ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

STUDY ON POWER TRANSFER CAPABILITY AND VOLTAGE STABILITY IMPROVEMENT USING STATIC VAR COMPENSATOR

CASE STUDY: HOLETA 500 /400 kV SUBSTATION

By

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This thesis submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfillment of the Requirements for the degree of Masters of Science in electrical Engineering

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Abebaw Yalew

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DEDICATED

To

My Dears: Solo and Girmish

Declaration

I ,the undersigned ,declare that this thesis is my original work, has not been presented for a degree in this or any other university ,and all sources of materials used for the thesis have been fully acknowledged.

<u>**Abebaw Yalew**</u> _________________

Name Signature

Place: Addis Ababa

Date of Submission: ______________

This Thesis has been submitted for examination with my Approval as a university Advisor.

<u>**Dr. –Ing. Getachew Biru**</u> ______________________

Advisor’s Name Signature


ETHIOPIAN ELECTRIC POWER
ETHIOPIAN ELECTRIC POWER CORPORATION
HOLETA 500kV SUBSTATION

Abstract

Voltage stability is a major concern while planning and operating an electrical power system. As electrical power demand increases, power system networks should be used in maximum of their capacity to meet the demand growth. In such case Flexible AC Transmission System (FACTS) can be used so that maximum capacity of system equipments utilized keeping the thermal limit and maintaining system voltage stability. Static Var Compensators (SVCs) can endlessly provide or consume the reactive power which is necessary to control the dynamic voltage oscillation helping to get stable transmission system and also help to achieve maximum power transfer.

Power transmission can always be improved by upgrading or adding new transmission lines. But sometimes due to financial constraints and lack of corridors for new transmission lines (environmental reasons), this may not be practical solution. SVC is feasible alternative for optimizing the existing transmission system so that maximum possible power will be transferred in the range of thermal limit and without affecting system stability.

Great Ethiopian Renaissance Dam (GERD) which is now under construction is going to generate around 6450 MW. This energy is far more than the current total generation capacity of the country. HOLETA 500 /400kV substation will be the gate way for this power to the grid. There are four 500 kV transmission lines coming from GERD to HOLETA 500/400 kV substation. SVCs are installed at HOLETA 500/400 kV substation to enable in evacuating the power generated at GERD power plant.

This thesis focuses to investigate the impact of the SVCs in HOLETA 500 /400kV substation on voltage stability and power transfer improvement. Three SVCs of total capacity 900 MVAr are used at HOLETA 500/400 kV substation. They are connected to the AC 400 kV system using 400/33 kV coupling transformers. The study also evaluated possible installation of SVCs at DEESA or GERD substation and observes the effect on the voltage stability and transferred power. In this study, the system is simulated using MATLAB 2017a /simulink environment.

It is observed that the best location of the SVCs is HOLETA 500/400kV substation as the power transferred and voltage stability is better than if it is in DEDESA or GERD. Using the SVCs in the network, didn't improve transfer of power. But the voltage at GERD bus bar becomes 509.3 kV from 568.6 kV. The voltage at HOLETA 400 kV bus bar becomes 338.4 kV from 362.8kV. The SVCs improve the voltage stability margin in the 500 kV network at GERD bus bar. The simulation also depicts that while the SVCs are used, reactive power of the system increases and system voltage reduces. The PV and QV curve Study shows that SVCs improve over voltage problem. During 50% loading in the absence of SVCs, the voltage at HOLETA 400 kV bus bar is 418.5 kV. But when the SVCs are present it is 396.3 kV which is very good for the system. Since the system is facing both over voltage and under voltage problem, the SVCs are helpful in controlling the over voltage problem.

When The SVCs are used with Reactors on the line, the voltage is reduced to 314.1kV from 338.4kV.The system is having 620 km of 500 kV transmission line length and heavy loading, 2591 MW at HOLETA 400 kV bus bar leading to under voltage. But GERD bus bar has no any load and very far away from the load center leading to over voltage. So for better voltage stability and power transfer improvement, series capacitive compensator should be inserted in the GERD-DEDESA-HOLETA 500/400 kV network as they reduce inductive reactance and boost receiving end voltage. In long term, additional FACTS device should be considered for better stability and transfer of power.

Keywords: Stability, simulation, power transfer, FACTS, SVC, MATLAB, simulink, PV and QV curves

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I will always thank Almighty God being every time on my side regardless of my goneness. My family always supports me to be a better man every day and I thank them. My friends always were behind me in supporting me to succeed. My staffs at work, their contribution in my successful finish of the course was immense.

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List of Acronyms and Abbreviations

FACTS	Flexible Alternating Current Transmission System
GERD	Great Ethiopian Renaissance Dam
HV	High Voltage
IPFC	Interline power Flow Controller
MVA	Mega Volt Ampere
SSSC	Static Synchronous Series Compensator
STATCOM	Static synchronous compensators
SVC	Static Var Compensator
TCSC	Thyristor controlled Series Capacitor
TCR	Thyristor Controlled Reactor
TSC	Thyristor Switched Capacitor
UPFC	Unified Power Flow Controller
EEP	Ethiopian Electric Power

CHAPTER ONE
1. Introduction

1.1. Background

High energy demand in transmission system is the biggest treat for a modern power system today. The voltage stability and high energy transfer capability are coming in front. Previously; the stress has been eased by adding more generating facilities to the grid and by building additional transmission lines.

Today it is much harder to acquire new rights of way to build new transmission lines in order to strengthen the grid. This calls for fresh approaches on how to utilize the existing grid more efficiently and to operate it closer to its thermal limit.

The introduction of the FACTS concept and components has led to new ways of increasing the stability limit of the existing power system. This is achieved by adding modern controllable components to the grid. An example of such a device is the Static Var Compensator (SVC), which is the focus of this thesis.

The two main objectives of FACTS are [1]:

1. To increase the capability of transmission lines.
2. Control power flow over a transmission line, electronically and statically, without the need of operator's actions and without need of mechanical manipulations or conventional breakers switching.

At present time, Ethiopian Electric Power grid is pushed to operate at almost full its capacity. More often interruptions are observed in the whole grid. Therefore, it is the time to make the grid smart, fault tolerant and self-healing as well as dynamically controllable. Moreover the Ethiopian grid is now going to receive more than 6000MW of power from a single source. Bringing this amount of big power through one substation will make the task so tough. Therefore SVC is installed at HOLETA 500/400 kV substations to successfully evacuate the whole power.

HOLETA 500/400 kV substation is one of the GERD transmission projects situated at 40 km to the west of Addis Ababa near to Holeta town. The substation landed on 33.342 hectares of land. It is the biggest and latest of all the substation ever built in Ethiopia.

The objective of this thesis is to evaluate the level of enhancement in power system voltage stability and power transfer capability by the application of these SVCs installed in this big substation.

Figure 1.1: Google earth photo showing the location of HOLETA 500/400 kV substation

Figure 1.2: Google earth photo showing the substation switchyard and control room

Nowadays power quality issue is coming in front in every discussion with big investors as well as with individual residents in Ethiopia. Addressing such problem is important to meet the customers need. The practical feasible solution will be to use FACTS in the power system network. Ethiopian Electric power grid is involving more than 4000MW and the transmission network is not redundant and frequently not capable of serving this power amount even when it is in healthy condition. Moreover, the transmission network is going to entertain more than 10,000 MW of power and therefore transferring this huge power requires appropriate technology.

The Ethiopian Electric Power (EEP) Load center serves Addis Ababa and its surroundings to supply with bulk power and sustainable way. But the generation plants are very far from the load center. Many and Long transmission line should be constructed to bring the big power to Addis Ababa and its surrounding. Lack of corridor and big compensation payment for relocation is creating years of delay and even failures of some transmission line and substation projects like Genale Dawa power plant and Aawasa – Yirgalem transmission projects. So problems facing during expansion of transmission line and power plants can be partially alleviated by installing FACTS devices since it aides in maximum utilization of the existing transmission circuits.

1.2. Problem Statement

The research deals with the stress that the upcoming great renaissance dam is bringing to the Ethiopian Electric Power grid. This huge Power is evacuated from the power station to the grid through HOLETA 500/400 kV substation and then to Sululta, Gelan and Sebeta II 400 kV substations. Therefore studying the power transfer and voltage stability improvement capability of SVCs at HOLETA 500/400 kV substation will be important on the power coming from renaissance dam sooner or later. There was also frequent design change made on the GERD project. Starting from 5250 MW, the power rating is raised to 6000 MW capacity and later to 6450 MW which is 1200 MW higher than originally planned. So can it be possible to evacuate this all power to the grid through HOLETA 500/400 kV substation?

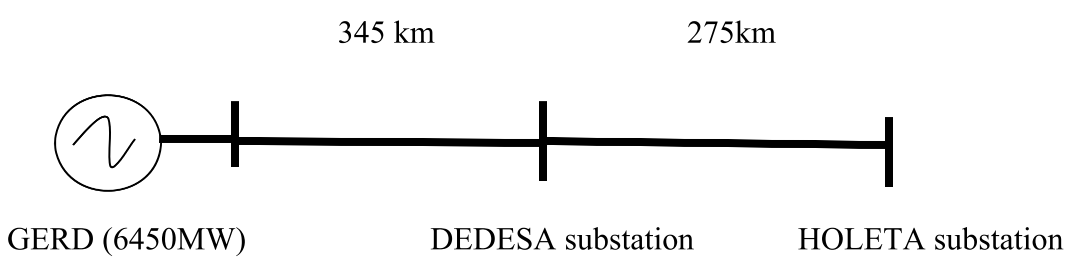

Figure 1.3: Single line diagram of GERD power plant and transmission system

Not only the high energy coming is the concern but also the long transmission line from GERD to HOLETA 500/400 kV substation is also serious concern for voltage stability in the grid.

The other motivating factor is the growing use of FACTS to automate and optimize power networks enabling power system to improve stability, mitigate dynamic sensitivities and reduce chance of system collapse under severe disturbances. The research is also inspired by difficulties in power transient instability due to outages, blackouts and system faults that occur due to dynamics in long transmission lines of interconnected systems and distance between load and generation [4].

Figure 1.4: HOLETA 500/400 kV Substation SCADA and Mimic Board.

The FACTS devices have great future in Ethiopian Electric Power grid. The power demand is increasing at an alarming rate, currently more than 4000MW but in the coming years it will be more than doubled. It is not always cost effective to construct transmission lines with the pace of demand growth. So the Ethiopian grid needs to deploy a number of FACTS devices to enhance its existing power system performance. Thus, both advantage and disadvantage of SVC and FACTS as a whole should be studied and evaluated.

1.3. Objectives

1.3.1. General Objectives

The Objective of this thesis is to study the impact of SVCs installed in HOLETA 500/400 kV substation for improving the performance of the system. The effect of the SVCs in terms of voltage stability and power transfer capability improvement will be studied on the line from renaissance dam to HOLETA 500/400 kV substation. Both mid-point injection and source side injection will be studied as well. Improvement options will be evaluated and recommendations will be drawn for further implementation to EEP.

Figure 1.5: TCR and TSC equipment at HOLETA 500/400 kV switchyard

1.3.2 Specific Objectives

- Data Collection
- Study the power transfer capacity and voltage profiles of GERD, DEDESA, HOLETA 500/400 kV and Gebreguracha substations with and without SVC devices.
- Model GERD-DEDESA-HOLETA 500/400 kV system with SVCs using MATLAB simulink software.
- Simulate SVCs in mid-point and source end injection if better performance of the SVCs is achieved.
- Evaluate the improvement in power transfer capacity of transmission system and voltage stability.
- Draw relevant conclusions and make recommendations to EEP.

