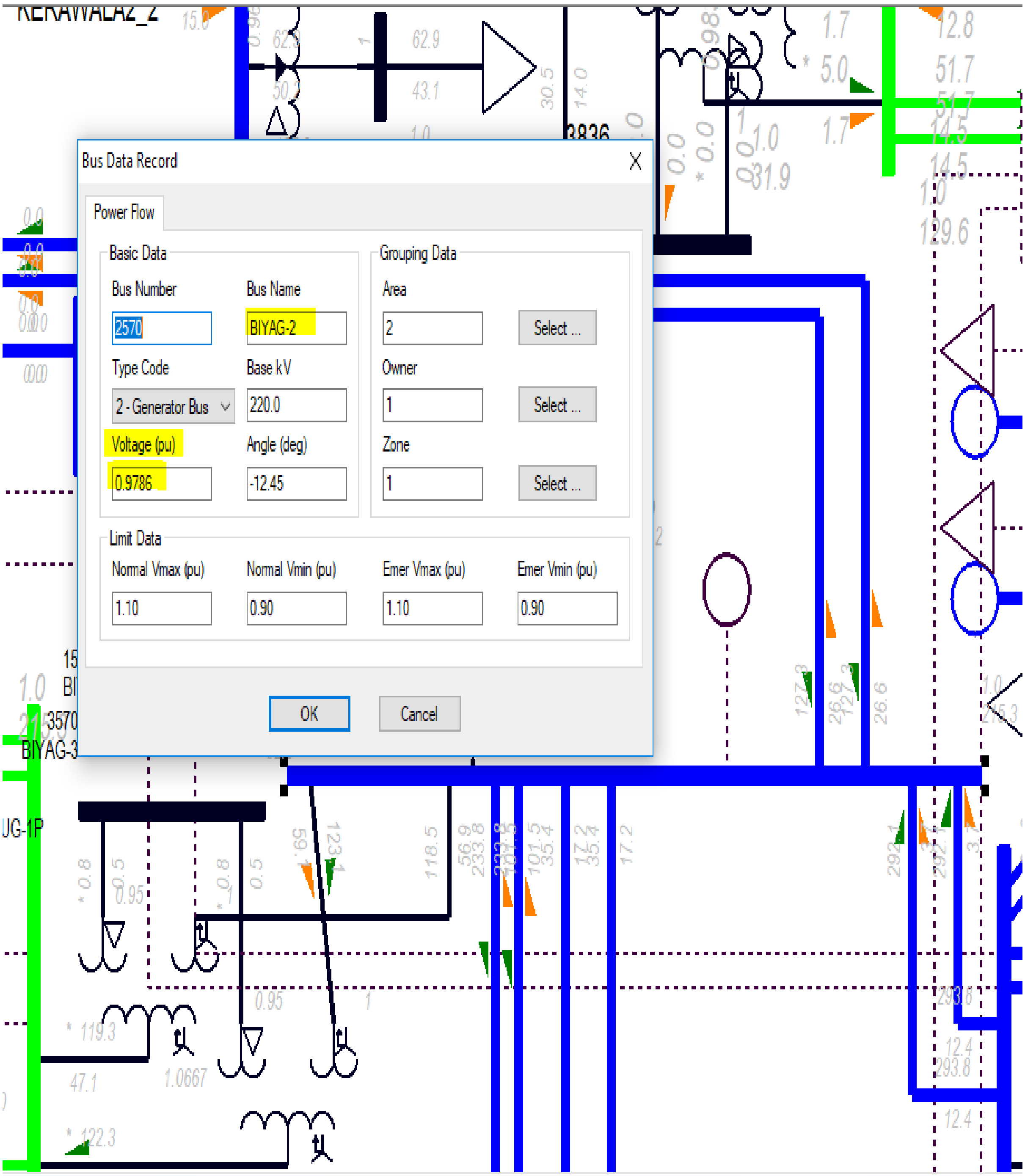


Figure 3.14: SVC operation in steady state by giving 100 MVar to the system



Bus Data Record

Basic Data

Bus Number	Bus Name
2570	BIYAG-2

Type Code	Base kV
2 - Generator Bus	220.0

Voltage (pu)	Angle (deg)
0.9786	-12.45

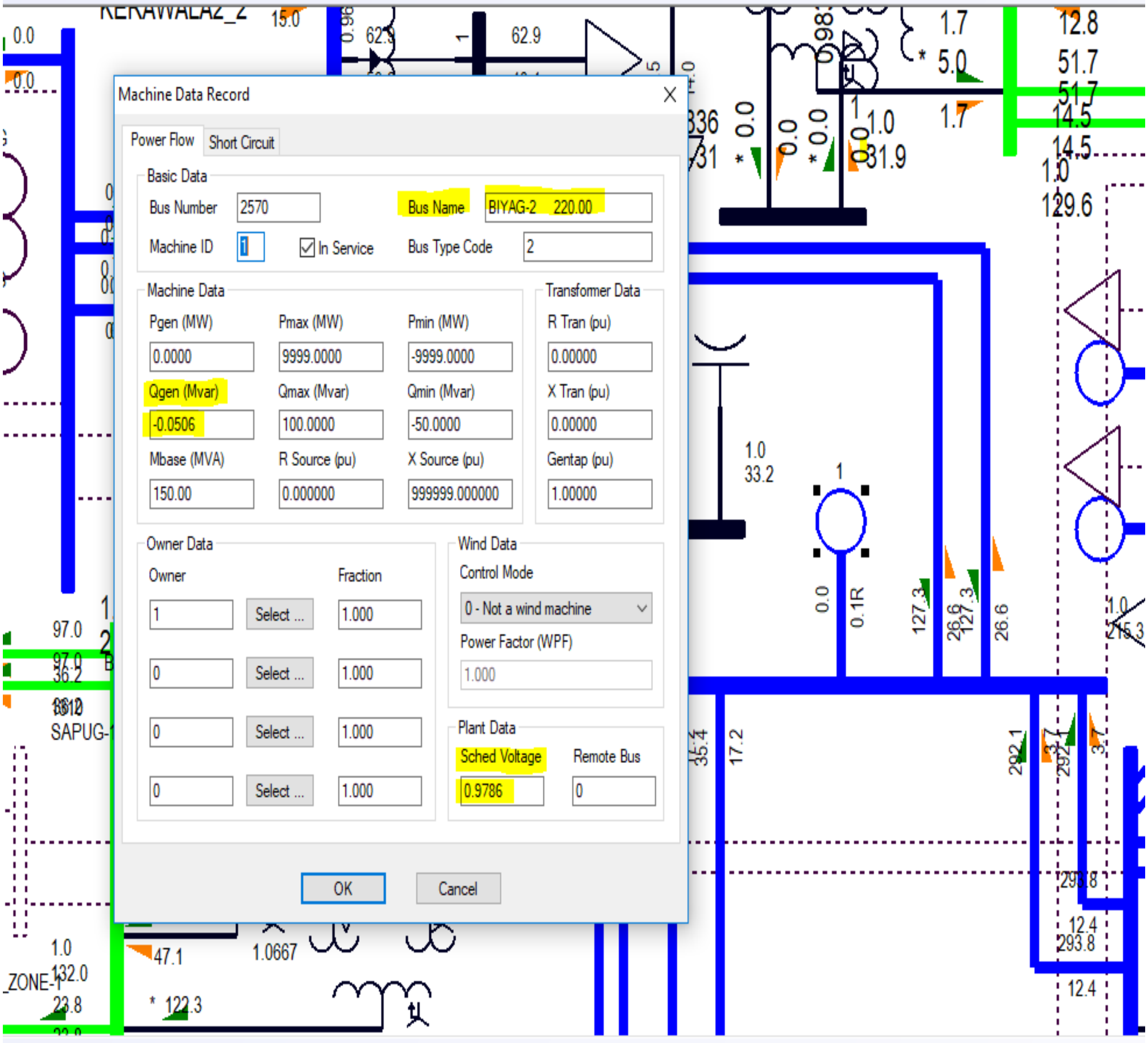
Grouping Data

Area	2
Owner	1
Zone	1

Limit Data

Normal Vmax (pu)	Normal Vmin (pu)	Emer Vmax (pu)	Emer Vmin (pu)
1.10	0.90	1.10	0.90

Figure 3.15: Biyagama Grid Substation 220 kV rated Bus Data record



Basic Data

Bus Number: 2570

Bus Name: BIYAG-2 220.00

Machine ID: 1

☑ In Service

Bus Type Code: 2

Machine Data

Pgen (MW)	Pmax (MW)	Pmin (MW)
0.0000	9999.0000	-9999.0000
Qgen (Mvar)	Qmax (Mvar)	Qmin (Mvar)
-0.0506	100.0000	-50.0000
Mbase (MVA)	R Source (pu)	X Source (pu)
150.00	0.000000	999999.000000

Transformer Data

R Tran (pu): 0.00000

X Tran (pu): 0.00000

Gentap (pu): 1.00000

Owner Data

Owner	Fraction
1	1.000
0	1.000
0	1.000
0	1.000

Wind Data

Control Mode: 0 - Not a wind machine

Power Factor (WPF): 1.000

Plant Data

Sched Voltage: 0.9786

Remote Bus: 0

Figure 3.16: SVC scheduled voltage changed to bus voltage

The SVC operation in the full range delivering 100 Mvar to the power system is shown by Figure 3.14. After performing steady state analysis, it was observed that the Biyagama GSS steady state bus voltage was 0.9786 per unit as evident by Figure 3.15. To restrict the SVC operation in steady state, the steady state voltage was adjusted to be the scheduled voltage. After running load flow analysis, it was observed that the SVC did not provide any reactive power in the steady state. So, it was verified that in this research the SVC operated only in the dynamic state as shown by Figure 3.16.

3.12 Droop setting, reactive power and Active power limits

The frequency control machine parameters are shown by Table 3.15. The turbine governor controllers that are in operation in all the simulation scenarios that were analysed in this study are given in Table 3.16 along with their droop settings. The Table 3.17 shows the active power and reactive power limits of the governors. That is the Generated active power (Pgen), Maximum active power (Pmax), Minimum active power (Pmin) and the Generated reactive power (Qgen), Maximum reactive power (Qgen), Minimum reactive power (Qmin).

