OPTIMUM REACTIVE POWER COMPENSATION & VOLTAGE CONTROL USING STATIC VAR COMPENSATOR FOR GRID SUBSTATIONS

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DECLARATION OF THE CANDIDATE AND SUPERVISORS

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Signature of the Supervisor
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ABSTRACT

As the volume of power transmitted in transmission lines increases, maintaining high quality and reliable power supply is required. Modern power systems sometimes operate with heavily loaded lines resulting in power system to work under condition of higher power loss and higher voltage deviation. Sometimes, it may lead to voltage instability or system collapse.

The emergence of power electronic based FACTS technology such as Static Var Compensator (SVC) has been of great help in improving the operation of power systems as it reduces the power system instability problem, power losses and voltage deviation. Placing FACTS devices at proper locations can serve the purpose of improving voltage levels and reducing losses in the system. Due to huge investments associated with SVC, a proper analysis and planning is required before the installation.

The objective of the study is to use optimization technique for minimization of power loss and voltage deviation along with installation cost calculation for the selection of SVCs for grid substations. Whole Sri Lankan power system has been modeled using the PSS/E (Power System Simulator for Engineers) software. The voltage deviation of all the buses in the network and the total active power loss in all the transmission lines are analyzed with SVCs and without SVCs using PSS®E software. Further, single line outages are considered as contingencies for optimal placement of SVC. Finally, optimum combinations of SVCs are selected to minimize the system voltage deviations and active power loss of transmission lines.

TABLE OF CONTENTS

1. Introduction

2. Static Var Compensator (SVC)

3. Existing Transmission System of Sri Lanka

3.4 Details of thermal power plants running for controlling the voltage

3.5 Losses due to running thermal power plants

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

FACTS	Flexible AC Transmission System
SVC	Static Var Compensator
TSC	Thyristor Switched Capacitor
TCR	Thyristor Controlled Reactor
FC	Fixed Capacitor
PS	Power Station
PSS/E	Power System Simulator for Engineers

LIST OF APPENDICES

Chapter 1

Introduction

1.1 Background

Power transfer in long transmission lines increases with the increasing demand on transmission network and so lines become stressed. Therefore, it is really important to maintain the power system within acceptable limits assuring high quality and reliable power supply. These inherent limits restrict the power transaction, which lead to under utilization of the existing transmission resources [1]. The inductive series impedance of high voltage overhead lines increases the reactive power consumption with the square of the current. Due to this reactive power, the capability of active power flowing of lines reduces and voltage drop appears leading also to a reduction of the power transmitted to the load.

Problem of improper reactive power planning may result in voltage instability and voltage collapse. Voltage instability is basically due to the lack of ability of a power system to maintain steady state voltages at all buses following a disturbance. To limit these effects, reactive power compensation equipment such as shunt capacitor banks, reactors are usually installed. Traditionally, fixed or mechanically switched shunt and series capacitors, reactors and synchronous generators were being used to solve much of these problems. However, there are some restrictions and disadvantages of being slow and unreliable of these conventional devices.

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 [2]. Cable connections have even higher var contribution. Without proper reactive power compensation, critical system operating conditions may occur resulting in 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. For the compensation of reactive power, shunt capacitors were first employed for power factor correction in the year 1914 [3]. The leading current drawn by the shunt capacitors compensates the lagging current drawn by the load. The selection of shunt capacitors depends on many factors, the most important of which is the amount of lagging reactive power taken by the load. In the case of widely fluctuating loads, the reactive power also varies over a wide range. Thus, a fixed capacitor bank may often lead to either over-compensation or under-compensation. Variable var compensation can be obtained using switched capacitors. Depending on the total var requirement, capacitor banks are switched into or switched out of the system. The smoothness of control depends on the number of capacitors switching units used. The switching is usually accomplished using relays and circuit breakers. However, these methods based on mechanical switches and relays have the disadvantage of being slow and unreliable. Also they generate high inrush currents and require frequent maintenance.

Synchronous condensers also play a major role in voltage and reactive power control for more than 50 years [2]. A synchronous condenser is a synchronous machine connected to the power system. The machine can provide continuous reactive power control with a proper automatic exciter circuit. Synchronous condensers have been used at both distribution and transmission voltage levels to improve the stability and to maintain voltages within desired limits under varying load conditions and contingency situations. However, synchronous condensers are rarely used today, because they require substantial foundations and a significant amount of starting and protective equipment [2]. They contribute also to the short circuit current and they cannot be controlled fast enough to compensate for rapid load changes. Further, their losses are much higher than those associated with static compensators and the cost is much higher compared with the static compensators.

The FACTS initiative was originally launched to solve the emerging system problems in the late 1980s due to restrictions on transmission line construction and to facilitate the growing power export and import. Fast response times, lower losses and less maintenance requirements of thyristor controlled FACTS devices resolve the limitations of rotating machines and shunt breaker switched capacitors. Today, FACTS devices fulfill the above all requirements and provide solutions to lot of issues and limitations in a transmission system.

Based on new power electronics converters and digital control schemes, reactive power compensators implemented with self-commutated converters have been developed. These can compensate not only reactive power, but also maintain the voltage, minimize flicker & harmonics, improve real power and can change transmission line impedance and phase-shift angle. It is important to note that even though the final effect is to improve power system performance, the control variable in all cases is basically the reactive power. Using self commutated converters the following high performance power system controllers have been implemented: Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), Dynamic Voltage Restorer (DVR), Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC) [2].

Although there are new several FACTS controllers employing thyristor controlled and switching converter based voltage sources, Static Var Compensator (SVC) is the most widely used shunt FACTS devices within power networks due to its low cost and good performance in system enhancement. Therefore, the SVCs for Sri Lanka Transmission Network is considered in this analysis.

The SVC can improve power system transmission and distribution performance in a number of ways. Installing SVC/SVCs at one or more suitable points in the transmission network, it is possible to increase the active power transfer capability and to reduce the losses while maintaining a smooth voltage profile under different network conditions.

So, the primary objective of applying a SVC in a power system is to maintain system voltage and increase the power transmission capability from the generators to the loads. Since SVCs cannot generate or absorb real power, the power transmission of the system is affected indirectly by voltage control [4]. 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.

The basic reactive components of a SVC are shunt capacitors and reactors. These capacitors are either fixed or varied in steps by thyristor switching and reactors are varied by means of thyristors. Based on these principles, various SVCs have been developed [5]. Those are Thyristor Switched Capacitor (TSC), Thyristor Controlled Reactor (TCR), Fixed Capacitors with TCR and TSC plus TCR.

It is also important to discuss how SVCs have been installed by different utilities. As stated in the paper "Reactive power compensation Technologies , State of the Art Review" by J. Dixon, L. Moran, J. Rodriguez and R. Domke, Northern States Power Co. (NSP) of Minnesota, USA is operating an SVC in its 500 kV power transmission network between Winnipeg and Minnesota. This device is located at Forbes substation, in the state of Minnesota. The purpose is to increase the power interchange capability on existing transmission lines. This solution was chosen instead of building a new line as it was found superior with respect to increased advantage utilization as well as reduced environmental impact. With the SVC in operation, the power transmission capability has been increased in about 200 MW. Further, without the SVC, power transmission capacity of the NSP network would be severely limited, either due to excessive voltage fluctuations following certain fault situations in the underlying 345 kV system or to severe over voltages at loss of feeding power.

As stated in the above said paper, an 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.

As mentioned above, SVC can control voltage under various load conditions, inject or absorb reactive power from system, increase transmission capacity by reducing transmission losses and also increase the stability of power transmission. However, a proper analysis is required for installing SVCs in Sri Lanka Transmission system with respect to power loss and voltage deviation as SVC's cost is comparatively high when it is compared with the traditional breaker switch capacitors.

The objective of this study is to find the optimum location and size of SVCs which minimize the power loss and voltage deviation. There are many methods and approaches to determine the optimal location of SVC in the power system using different techniques such as genetic algorithm (GA), simulated annealing (SA) and artificial immune system (AIS) [6]. In this analysis, a multi-objective function is considered in searching for a solution consisting of both the SVC location and size that minimizes the voltage deviation and active power loss.

1.2 Motivation

Breaker switched capacitor banks are used to compensate the reactive power in grid substations (GSS) in Sri Lanka. Installed capacitor banks in GSS are operated according the power factor in 33kV bus. But, in most of the time, power factor is in desired range due to the power correction in low voltage side and consumer level. So, capacitor banks are not operated giving required reactive power for maintaining the voltage. As an example, there is 50 Mvar capacitor bank in Kotugoda grid substation. But, the capacitor bank needs to provide only 15 Mvar due to the above reason.

Therefore, Sri Lankan utility has to run high cost thermal power plant such as Kelanitissa PS, Kerawalapitiya PS and Sapugaskanda PS to fulfill the reactive power requirement and to control the voltage.

In addition to above, existing capacitor banks have 5 Mvar switching steps. So, it is not possible to obtain an intermediate value. Therefore, there is always unserved reactive power. This is also a serious issue to be overcome.

Further, it is not possible to maintain the voltage in hydro maximum situation and thermal power plants are also required to be run to get the reactive power requirement in this situation. Also, the inductive series impedance of heavily load transmission lines like Biyagama- Kotmale increases reactive power consumption with the square of the current. Due to this reactive power, the capability of active power flowing of the line reduces and voltage drop appears, leading also to a reduction of the power transmitted to the load.

Therefore, developing a methodology to optimize the reactive power management in the systems using new technology has a great value for the utilities and to the country.

1.3 Objectives of the study

- The main objective of this study is to find out the optimum SVC combinations for Sri Lanka Transmission network to minimize the system voltage deviation and active power loss of transmission lines.

1.4 Outcomes of the study

The research findings will enable followings.

- Maintaining the system voltage at desired level and reducing voltage drops during severe disturbances.
- Increasing the power transfer in long transmission lines.
- Minimizing the use of thermal power plants which are running for only maintaining the system voltage.
- Reducing the construction of new transmission lines which are constructed to maintain the voltage at different contingency situations.

1.5 Scope of the work

As mentioned above, reactive power requirement is fulfilled by running thermal power plants during hydro maximum situation. Therefore, Hydro Maximum situation is considered for this analysis. The methodology of this analysis is described below.

- ➢ Analyze system reactive power requirement, power factor and voltage profile of 132kV/220kV buses of grid substations.
- ➢ Study the existing reactive compensation methodologies.
- ➢ Identify the grid substations those SVCs required to be installed.
- ➢ Load flow is carried out using PSS/E software for different combinations of SVCs for selected grid substations.

- For each different combination, following parameters are noted comparing the values with SVC and without SVC
  - The total active power loss in power system
  - Voltage deviation of all the buses in the system
  - Total investment cost for particular SVC combination
- Check the relationship between reduction of power loss and voltage deviation with SVC cost.
- Check the possibility of developing a single function between power loss and voltage deviation with SVC cost.
- If proper relationship cannot be developed between above, optimum SVC combinations are selected to minimize voltage deviation and power loss and then SVC cost is separately considered.
- Select the optimum SVC combinations which minimize voltage deviation and power loss and analyze for them single contingency situation.

Chapter 2

Static Var Compensators

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

2.1.1 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 [2]. 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.

2.1.2 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 [2]. 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° [2]. However, they do generate harmonic currents that must be absorbed by filters.

2.1.3 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 [3]. 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 a per-cycle basis, allowing for very rapid higher control of system voltage.

2.2 Basic operation of SVC

The SVC with combination of Fixed Capacitor (FC) plus TCR is used for this 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 [4]. 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 [4]. 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].