1.4. Methodology

The methodology of this thesis starts from identifying research area and reading different helpful literature. The problem of power transfer and voltage stability is happening every time in Ethiopian power grid. For example it happened during the energization of Tekeze power plant. For this problem, GERD-DEDESA-HOLETA power transmission system is selected as a case study area.

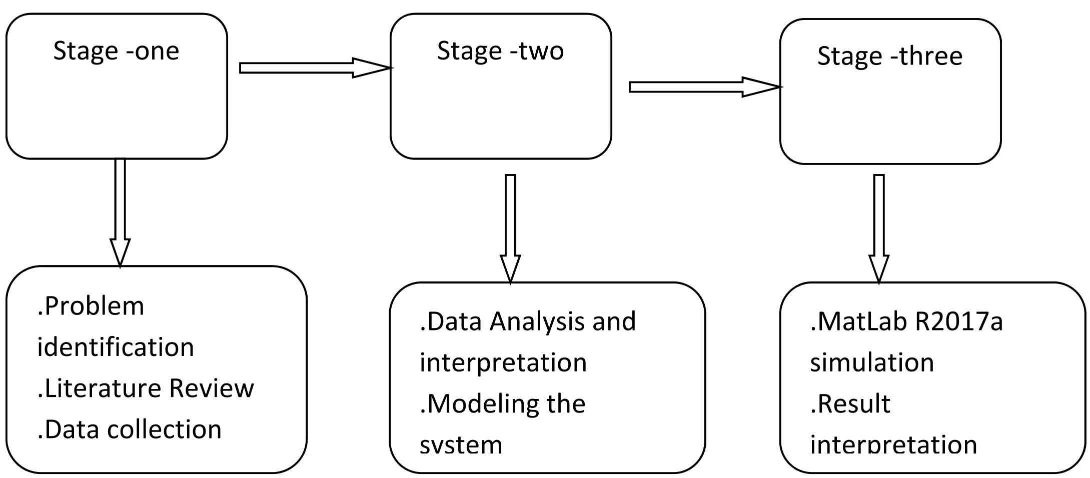

Figure 1.6: Methodology of the thesis

The GERD power plant, DEDESA substation and HOLETA 500/400 kV substation are studied in detail. Data collection and analysis is done for the selected system. Mat Lab R2017a Simulink software is used for simulation. Simulation is done both with and without SVCs. The SVCs are also installed in DEDESA and GERD substations and simulation made to see their effect on the system. Simulation is also made with the presence of reactors on the system and their effect is studied.

1.5. Organization of the Thesis

CHAPTER ONE introduces the work carried out in this thesis, the problems, the problems and its objectives.
CHAPTER TWO focuses on power system stability and theoretical description of FACTS devices.
CHAPTER THREE describes the modeling, the software used and the data collection.
CHAPTER FOUR presents simulation and analysis of the result.
CHAPTER FIVE presents the conclusions, recommendations and suggestions for future work.

CHAPTER TWO

2. Impact of FACTS devices on System Stability and Literature Review

2.1. Introduction

FACTS can be used for several power system performance enhancements, for example TCSC can be used to improve the system transient rotor angle stability, damping of the power oscillations, and alleviation of SSR (Sub-Synchronous Resonance). However, SVC can be used to increase the system steady-state power transfer capacity, enhancement of the system transient rotor angle stability, and prevention of voltage instability. The effectiveness of the FACTS devices depends largely on their placement with the careful selection of control signals for achieving different functions.

Overall, FACTS devices are cost effective and are important in controlling system stability. They are not exploited in Ethiopia so far. Their market in Ethiopia will flourish soon and experts in such field should awake early and work on it.

2.2. Power system stability

The stability of a system is defined as the tendency and ability of a system to develop restoring forces equal to greater than the disturbing forces to maintain the state of equilibrium [5].

Let a system be in some equilibrium state. If upon an occurrence of a disturbance and the system is still able to achieve the equilibrium position, it is considered to be stable. The system is also considered to be stable if it converges to another equilibrium position in the proximity of initial equilibrium point. If the physical state of the system differs such that certain physical variable increases with respect to time, the system is considered to be unstable [5].The system stability that is of the most concern is the characteristic and the behavior of the power system after a disturbance.

As the number of user's increases, the load demand also increases linearly. Since concern for stability limits the transfer capability of the system, there is a need to ensure stability and reliability of the power system due to economic and other reasons.

Different types of power system stability have been classified in to rotor angle stability, frequency stability and voltage stability [5].

Therefore total power transfer capability with SVC devices including transmission power losses will be formulated in sense that maximum power can be transferred from a specific set of generators in source area to loads in sink area within the real and reactive power generation limits, line flow limits, voltage limits, and SVC devices operation limits. SVC is used to control bus voltage, reactive power injection, stability control, oscillation damping and unbalanced compensation [5].

The equations for system flow and stability are given as:

$$P_{Gi} - P_{Di} + P_L + P_{FDi}(V_{FDi}) + V_i V_j Y_{ij} cos(\theta_{ij} - \sigma_i + \sigma_j) = 0 \quad (2.1)$$

$$Q_{Gi} - Q_{Di} + Q_L + Q_{FDi}(V_{FDi}) + V_i V_j Y_{ij} \sin(\theta_{ij} - \sigma_i + \sigma_j) = 0 \quad (2.2)$$

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max}$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max}$$

$$V_i^{\min} \le V_i \le V_i^{\max}$$

$$P_{FDi}^{\min} \le P_{FDi} \le P_{FDi}^{\max}$$

$$Q_{FDi}^{\min} \le Q_{FDi} \le Q_{FDi}^{\max}$$

Where,

P_{Gi}, Q_{Gi}: Real and reactive power generations at bus i
P_{Di}, Q_{Di}: Real and reactive loads at bus i
V_i, V_j: Voltage magnitudes at bus i and j
$P_{FDi}(V_{FDi}, \alpha_{FDi})$: Injected real power of SVC at bus i
$Q_{FDi}(V_{FDi}, \alpha_{FDi})$: Injected reactive power of SVC at bus i
N: total number of buses
σ_i, σ_j: Voltage angles of bus i and j
Y_{ij}: Magnitude of the ijth element in bus admittance matrix
θ_{ij}: Angle of the ijth element in bus admittance matrix

And the equation for the power transmission is given

$$P = \frac{V_s V_r}{X_L} \mathrm{Sin}(\sigma_s - \sigma_r) = \frac{V^2}{X_L} \sin\sigma \quad (2.3)$$

$$Q=\frac{V_s V_r}{X_L}[1-\cos(\sigma_s-\sigma_r)]=\frac{V^2}{X_L}(1-\cos\sigma) \tag{2.4}$$

$$\sigma=(\sigma_s-\sigma_r) \tag{2.4}$$

$$|Vs|=|Vr|=|V| \tag{2.5}$$

Where,

P: active power in p.u.
Q: reactive power in p.u.
V_s: sending end voltage in p.u.
V_r: Receiving end voltage in p.u.
X_L: Line reactance in p.u.
σ_s : Voltage angle at sending end
σ_r : Voltage angle at receiving end

2.3. FACTS devices and their application in improving system stability

This portion of the thesis will describe the main theoretical feature of Flexible Alternating Current Transmission Systems(FACTS).These power electronics based devices offer the possibility to increase the transmission network capacity as well as the system flexibility, reliability, security and controllability with a limited environmental impact. FACTS provide effective solutions to several grid connected problems. This part provides information about how FACTS devices are classified based on their construction and operation. The configuration, operating principle, working and application of various FACTS devices are presented in this chapter.

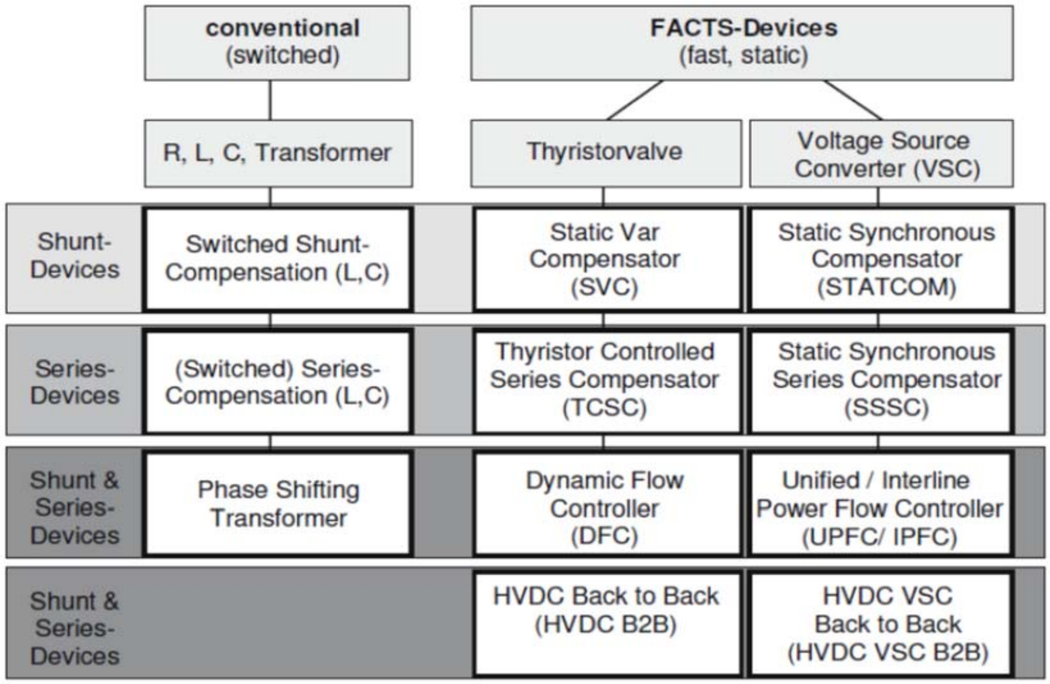

Figure 2.1: Overview of major FACTS devices

The above figure shows conventional device on the left and the FACTS device to the right side. For the FACTS side the taxonomy is in terms of dynamic and static [6]. The term dynamic implies the fast controllability of FACTS devices facilitated by power electronics devices. This is one of the main differentiation factors from the conventional devices. The term static implies that no moving parts like mechanical switches are present in the devices to perform the dynamic controllability. Hence most of the FACTS device can be static as well as dynamic [6].

Based on the positioning of FACTS device on the transmission line network they are divided as follows [3]:

1. Series controllers
2. Shunt controllers
3. Combined Series-Shunt controllers

2.3.1. Series FACTS controllers

2.3.1.1. Thyristor Controlled Series capacitor(TCSC)

It consists of a series compensating capacitor shunted by a Thyristor Controlled Reactor (TCR). TCR behaves as continuously variable reactive impedance, at the fundamental system frequency which can be controlled by a delay angle.

2.3.1.2. Static Synchronous Series Compensator (SSSC)

The static synchronous series compensator (SSSC) is used in controlling active and/or reactive power-flow through a line. It consists of a series transformer, a voltage source convertor and a DC link capacitor.

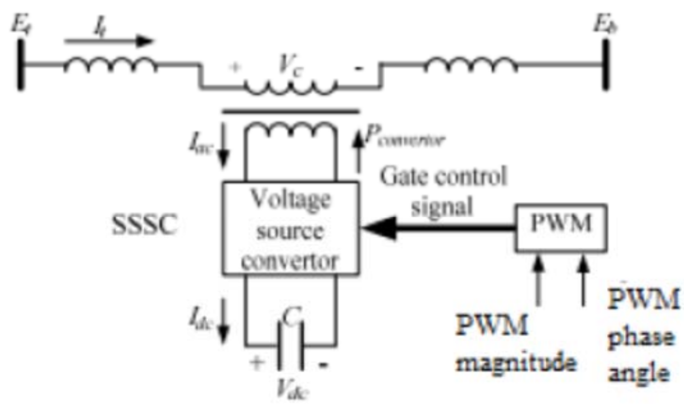

Figure 2.2: Single line diagram of a SSSC

It is capable of matching a compensation reactance (both inductive and capacitive) in series with the transmission line inductive reactance [3].