Table 3.15: Parameters of frequency controlling machine

Frequency controlling machine	**Pgen (MW)**	**Pmax (MW)**	**Droop setting**
Pumped storage power plant units 1,2,3	45	206	0.0106

Table 3.16: Governors and their droop setting

Governors	**Pgen (MW)**	**Pmax (MW)**	**Droop setting**
Kotmale hydro power plant generator unit 2 and unit 3	0	67	0.05
Victoria hydro power plant			
unit 1	31	70	0.045
unit 2	0	70	0.045
unit3	0	70	0.045

Table 3.17: Active power and Reactive power limits of governors

Governors	Pgen (MW)	Pmax (MW)	Pmin (MW)	Qgen (Mvar)	Qmax (MVar)	Qmin (MVar)
Kotmale hydro power plant Generator1	67	67	0	22.9	42	-12.5
Kotmale hydro power plant Generator 2	0	67	0	20.5	42	-12.5
Kotmale hydro power plant Generator 3	0	67	0	21.1	42	-12.5
Victoria hydro power plant Generator 1	31.7	70	0	14	43	-10
Victoria hydro power plant Generator 2	0	70	0	0.2	43	-10
Victoria hydro power plant Generator 3	0	70	0	0.2	-10	-10
Pumped Storage power plant Unit 1	45	206	0	67.3	67.3	-67.3
Pumped Storage power plant Unit 2	45	206	0	67.3	67.3	-67.3
Pumped Storage power plant Unit 3	45	206	0	67.3	67.3	-67.3

3.13 Solar ramp rates

The fastest ramp rate observed is for Pooneryn solar power plant as evident from Figure 3.17. The ramp rates were observed to find the time at which a contingency could be given to observe the behaviour of the power system at its worst case. The worst case occurs at 50 s in a 100 s time frame. Therefore, the tripping for dynamics was done at 50 s.

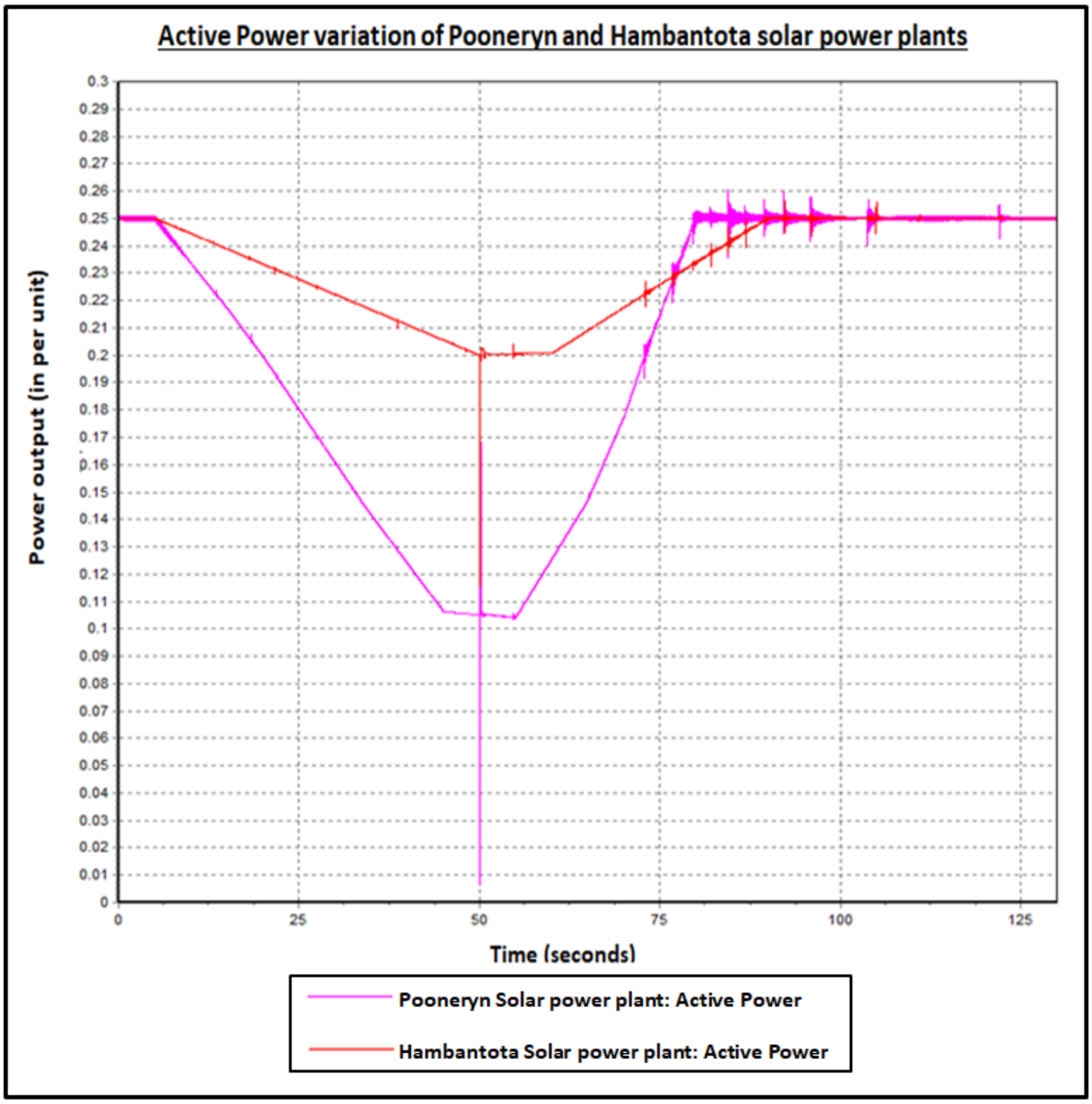


Figure 3.17: Solar ramp rates

3.14 CASE STUDY 1: Maximum Renewable Energy Scenario

The **Scenario 1**: Maximum Wind and Solar- Day peak- Year 2030 (Worst case) was simulated in PSS/E. The steps undertaken were as follows:

- a single machine of 300 MW of Lakvijaya coal power plant was disconnected at 50 s
- the voltage behavior with and without the SVC was observed for (n-1) contingency

3.14.1 Active power generation of governors under the Maximum Renewable energy scenario

The Active power variation of governor control machines was observed with the SVC under operation at the Biyagama GSS as shown by Figure 3.18.

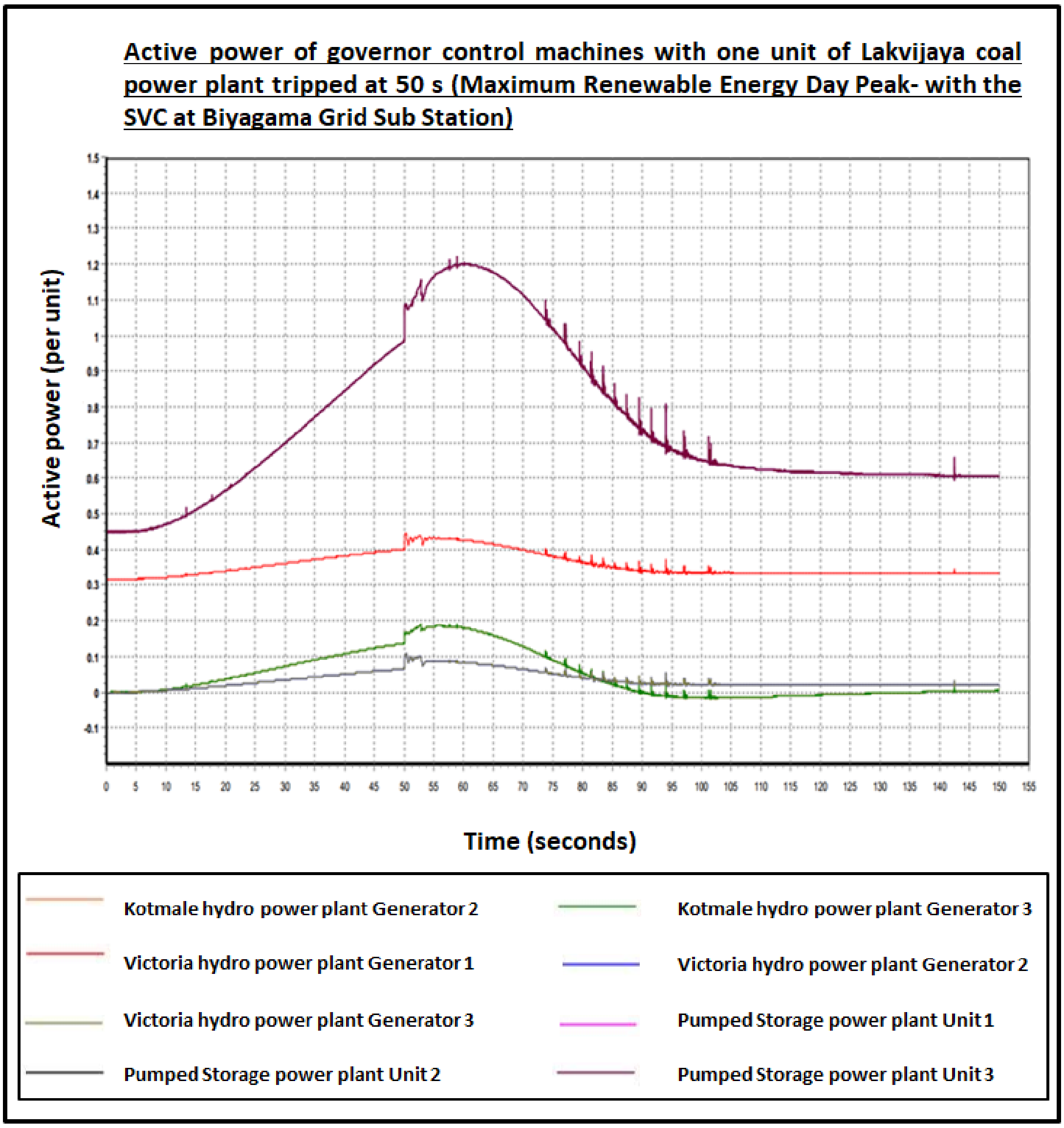


Figure 3.18: Active power generation of governors (Maximum Renewable energy scenario- with the SVC placed at the Biyagama Grid Substation)

Initially up to 50 s, the active power rose gradually due to the decreasing solar ramp rate until 50 s, there is decreased solar generation so governors had provided support.