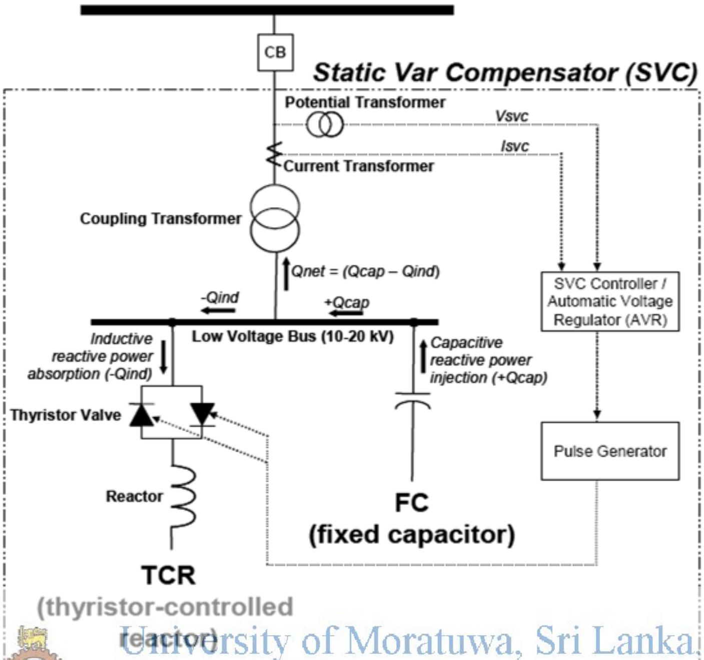

Figure 2.1 : Basic arrangement of SVC

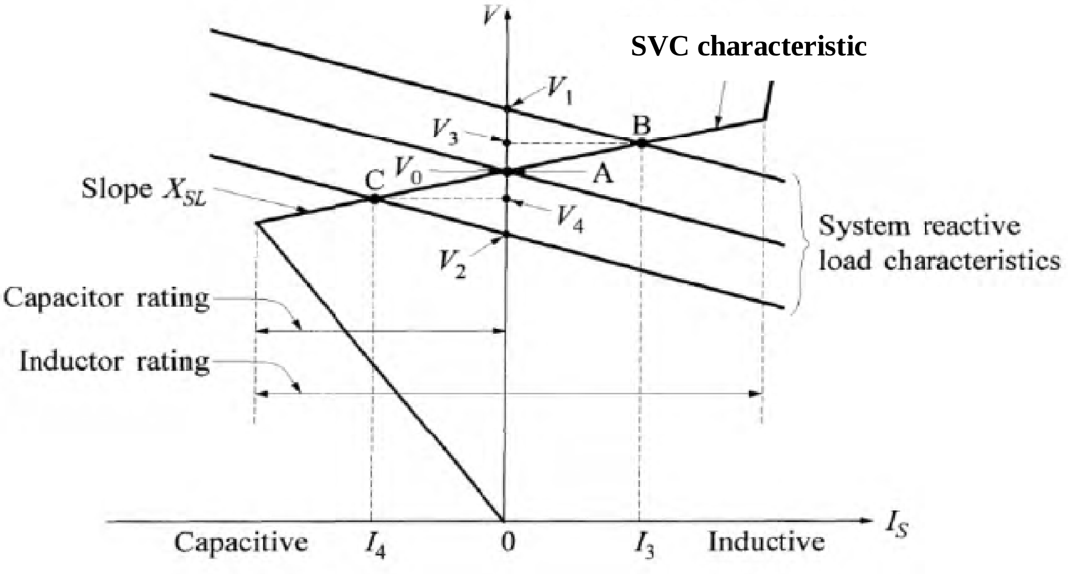

Figure 2.2 : Graphical solution of SVC operating point for given system

If the system voltage increases due to decrease in system load level, voltage will increase to V_1 without a SVC. But, with SVC, operating point moves to B by absorbing inductive current I_3 holding the voltage at V3. Similarly, if the voltage decreases due to increase in system load level SVC will hold the voltage at V_4 instead of at V2 without the SVC.

2.3 SVCs for Sri Lanka Transmission System

Considering the voltage profile, the reactive power requirement of the system and the cost, implementing of SVCs with the combination of Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR) is analyzed in this study.

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 [7]. 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 [7]. The capacitor groups are tuned to the 5^{th} & 7^{th} 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 for Pannipitiya GS is shown in figure 2.4, 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.

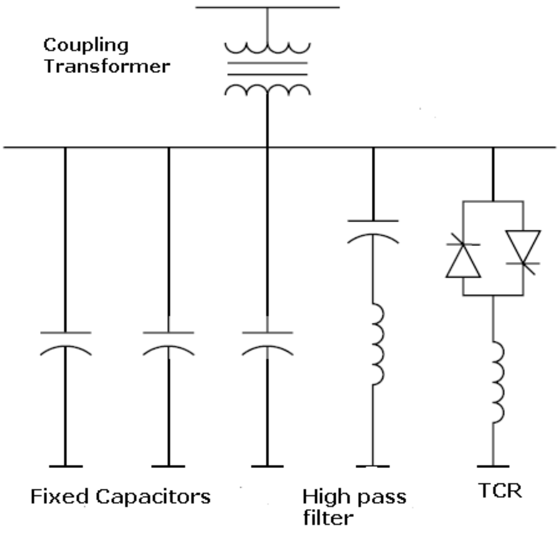

Figure 2.3 : Fixed Capacitor and TCR combination of SVC

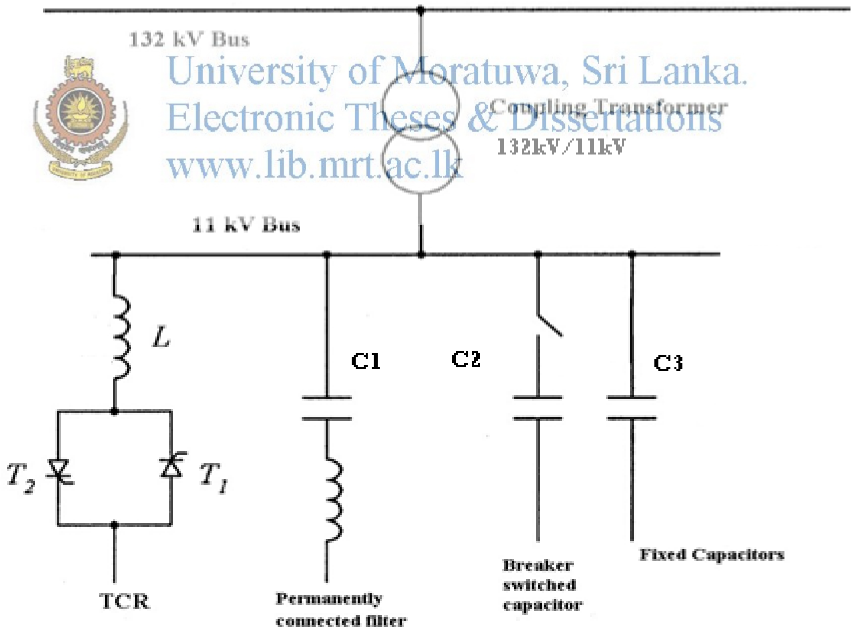

Figure 2.4 : SVC arrangement for Pannipitiya GS

The control objective is to maintain the voltage at 132 kV bus at Pannipitiya GS above 1.00 p.u. If the voltage of 132kV 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. Also, 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.

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

$$Q=BxV^2$$

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 2.5. 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.

$$V_{error}=V_{ref}-V-(I_{svc}*X_{sl})$$

V_{error} : Voltage error signal to PI controller

I_{svc} : SVC current

V_{ref} : Reference voltage signal

X_{sl} : Slope reactance of SVC

V : Voltage of HV bus

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

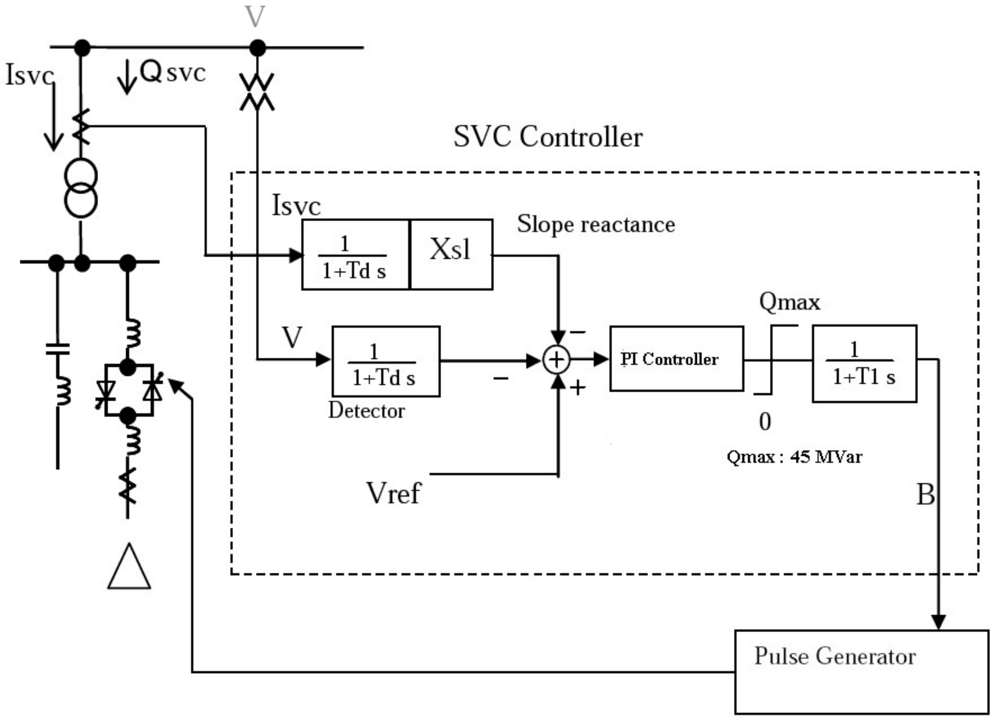

Figure 2.5: SVC control diagram

Chapter 3

Existing Transmission System of Sri Lanka

3.1 Existing reactive power compensation methodology

The reactive power flow in the network creates excessive network losses, under voltage conditions and limits the utilization of transmission line and transformer capacities. Sri Lankan utility currently uses capacitor banks to compensate the reactive power in following Grid Substations.

Table 3.1: Existing installed capacitor banks

Grid Substation	Voltage level (kV)	Total Mvar
Thulhiriya	33	10
Ampara	33	30
Kiribathkumbura	33	20
Kurunegala	33	10
Kotugoda	33	50
Kurunegala	33	10
Habarana	33	10
Mathugama	33	20
Puttalama	33	20
Panadura	33	20
Athurugiriya	33	20

Source: System Control Center, CEB

Above installed capacitor banks are breaker switched shunt capacitors and operated according the power factor in 33kV bus. So, even in low voltage conditions capacitor banks are not operated as power factor is in desired range due to power correction in low voltage side and consumer level. As an example, there is 50 Mvar capacitor bank in Kotugoda grid substation. But, in the most of time, it supplies only 15 Mvar due to the power factor has a desired value. Also the 30 Mvar capacitor bank in Ampara GS normally operates below 5Mvar due to the above reason. So, the voltage drops in 132 kV bus of Ampara GS cannot be minimized with this capacitor bank although power factor is corrected.

The step size of each bank is 5Mvar. So, there is a difficulty to obtain an intermediate value such that the reactive power requirement is 14 Mvar in a particular moment, it is possible to get only 10 Mvar. These capacitor banks are fixed a such way that using symmetrical banks for each bus section in the 33kV bus bar. All the capacitor banks in the network are connected to the 33kV load bus in the relevant grid substations and there are no capacitor banks at the transmission level due to higher cost for high voltage levels.