2.3.2. Shunt FACTS controllers

A controller which is connected in parallel with the transmission line called a shunt controller. The shunt controller could be variable impedance, variable sources or a combination of these. In principle, all shunt controllers inject current in to the system at the point of connection. As long as the injected current is in phase quadrature with line voltage, the shunt controller only supplies or consumes reactive power. Any other relationship will involve handling of real power as well.

2.3.2.1. Static VAR Compensator (SVC)

With proper coordination of the capacitive reactance and inductive reactance, the Var output of the SVC can be varied continuously between the capacitive and inductive ratings of the equipment. The SVC is mainly used for reactive power compensation, voltage regulation and power factor corrections [3]. The Static Var Compensator (SVC) is a combination of the Thyristor-Switched Capacitor (TSC) and Thyristor Controlled Reactor (TCR). It has capacitive as well as inductive compensation.

A. Thyristor Controlled Reactor (TCR)

The Thyristor-Controlled Reactor (TCR) is a shunt compensator, which produces an equivalent continuous variable inductive reactance by using phase-angle control. The magnitude of the current is controlled on the basis of the firing angel α. The value of firing angle α may vary from 90° to 180°, measured from the zero crossing of the voltage. At α=90°, the reactor is fully inserted in the circuit and for α=180°, the reactor is completely out of the circuit [3].

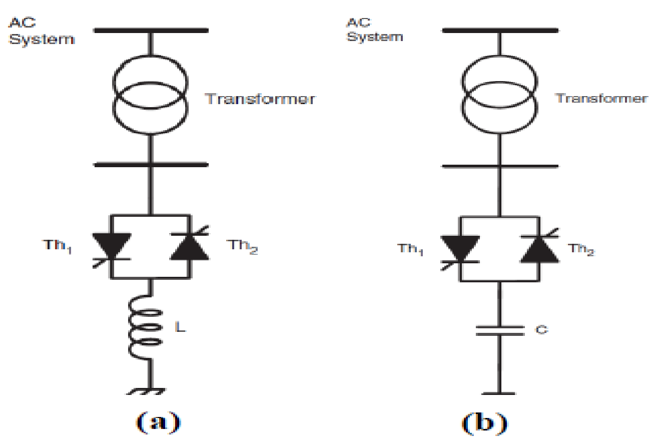

Figure 2.3: a) TCR and b) TSC

B. Thyristor Switched Capacitor (TSC)

The Thyristor-Switched Capacitor (TSC) is a shunt compensator, which produces an equivalent continuous variable inductive capacitance. The thyristor is turned-on only when zero-voltage switching is achieved; hence it is called as Thyristor-Switched Capacitor (TSC) [3]. This means that the voltage across the thyristor terminals has to be zero at the turn-on instant.

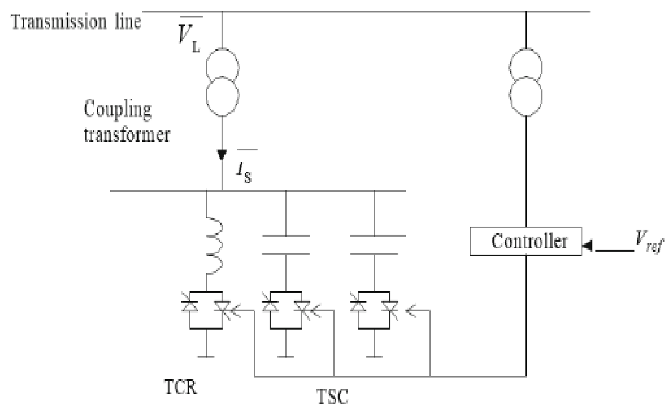

Figure 2.4: SVC single line diagram

SVC consists of Thyristor Switched Capacitors (TSC) and Thyristor Switched or Controlled Reactors (TSR/TCR). SVC installations consist of a number of building blocks. The most important is the thyristor valve [3], i.e. stack assemblies of series connected anti- parallel thyristors to provide controllability. The coordinated control of the combination of TSC and TCR varies the reactive power. It operates as a shunt-connected variable reactance. Its main task is to produce or draw reactive power to regulate the voltage level of the power system.SVC improves network stability, increases transfer capability and reduce losses, maintains a smooth voltage profile, continuously provides reactive power and mitigates active power oscillations under different network conditions. SVC is normally used for voltage regulation and for improving the transient and dynamic stability. Voltage support capability of the SVC deteriorates with decreasing system voltage [3].

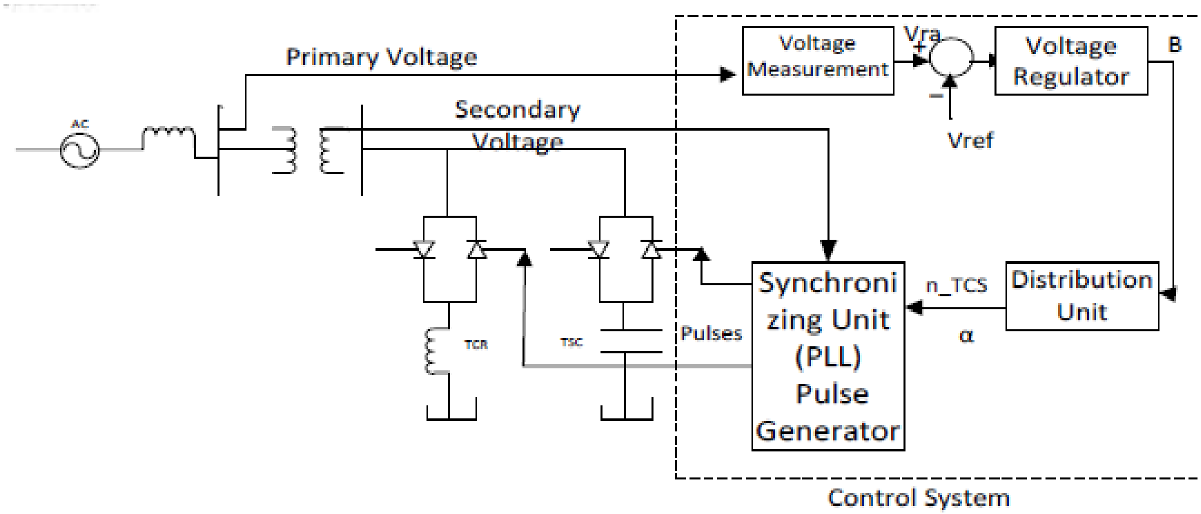

Figure 2.5: Single line diagram with control system of SVC in block diagram.

As the name implies, static var generator can be adjusted to exchange capacitive or inductive current so as to control specific power system variables. The figure above shows single line diagram of SVC and simplified control system [5].

The control system consists of the following main components:

1. A measurement system measuring the positive sequence voltage to be controlled.
2. A voltage regulator that uses the voltage error (difference between the measured voltage, V_m and the reference voltage V_{ref}) to determine the SVC susceptance needed to keep the system voltage constant.
3. A distribution unit that determines the thyristor switched capacitor (TSCs) that must be switched in and out, and computes the firing angle of thyristor controlled reactor.
4. A synchronizing system using a phase locked loop (PLL) synchronized on the secondary voltages and a pulse generator that send appropriate pulses to the thyristor.

C. SVC V-I characteristic

As previously stated in some paragraph, the SVC can be operated in two different modes:

1. In voltage regulation mode(the voltage is regulated within limits as explained below)
2. In var control mode (the SVC susceptance is kept constant)

As long as the SVC susceptance B stays within the maximum and minimum susceptance values imposed by the total reactive power of capacitor banks (B_{cmax}) and reactor banks (B_{lmax}), the voltage is regulated at the reference voltage V_{ref}. However, a voltage droop is normally used (usually between 1% and 4% at maximum reactive power output), and the V-I characteristic has the slope indicated in the figure.

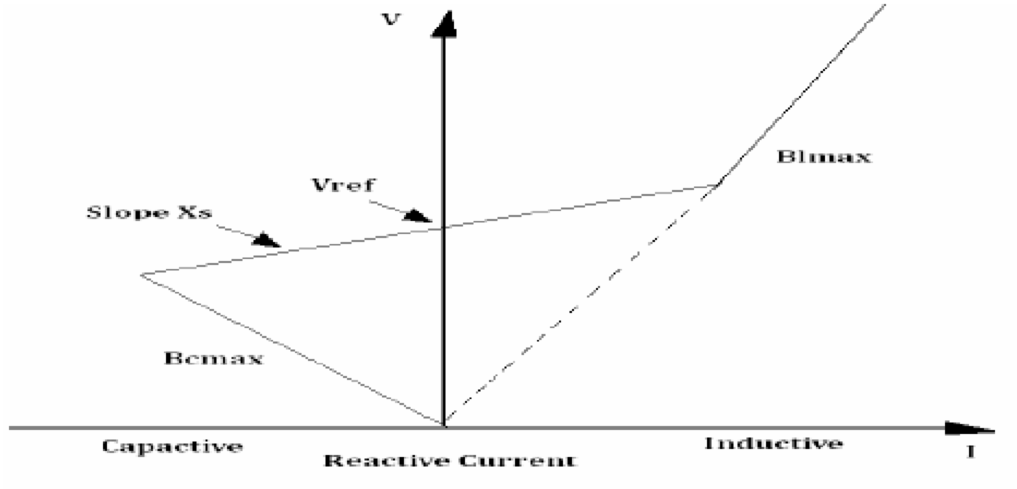

Fig 2.6: SVC V-I characteristic

The V-I characteristic is described by the following three equations:

$$V = \begin{cases} V_{ref} + X_s \, . I & if\ SVC\ is\ in\ reulation\ range\ (-Bcmax < B < Blmax) \\ -\frac{I}{Bcmax} & if\ \ SVC\ is\ fully\ capcitive\ (B = Bcmax) \\ \frac{I}{Bcmax} & if\ SVC\ is\ fully\ inductive\ (B = Blmax) \end{cases}$$

Where

V: Positive sequence voltage

I: Reactive current (pu/P_{base}) (I>0 indicates an inductive current)

Xs: Slope or droop reactance (pu/P_{base})

Bcmax: maximum capacitive susceptance (pu/P_{base}) with all TCSs in service, no TSR

Or TCR

Blmax: maximum inductive susceptance (pu/P_{base}) with all TSRs in service or TCRs at

Full conduction, no TSC

Pbase: Three-phase base power specified in the block dialog box

D. SVC Dynamic Response

When the SVC is operating in voltage regulation mode, its response speed to a change of system voltage depends on the voltage regulator gains (proportional gain K_p and integral gain K_i), the droop reactance X_s, and the system strength (short circuit level).

For an integral–type voltage regulator (K_p=0), if the voltage measurement time constant Tm and the average time delay Td due to valve firing are neglected, the closed-loop system consisting of the SVC and the power system can be approximated by a first – order system having the following closed-loop time constant:

$$T_c = \frac{1}{K_i(X_s + X_n)}$$

Where

T_c: Closed loop time constant

K_i: Proportional gain of the voltage regulator (pu_B/pu_V/S)

X_s: Slope reactance pu/P_{base}

X_n: Equivalent power system reactance (pu/P_{base})

This equation demonstrates that you obtain a faster response when the regulator gain is increased or when the system short-circuit level decreases(higher X_n values).If you take into account the time delays due to voltage measurement system and valve firing ,an oscillatory response and eventually an instability with too weak a system or too large a regulator gain.