The Pumped Storage power plants (PS 1, PS 2, PS 3) showed similar governor behaviour. The Pumped Storage machines are loaded to 45 MW in steady state and due to the fault situation it reached 120 MW, that is, out of the 206 MW of maximum power (Pmax) it can supply and later settled at 60 MW.

The Victoria hydro power plant generator 1 is operating at 31 MW in the steady state and increases its generation up to 45 MW due to the fault situation and settles at 31 MW. The Kotmale Generator 2 and 3 is initially at zero output and rises to 20 MW and settles back to 0 MW. The Victoria hydro power plant generator 2 and 3 is initially at 0 MW and rises to 10 MW and comes back to 0 MW.

3.14.2 Voltage variation of 220 kV busses under the Maximum Renewable energy scenario

The voltage variation of the 220 kV busses at the Biyagama, Pannipitiya and Kotugoda Grid Substations were observed with and without the SVC placed at the Biyagama Grid Substation under n-1 contingency is shown by Figure 3.19.

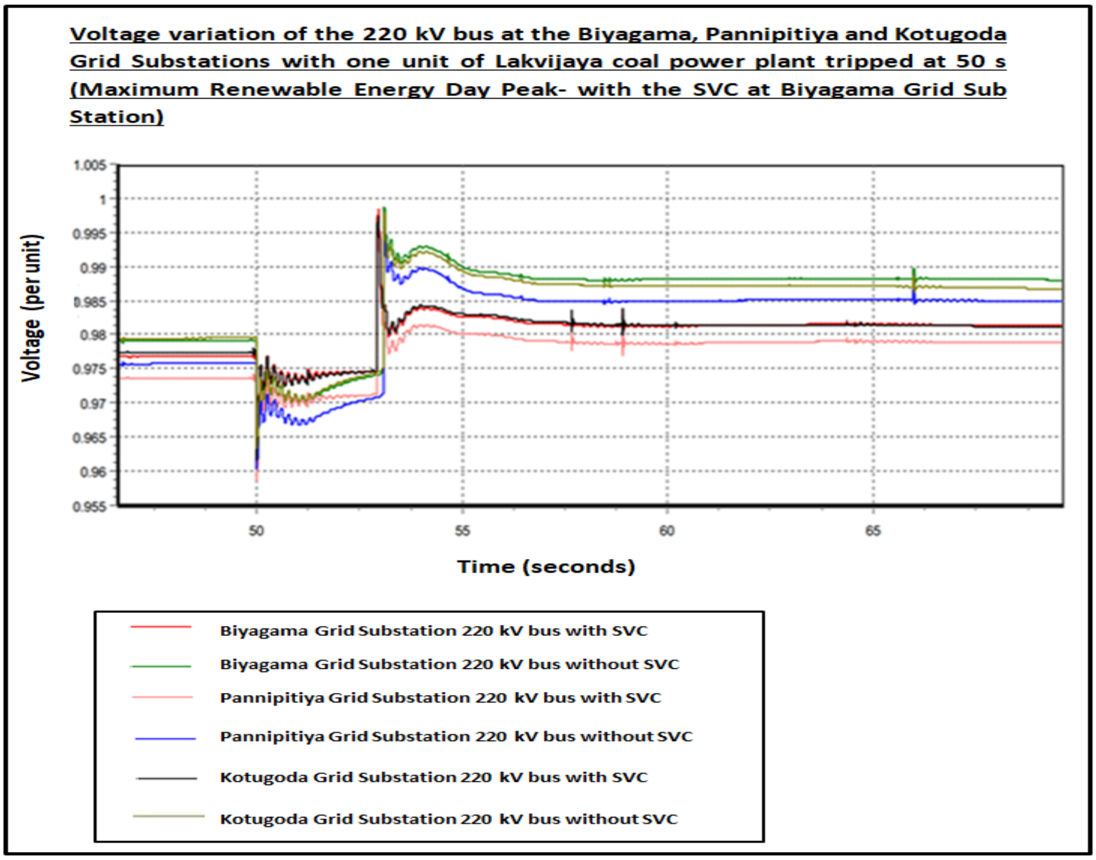


Figure 3.19: Voltage variation of 220 kV busses (Maximum Renewable Energy scenario with and without SVC)

Without the SVC in operation at the Biyagama Grid Substation, the highest voltage rise due to the fault was seen at the Biyagama 220 kV bus. Pannipitiya Grid Substation voltage rise was less than the voltage rise observed at the Kotugoda and Biyagama 220 kV busses. The Biyagama bus post disturbance voltage settled at a higher value and the Kotugoda 220 kV bus and Pannipitiya 220 kV bus followed it.

With the SVC at Biyagama GSS, the highest voltage rise due to the fault was seen at the Biyagama Grid Substation and next was the Kotugoda Grid Substation. The lowest voltage rise was seen at the Pannipitiya Grid Substation 220 kV bus. The Biyagama 220 kV bus post disturbance voltage settled at a higher value, the Kotugoda and Pannipitiya 220 kV buses followed.

However, the Biyagama 220 kV bus had higher steady state voltage, the next highest is the Kotugoda 220 kV bus and the third highest is the Pannipitiya 220 kV bus.

3.14.3 Reactive power variation of governor control machines and the SVC response under the Maximum Renewable energy scenario

The reactive power response of the SVC installed at Biyagama Grid Substation is shown by the curve plotted in red colour in Figure 3.9. The reactive power increased to 25 Mvar. That is the SVC injected 25 Mvar to the power system during the fault and then settles at - 45 Mvar.

The reactive power of the Pumped storage power plants 1, 2 and 3 rises by 1 Mvar from 60 Mvar at Steady state and decreases to 55 Mvar after that it increases gradually and settles at 64 Mvar.

Victoria generator 1 supplies around 14 Mvar in steady state and rises upto16 Mvar during the fault and drops to 11 Mvar and then gradually increases to 12 Mvar. Likewise, Kotmale generator 2, 3 and Victoria generator 2, 3 provides around 1 Mvar reactive power during the fault.

From Figure 3.20, it can be seen that the reactive power provided fed into the power system during the loss of a single generator of Lakvijaya coal power plant by the governors are a minimum as the SVC had provided a major portion of the reactive power requirement of the power system.

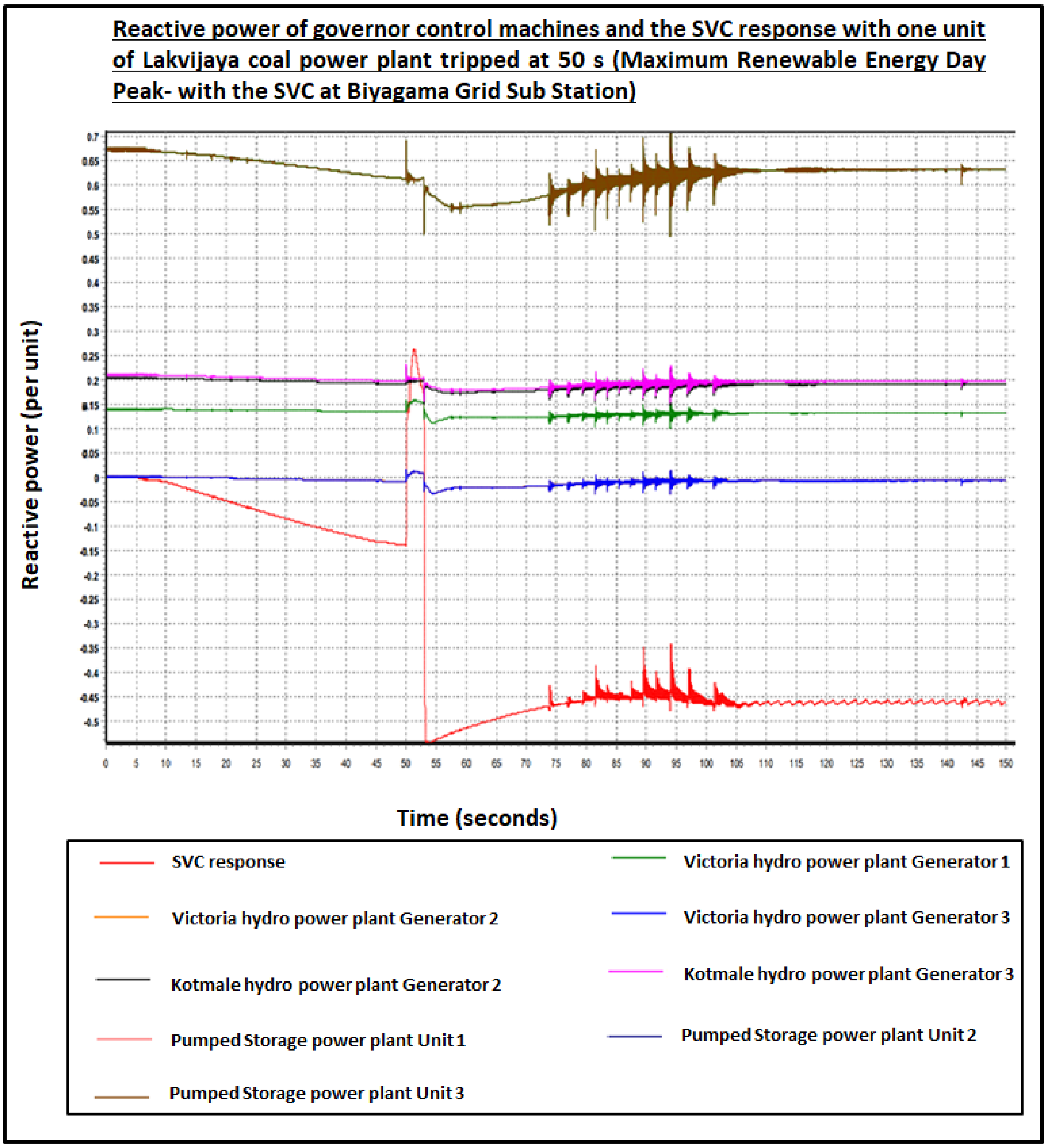


Figure 3.20: Reactive power variation of governor control machines and the SVC response (Maximum Renewable Energy Day Peak scenario- with and without SVC)

3.15 CASE STUDY 2: Minimum Renewable Energy Scenario –Day Peak

The **Scenario 2**: Minimum Renewable Energy - Day peak- Year 2030 was simulated in PSS/E. The steps undertaken were as follows:

- a single machine of 300 MW of Lakvijaya coal power plant was disconnected at 50 s
- the voltage behavior with and without the SVC was observed for (n-1) contingency

3.15.1 Voltage variation of 220 kV busses under the Minimum Renewable Energy Scenario –Day Peak

In the Minimum Renewable Energy Day Peak scenario with the SVC at Biyagama Grid Substation, the steady state voltage is 0.9715 per unit. With the SVC, the voltage increase during the fault is less and it settles to 0.9716 per unit faster than the without SVC situation.