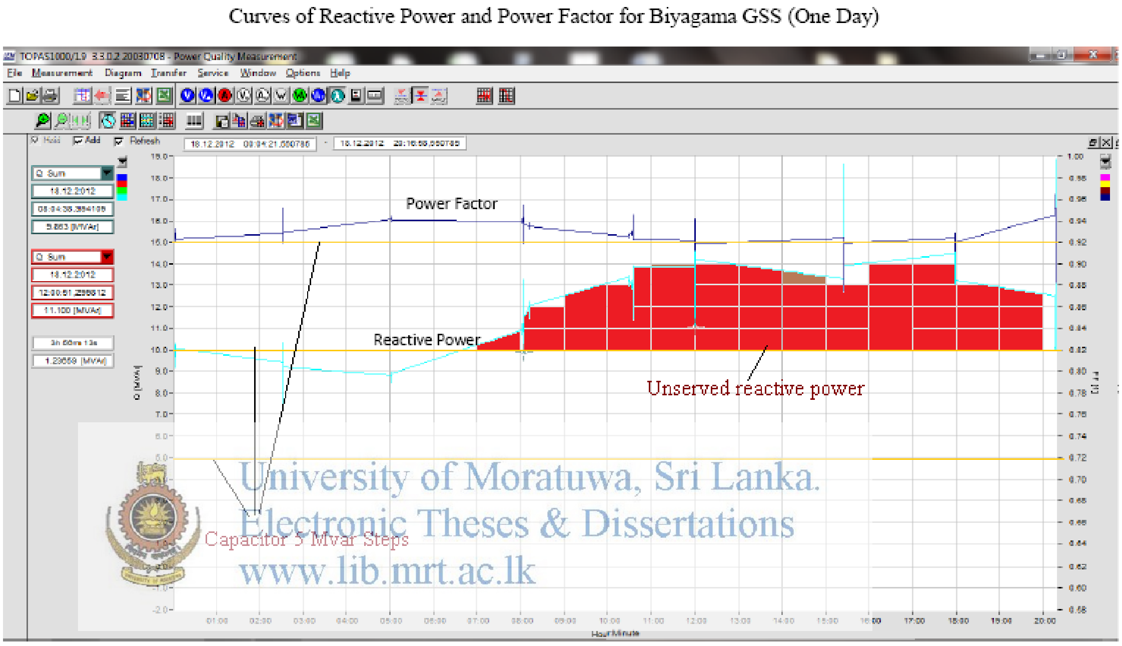
Curves of Reactive Power and Power Factor for Biyagama GSS (One Day)

Figure 3.1: Reactive power & power factor curve in Biyagama GS

3.2 Reactive power requirement

If the reactive power is supplied by a power plant in far away, loss is high due to the high current flow in the transmission line or inadequate capacity transmission lines.

It is possible to observe a high power loss in heavily loaded Biyagama- Kotamale 220kV Transmission line due to inductive series impedance resulting reducing the power transfer capacity. In hydro maximum situation, the voltage of 132kV/220kV bus bars mostly in Colombo region cannot be maintained at acceptable levels. So, in this situation, voltage is controlled by running high cost thermal power plant such as Kelanitissa PS and Sapugaskanda PS incurring substantial losses to the utility.

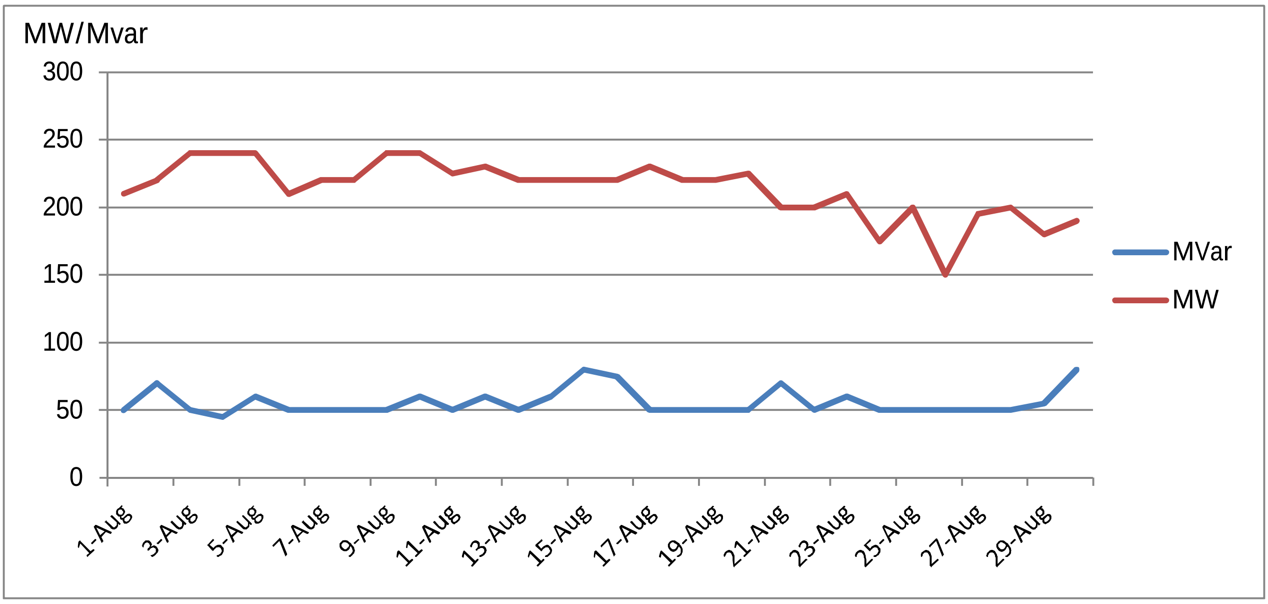

Figure 3.2: Reactive power flow in Kothamle line 1 at Biyagama GS in August 2013-Night Peak

3.3 Voltage Drops

As explained in above section, installed capacitor banks have not been able to maintain the voltage at desired level without running thermal power plants. Therefore, system voltage drops are required to be analyzed before selecting a SVC for a particular Grid Substation.

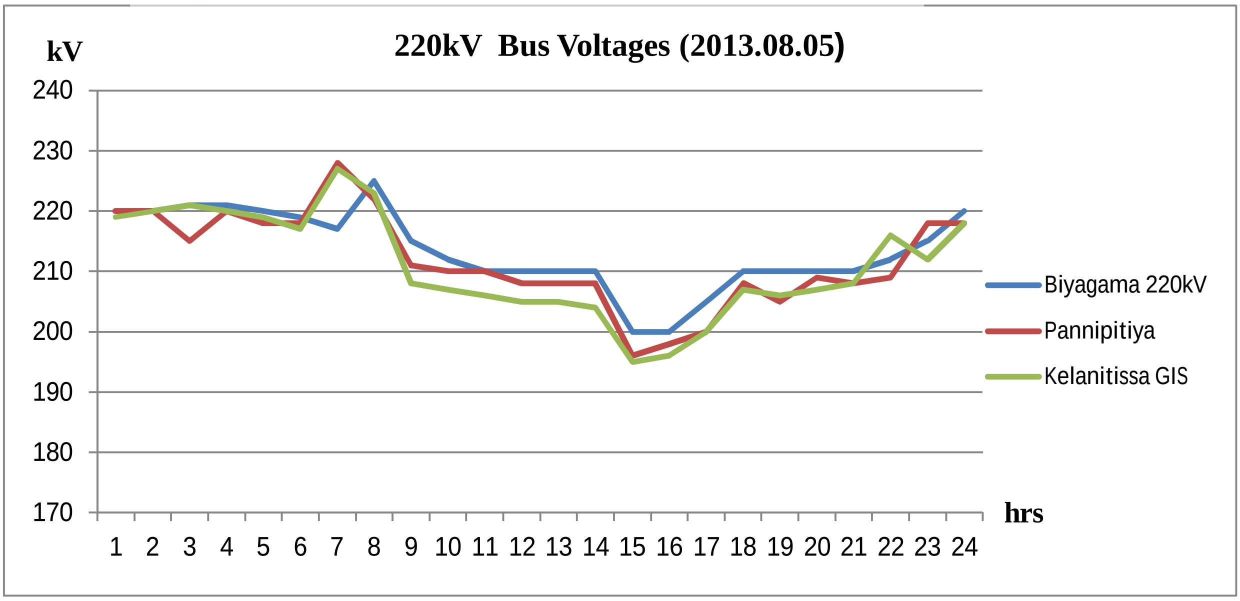

Figure 3.3: 220kV Bus Voltages of Biygama, Pannipitiya, Kelanitissa GSS on 05.08.2013, (Hydro Maximum Situation)

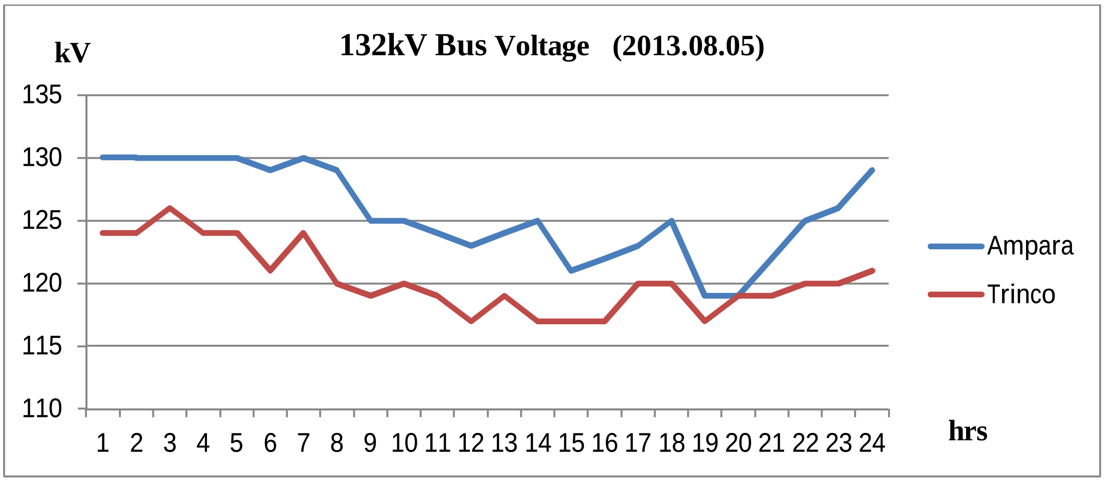

Figure 3.4: 132kV Bus Voltages of Ampara and Trincomalee GS on 05.08.2014, (Hydro Maximum Situation)

By analyzing above graphs, it can be observed that the system is running with considerable voltage deviations.

3.4 Details of thermal power plants running for controlling the voltage

3.4.1 Kelanitissa Power Plant

The smaller GTs (GT1-5) in the Kelanitissa normally run in the synchronous condenser mode to supply reactive power (var) to the system. In this mode, the synchronous generator acts like a synchronous motor. It draws small amount of real power (in kW range) and it delivers huge amount of reactive power (in Mvar range) to the system. Therefore, in this situation, Kelanitissa PS is functioned as a voltage stabilizer by supplying reactive power to the system.

Table 3.2: Kelantissa Power station Day time Generation data

05.08.2013		7:30	8:00	8:30	9:00	9:30	10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30
KELANITISSA																
Kps Steam 01	MW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mvar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kps Steam 02	MW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mvar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kps - Gt 01	MW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mvar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kps - Gt 02	MW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mvar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kps - Gt 03	MW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mvar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kps - Gt 04	MW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mvar	7	9	10	8	8	8	8	8	8	8	8	8	8	8	9
Kps - Gt 05	MW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mvar	8	10	11	10	9	10	10	10	10	10	9	9	9	9	10
Kps - Gt 06	MW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mvar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3.3: Kelantissa Power station night time Generation data

05.08.2013		15:00	15:30	16:00	16:30	17:00	17:30	18:00	18:30	19:00	19:30	20:00	20:30	21:00	21:30	22:00
KELANITISSA																
Kps Steam 01	MW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mvar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kps Steam 02	MW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mvar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kps - Gt 01	MW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mvar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kps - Gt 02	MW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mvar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kps - Gt 03	MW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mvar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kps - Gt 04	MW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mvar	10	9	8	7	4	3	3	4	5	5	5	4	4	4	5
Kps - Gt 05	MW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mvar	12	12	9	9	3	2	3	4	4	4	4	3	3	4	5
Kps - Gt 06	MW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mvar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

3.4.2 Sapugaskanda Power Plant

Sapugaskanda Power Station consists of four 20 MW generators and eight 10MW generators run on heavy fuel oil. In hydro maximum situation, these power plants are not required to operate. But, some of above eight generators are operated to obtain reactive power for the purpose of maintaining the voltage.