2.3.2.2. Static synchronous Compensator (STATCOM)

STATCOM controls transmission voltage by reactive power shunt compensation. A typical STATCOM consists of a coupling transformer, an inverter and an energy storage element like battery or DC capacitor [3].

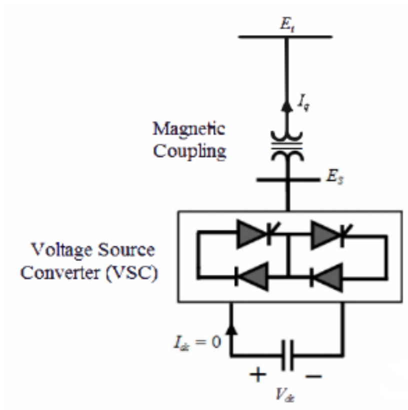

Figure 2.7: Single line diagram of STATCOM

A STATCOM is built with thyristors with turn-off capability like GTO, IGBT or IGCT. The advantage of a STATCOM is that the reactive power provision is independent of the actual voltage at the connection point. Even during most severe contingencies; the STATCOM keeps its full capability. This is a solid-state synchronous condenser connected in shunt with the AC system. The output current is adjusted to control either the nodal voltage magnitude or the reactive power injected at the bus.

STATCOM can be used for filtering harmonics, improving transient and dynamic stability, dynamic over voltages and under voltages, voltage collapse, steady state voltage, excess reactive power flow and adverse transients [3].

The STATCOM can help wind farms in improving voltage regulations, power factor and stability of power load. STATCOM reactive power flow is determined between the grid voltage and the voltage of the power converter.

The control of reactive power in the STATCOM is done by controlling its terminal voltage [3].

1. If the source voltage is larger than STATCOM voltage then the STATCOM reactive power is inductive

2. If the source voltage is smaller than STATCOM voltage then the STATCOM reactive power is capacitive

2.3.3. Combined Series-Shunt Controllers

2.3.3.1. Unified Power Flow Controller (UPFC)

A combination of STATCOM and SSSC, which are coupled using a common dc link, to allow bidirectional flow of active power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM, are controlled to provide concurrent active and reactive series line compensation without an external electric energy source [3].The UPFC, by means of angularly unconstrained series voltage injection, is able to control concurrently or selectively the transmission line voltage, impedance, and angle or, alternatively, the active and reactive power flow in the line [3].

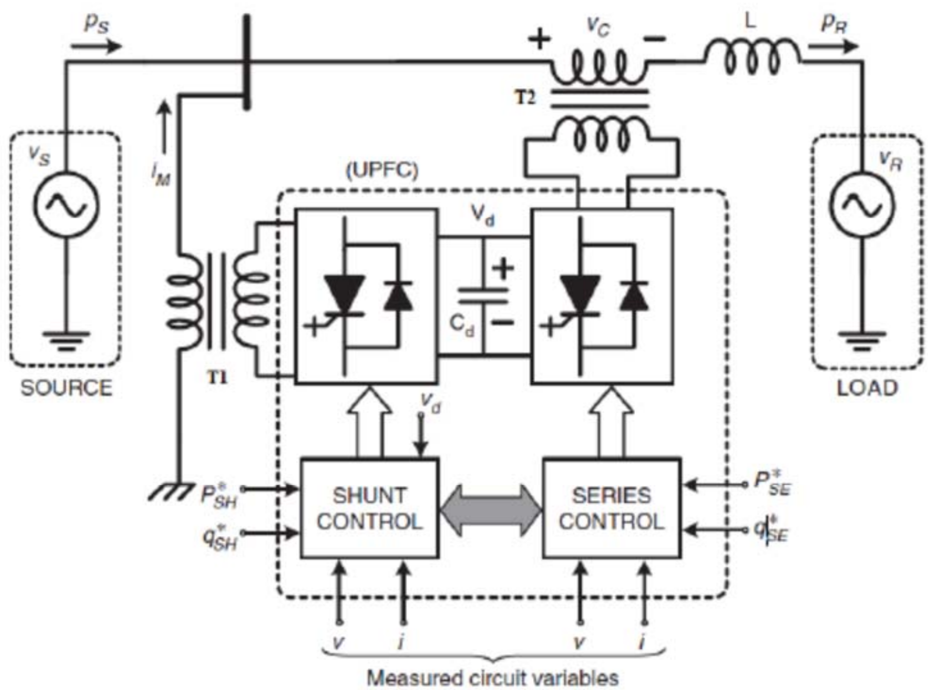

Figure 2.8: Single line diagram of UPFC

UPFC regulates voltage by continuously variable in-phase voltage injection. Functionally, this is similar to that obtainable with a transformer tap changer having infinitely small steps. Series reactive compensation is similar, but more general than, controlled series capacitive and inductive series compensation. This is because the UPFC injected series compensating voltage can be kept constant, if desired, independent of line current variation, whereas the voltage across the series compensating (capacitive and inductive) impedance varies with the line current[3].

The UPFC can function as a perfect phase shifter. From the practical viewpoint, in contrast to conventional phase shifters, the AC system does not have to supply the reactive power that the phase-shifting process demands. Since, it is actually generated by the UPFC converter, multifunction power flow control, is executed by simultaneous terminal voltage regulation, series capacitive line compensation and phase shifting, enhancement of transmission capacity, transient stability, power oscillation damping, and voltage stability. For its speed and control characteristics, the UPFC is the most complete and powerful FACTS device in performing those steady-state and dynamic functions [3].

Table 2.1: Application of FACTS devices

ISSUE	DEVICE
Steady State Voltage Control	SVC
Dynamic and Post contingency voltage control	SVC,STATCOM
Transient stability improvement	SVC
Power Oscilation damping	SVC,TCSC
Power Quality Improvement	SVC,STATCOM
Sub-Synchronous resonanace mitigation	TCSC

2.4. Literature Review

Simulation and Discussion is made for both transmissions with FACTS devices and without FACTS. The power flow obtained with compensation i.e.by introducing FACTS controller in the transmission line is seen to be increased [6]. In energy transmission system FACTS are effective equipments on power control. They help facilitating the improvement in power transmission capability, while minimizing the transmission line losses and impact on the environment. They also aid in the improvement of power quality while maintaining the stability of the system. The compensation obtained was better than that of a normal transmission line without FACTS [6].

Study results indicate that among the FACTS devices evaluated, the UPFC was the most viable option for San Diego Gas &Electric (SDG&E) to express the potential to increase its import capability. The UPFC could also provide dynamic reactive power support [2].

Utilization of the existing power system can be improved through the application of advanced FACTS power electronic devices. A detailed study [3] had been made on the Thyristor Controlled Reactor and Thyristor Switched Series Capacitor on their application of voltage control. Static Var compensator is applied for testing its effectiveness in the reactive power compensation and voltage regulation. A new generation of FACTS devices called the Distributed FACTS devices were analyzed for power flow control [3].

The massive growth of interconnected power systems due to increasing demand for electrical energy has given rise to numerous challenges. These include power swings and oscillation due to outages, blackouts, natural disturbances and system faults that occur along transmission lines, load and generation points. Blackouts have been witnessed in the recent years in countries around the world. These major disturbances causes power system instability and pose difficult to system operation, planning and maintenance scheduling[4].In these circumstances, FACTS controllers such as Interline Power Flow controller(IPFC),static Synchronous Series Compensator(SSSC) and Unified Power Flow Controller(UPFC) can considerably improve transient Stability thus enhance overall system stability during disturbances[4]. In this research [4], use of UPFC, SSSC and IPFC FACTS controllers were applied in Transient Stability Enhancement (TSE) analysis considering dynamic environment of the standard IEEE 14 bus test system. By incorporating fast acting and appropriately located FACTS devices, the corresponding time domain responses were obtained and analyzed with and without the devices. The results have shown significant enhancement of the transient stability when the FACTS devices are applied by considerably reducing post-fault settling time of power system as well as effectively damping network oscillation in contrast with when the devices are not applied [4].

In the thesis [5], different control design methodologies for designing FACTS power flow controllers and power oscillations damping controllers in power systems have been illustrated. The injection models of the Thyristor Controlled Series Capacitor (TCSC), Unified Power Flow Controllers (UPFC) and Static VAR Compensator (SVC) with their power flow controllers have been demonstrated.

FACTS devices has been investigated and adopted in the power engineering area for fast control characteristics and continuous compensation. The paper focuses on the operation of the FACTS devices under general fault that may cause any other transmission lines to be over flowed [1].

Investigation is made for various options to increase the power transfer in Western Australia network [8]. Results show both STATCOM and SVC can increase the transmission line power transfer capability. However, STATCOM has better dynamic performance and can help in recovering system voltage faster than SVC. This helps to shift the boundary points of the stability limits, as a result of that power transfer capability can be improved [8].

Shunt Connected compensation (SVC and STATCOM) based FACTS devices for the control of voltage and power flow in the long transmission line are well studied [5].It also studied in resolving the optimal location of shunt Flexible A.C. Transmission System (FACTS) devices for a long transmission line for voltage and power transfer improvement. The result also shows that optimal location depends on voltage magnitude, the line loading and system initial condition.

Overall, different studies show FACTS devices are becoming more common in electrical power networks and are useful in controlling electrical characteristics dynamically.

CHAPTER THREE

3. Modeling of GERD-DEDESA-HOLETA Power System Network

3.1. Introduction

The single line diagram showed below in figure 3.1 represents four bus systems with voltage level of 500 kV and 400 kV. This system consists of GERD, DEDESA, HOLETA and HOLETA 400 kV buses. The transmission line length of GERD to DEDESA is 345 km with four parallel lines. The line from DEDESA to HOLETA is 275 km of four parallel lines as well. The generators are modeled for synchronous machine with salient pole rotor type with parameters nominal power, line-to-line voltage, frequency, reactance's, stator resistance (R_s) and time constants (all data's in Appendix A).

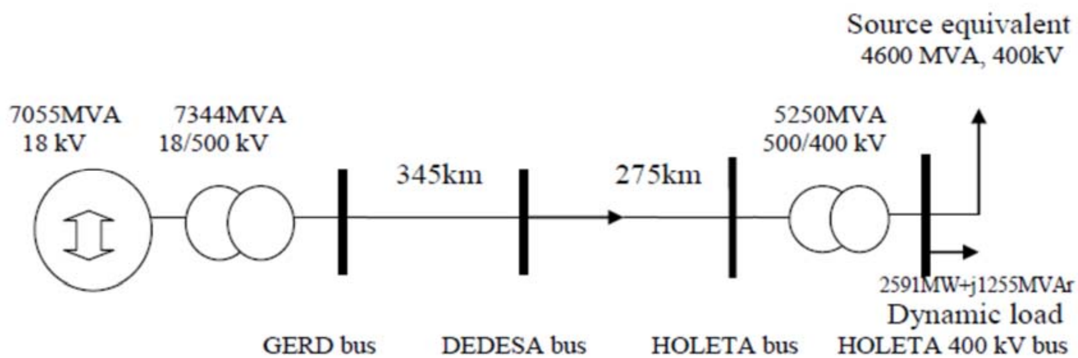

Figure 3.1: Single line diagrams of 4-bus 500/400 kV and 400 kV transmission systems

The GERD generators are with 18 kV phase to phase voltages, 417 MVA generating capacity of two generators which are arranged for early generation and 444.4MVA generators which are fourteen in number with a total of 7055.6 MVA[13].

$$\begin{aligned} total\ power &= (417\ MVA * 2\ ) + 444.4\ MVA * 14 \\ &= 834\ MVA + 6221.6\ MVA \\ &= 7055.6\ MVA \end{aligned}$$

In the model, there are also three phase step up transformers 18kV/500kV, 7344 MVA capacity. There is also a step down transformers 500kV/400kV, 5250 MVA capacity with YnD11 configuration, nominal power, frequency and winding parameters set up made. They are found in HOLETA 500/400 kV substation and are 21 single phase autotransformers of capacity 250 MVA each. Therefore, a total of 5250 MVA maximum capacity is available in HOLETA substation.SVC transformer of size 945MVA; 400kV/33kV is also used in the model and is found in the system. The SVC is modeled in phasor type because it is simple for modeling. The model types are available at Simsacpe software/MATLAB simulink/R2017a. The SVC nominal voltage, frequency, three phase power and reactive power limits are incorporated in the model. The voltage regulation mode controller is used in this study. The SVC is connected to the system with 33 kV voltage levels (all used data's in the model are shown in Appendix A).The equivalent source network of the system external to the 500/400 kV network is taken to be 4600 MVA and 400 kV. This is by considering the existing 4200 MW system capacity and 0.9 power factor. The system load is also taken to be dynamic and it is 2591MW+j1255MVAr.