For the Biyagama GSS without the SVC, the steady state voltage is 0.9716 per unit . Without the SVC, the voltage rose to around 0.9721 per unit and settled at a higher value of 0.9719 per unit.

It is evident that when having one unit of Lakvijaya coal power plant tripped in the situation with the SVC in operation, the voltage settled close to steady state voltage unlike without the SVC situation as shown by Figure 3.10.

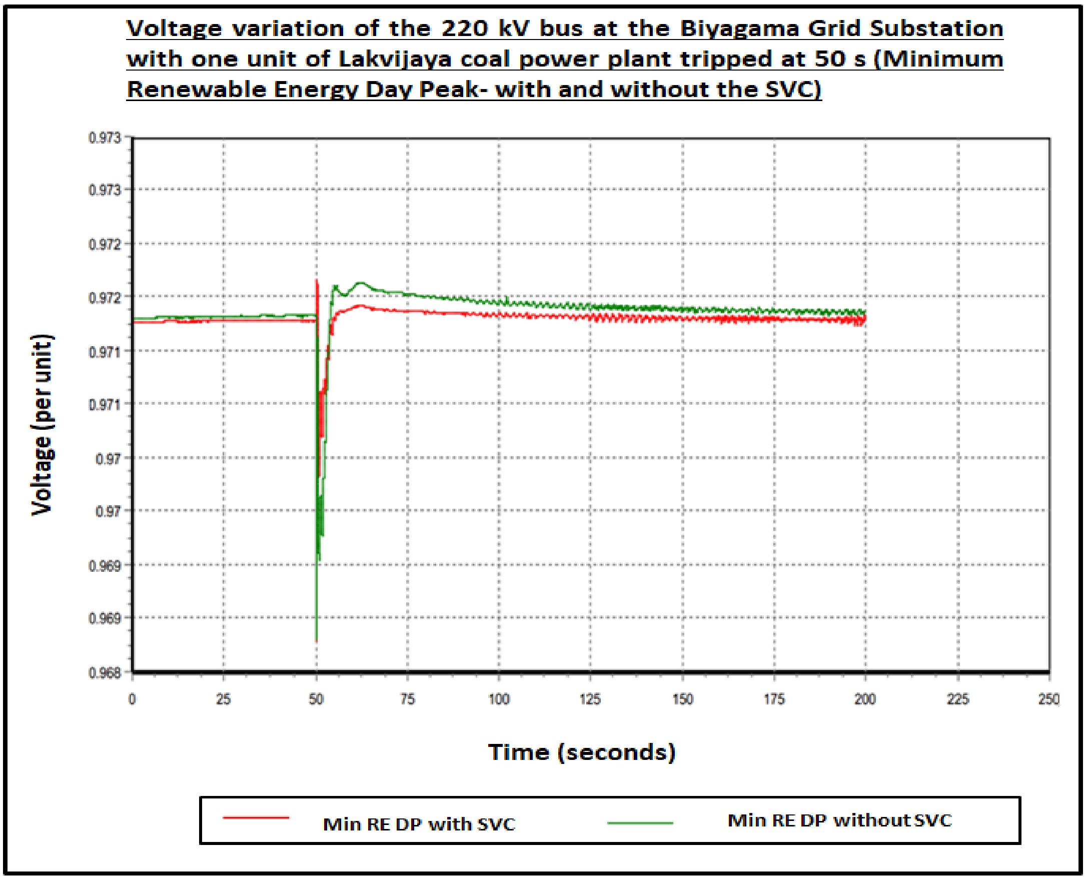


Figure 3.21: Voltage variation of the 220 kV bus at the Biyagama Grid Substation under Minimum Renewable Energy Scenario –Day Peak (with and without SVC)

3.16 CASE STUDY 3: Minimum Renewable Energy Scenario –Night Peak

The **Scenario 3**: Minimum Renewable Energy - Night peak- Year 2030 was simulated in PSS/E. The steps undertaken were as follows:

- a single machine of 300 MW of Lakvijaya coal power plant was disconnected at 50 s
- the voltage behavior with and without the SVC was observed for (n-1) contingency

3.16.1 Voltage variation of 220 kV busses under the Minimum Renewable Energy Scenario –Night Peak

In the Minimum Renewable Energy Scenario –Night Peak, with the SVC at the Biyagama Grid Substation, the steady state voltage was 0.9805 per unit which is higher than the steady state voltage of Minimum Renewable Energy Day Peak scenario (in the Min RE DP it was 0.9715 per unit) as shown by Figure 3.17.With the SVC, the voltage increase during the fault is less and it settles to 0.9716 per unit faster than the without SVC situation.

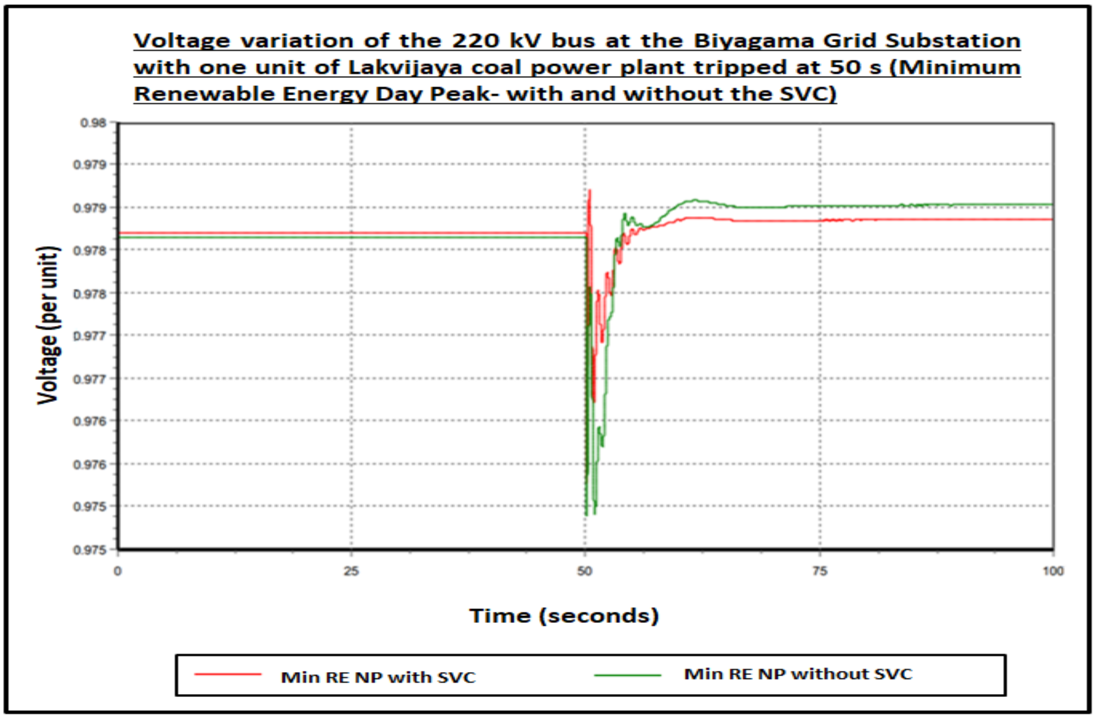


Figure 3.22: Voltage variation of the 220 kV bus at the Biyagama Grid Substation under Minimum Renewable Energy Scenario –Night Peak (with and without SVC)

For the Biyagama Grid Substation without the SVC, the steady state voltage is 0.98 per unit. During the fault, in the without SVC situation, the voltage rose to around 0.981per unit and settled at a higher value of 0.979 per unit in comparison to the with SVC scenario.

3.17 n-2 Contingency analysis

The steps undertaken were as follows:

- Two 300 MW machines of Lakvijaya coal power plant was disconnected at 50 s
- the voltage behavior with and without the SVC was observed for (n-1) contingency