Table 3.4: Sapugaskanda Power plant Generation data (05.08.2013)

		10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00	15:30	16:00	16:30	17:00	17:30	18:00
Sapu 05	MW	7	7	7	7	7	7	7	7	7	7	7	7	9	9	9	9	9
	Mvar	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	5
Sapu 06	MW	7	7	7	7	7	7	7	7	7	7	7	7	9	9	9	9	9
	Mvar	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	5
Sapu 07	MW	7	7	7	7	7	7	7	7	7	7	7	7	9	9	9	9	9
	Mvar	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	5
Sapu 08	MW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mvar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sapu 09	MW	7	7	7	7	7	7	7	7	7	7	7	7	9	9	9	9	9
	Mvar	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	5
Sapu 10	MW	7	7	7	7	7	7	7	7	7	7	7	7	9	9	9	9	9
	Mvar	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	5
Sapu 11	MW	0	0	0	0	7	7	7	7	7	7	7	7	9	9	9	9	9
	Mvar	0	0	0	0	4	4	4	4	4	4	4	4	5	5	5	5	5
Sapu 12	MW	7	7	7	7	7	7	7	7	7	7	7	7	9	9	9	9	9
	Mvar	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	5

3.5 Losses due to running thermal power plants

The running time of following power plants depends on the system operations and these power plants are not operated regularly during the hydro maximum situation.

3.5.1 Kelanitissa Gas Turbine

Approximate active power drawn from the system for one GT	= 0.45 MW
Average running time per day	= 15 hrs
Total units per day	= 0.45x15x1000 kWh
	= 6,750 kWh
Average Cost per unit (Rs./kWh)	= Rs. 17.93
Total cost per day for 2 GTs	= Rs. 2x17.93 x 6,750.00
	= Rs. 242,055.00

If two GTs are running to supply reactive power, the utility losses Rs. 242,055.00 approximately per day.

3.5.2 Kelanitissa combined cycle power plant

In hydro maximum situation, this plant is operated in open cycle to control the voltage.

Unit cost of Kelanitisa PS to run Open Cycle is Rs. 40 (Rs./kWh) and here, it is considered that average unit cost for hydro generation is Rs. 3.00 (Rs./kWh). This power station has to be run to get the reactive power only for maintaining the system voltage. If this reactive power can be supplied by a reactive power compensator, there is no need of running this thermal power station during hydro maximum situation. So, utility has to spend additional Rs. 37.00 per unit to run this power plant for the purpose of voltage control.

Generated Power = 40 MW
Average running time per day = 6 hrs
Total units per day = 40x6x1000 kWh
= 240,000 kWh
Aprox. cost per day = Rs. 240,000x 37
= Rs. 8,880,000.00

3.5.3 Asia power station

In hydro maximum situation, this power station is also operated to maintain the voltage.

Unit cost for Open Cycle = Rs. 24.00
Average unit cost for hydro generation = Rs. 3.00
Generated Power = 40 MW
Average Running time per day = 06 hrs
Total units per day =40x6x1000kWh =240,000 kWh
Aprox. cost per day = Rs. 240,000x (24-3)
= Rs. 5,040,000.00

3.5.4 Sapugasknada power station

In hydro maximum situation, this power station is also operated to control the voltage.

From Sapugakanda **plant A** = 16x2 = 32 MW
Unit cost = Rs. 23.15
Average unit cost for hydro generation = Rs. 3.00
Average running time per day = 06 hrs
Total units per day =32x6x1000kWh=192,000 kWh
Aprox. Total loss = Rs. 192,000 x (23.15-3.00)
= Rs. 3,868,800.00

From Sapugakanda **plant B** = 9x4 = 36 MW
Unit cost = Rs. 20.03

Average unit cost for hydro generation = Rs. 3.00
Average running time per day = 06 hrs
Total units per day =36x6x1000kWh=216,000 kWh
Aprox. Total loss = Rs. 216,000x (20.03-3.00)
= Rs. 3,678,480.00

Total cost per day = Rs. 7,547,280.00

As mentioned above, these power plants are not operated on a regular basis to get reactive power for the purpose controlling voltage. So, it is difficult to calculate total loss per month or total loss per year for the above power stations. However, if above three power plants run 25 days per year to control the voltage, the utility looses approximately Rs. 500 million per year.

Methodology, Simulation and Analysis of SVC selection

For system studies, the utility mainly considers following generation and loading scenarios.

1. Thermal Maximum Night Peak (TMNP)
2. Thermal Maximum Day Peak (TMDP)
3. Hydro Maximum Night Peak (HMNP)
4. Hydro Maximum Day Peak (HMDP)
5. Off Peak (OP)

As described in above section, in order to maintain 132kV and 220kV bus voltage at grid substations in hydro maximum scenario, high cost thermal power plants are required to be run. Therefore, for this analysis, Hydro Maximum Night peak scenario is mainly considered and Hydro Maximum Day Peak scenario is also analyzed.

4.1 Function of Voltage deviation, Power loss and SVC Cost

Initially, the possibility of developing a function is considered to get the optimum SVC locations and sizes that minimize the voltage deviation, active power loss and SVC cost. The objective function, F(x) can be defined as follow.

$$F(x) = a\,P_L + b\,V_d + c\,C_{svc}$$

P_L = Power Loss, **V_d**= Voltage deviation **C_{svc}**= SVC Cost

a, b,c = corresponding coefficients for Power loss, Voltage deviation, SVC cost

4.1.1 Active power loss

The total active power loss in a power system can be calculated using following equation[5].

$$P_{loss} = \sum_{l=1}^{b} R_l\, I_l^2 = \sum_{i=1}^{b} \sum_{j=1, i\neq j}^{b} \left[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)\right] Y_{ij}\cos\emptyset_{ij}$$

Where

b : Number of lines
Ri : Resistance of the line
Ii : Current through line
Vi : Voltage at the node i
δi : Angle at the node i
Yi &$\emptyset i$: Magnitue and angle of the line admittance

$$P_L = \frac{\text{Total active power loss with SVC}}{\text{Total active power loss in Normal Condition}}$$

$$P_L = \frac{\sum P_{loss}\, with\ SVC}{\sum P_{loss}\, normal\ condition}$$

The active power loss in each transmission line is considered here.

4.1.2 Voltage deviation

The voltage deviation index for a power system can be considered as the deviation of voltage magnitudes of each and every bus from unity.

$$V_{div} = \sum_{i=1}^{b} \left(\frac{V_{iref} - V_i}{V_{iref}} \right)^2$$

b : number of lines
V_{iref} : 1

$$\mathrm{V_d} = \frac{\text{Total of square of voltage deviation of the system with SVC}}{\text{Total of square of voltage deviation of the system in Normal Condition}}$$

$$\mathrm{V_d} = \frac{\sum(1 - \mathrm{V_i}\ \text{with SVC})^2}{\sum(1 - \mathrm{V_i}\ \text{in normal condition})^2}$$

Voltage deviation of each 33kV, 132kV and 220kV buses in CEB network is considered here using results obtained from PSS/E software.

4.1.3 Cost of SVC

The total SVC cost in US$/kVAr is given by following equation [5].

$$\mathrm{C_{SVC}} = \sum_{k=1}^{n} 0.0003\mathrm{Q_k}^2 - 0.3051\mathrm{Q_k} + 127.38$$

Qk is the reactive power capacity of k_{th} installed SVC, in Mvar

4.2 Analysis using PSS/E software

4.2.1 Selected SVC Combination

Considering the voltage drops, reactive power requirement of particular grid substation as per CEB Transmission Planning forecast and retirement of thermal power plant such as Embilipitiya ACE power, the location and capacity of SVC is basically selected. Further, as there are voltage drops mainly in Colombo region grid substations during the hydro maximum situation, it is also a major consideration for selecting the location of SVC. System data file for PSS/E analysis was obtained from System control center, CEB in August, 2013.

Table 4.1 Selected SVC Combinations with Capacities

Combination	Grid Substation	Voltage Level (kV)	Proposed Capacity (Mvar)
1	Pannipitiya	132	45
2	Biyagama	220	45
3	Kolonnawa	132	36
4	Kotugoda	220	45
5	Pannipitiya	132	45
	Biyagama	220	45
6	Pannipitiya	132	45
	Kolonnawa	132	36
7	Pannipitiya	132	45
	Kotugoda	220	45
8	Kolonnawa	132	36
	Biyagama	220	45
9	Kotugoda	220	45
	Biyagama	220	45
10	Kotugoda	220	45
	Kolonnawa	132	36
11	Galle	132	27
12	Trincomalee	132	18
13	Embilipitiya	132	36
14	Galle	132	27
	Embilipitiya	132	36

4.2.2 Generation & load details for Hydro Maximum night peak and Capacitor banks details

4.2 Generation details

Bus Name	P_{Gen}(MW)	Q_{Gen} (Mvar)
Laxapana	40	5
Wimalasurendra	50	0
Polpitiya	74	34
Canyon	56	0
Samanalawewa	100	54
Ukuwela	34	20
Bowathenna	30	15
Kukuleganga	60	30
KDH	0	0
Embilipitiya	0	30
Puttalam	83	30
Barge	60	30
Randenigala	113.5	1.1
Chunnakaum	24	5.5
Wind	0	0
New Laxapana 1	50	7.7
New Laxapana 2	50	21.6
Kothamale Gen 1	60	45
Kothamale Gen 2	60	45
Kothamale Gen 3	60	45
Upper Kothmale 1	70	27.4
Upper Kothmale 2	70	27.4
Victoria 1	70	25.1
Victoria 2	70	25.1
Victoria 3	70	25.1
Rantabe 1	25	0.9
Rantabe 2	25	0.8
GT 07	0	0
KCCP GT 15.000	40	90
KCCP ST 11.500	59	35
AES GT	0	0
AES ST	0	0
Kerawalapitiya-G	0	0
Kerawalapitiya-S	0	0
Sapugaskanda	14	7.2
Sapugaskanda 2	44	16
Puttalam Coal 1	150	80.4
Puttalam Coal 2	150	80.4
Wind NOR 33.000	0	0
Total	**1861.5**	**849.7**

4.3 Load details

Bus Name	Voltage(kV)	MW	Mvar
Hambantota	33	1.18	0.92
Horana	33	43.07	20.7
Katunayaka	33	48.38	22.77
Kosgama	33	47.79	24.15
Seethawaka	33	21.24	13.8
Nuwaraeliya	33	14.16	0
Thulhiriya	33	27.14	20.7
Kolonnawa –A	33	55.578	26.2315
Kolonnawa-B	33	20.06	10.557
Pannipitiya	33	67.26	37.95
Biyagama	33	84.96	42.55
Kotugoda	33	42.008	16.56
Kotugoda New	33	23.6	11.5
Sapugaskanda	33	57.23	32.2
Bolawatta	33	54.87	33.143
Badulla	33	20.65	8.395
Balangoda	33	9.145	10.005
Deniyaya	33	15.93	6.141
Galle	33	23.718	17.25
Galle- B	33	14.042	4.4965
Embilipitiya	33	18.88	6.9
Mathara	33	48.38	19.55
Kurunegala	33	50.74	24.15
Habarana	33	43.66	31.05
Anuradhapura-A	33	15.4934	4.1055
Anuradhapura-B	33	4.13	1.173
New Anuradhpura	33	18.88	4.37
Trincomalee	33	33.276	10.6605
Kilinochhi	33	9.204	1.403
Chunnakum	33	21.712	9.2
Rathnapura	33	0	10.35
Kiribathkumbura	33	70.8	31.05
Valachchenei	33	17.405	8.211
Rathmalana	33	63.72	33.2925
Mathugama	33	37.524	21.85
Puttalama	33	15.93	4.6
Cement	33	17.2516	8.05
Athurugiriya	33	37.76	8.763
Veyangoda	33	37.76	8.763
Jayawardanapura	33	16.756	7.015
Panadura	33	49.56	26.45
Madampe	33	29.5	13.8
Kelaniya	33	20.65	12.4775
Ambalangoda	33	26.432	13.34
Dehiwala	33	37.052	21.16
Pannala	33	42.952	24.38
Aniyakanda	33	23.6	13.8
Colombo Sub I	11	32.85	14.364
Colombo Sub A	11	45.666	17.37
Colombo Sub E	11	48.753	19.242
Colombo Sub F	11	41.4	18
Puttalam Coal	20	23.6	13.8
Colombo Sub C	11	27.376	11.73
Total		**1842.31**	**874.424**

Table 4.4: Capacitor banks in operation during the analysis

Grid Substation	Voltage level (kV)	Total Mvar	Obtainable capacity for hydro maximum night peak situation (Mvar)
Thulhiriya	33	10	10
Ampara	33	30	0
Kiribathkumbura	33	20	20
Kurunegala	33	10	10
Kotugoda	33	50	15
Habarana	33	10	10
Mathugama	33	20	15
Puttalama	33	20	0
Panadura	33	20	10
Athurugiriya	33	20	10

4. 3 Results

For each combination, values for P_L, V_d are calculated using PSS/E load flow results. Each SVC is added to particular buses under Switched Shunt in PSS/E software and control mode was set to continuous.