Figure 3.2: Single phase 500/400 kV autotransformer.

3.2. Data collection

HOLETA 500/400 kV substation, DEDESA 500/400 kV substation, GERD substation and the power plant data's are collected as can be seen in the Appendix A. Data collection is made by going to the sites and collect from the name plates and drawings. Data is also taken from the daily log sheet, Communicating with project offices and accessing different contractual agreements. Transmission line data's like line length and impedance per km is also gathered. The important part of the thesis, SVC data is collected as seen in detail in the Appendix A. Data is collected at HOLETA 400 kV bus bar for different days while SVCs are online and offline. To see the overall effect of the SVCs, Voltage profile of Gebereguracha 400/230/66/33 kV substation is also recorded from the daily log sheet. GERD generators data are gathered from the contract document and are used for simulation.

Proper simulation was made by MATLAB simulink and analysis is conducted. Evaluation is made on the system with and without SVCs in terms of voltage stability and power transfer capability improvement in GERD-DEDESA-HOLETA 500/400 kV transmission network.

Table 3.1: Data of generators at GERD (16 in number)

Generator Type	Synchronous generator with salient poles
Prime mover	Francis turbine
Rated power output	444.4 MVA
Rated stator voltage	18kV
Operating range of the stator voltage	± 5 %
Rated frequency	50 Hz
Rated power factor	0.9
Number of phases	3
Number of poles	48
Rated speed	125 rpm
Rated excitation current	2600 A
Rated excitation voltage	353 V @ 130 °c
Type of excitation	Static
Continuous generator output charging a transmission line at a rated frequency	301.5 MVAr
Reactance (in p.u. ref to 0.729 ohm)	Unsaturated saturated
Xd	1.208 0.986

x'd	0.314 0.820
x''d	0.265 0.194
Xq	0.820
x'q	0.820
x''q	0.3350.307
x2	0.296
x0	0.092
Time constants	
T'd0	10.30 s
T'd	2.675 s
T''d	0.054 s
T''d0	0.064 s
T''q	0.001 s
T''q0	0.003 s
Ta	0.362 s
Stator winding resistance(3 phase in series)	4.67 mΩ
Rotor winding resistance	94.91 mΩ
Stator winding capacitance	2.20 µF per phase

This all above data's are used in the simulation model. The capacity of the generators for the early generation is different. But the characteristics are considered the same for the simulation purpose.

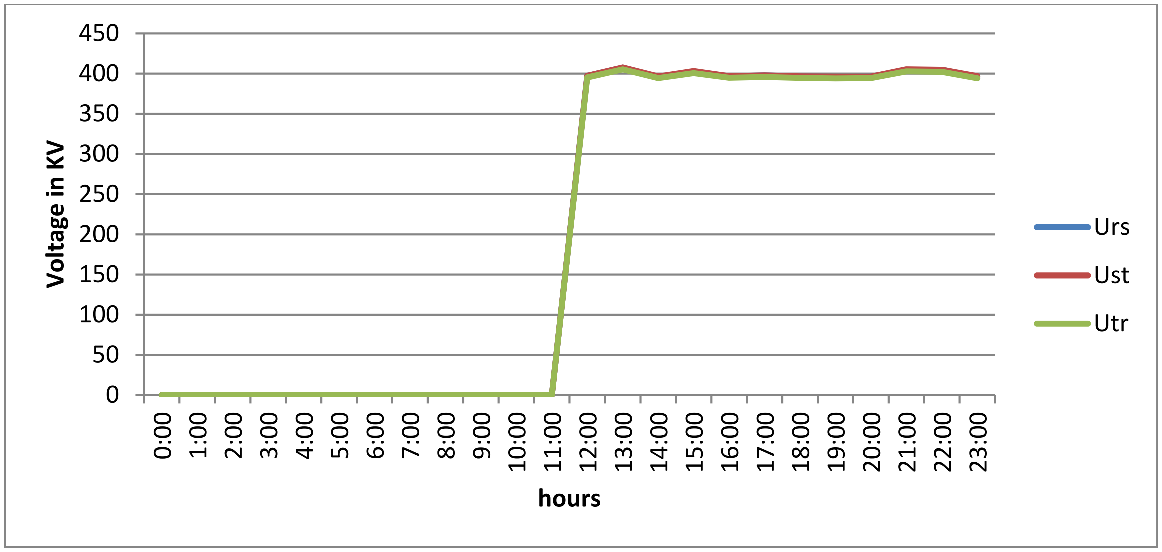

Figure 3.3: Showing voltage profile on 2017/09/08 at HOLETA 400 kV bus bar 2

As can be seen in Figure 3.4 the voltage was zero before September 08/2017 because HOLETA substation was not energized.

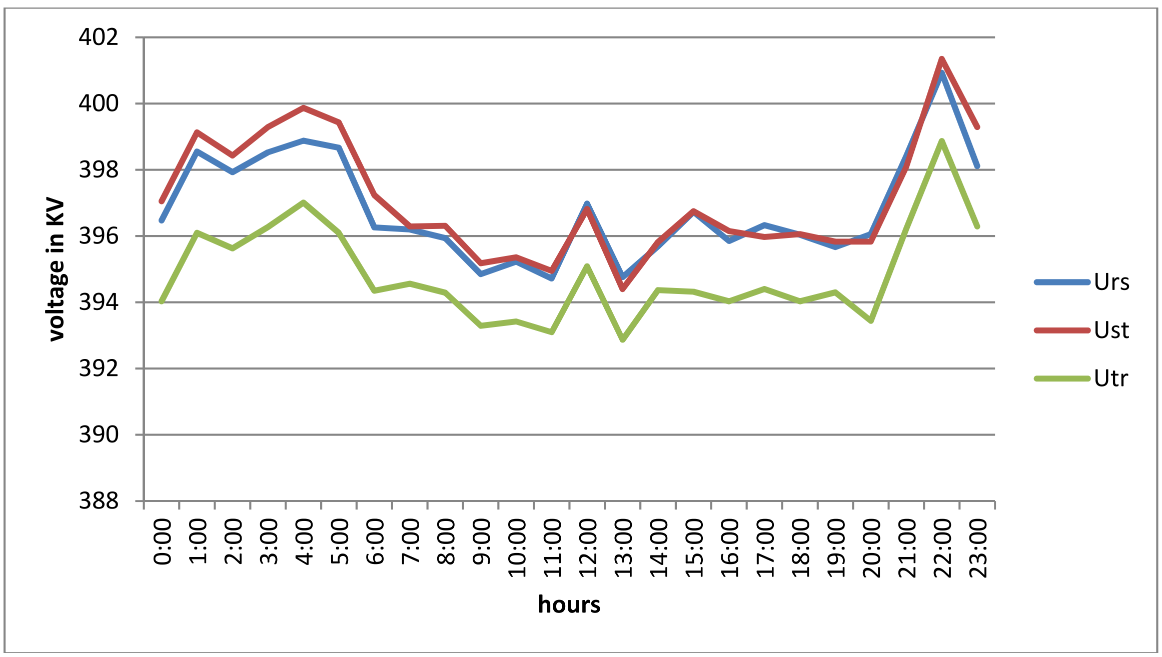

Figure 3.4: Showing voltage profile on 2017/09/14 at HOLETA 400 kV bus bar 2

Figure 3.5 shows phase to phase voltage is not uniform and is varying from around 393kV Utr minimum voltage to 401kV Ust maximum voltages. This graph is simulated from the data taken on the actual reading of the 24 hour working SCADA system of the substation.

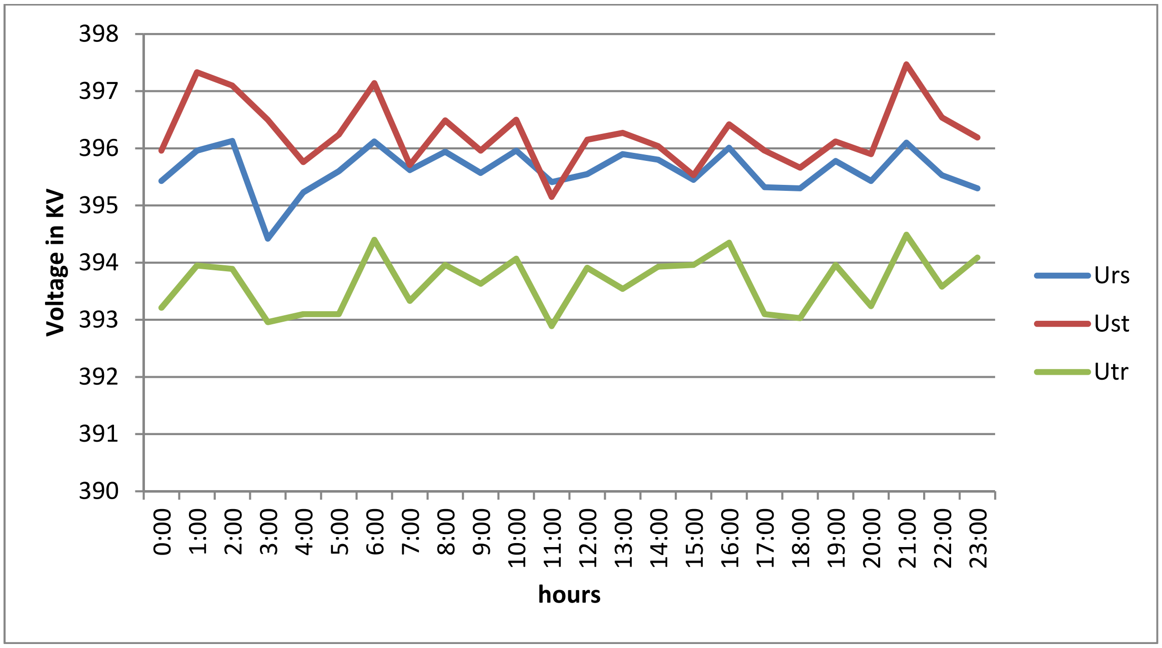

Figure 3.5: Showing voltage profile on date 2017/09/21 On HOLETA 400 kV bus bar 2