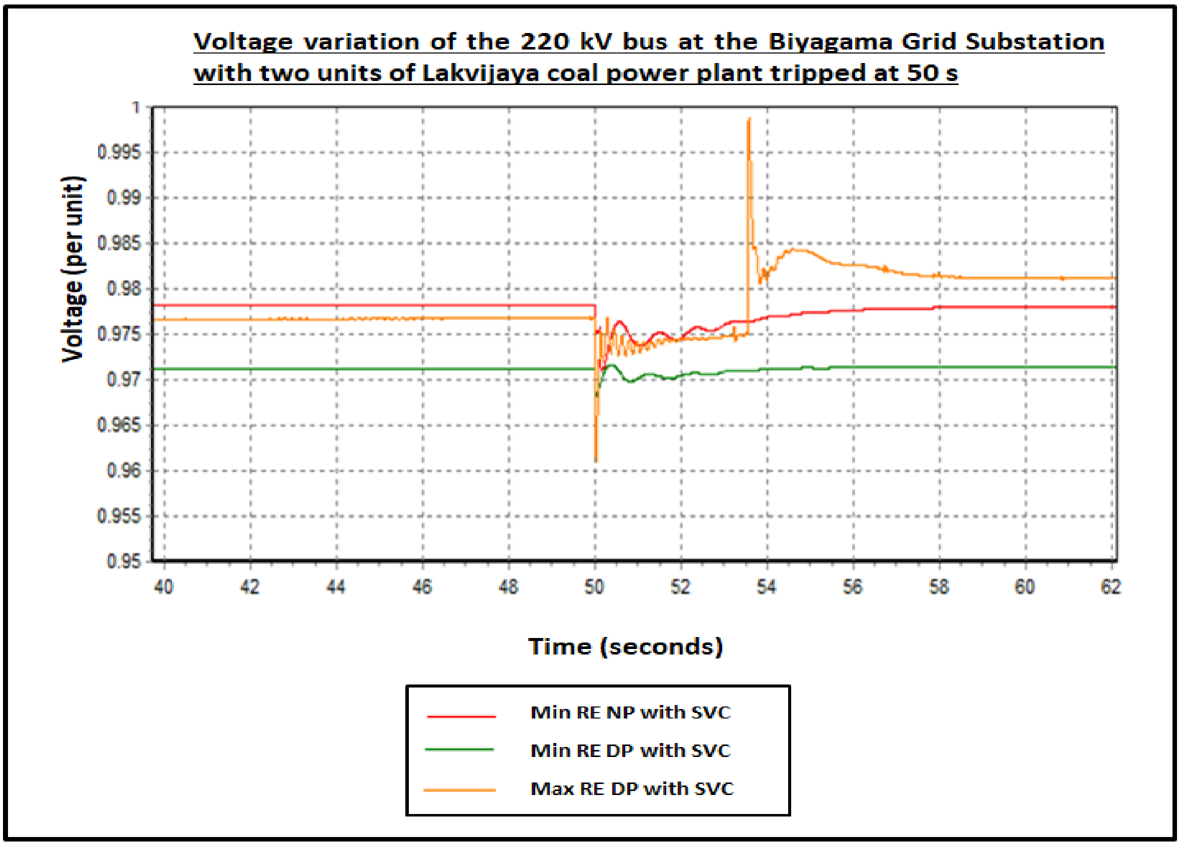


Figure 3.23 : Comparison of Voltage variation of 220 kV busses under Maximum Renewable Energy scenario- Day Peak, Minimum Renewable Energy scenario- Day Peak, Minimum Renewable Energy scenario- Night Peak scenarios (with SVC)

During n-2 contingency, in the Maximum Renewable Energy Scenario –Day Peak with the SVC at Biyagama Grid Substation, the voltage variation is highest in comparison to the other scenarios as evident from figure 3.18. The voltage variation for Minimum Renewable Energy Scenario –Night Peak is higher than Minimum Renewable Energy Scenario – Day peak due to the low load condition at Night Peak.

CHAPTER 4

4 Determination of Optimal location of SVC and Optimal location of SVC capacity

4.1 SVC placement at Biyagama Grid Substation, Kotugoda Grid Substation and Pannipitiya Grid Substation

When the SVC is placed at Biyagama and Kotugoda Grid Substation’s, the voltage of the 220 kV busses were observed as shown by Figure 4.1 and comparison was made to find the best location for SVC placement.

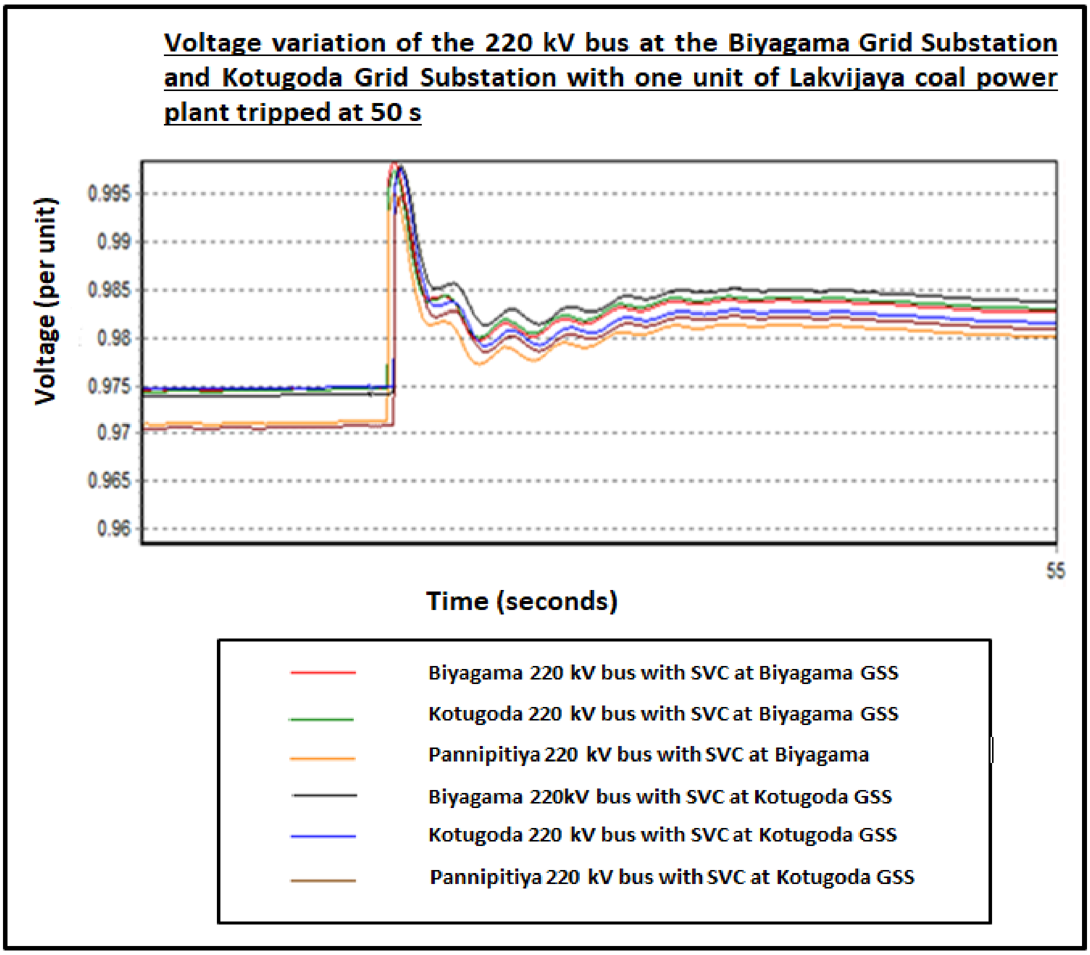

Voltage variation of the 220 kV bus at the Biyagama Grid Substation and Kotugoda Grid Substation with one unit of Lakvijaya coal power plant tripped at 50 s

Figure 4.1: Voltage variation of Biyagama and Kotugoda 220 kV busses with SVC at Biyagama and Kotugoda Grid Substation’s under n-1 contingency

In the Maximum Renewable Energy Day Peak scenario, by having the SVC integrated and in operation at the Kotugoda Grid Substation, the 220 kV bus bar voltage rise was lower than the Biyagama 220 kV bus. When the SVC was installed at the Biyagama Grid Substation, the steady state voltages are higher than that of when the SVC is at the Kotugoda Grid Substation. The Biyagama Grid Substation voltage rise was higher than the Kotugoda voltage rise and in the post disturbance situation the voltage settled at a lower value which is close to its steady state voltage. As the steady state voltages are higher when SVC is placed at Biyagama Grid Substation, the option of having a SVC at Kotugoda Grid Substation is not feasible with the observed results from Figure 4.1.

When the SVC is placed at Biyagama, Kotugoda and Pannipitiya Grid Substation's the voltage of the three busses are observed and comparison is made to find the best location as shown by Figure 4.2.

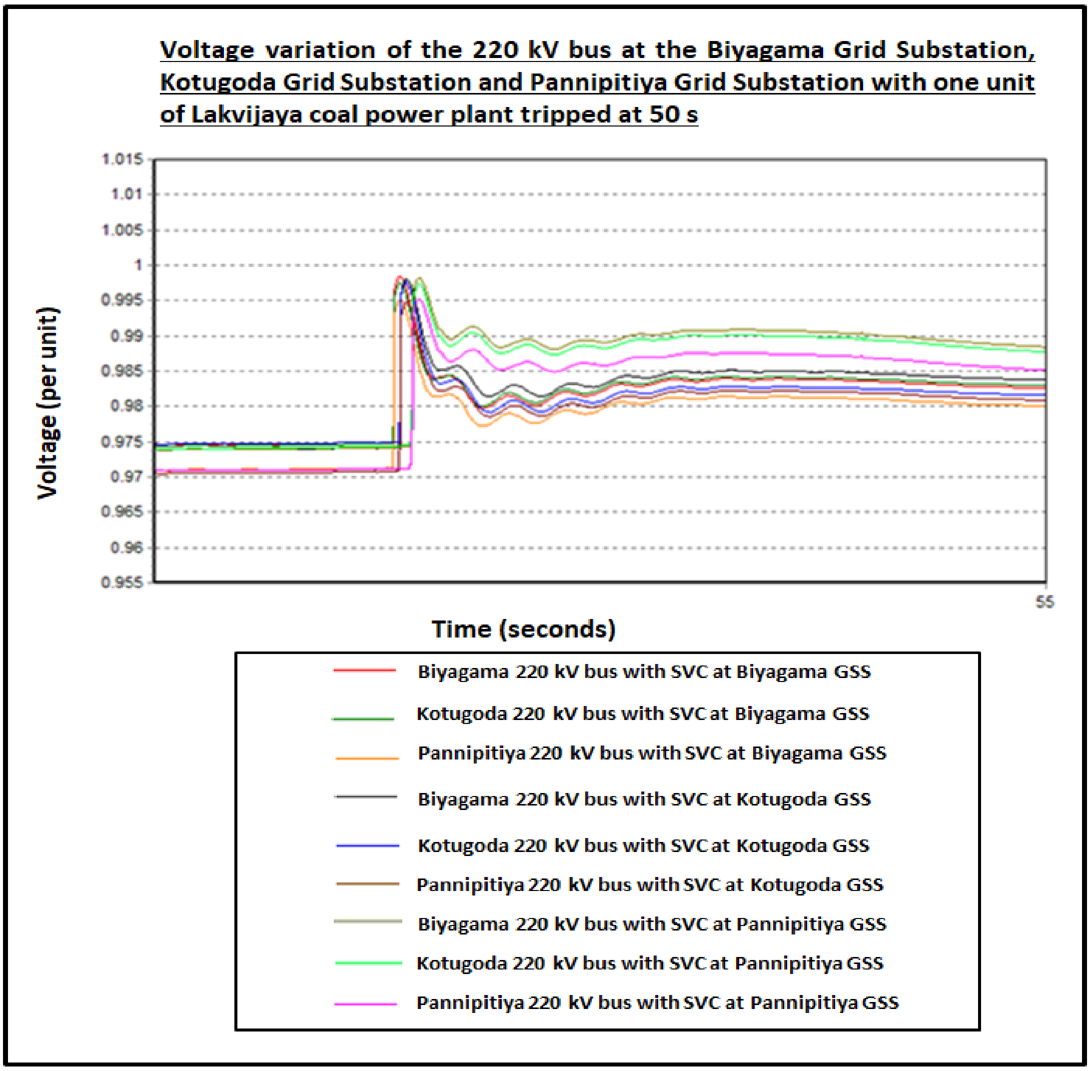


Figure 4.2: Voltage variation of Biyagama, Kotugoda Pannipitiya 220kV busses with SVC under n-1 contingency

In the Maximum Renewable Energy –Day Peak scenario, when the SVC is installed at Biyagama Grid Substation, the steady state voltages are higher than that of when SVC is at Kotugoda Grid Substation or Pannipitiya Grid Substation.