Although SVC capacity is selected considering the reactive power requirement, actual required capacity of the SVCs can be obtained after running PSS/E. Then, SVC cost is calculated using equation (4.1.3).

Table 4.5: PSS/E results for voltage deviation, power loss and SVC cost for Hydro maximum night peak

Combination	**Grid Substation**	**Voltage Level (kV)**	**Proposed Capacity (Mvar)**	**Actual Capacity (Mvar)**	**Power loss (P_L)**	**Voltage Deviation (V_d)**	**SVC Cost (USD/ Million)**
1	Pannipitiya	132	45	45	**0.9854**	**0.8887**	5.14
2	Biyagama	220	45	45	**0.9864**	**0.9137**	7.71
3	Kolonnawa	132	36	36	**0.9885**	**0.9064**	4.2
4	Kotugoda	220	45	45	**0.9895**	**0.9152**	7.71
5	Pannipitiya	132	45	42.84	**0.9816**	**0.8719**	12.85
	Biyagama	220	45	45			
6	Pannipitiya	132	45	45	**0.9833**	**0.8829**	8.47
	Kolonnawa	132	36	36			
7	Pannipitiya	132	45	42.91	**0.9836**	**0.8724**	12.85
	Kotugoda	220	45	45			
8	Kolonnawa	132	36	36	**0.9829**	**0.8813**	12.15
	Biyagama	220	45	45			
9	Kotugoda	220	45	45	**0.9845**	**0.8779**	15.42
	Biyagama	220	45	45			
10	Kotugoda	220	45	45	**0.9864**	**0.8841**	12.15
	Kolonnawa	132	36	36			
11	Galle	132	27	27	**0.9652**	**0.6694**	3.22
12	Trincomalee	132	18	17.24	**0.9899**	**0.8901**	2.1
13	Embilipitiya	132	36	36	**0.9966**	**0.8724**	4.2
14	Galle	132	27	27	**0.9652**	**0.6278**	6.88
	Embilipitiya	132	36	36			

4.3.1 Relationship between Voltage deviation, Power loss and SVC cost

Before developing a function between power losses, voltage deviation with respect to SVC cost, the relationship between each two parameter is analyzed.

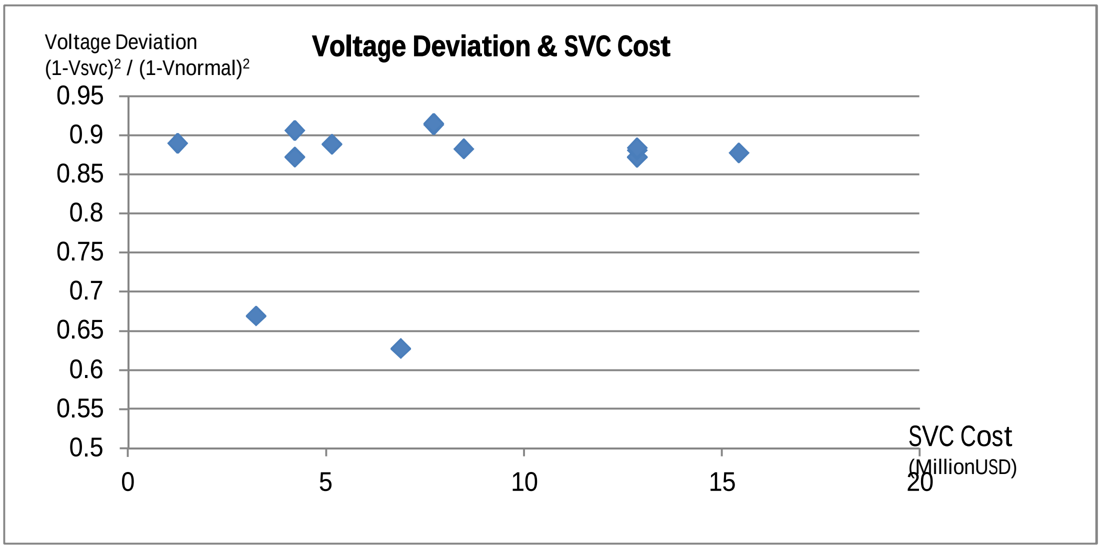

Figure 4.1 : Relationship between Voltage Deviation & SVC Cost

It can be observed from above results that voltage deviation is not properly minimized with SVC cost (the capacity of SVC reflects the cost). The location of the SVC is also effecting on minimizing the voltage deviation and 07 nos. of different locations are considered in this analysis. Therefore, it is difficult to develop a proper relationship between SVC cost and voltage deviation unless the location is same.

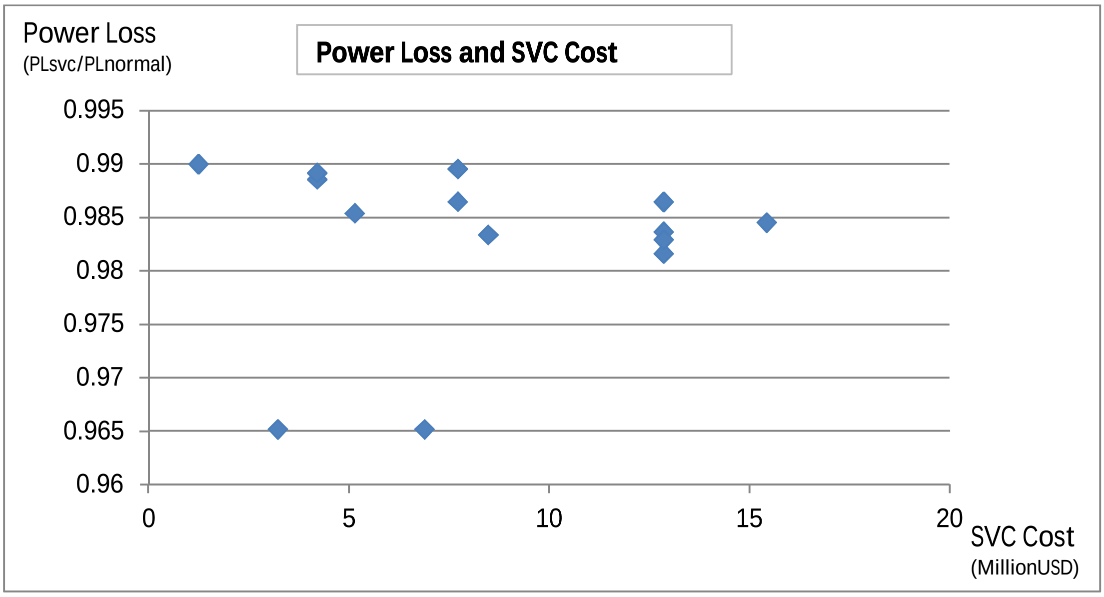

Figure 4.2: Relationship between Power loss & SVC Cost

As voltage is related to power loss, it is also difficult to develop a proper relationship between power loss and SVC cost. Therefore, according to the above results, optimum combination cannot be selected based on single function consisted of power loss, voltage deviation and SVC cost, Therefore, minimization of only real power loss and bus voltage deviation is considered in finding optimal location and size of SVC. Then, SVC cost is considered separately.

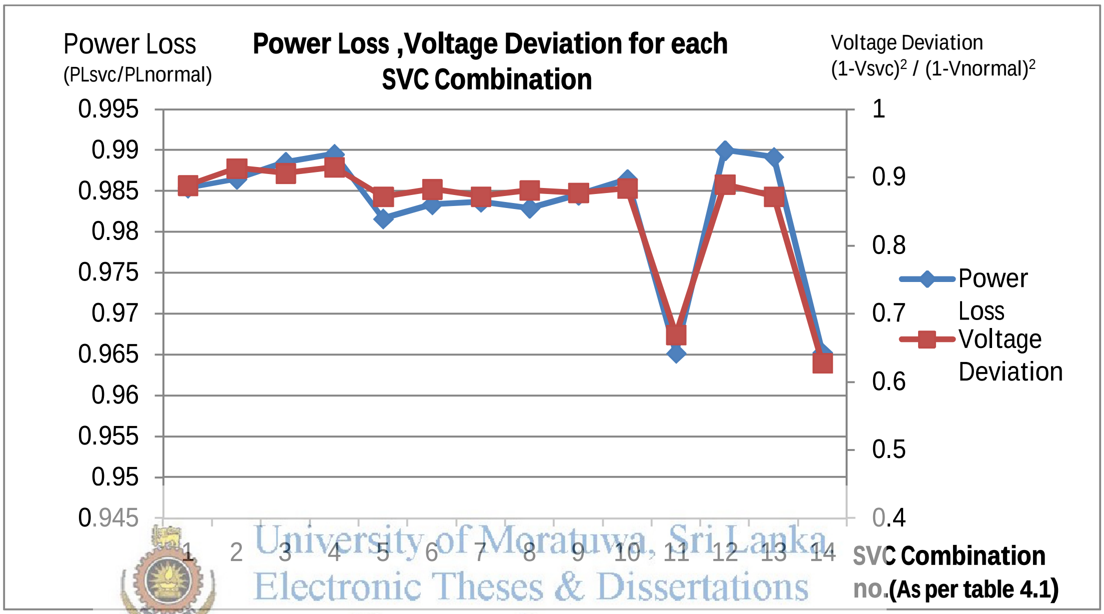

Figure 4.3 : Voltage Deviation, Power Loss for each SVC Combination

The power loss and the voltage deviation are plotted in same graph for each SVC combination. After identifying minimum points for power loss and voltage deviation in each case, the optimum combinations can be selected.

However, to effectively select the optimum SVC combinations, power loss and voltage deviation should be converted to single objective function as described in next section.