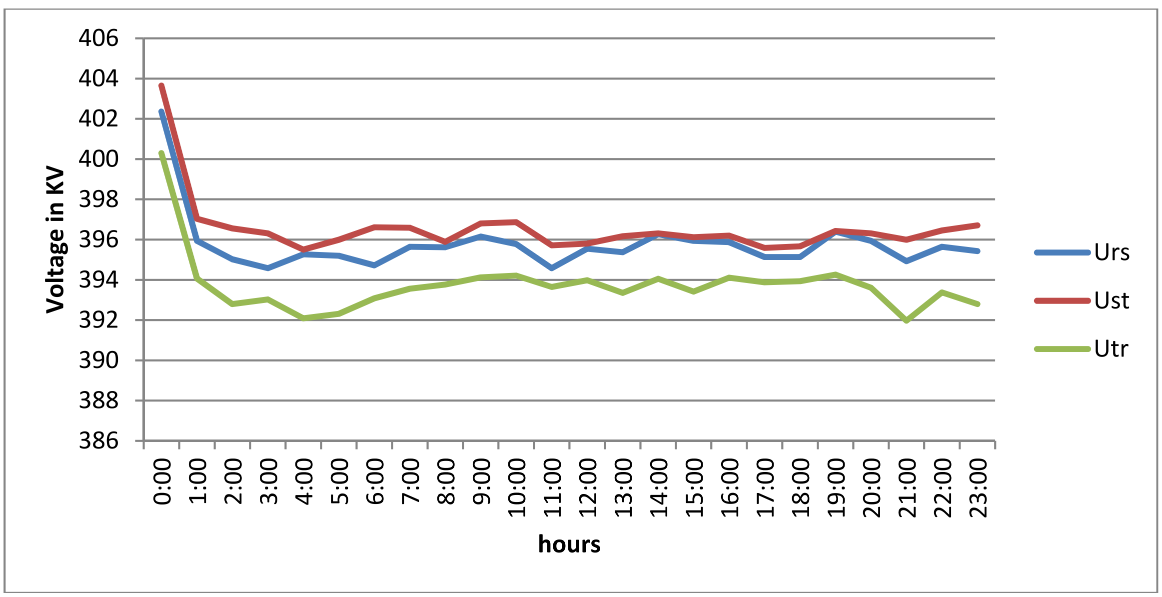

Figure 3.6: Voltage profile at HOLETA substation on 400 kV bus bar 2 on date 2017/09/30

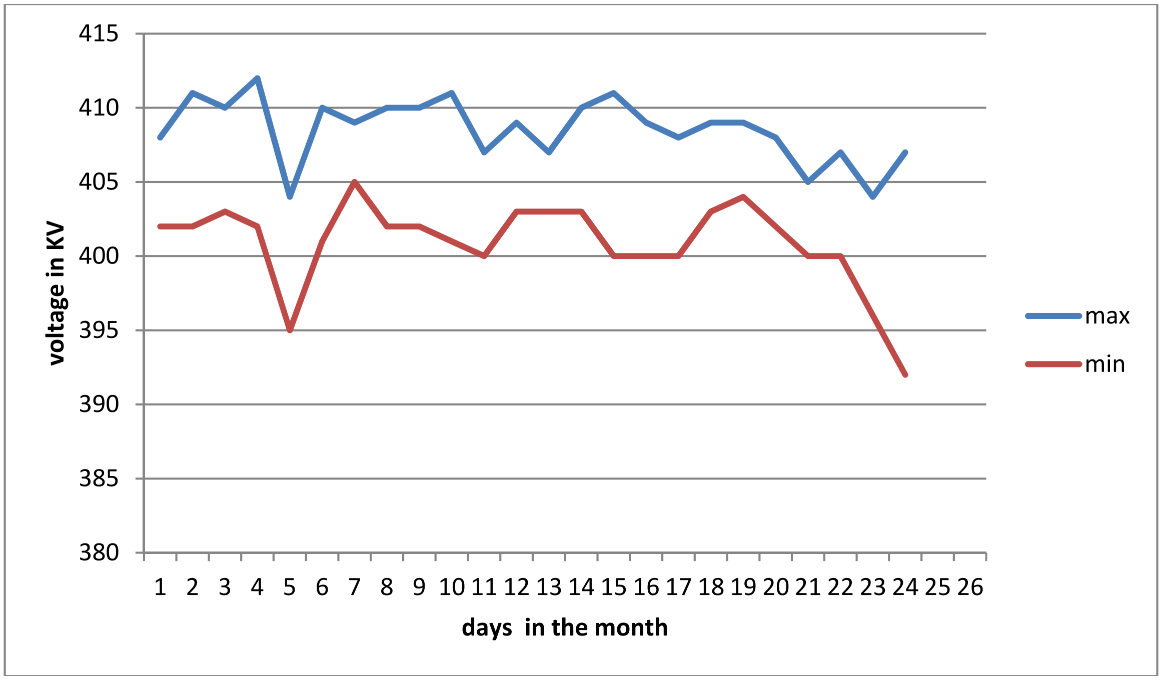

Figure 3.7: Showing voltage profile at Gebereguracha 400 kV bus bar on June 2017

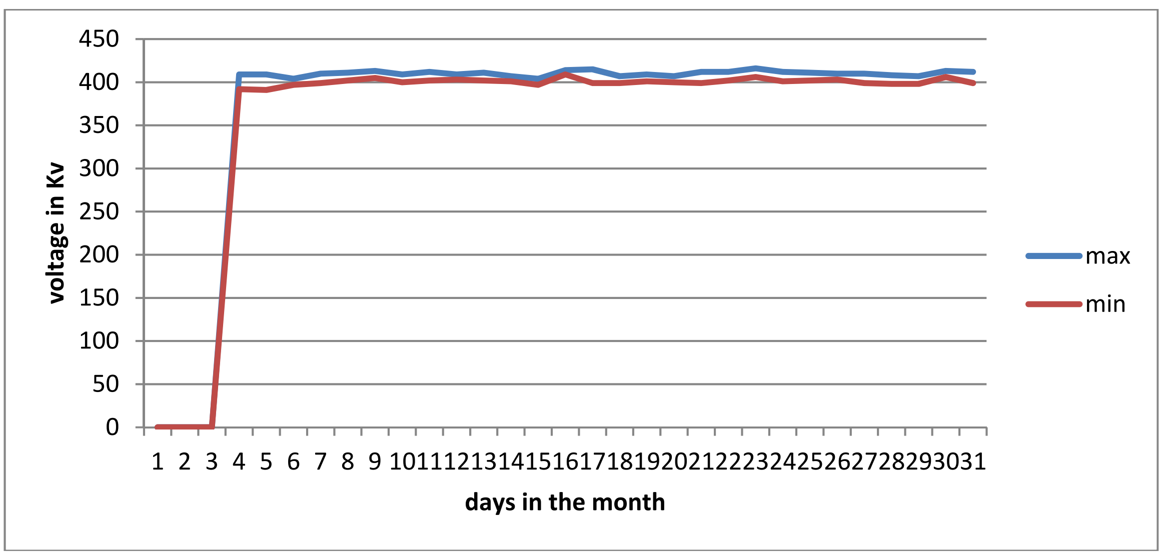

Figure 3.8: Showing voltage profile at Gebereguracha 400 kV bus bar on July 2017

The substation was working on and off due to over voltage issue. The data recorded is daily maximum and minimum average voltage.

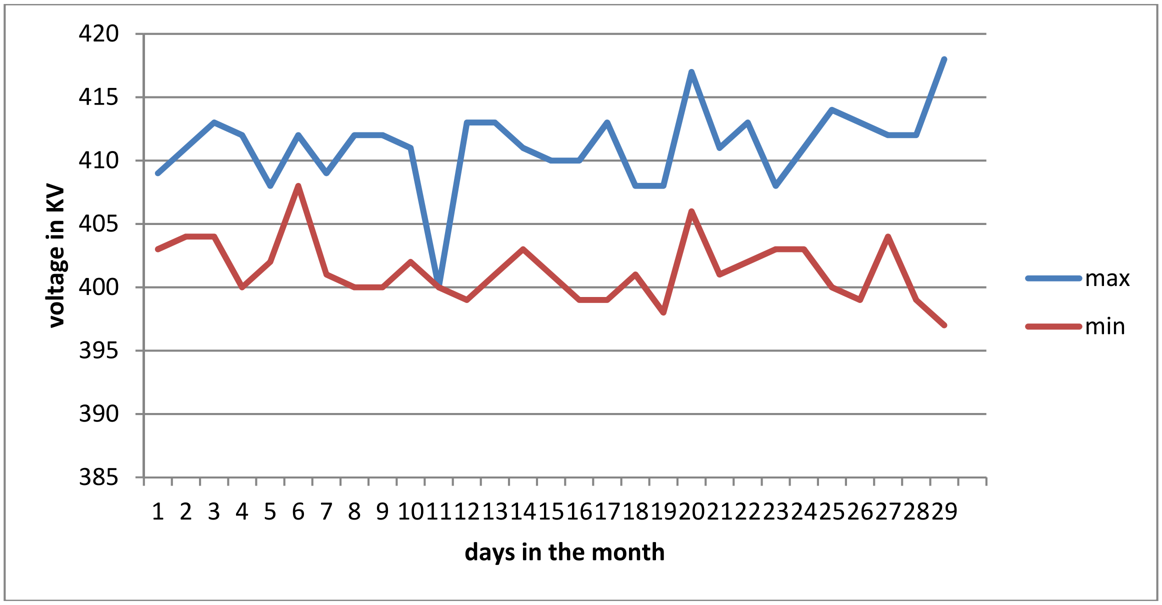

Figure 3.9: Showing voltage profile at Geberegurachа 400 kV bus bar on August 2017

From the data collected on the 400 kV networks, it is observed that the voltage is very much regulated nearly 400 kV after the energization of SVCs. The first SVC to be energized is SVC 3 on September 8/2017 at 2 pm in the afternoon. This was actually after three hours the 400 kV bus bar II was energized. In between it is observed that the bus bar voltage was reaching 407.42 kV at HOLETA 400 kV bus bar 2 which can go up to 420kV in worst case [54]. In Geberegurachа substation, it is observed that the 400kV bus bar voltages were reaching 418 kV which was leading the national grid control center to interrupt the line coming from Sululta through which Gebreguracha substation is connected to HOLETA 500/400 kV substation. This was resulting in Geberegurachа and its surrounding areas in darkness every night. But after the energization of the SVCs, the voltage at Gebreguracha 400 kV bus bar is not critical anymore to the system and the line is working 24/7 unless there is another type of fault on it.