As the steady state voltages are higher and closer to 1 per unit when SVC is placed at Biyagama Grid Substation, the option of having a SVC at the Biyagama Grid substation is the most feasible option in comparison to installing the SVC at the Kotugoda or Pannipitiya Grid Substations.

4.2 P-V and Q-V curves

The objective of P-V and Q-V curves is to determine the ability of a power system to maintain voltage stability at all the buses in the power system under normal and abnormal operating conditions.

4.3 P-V curves

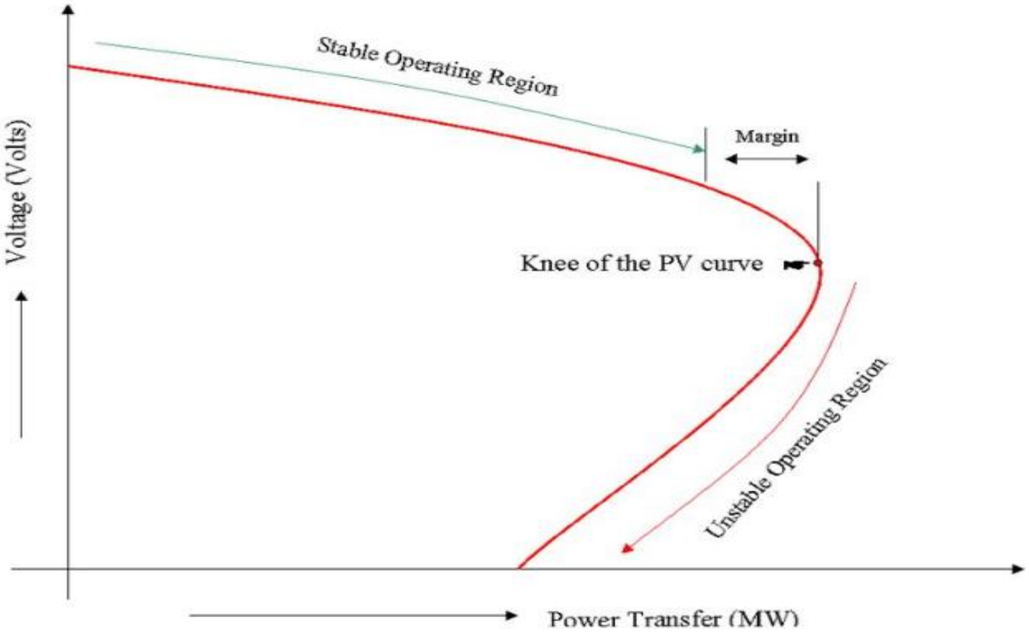


Figure 4.3: P-V curve

The P-V curve is a representation of voltage change as a result of increased power transfer between two systems.

The P-V curve analysis demonstrates the effect of active power flow on voltage instability.

They are useful, for example:

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

4.4 Q-V curves

The Q-V curve is a representation of the reactive power demand by a bus or buses as the voltage level changes.

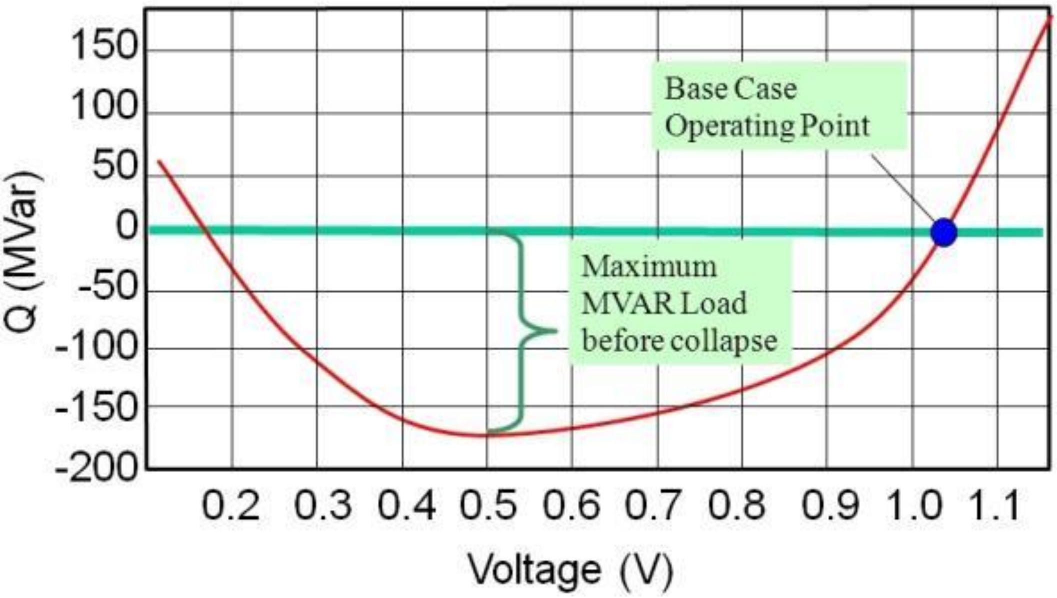


Figure 4.4: Q-V curve with base case operating point

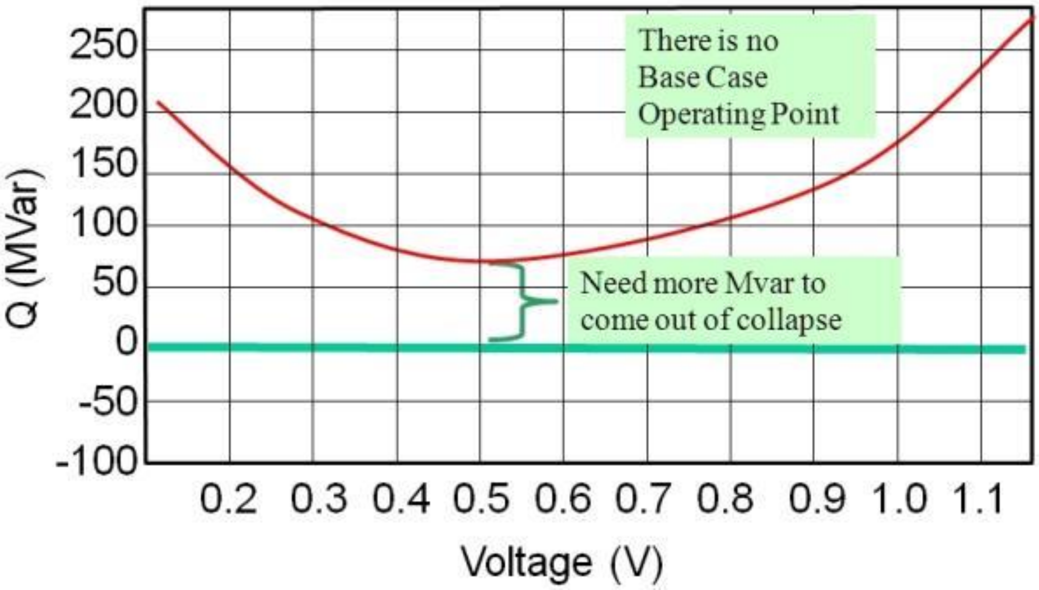


Figure 4.5: Q-V curve with no base case operating point

Q-V curves are commonly used to identify voltage stability issues and also to determine the reactive power margin for specific locations in the power system under various loading and contingency conditions as shown by Figure 4.4. and 4.5.

4.5 P-V and Q-V curves for scenarios

The P-V curves for the three scenarios with and without the SVC are shown by Figure 4.6. The Maximum Active Power transferred (in MW) is shown in Table 4.1.

Table 4.1: Maximum Power transferred (in MW) with the -50/100 Mvar SVC and without the SVC

Scenario	**Maximum power transferred(MW)**	
	with SVC	**without SVC**
Maximum Renewable Energy	**300**	262.5
Minimum Renewable Energy- Day Peak	**1468.75**	1381.25
Minimum Renewable Energy- Night Peak	**1887.5**	1812.5

The Q-V curves for the three scenarios with and without the SVC are shown by Figure 4.7. The Maximum Reactive Power transferred (in Mvar) is shown by Table 4.2.

Table 4.2: Reactive Power transfer limit (in Mvar) with the -50/100 Mvar SVC and without the SVC

Scenario	**Reactive Power transfer limit (Mvar)**	
	with SVC	**without SVC**
Maximum Renewable Energy	**-87.022**	-85.162
Minimum Renewable Energy- Day Peak	**-371.158**	-327.824
Minimum Renewable Energy- Night Peak	**-499.242**	-498.951

Table 4.3: Reactive Power transfer limit of the power system (Mvar)

Scenario (with SVC)	**Reactive Power transfer limit (MVar)**	
	with SVC capacity: -50/100 Mvar	**with SVC capacity: -50/200 Mvar**
Maximum Renewable Energy	**-87.022**	**-98.012**

According to Table 4.1, it is evident from the Maximum Active Power transferred (in MW) that for the Maximum Renewable energy scenario, with and without SVC there is 12.5% variation. In Minimum Renewable energy scenario Day Peak there is 5.95% variation, Minimum Renewable energy Night peak scenario there is 5.95% variation.

There is a significant variation in the Maximum Active Power transferred (in MW) in Maximum Renewable energy scenario considering with and without SVC situation.