4.3.2 Linear Combination between Power Loss and Voltage Deviation

Linear combination of real power loss and voltage deviation can be defined as follows:.

$$Ƒ(x) = w1 \times ƒ1(x) + w2 \times ƒ2(x)$$

Where, Ƒ (x) is the weighted sum of real power loss and bus voltage deviation objective functions which are combined to form single objective function using weighing factor w

f1(x) = Voltage Deviation for each combination

f2(x) = Power Loss for each combination

W1= 1-W2

W1 = 0.05 -0.95

Table 4.6: Weighted sum of Voltage Deviation, Power Loss for each SVC Combination

W1	W2		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
0.05	0.95	F(x)	0.89362	0.91738	0.91059	0.91898	0.87748	0.88798	0.87802	0.88639	0.88324	0.88929	0.68422	0.89518	0.87830	0.64470
0.1	0.9		0.89845	0.92102	0.91469	0.92269	0.88296	0.89300	0.88358	0.89147	0.88857	0.89441	0.69901	0.90017	0.88414	0.66157
0.15	0.85		0.90328	0.92465	0.91880	0.92640	0.88844	0.89802	0.88914	0.89656	0.89390	0.89952	0.71380	0.90516	0.88997	0.67843
0.2	0.8		0.90811	0.92829	0.92290	0.93012	0.89392	0.90304	0.89470	0.90164	0.89924	0.90464	0.72859	0.91015	0.89581	0.69530
0.25	0.75		0.91294	0.93193	0.92700	0.93383	0.89941	0.90806	0.90026	0.90672	0.90457	0.90975	0.74338	0.91514	0.90165	0.71217
0.3	0.7		0.91777	0.93556	0.93111	0.93755	0.90489	0.91308	0.90583	0.91180	0.90990	0.91487	0.75817	0.92013	0.90748	0.72904
0.35	0.65		0.92261	0.93920	0.93521	0.94126	0.91037	0.91810	0.91139	0.91688	0.91523	0.91998	0.77295	0.92512	0.91332	0.74591
0.4	0.6		0.92744	0.94284	0.93932	0.94498	0.91585	0.92312	0.91695	0.92196	0.92056	0.92510	0.78774	0.93011	0.91915	0.76278
0.45	0.55		0.93227	0.94648	0.94342	0.94869	0.92133	0.92815	0.92251	0.92704	0.92589	0.93021	0.80253	0.93510	0.92499	0.77965
0.5	0.5		0.93710	0.95011	0.94753	0.95240	0.92682	0.93317	0.92807	0.93212	0.93122	0.93532	0.81732	0.94009	0.93082	0.79652
0.55	0.45		0.94193	0.95375	0.95163	0.95612	0.93230	0.93819	0.93363	0.93720	0.93655	0.94044	0.83211	0.94508	0.93666	0.81339
0.6	0.4		0.94676	0.95739	0.95574	0.95983	0.93778	0.94321	0.93919	0.94228	0.94188	0.94555	0.84690	0.95007	0.94249	0.83026
0.65	0.35		0.95159	0.96103	0.95984	0.96355	0.94326	0.94823	0.94475	0.94736	0.94721	0.95067	0.86169	0.95506	0.94833	0.84713
0.7	0.3		0.95642	0.96466	0.96395	0.96726	0.94874	0.95325	0.95031	0.95245	0.95254	0.95578	0.87647	0.96006	0.95417	0.86399
0.75	0.25		0.96125	0.96830	0.96805	0.97097	0.95423	0.95827	0.95587	0.95753	0.95788	0.96090	0.89126	0.96505	0.96000	0.88086
0.8	0.2		0.96608	0.97194	0.97215	0.97469	0.95971	0.96329	0.96143	0.96261	0.96321	0.96601	0.90605	0.97004	0.96584	0.89773
0.85	0.15		0.97091	0.97558	0.97626	0.97840	0.96519	0.96832	0.96699	0.96769	0.96854	0.97113	0.92084	0.97503	0.97167	0.91460
0.9	0.1		0.97574	0.97921	0.98036	0.98212	0.97067	0.97334	0.97255	0.97277	0.97387	0.97624	0.93563	0.98002	0.97751	0.93147
0.95	0.05		0.98057	0.98285	0.98447	0.98583	0.97615	0.97836	0.97811	0.97785	0.97920	0.98136	0.95042	0.98501	0.98334	0.94834

C1-C14: Different SVC combinations

F(x) values are plotted against each SVC combination and minimum points of F(x) give the optimum combinations.

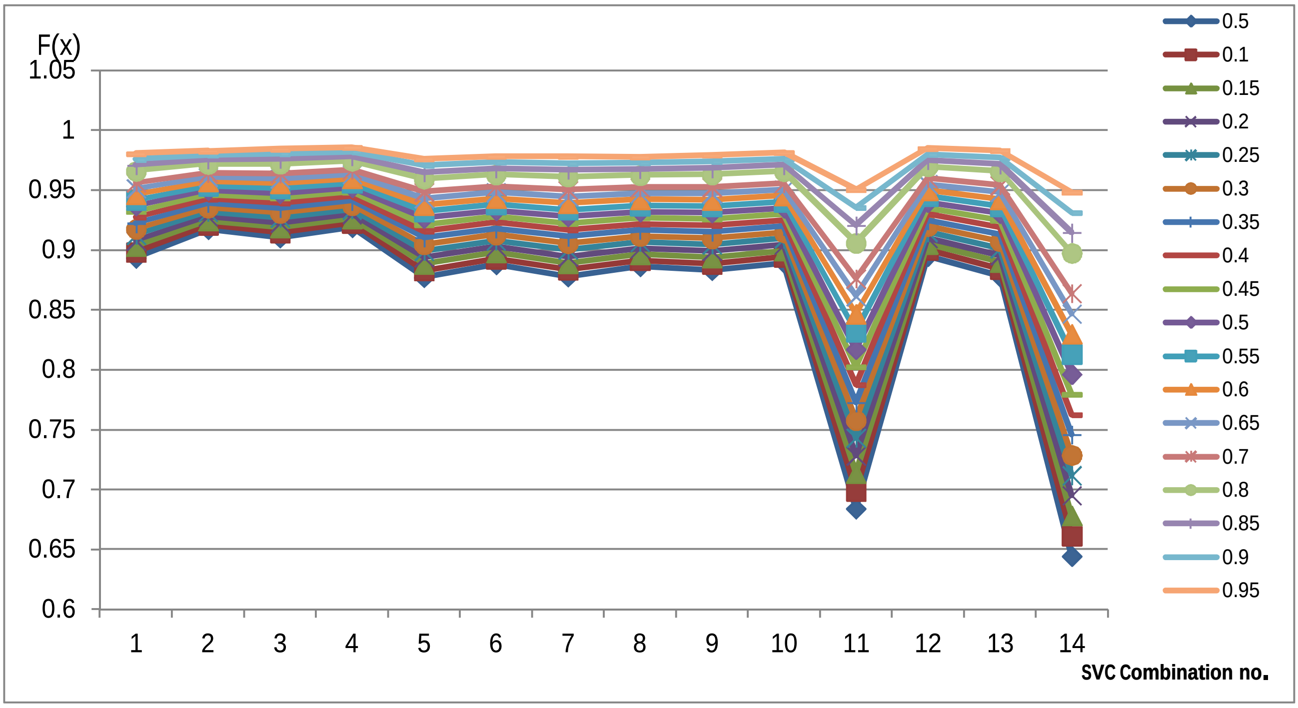

Figure 4.4: F(x) value for each SVC Combination

SVC cost also can be included to the above graph. Then, it will be possible to decide the cost for minimizing voltage deviation and power loss with respect to selected SVC combinations.

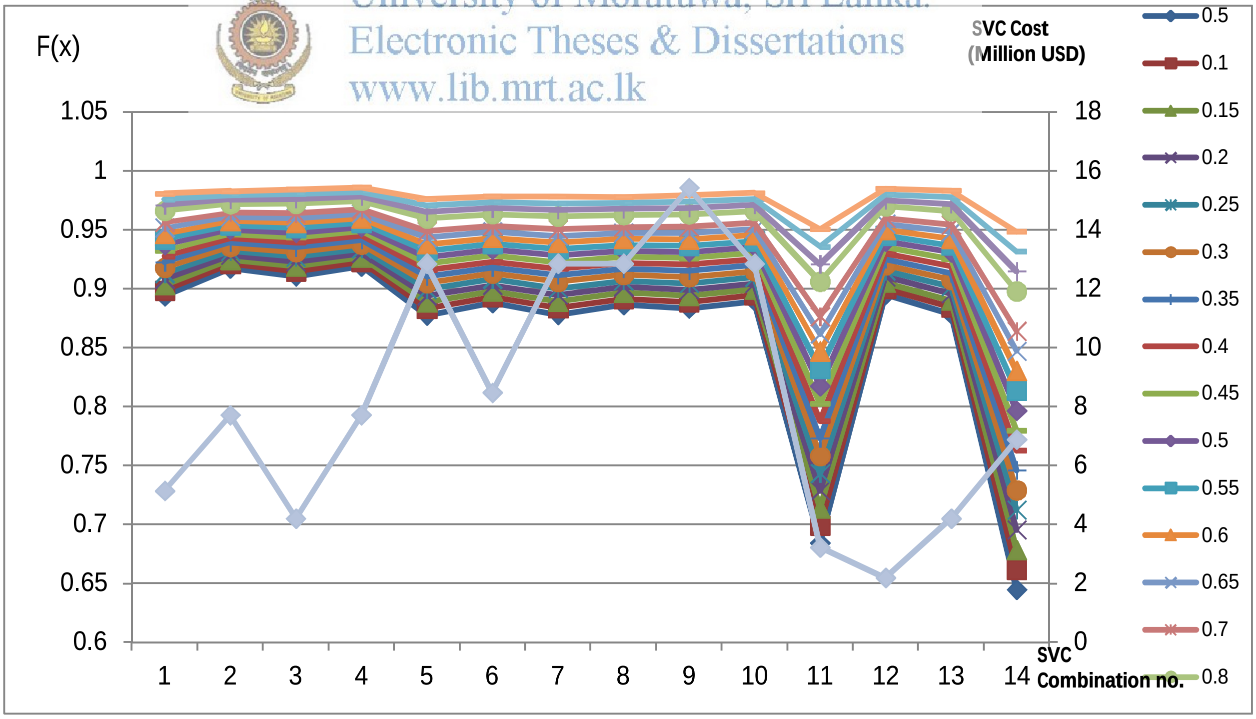

Figure 4.5: F(x) value and SVC cost for each SVC Combination

However, as described above there is no regularity between voltage deviations, power loss and SVC cost due to the fact that location of the SVC also effects on the results. So, it is not possible to predict obtainable minimization of voltage deviation and power loss unless the location is specified.

According to the above results, the optimum combinations which minimize the power loss and voltage deviation can be ranked.

Table 4.7: Optimum SVC combinations for Hydro Maximum night peak

Rank	Combination No.	Grid Substation	Voltage Level (kV)	Proposed Capacity (Mvar)	Actual Capacity (Mvar)
1	14	Galle	132	27	27
		Embilipitiya	132	36	36
2	11	Galle	132	27	27
3	5	Pannipitiya	132	45	42.84
		Biyagama	220	45	45
4	7	Pannipitiya	132	45	42.91
		Kotugoda	220	45	45
5	13	Embilipitiya	132	36	36
6	9	Kotugoda	220	45	45
		Biyagama	220	45	45
7	8	Kolonnawa	132	36	36
		Biyagama	220	45	45
8	6	Pannipitiya	132	45	45
		Kolonnawa	132	36	36
9	10	Kotugoda	220	45	45
		Kolonnawa	132	36	36
10	1	Pannipitiya	132	45	45
11	12	Trincomalee	132	18	17.24
12	3	Kolonnawa	132	36	36
13	2	Biyagama	220	45	45
14	4	Kotugoda	220	45	45

According to the above results, minimum voltage deviation and minimum power loss can be obtained installing 36Mvar SVC at Embilipitiya GS and 27 Mvar SVC at Galle GS. Figure 4.7 shows the improvement of voltage in 132 kV bus in Galle GS with above SVC combination. The second optimum combination is installing 27 Mvar SVC at Galle GS (Existing SVC at Galle GS is out of order.). This is also the second least cost option. So, if the cost is concerned this can be considered as optimum combination.