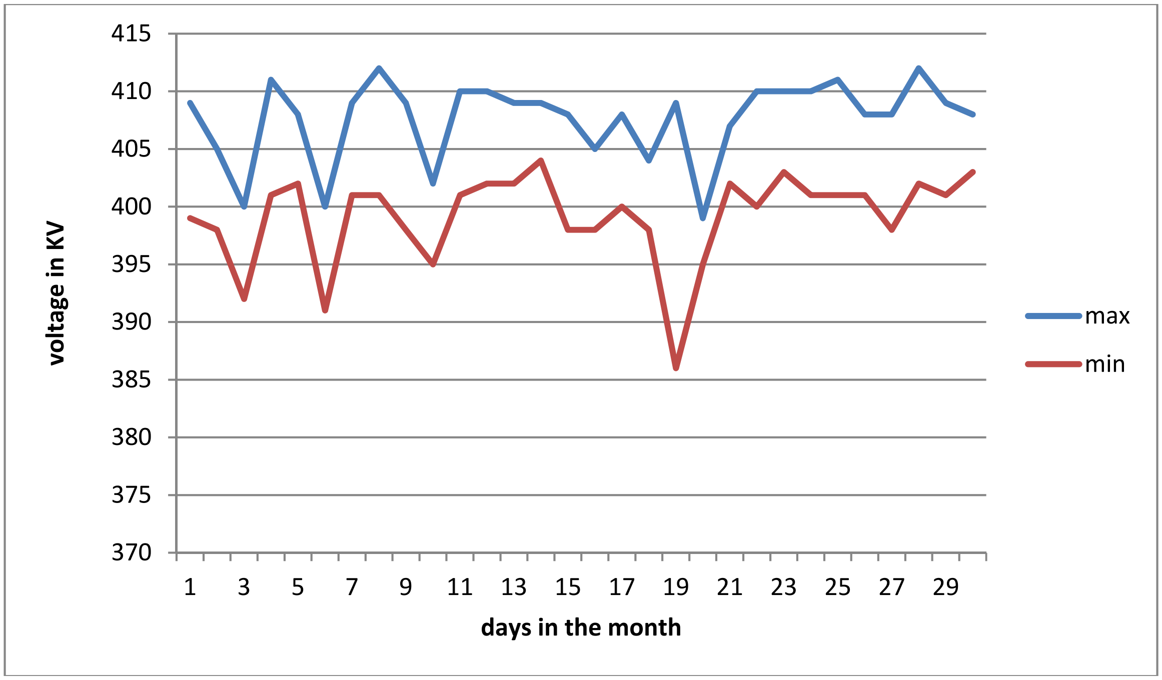

Figure 3.10: Showing voltage profile at Geberegurachа 400 kV bus bar on December 2017

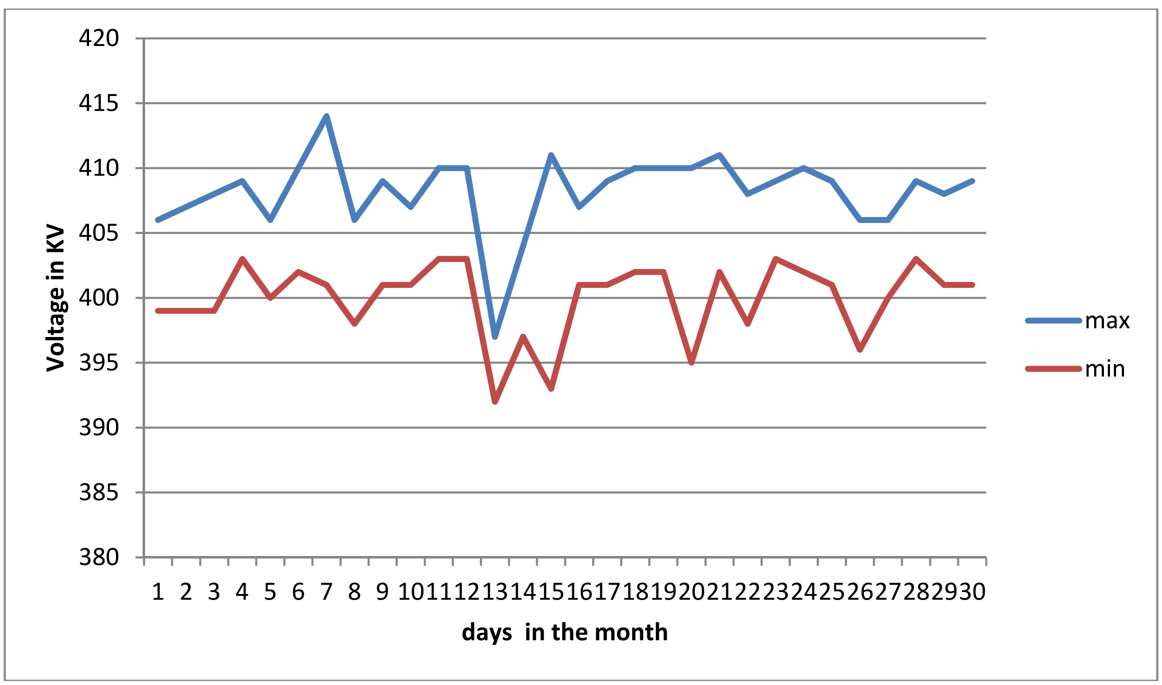

Figure 3.11: Showing voltage profile at Geberegurachа 400 kV bus bar on January 2018

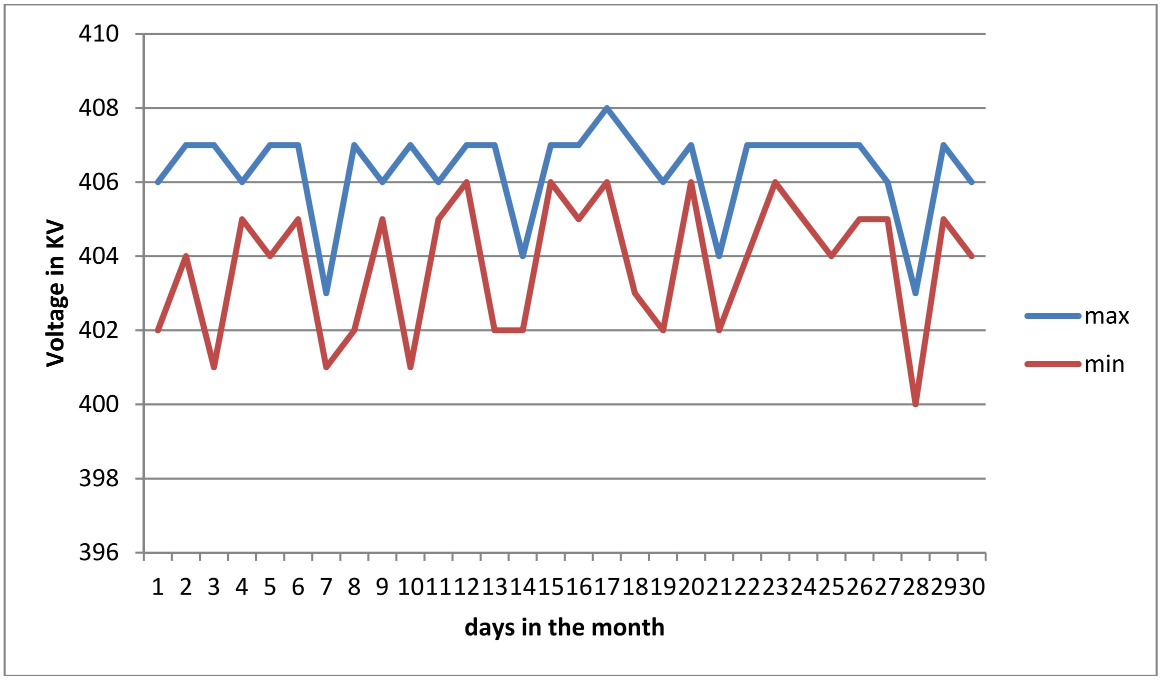

Figure 3.12: Showing voltage profile at Gebereguracha 400 kV bus bar on October 2018

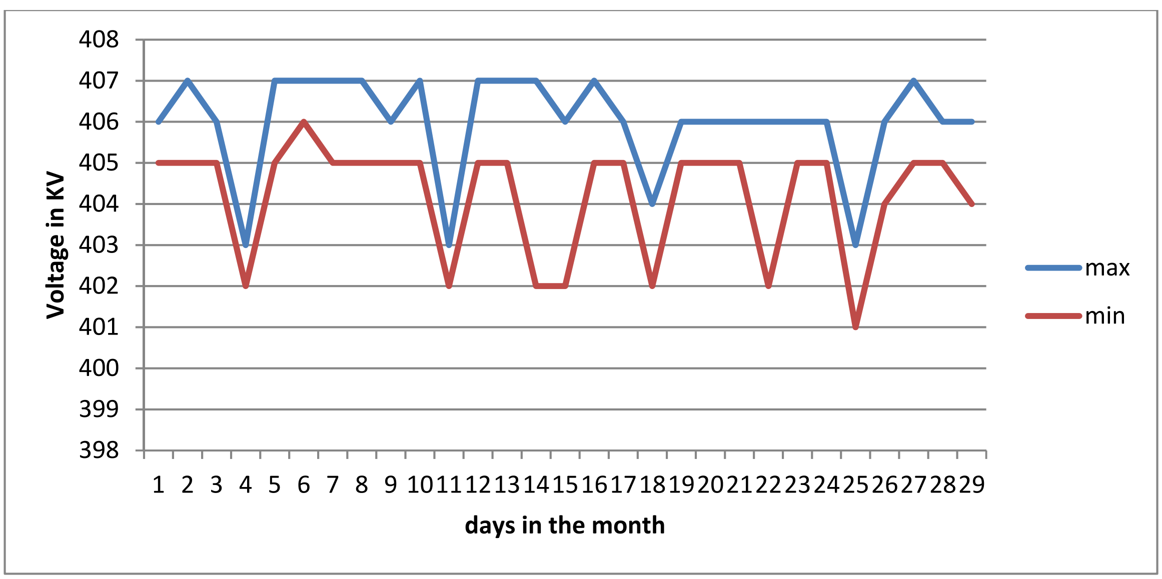

Figure 3.13: Showing voltage profile at Gebereguracha 400 kV bus bar on November 2018

The recorded data taken from the Gebreguracha substation shows that the system problem was over voltage and after the smooth operation of the SVCs at HOLETA 500/400 kV substation, this overvoltage problem was solved.

On this voltage stability scheme the SVCs are doing a great job. But above all the main intention of this study is to see the capability of SVCs in evacuating the GERD power and the voltage stability they can bring to the network.

3.3. Software used for Modeling

The software used for this study is MATLAB/R2017a/SIMULINK /simscape. It is a comprehensive and almost easy to use for scientific computing. It provides to engineers, researchers and any scientific studies, an interactive system that integrates a lot of scientific numerical computation and visualization algorithms .It is a powerful, almost open and programmable system allowing especially remarkable gains in productivity and creativity.

3.4. Software model of GERD-DEDESA-HOLETA network

The simulation will be run having GERD generators, step up transformers at GERD, transmission line from GERD to DEDESA and from DEDESA to HOLETA 500/400 kV substation. It is simulated with SVCs as well as without it. It uses 33 kV bus bar at HOLETA 500/400 kV substation for the integration of SVCs. There are three 400kV/33kV transformers. The simulation is conducted with SVCs in all three positions i.e. end point, midpoint and source end to find best location. In the case of DEDSA and GERD, different type of SVC transformers with rating 500/33 kV voltage level are used. Then, the SVCs are simulated with and without compensation devices (Reactors).