However, the reactive power transfer limit showed only a 2.29 % variation with the -50 /100 Mvar SVC, which is an insignificant value.

With the proposed capacity of -50/100 Mvar, the system effect by having a SVC is insignificant so the author proposed to further increase the SVC capacity. That is to increase the reactive power transfer limit of the system.

Thus, an increased capacity of -50/200 Mvar SVC was considered for the analysis.

With the increased capacity of the SVC from -50/100 Mvar to -50/200 Mvar SVC, the reactive power transfer limit increased meaning that the reactive power that is handled without collapse of voltage in the power system further increased to up to 12% as shown by Figure 4.8 and Table 4.3 which is a significant rise in comparison to without SVC situation in the Maximum Renewable Energy scenario.

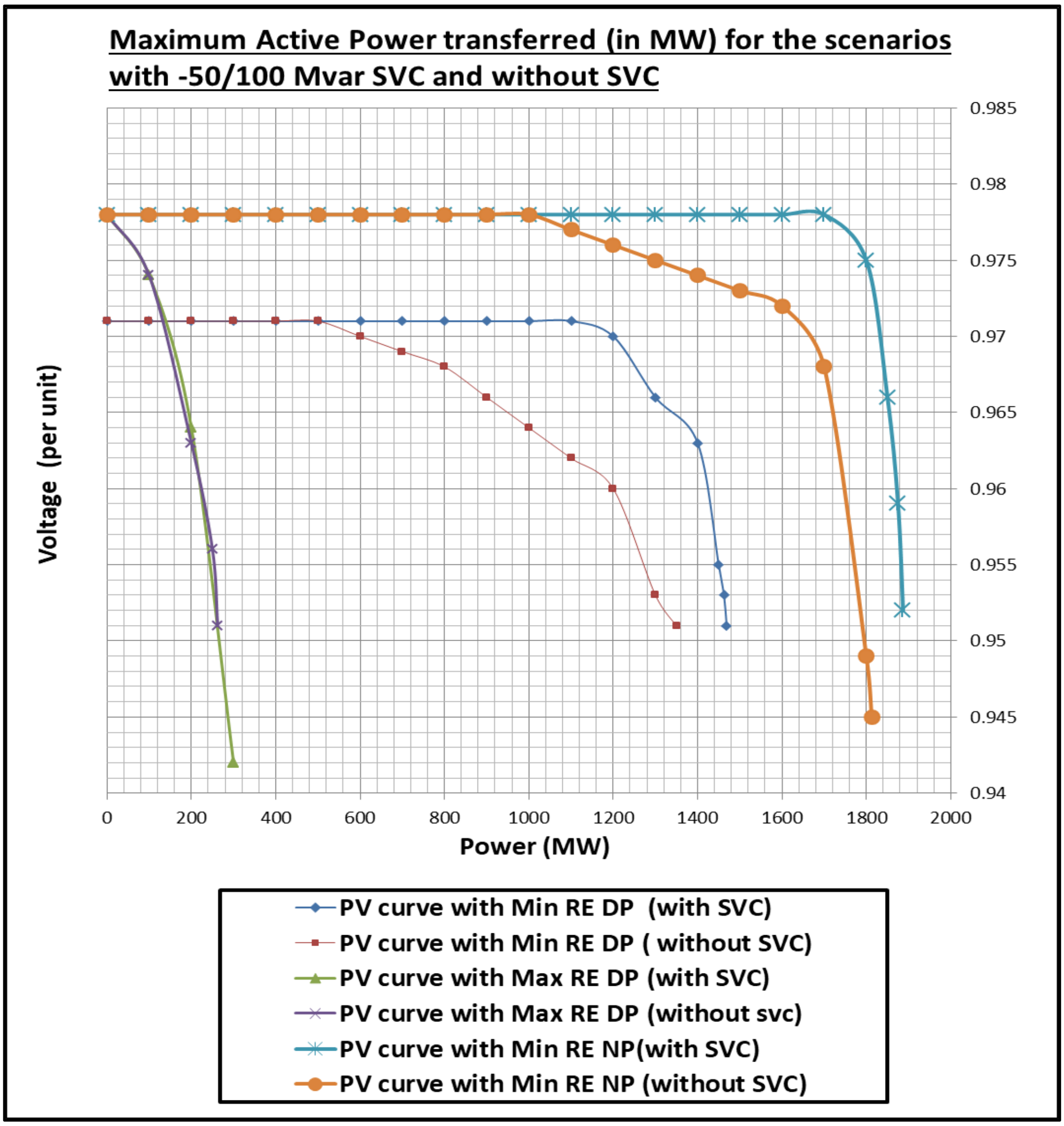


Figure 4.6: Comparison of PV curves for three scenarios (with the -50/100 Mvar SVC and without SVC)

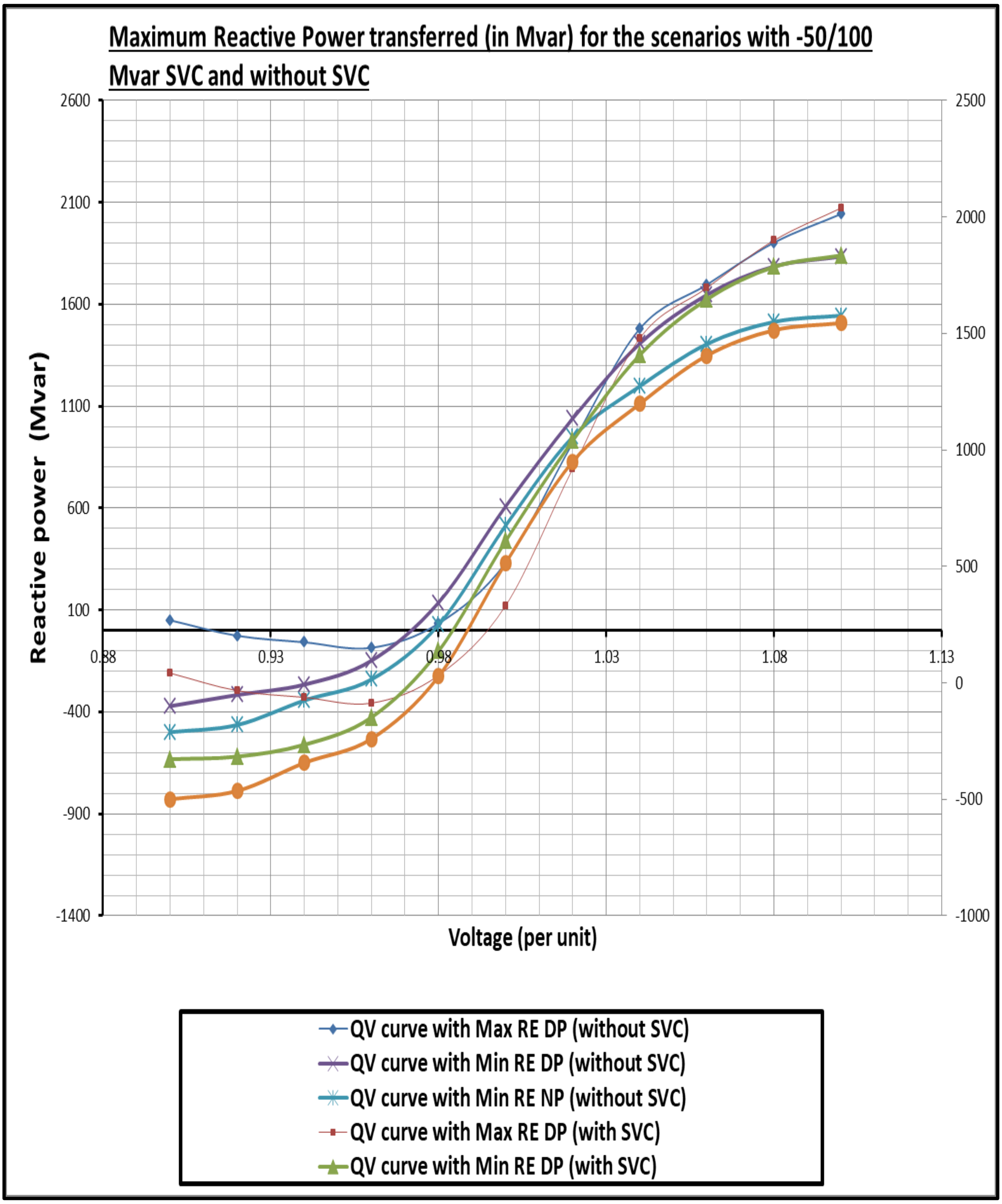


Figure 4.7: Comparison of Q-V curves for three scenarios (with the -50/100 Mvar SVC and without the SVC