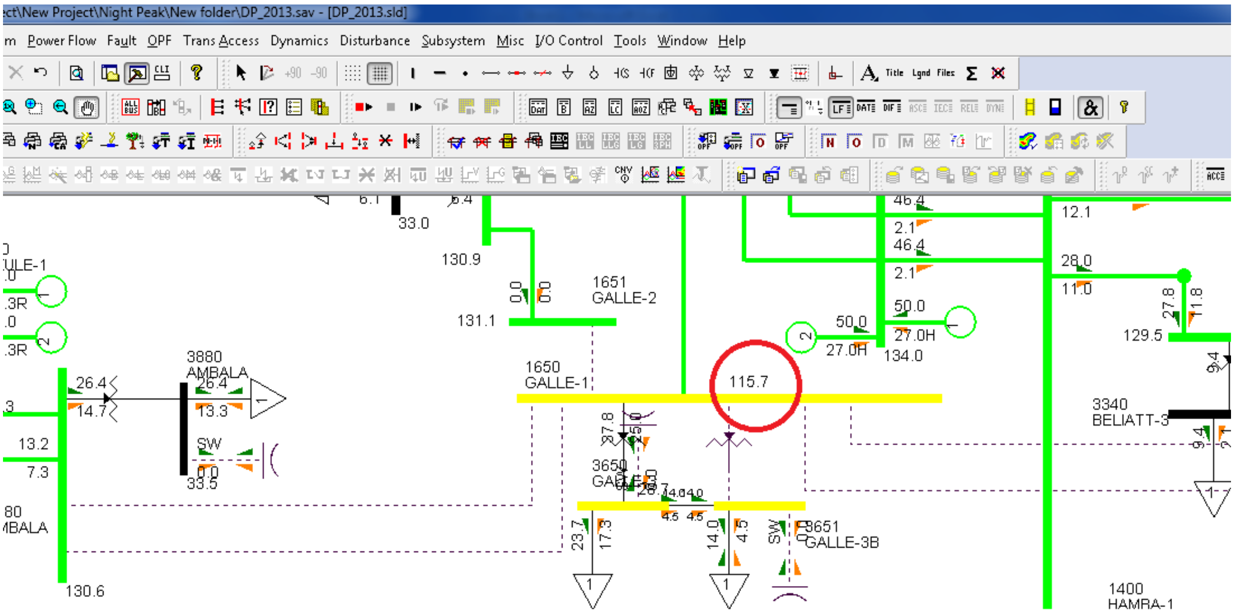

Figure 4.6: Voltage of Galle 132kV bus in Hydro maximum night peak without SVC

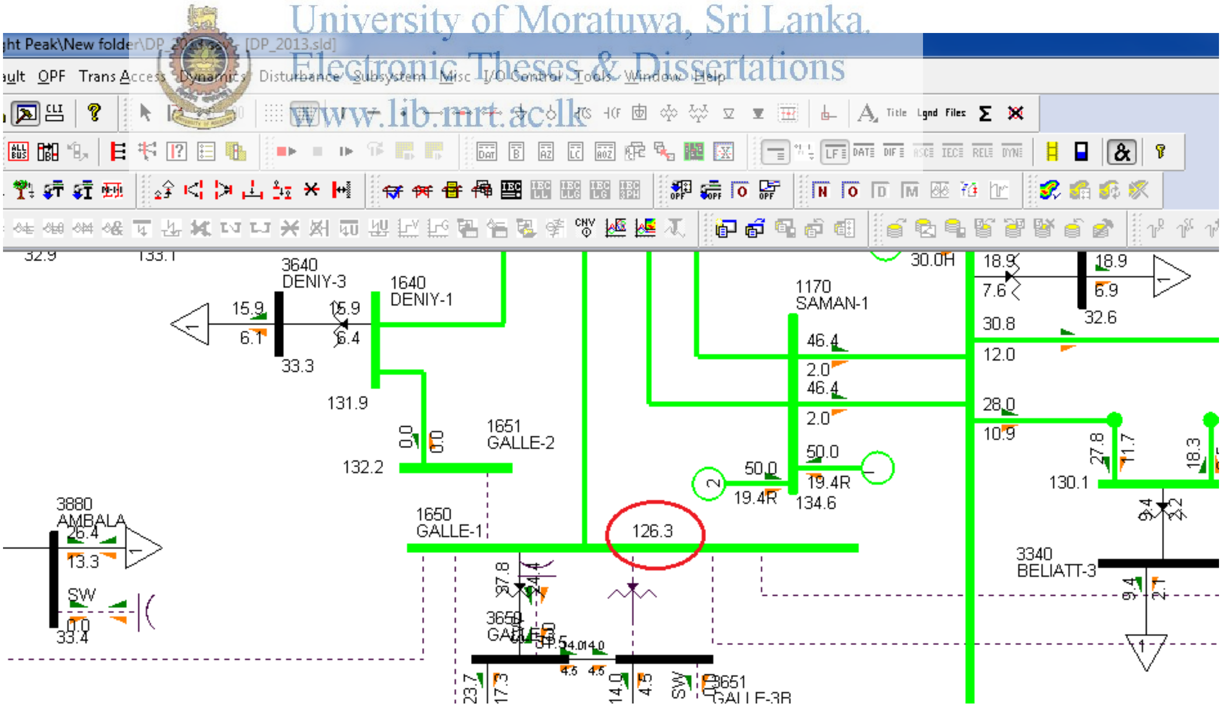

Figure 4.7: Voltage of Galle 132kV bus in Hydro maximum night peak with Embilipitiya 36Mvar & Galle 27Mvar SVC

4.4 Results for Hydro Maximum Day Peak Scenario

Same analysis was carried out for Hydro Maximum day peak scenario for further reference. Results are shown in table 4.8.

Table 4.8: PSS/E results for voltage deviation, power loss and SVC cost for Hydro maximum day peak

Combination	Grid Substation	Voltage Level (kV)	Proposed Capacity (Mvar)	Actual Capacity (Mvar)	Power loss (P_L)	Voltage Deviation (Vd)	SVC Cost (USD/Million)
1	Pannipitiya	132	45	42.84	**0.99339**	**0.91980**	4.92
2	Biyagama	220	45	45	**0.99666**	**0.96964**	7.71
3	Kolonnawa	132	45	30.82	**0.99670**	**0.92832**	3.64
4	Kotugoda	220	45	45	**0.99705**	**0.97739**	7.71
5	Pannipitiya	132	45	16.54	**0.98704**	**0.85627**	9.9
	Biyagama	220	45	45			
6	Pannipitiya	132	45	42.84	**0.99004**	**0.89131**	4.92
	Kolonnawa	132	45	0			
7	Pannipitiya	132	45	27.42	**0.98704**	**0.85627**	11.26
	Kotugoda	220	45	45			
8	Kolonnawa	132	45	11.17	**0.99040**	**0.88716**	9.2
	Biyagama	220	45	45			
9	Kotugoda	220	45	45	**0.99040**	**0.88716**	15.42
	Biyagama	220	45	45			
10	Kotugoda	220	45	45	**0.98983**	**0.89337**	6.45
	Kolonnawa	132	45	13.36			
11	Galle	132	27	27	**0.97280**	**0.63140**	3.22
12	Trincomalee	132	18	8	**0.99311**	**0.92400**	0.99
13	Embilipitiya	132	36	36	**0.99365**	**0.89004**	4.2
14	Galle	132	27	27	**0.97164**	**0.60368**	6.88
	Embilipitiya	132	36	36			

- ➢ Generation details in hydro maximum day peak:

  1617.70 MW & 736.7 Mvar

- ➢ Load details in hydro maximum day peak :

  1606.06 MW & 768.03 Mvar

Table 4.9: Optimum SVC combinations for Hydro Maximum day peak

Rank	Combination	Grid Substation	Voltage Level (kV)	Proposed Capacity (Mvar)	Actual Capacity (Mvar)
1	14	Galle	132	27	27
		Embilipitiya	132	36	36
2	11	Galle	132	27	27
3	5	Pannipitiya	132	45	16.54
		Biyagama	220	45	45
4	7	Pannipitiya	132	45	27.42
		Kotugoda	220	45	45
5	8	Kolonnawa	132	36	11.17
		Biyagama	220	45	45
6	9	Kotugoda	220	45	45
		Biyagama	220	45	45
7	13	Embilipitiya	132	36	36
8	6	Pannipitiya	132	45	42.84
		Kolonnawa	132	36	0
9	10	Kotugoda	220	45	45
		Kolonnawa	132	36	13.36
10	1	Pannipitiya	132	45	42.84
11	12	Trincomalee	132	18	8
12	3	Kolonnawa	132	36	30.82
13	2	Biyagama	220	45	45
14	4	Kotugoda	220	45	45

The results obtained from hydro maximum night peak condition and hydro maximum day peak are almost similar except the rank of 8th and 13th combinations. The rank of the 8th combination of for hydro maximum night peak is 7 and 5 for hydro maximum day peak. Similarly, the rank of 13th combination for hydro maximum night peak is 5 and 7 for hydro maximum day peak. The required capacity of SVCs of some GSS for hydro maximum day peak is less than hydro maximum night peak capacity. Therefore, SVCs capacity should be selected according to the results of hydro maximum night peak condition.

4.5 Reduction of Mvar generation.

As SVCs supply the reactive power requirement, the reactive power generation of the system reduces increasing the active power transfer in the network. The maximum reduction of reactive power generation can be observed for combination no. 07 (Pannipitiya GS 45 Mvar and Kotugoda GS 45 Mvar SVCs)

Table 4.10: Reactive power generation with and without SVCs

Combination	Grid Substation	Voltage Level (kV)	Proposed Capacity (Mvar)	Actual Capacity (Mvar)	Generated reactive power without SVC (Mvar)	Generated reactive power with SVC (Mvar)
1	Pannipitiya	132	45	45	925.7	870.9
2	Biyagama	220	45	45		891.0
3	Kolonnawa	132	36	36		888.6
4	Kotugoda	220	45	45		891.5
5	Pannipitiya	132	45	42.84		840.7
	Biyagama	220	45	45		
6	Pannipitiya	132	45	45		844.9
	Kolonnawa	132	36	36		
7	Pannipitiya	132	45	42.91		840.7
	Kotugoda	220	45	45		
8	Kolonnawa	132	36	36		845.0
	Biyagama	220	45	45		
9	Kotugoda	220	45	45		847.6
	Biyagama	220	45	45		
10	Kotugoda	220	45	45		851.9
	Kolonnawa	132	36	36		
11	Galle	132	27	27		896.6
12	Trincomalee	132	18	17.24		905.8
13	Embilipitiya	132	36	36		883.6
14	Galle	132	27	27		854.5
	Embilipitiya	132	36	36		

4.6 Voltage deviation under single contingency condition for hydro maximum night peak.

Ability to maintain the system voltage during transmission line outages can be illustrated for above each combination. Voltage deviation is considered under single contingency situation of Panadura, Mathugama, Pannipitiya 132kV transmission lines.

Table 4.11: Voltage deviation under single contingency situation

Contingency	**Rank**	**Combination**	**Grid Substation**	**Proposed Capacity (Mvar)**	**Actual Capacity (Mvar)**	**Voltage deviation without SVC ∑(1-Vi)2**	**Voltage deviation with SVC ∑(1-Vi)2**
Panadura, Mathugama, Pannipitiya 132kV line	1	14	Galle	27	27	0.1645	0.1048
			Embilipitiya	36	36		
	2	11	Galle	27	27		0.1049
	3	5	Pannipitiya	45	42.84		0.1469
			Biyagama	45	45		
	4	7	Pannipitiya	45	42.91		0.1442
			Kotugoda	45	45		
	5	13	Embilipitiya	36	36		0.1456
	6	9	Kotugoda	45	45		0.1446
			Biyagama	45	45		
	7	8	Kolonnawa	36	36		0.1460
			Biyagama	45	45		
	8	6	Pannipitiya	45	45		0.1462
			Kolonnawa	36	36		
	9	10	Kotugoda	45	45		0.1458
			Kolonnawa	36	36		
	10	1	Pannipitiya	45	45		0.1469
	11	12	Trincomalee	18	17.24		0.1498
	12	3	Kolonnawa	36	36		0.1497
	13	2	Biyagama	45	45		0.1517
	14	4	Kotugoda	45	45		0.1534

The total voltage deviation ($\sum(1\text{-}Vi)^2$) of the system is 0.1645 p.u. under outage of Panadura, Mathugama, Pannipitiya 132 kV line. This total system voltage deviation can be reduced to 0.1048 p.u. by installing 36Mvar SVC at Embilipitiya GS and 27Mvar SVC at Galle GS.