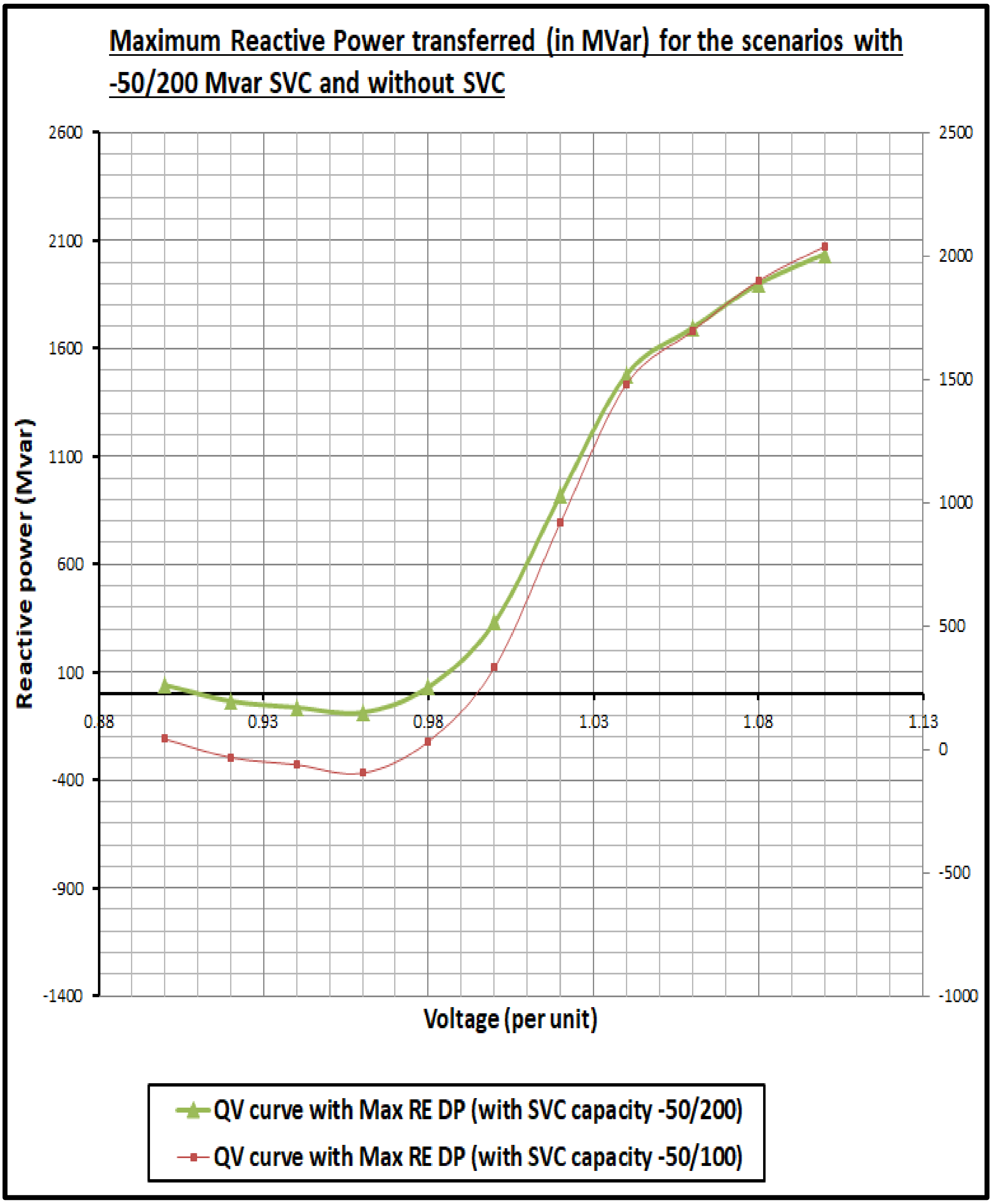


Figure 4.8: Comparison of QV curves for Maximum Renewable energy scenario (with -50/200 Mvar SVC and without SVC)

CHAPTER 5

5 Conclusions and Recommendations

In the Minimum Renewable Energy Day Peak and Night Peak situation, the steady state voltage of Kotugoda Grid Substation is close to 1 per unit, next highest is observed at the Biyagama Grid Substation and Pannipitiya Grid Substation.

From the case study of Maximum Renewable Energy, which is the worst situation with 100 % solar and wind penetration, the best location of SVC is at the Biyagama Grid Substation. This is because the steady state voltages are higher than the other two locations. That is the voltages are closer to 1 per unit. The next best location is Kotugoda Grid Substation and thirdly is the Pannipitiya Grid Substation. Considering the SVC placement at Biyagama, Kotugoda and Pannipitiya Grid Substation's, the optimal location of the SVC is at the Biyagama Grid Substation . Furthermore, considering the space available at the Biyagama Grid Substation it is an optimal location.

However, it is worthwhile to note that the remaining Grid Substation's needs to be analysed to give an overall conclusion on the SVC optimal location in the Sri Lankan Power System. The space available in the substation to accommodate a SVC will also be the determining factor.

With the proposed -50/+100 Mvar SVC, there is no significant effect in the voltage variation in comparison to the with and without SVC situation in the dynamic state. It was evident from this study, that the voltages of major Grid Substation's in Colombo area which are the Biyagama, Kotugoda Pannipitya Grid Substation's stay between allowable limits in the with and without SVC cases in year 2030 even with maximum renewable energy in the system under steady state analysis and contingency analysis including loss of one large generator (n-1) and loss of two large generators (n-2). The reactive power limits of the generators were not exceeded.

The reason for this is that the transmission network is strengthened by 2030 with adequate capacity. A reliable transmission network is available to cope up with the load growth and future generation additions incorporating renewables according to the latest available Long term Transmission Development Plan 2030-2037 by year 2030.

In order to utilise the need for a SVC fully in the Sri Lankan Power system without relying on the existing and future connected capacitor banks and reactor banks only for reactive power compensation, this study proposes a capacity increase of the proposed SVC of Ceylon Electricity Board (CEB).

It is proposed to increase the capacity of the SVC to -50/200 Mvar SVC, thus increasing the amount of reactive power that could be handled by the system without going into a state of voltage collapse. So, the reactive power can be further increased to up to 12% with increase of SVC capacity and the voltages of the busses at steady state can be improved closer to 1 per unit.

This will improve the voltage stability further and allows increased additions of renewable energy to the future power system of Sri Lanka.

Furthermore, it is recommended through the study in this thesis that Ceylon Electricity Board (CEB) considers to use two or more parallel operating SVC’s for redundancy purpose. However, this comes with the issue of increased cost to the utility so it may attract reluctance.

However, it is suggested to extend this study to study SVC behaviour in both steady state and dynamic state to determine the optimal capacity of operation in the two ranges. After the commissioning of the SVC at Biyagama Grid Substations, this study could be extended by using the practically available operation parameters of the SVC. This would highlight the positivity of recommendation of increasing the SVC capacity through this study even at the expense of higher cost.

Moreover, this study can be continued by performing further simulations by developing a new simulation model, that is, the conventional synchronous generators in the power system of year 2030 which includes coal power plants and Liquid Natural Gas (LNG) power plants could be replaced with solar power plants (no reactive power injection to the utility grid) according to the CEB long term generation expansion plan 2020-2039 and simulated with and without the SVC in operation under contingencies to determine the effect on the voltage stability of the busses in the power system and hence determine the optimum operating conditions of the SVC.

However, at this stage it is worthwhile to note that replacing conventional generators and having a reactive power controlling device such as SVC in the power system will add an increased cost and will be highly expensive in cost terms but with the rising trend to move on to renewable technologies it would be appreciated by the wider stakeholders and community.

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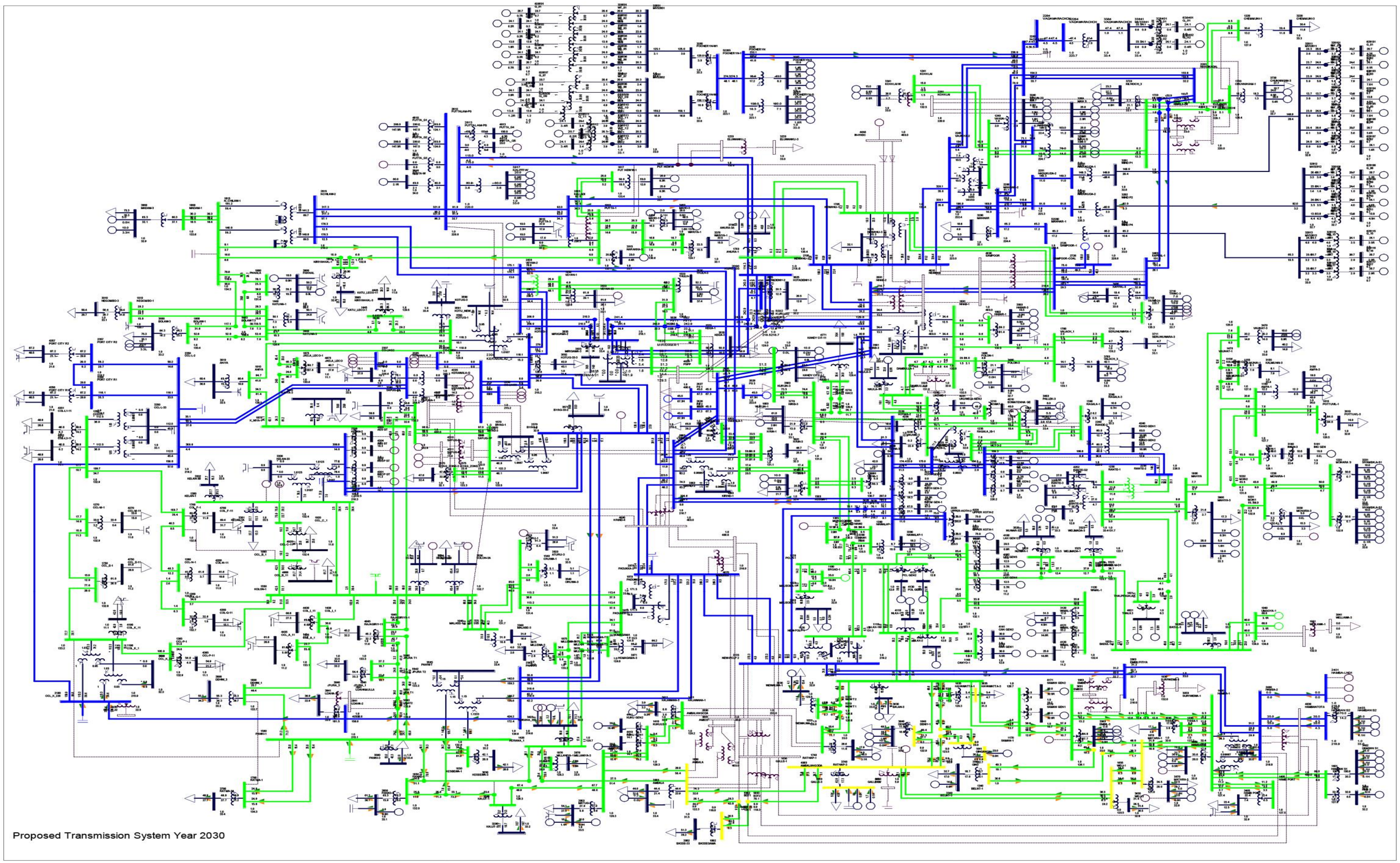
Appendix A: Schematic Diagram of the year 2030 Transmission system of Sri Lanka



Appendix B: 220 kV Kelanitissa Grid Substation -Digital Fault Recorder BEN 6000 data for tripping of 1 unit of West Coast Power (WCP) Private Limited on 17.07.2019