4.7 Actual Voltage deviation for Hydro Maximum night peak

As mentioned in table 4.5, V_d value which is the ratio between total of square of voltage deviation of the system buses with SVC and total of square of voltage deviation in normal condition. Following table shows the total actual system voltage deviation, $\sum (1\text{-}Vi)^2$ with and without SVCs.

Table 4.12: Actual Voltage deviation for hydro maximum night peak in all buses

Combination	Grid Substation	Voltage Level (kV)	Proposed Capacity (Mvar)	Actual Capacity (Mvar)	Total voltage deviation without SVC	Total voltage deviation with SVC
1	Pannipitiya	132	45	45	0.1652	0.1468
2	Biyagama	220	45	45		0.1500
3	Kolonnawa	132	36	36		0.1497
4	Kotugoda	220	45	45		0.1512
5	Pannipitiya	132	45	42.84		0.1440
	Biyagama	220	45	45		
6	Pannipitiya	132	45	45		0.1458
	Kolonnawa	132	36	36		
7	Pannipitiya	132	45	42.91		0.1441
	Kotugoda	220	45	45		
8	Kolonnawa	132	36	36		0.1456
	Biyagama	220	45	45		
9	Kotugoda	220	45	45		0.1450
	Biyagama	220	45	45		
10	Kotugoda	220	45	45		0.1460
	Kolonnawa	132	36	36		
11	Galle	132	27	27		0.1106
12	Trincomalee	132	18	17.24		0.1470
13	Embilipitiya	132	36	36		0.1441
14	Galle	132	27	27		0.1037
	Embilipitiya	132	36	36		

4.7.1 Voltage deviation of selected buses

Above analysis is carried out for the total 33kV, 132kV and 220kV buses in the network. However, it is also possible to carry out this analysis for any selected set of buses in the network. So, voltage improvement of following 132kV/220kV buses in Colombo region GSS is analyzed for each SVC combinations.

Kelaniya, Horana, Kosgama, Seethawaka, Kolonnawa, Pannipitiya (both 132kV & 220kV), Athurugiriya, Veyangoda (both 132kV & 220kV) , Sri

Jayawardanapura, Panadura, Dehiwala, Kelanitissa, Kerawalapitiya, Biyagama, and Colombo Substations A,E & F

Table 4.13: Actual Voltage deviation in selected buses in Colombo region GSS for hydro maximum night peak.

Combination	Grid Substation	Voltage Level (kV)	Proposed Capacity (Mvar)	Actual Capacity (Mvar)	Total voltage deviation without SVC $\sum (1-V_i)^2$	Total voltage deviation with SVC $\sum (1-V_i)^2$
1	Pannipitiya	132	45	45	0.0237	0.0157
2	Biyagama	220	45	45		0.0179
3	Kolonnawa	132	36	36		0.0179
4	Kotugoda	220	45	45		0.0180
5	Pannipitiya	132	45	42.84		0.0134
	Biyagama	220	45	45		
6	Pannipitiya	132	45	45		0.0146
	Kolonnawa	132	36	36		
7	Pannipitiya	132	45	42.91		0.0135
	Kotugoda	220	45	45		
8	Kolonnawa	132	36	36		0.0141
	Biyagama	220	45	45		
9	Kotugoda	220	45	45		0.0139
	Biyagama	220	45	45		
10	Kotugoda	220	45	45		0.0147
	Kolonnawa	132	36	36		
11	Galle	132	27	27		0.0218
12	Trincomalee	132	18	17.24		0.0211
13	Embilipitiya	132	36	36		0.0213
14	Galle	132	27	27		0.0212
	Embilipitiya	132	36	36		

According to the above results, Combination 7th (45 Mvar SVC at Pannipitiya GS and 45 Mvar SVC at Biyagama GS) is the optimum combination only voltage deviation is concerned. The rank of the combination is different from the total bus system. Therefore, this analysis can be carried out for any set of selected buses and it is possible to select best combination accordingly. Further, this selection can be done considering voltage deviation only, power loss only and considering both voltage deviation and power loss.

4.8 Reduction of power loss

A summary of reduction of power loss for each combination is mentioned below.

Table 4.14: Reduction of power loss for each SVC combination.

Combination No.	Grid Substation	SVC Capacity (Mvar)	Day peak		Night peak		Units saving per day* (kWh)
			Power loss reduction with SVC (p.u)	Power loss reduction in MW (100 MVA base)	Power loss reduction with SVC (p.u)	Power loss reduction in MW (100 MVA base)	
1	Pannipitiya	45	0.00608	0.6	**0.01501**	1.5	11700
2	Biyagama	45	0.00367	0.36	**0.01286**	1.29	8190
3	Kolonnawa	36	0.00478	0.47	**0.01314**	1.31	9570
4	Kotugoda	45	0.00313	0.31	**0.01153**	1.15	7170
5	Pannipitiya	42.84	0.00928	0.92	**0.01641**	1.64	15960
	Biyagama	45					
6	Pannipitiya	45	0.00879	0.87	**0.01481**	1.48	14880
	Kolonnawa	36					
7	Pannipitiya	42.91	0.00582	0.58	**0.01568**	1.57	11670
	Kotugoda	45					
8	Kolonnawa	36	0.00652	0.65	**0.01680**	1.68	12840
	Biyagama	45					
9	Kotugoda	45	0.01105	1.1	**0.01531**	1.53	17790
	Biyagama	45					
10	Kotugoda	45	0.00644	0.64	**0.01394**	1.39	11850
	Kolonnawa	36					
11	Galle	27	0.15287	1.52	**0.02156**	2.15	24690
12	Trincomalee	17.24	0.00112	0.11	**0.00774**	0.77	3630
13	Embilipitiya	36	0.01143	1.14	**0.01682**	1.68	18720
14	Galle	27	0.21178	2.11	**0.02985**	2.98	34260
	Embilipitiya	36					

*Unit (kWh) saving due to reduction of power loss

Eg: for combination no. 14 (27Mvar SVC at Galle GS and 36 Mvar SVC at Embilipitiya GS)

Number of hours considered for day peak = 12 hours

Number of hours considered for night peak = 3 hours

Units saving per day = 2.11x1000x12 + 2.98x1000x3

= 34,260 kWh

If average generation cost is considered as Rs. 5 (Rs./kWh), the total saving per day with above SVC combination is Rs. 171,300.00

Chapter 5

Discussion & Conclusion

5.1 Discussion

Sri Lanka can reach to the 100% electrification level of the country within next two years. In this process, maintaining the consumer satisfaction is also major responsibility of the utility avoiding power quality issues. So, it is important to discuss how power quality issues come to the system and how to solve them.

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. A good quality power system also requires distortion loss voltage and current waveforms. These waveforms get distorted due to the presence of non linear load such as adjusted speed drives, induction motors, arc furnaces, converters and heating & welding elements.

In transmission level, at lighter load condition, transmission line is over compensated. The voltage increases across the series line reactance due to the charging line current of shunt line capacitance is greater than the voltage drop by the load current. This surplus charging current flows through the sending end and receiving end generators forcing to absorb the corresponding reactive power. Similarly, in under compensation, corresponding reactive power must be supplied.

Basically, voltage variation is due to the imbalance in generation and consumption of reactive power in the system. Above issues can be corrected by compensation that is generation or absorption of a suitable quantity of reactive power. There are two main types of compensation; Load compensation and Line compensation.

Load compensation is the management of reactive power to improve the quality of the supply, specially the voltage and the power factor. The reactive power is adjusted with respect to an individual load and the compensation device is connected to the load itself. Compensation of lines is meant the use of electrical circuits to modify the electrical characteristics of the lines. A flat voltage profile on a line can be achieved if the loading of the line corresponds to its surge impedance loading. Therefore, to achieve flat voltage profile, the compensating devices such as capacitors and inductors should be chosen such that the effective surge impedance of the line should give virtual natural loading equal to the actual load. However, practically, actual loads keep changing with time. So, the corresponding devices should also vary without a delay. Then, the effective impedance matches with the actual loading every time.

Also with ever increasing demand of electric power, the existing transmission network becomes weak resulting poor quality of unreliable power supply. In order to enhance the power transfer capability of the existing transmission network, huge sum of finances are required. It is also difficult to find right of way for the new lines. Lot of research has gone into developing new technologies over the past few years to gain increased efficiency 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.

Sri Lankan utility is still in first generation of reactive power compensation technologies and there are new breaker switched capacitors to be constructed in several grid substations. Although these capacitor banks would help to correct the power factor, it would not be effective solution to voltage drops of the system and also there would be no considerable effects to power transfer capacity of transmission lines. To maintain the voltage at some grid substations under single contingency situation it has been proposed to construct new transmission lines. Also addition of new transformer bays also has been proposed to increase capacity. As described in section 1.1, some countries have achieved required capacity by installing SVCs at suitable locations without constructing new lines or bays. So, this is high time for utility to move to second generation of reactive power compensation technologies. As shown in this analysis, utility can minimize voltage drop issues after installing SVCs at selected grid substations and also can increase the power transfer capacity in the system.

This analysis is basically carried out for all 33kV, 132kV and 220 kV busses of the system and for all the transmission lines. However, any set of buses and lines can be analyzed to get required results. Further, this analysis can be carried based on different scenarios; minimizing the voltage deviation or minimizing the power loss and also minimizing the both. If the voltage drops is the major issue, SVC capacity and its location can be selected considering only the results of reduction of voltage deviations with SVCs. Mainly, grid substations in Colombo region face voltage drop issues during hydro maximum situation. So, as described in section 4.7.1, it possible to select those grid substations and carry out analysis for them. Also same analysis can be carried out for voltage drops of the system under different contingency situation and SVC can be selected accordingly. However, the main issue addressed in this study is difficulties in maintaining voltage in grid substations in hydro maximum situation. For optimum selection of SVCs with economic consideration, reduction of power loss is also considered.

5.2 Conclusion

The main reason for being reluctant to go for a solution like SVC for voltage compensation is the installation cost. However, the utility spend large amount of money to run thermal power plant to maintain the voltage. Also new transmission lines are constructed to improve the system voltage during different contingency situations. The reduction of power loss is significant with SVC as described in section 4.8. Further, reactive power obtained from the system has reduced as mentioned in section 4.5. Therefore, ability of supplying active power also increases according to generator capability curve. So, after installing SVCs, there is no need of running thermal power plants and to construct new transmission lines to maintain the voltage.

In this analysis, optimum SVC combinations have been ranked considering minimum voltage deviation and minimum power loss and the SVC cost is separately considered. The utility can select suitable SVC combinations depend on up to which level voltage deviation should be minimized and power loss should be reduced. For an example, total system voltage deviation, $(1-V_i)^2$ can be reduced from 0.1652 pu to 0.1037 pu and power loss can be reduced by 2.98MW by installing 36 Mvar SVC at Embilipitiya GS & 27 Mvar SVC at Galle GS under hydro maximum night peak condition. However, if voltage drops of Grid substations in Colombo region are considered the optimum combination is installing 45 Mvar SVC at Biyagama GS and 45 Mvar at Pannipitiya GS. Therefore, initially, it is recommended to install SVCs at Biyagama and Pannipitiya GSS as a solution to voltage drops in Colombo region grid substations and install SVCs at Embilipitiya and Galle GSS considering the whole system.

As motioned in section 2.5, Sri Lankan utility loose Rs. 500 million approximately per year (This value is calculated based certain assumptions as described in section 2.5 and this value depends on the system operation) for running thermal power plant to maintain the voltage. If first three optimum combinations are installed the total cost would be Rs. 2500 million approximately. Considering also the saving due to power loss reduction, installation cost of SVCs can be recovered from less than 05 years. Minimization of voltage deviation under normal condition and under disturbances, improvement of system stability and power transfer capacity with installing SVCs will also add more economical benefits.

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