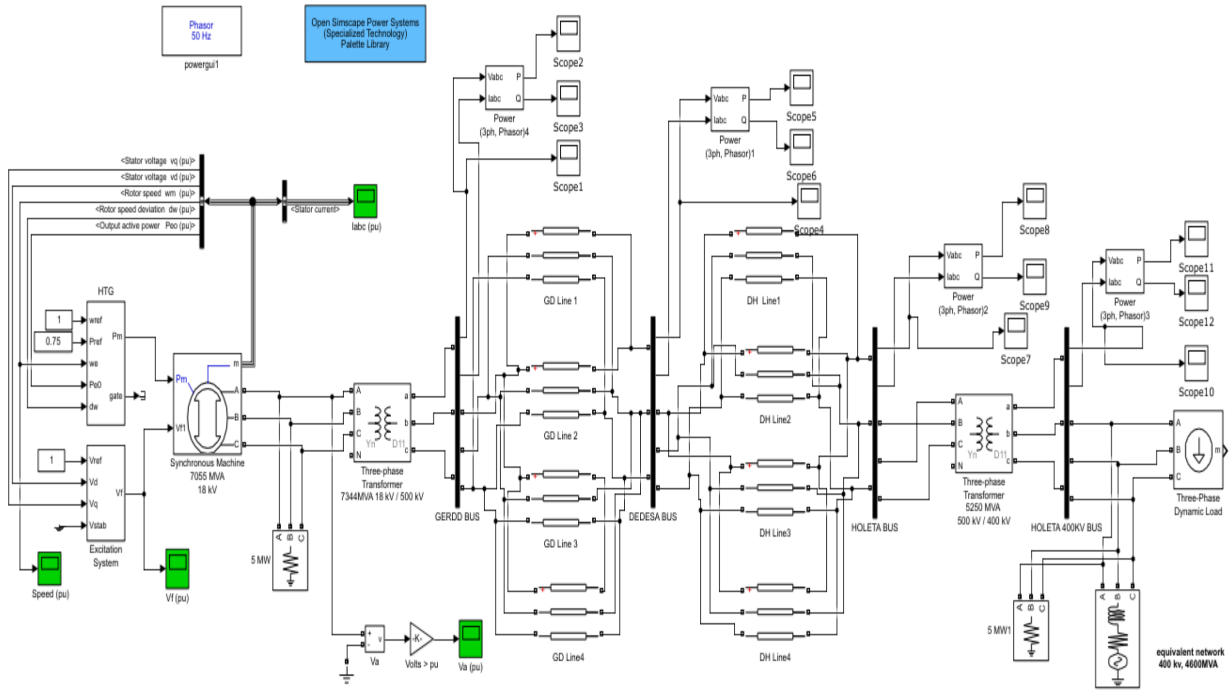

Figure 3.14: Model of the system without SVCs

As Figure 3.3 depicts that, it is done using Mat Lab 2017a software. The model consists of all the components starting from GERD power plant up to HOLETA 500/400 kV substation. All the transmission line between each substation is modeled. The step up transformers at GERD and the step down transformers at HOLETA500/400 kV substation are included in the model with their characteristics.

CHAPTER FOUR

4. Simulation Studies and Analysis of Results

4.1. Introduction

The Entire network, GERD-DEDSA-HOLETA 500 kV network and also the 400 kV components at HOLETA 500/400 kV network are simulated in the MAT Lab 2017a Simulink software. The Simulation studies with different conditions. By installing the SVCs at different locations in the grid, the simulation tries to study the difference in voltage stability and the power transfer improvement in the grid. The simulation tries to incorporate the reactors in the system and observes the system behavior and draw a conclusion.

The other entire network in the country is modeled with an equivalent network and voltage level of 400 kV. The Load is also taken to be dynamic and 2591 MW. This is the existing peak load magnitude.

The study uses PV and QV curves to study the voltage stability of the system with different loading conditions. The EXCEL is used to draw the curves.

4.2. Existing System analysis under normal operating conditions

As can be seen in the figure 3.3, the model contains generator, step up transformer from 18kV to 500/400 kV at GERD and four parallel 500kV transmission lines between GERD and DEDESA .There is also four parallel line between DEDSA and HOLETA 500/400 kV substation. In HOLETA 500/400 kV substation there are also step down transformers from 500kV to 400 kV. Equivalent source network and dynamic system load is also connected at the 400kV bus bar. In all the buses, there are scopes to measure bus bar voltage, active power and reactive power. Simulation is run and results are shown graphically below for all the buses.

The summarized simulation output with different parameters on all four buses is given in Table 4.1.

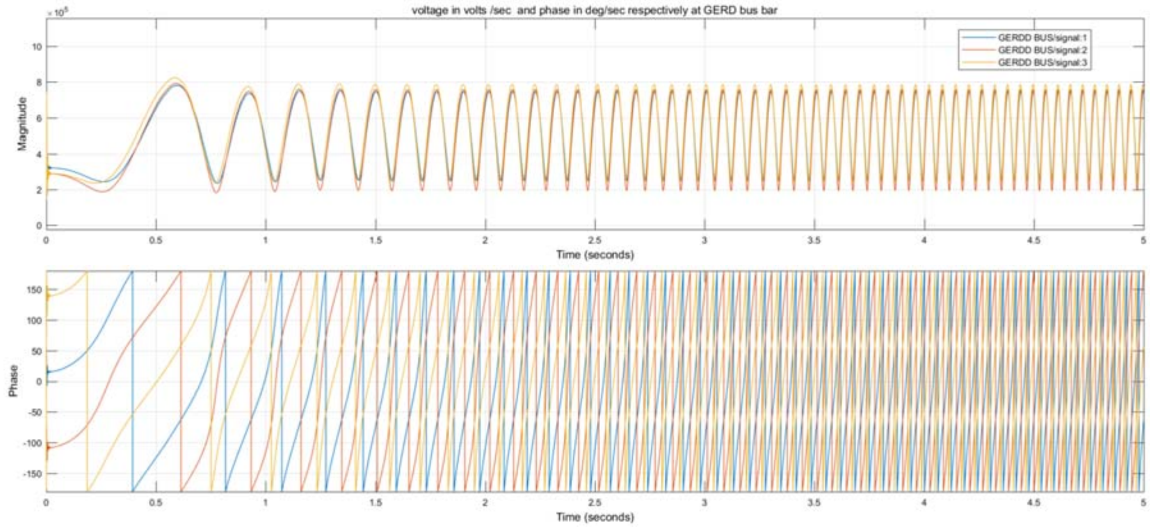

Figure 4.1: Graph showing voltage magnitude and phase vs. time at GERD bus bar

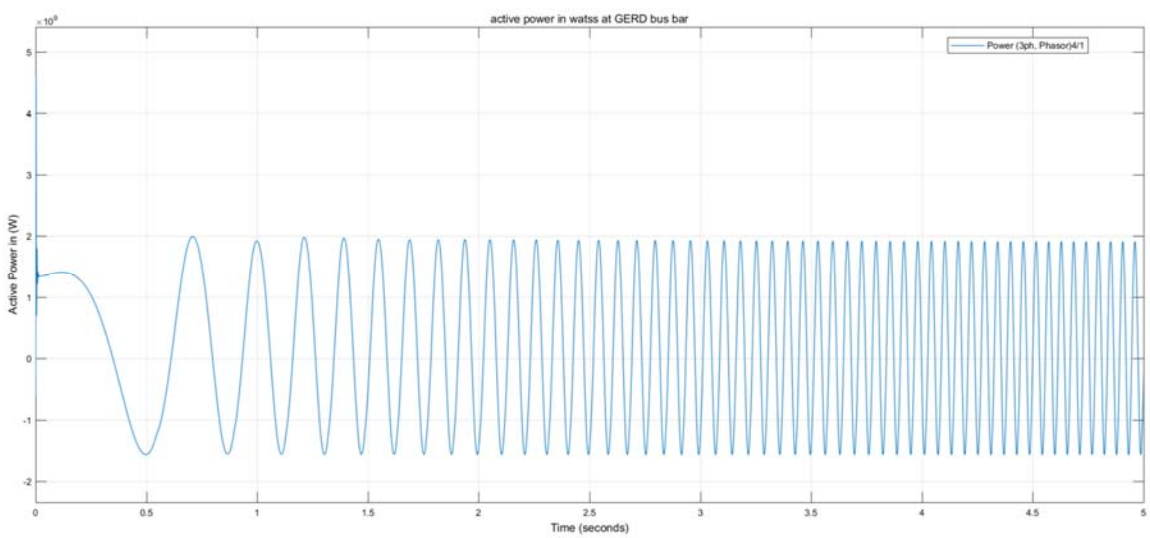

Figure 4.2: Graph showing active power vs. time at GERD bus bar

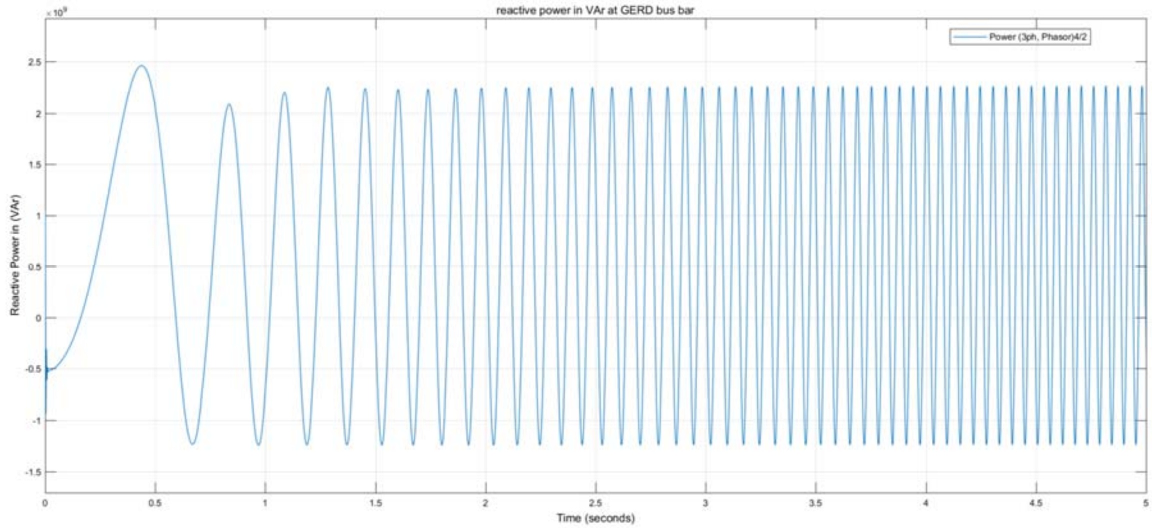

Figure 4.3: Graph showing reactive power vs. time at GERD bus bar

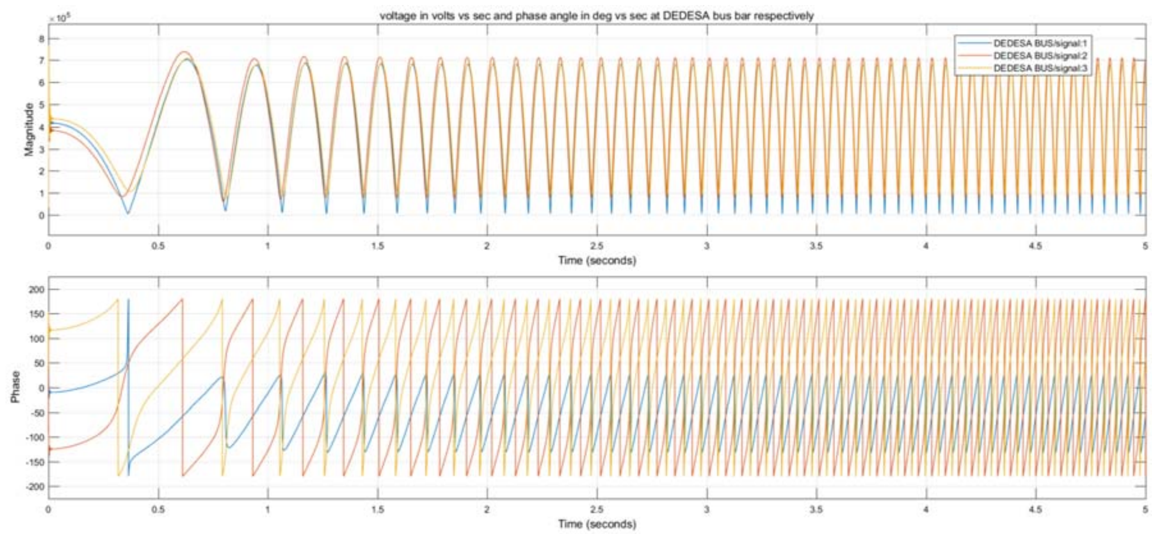

Figure 4.4: Graph showing voltage magnitude and phase vs. time at DEDESA bus bar

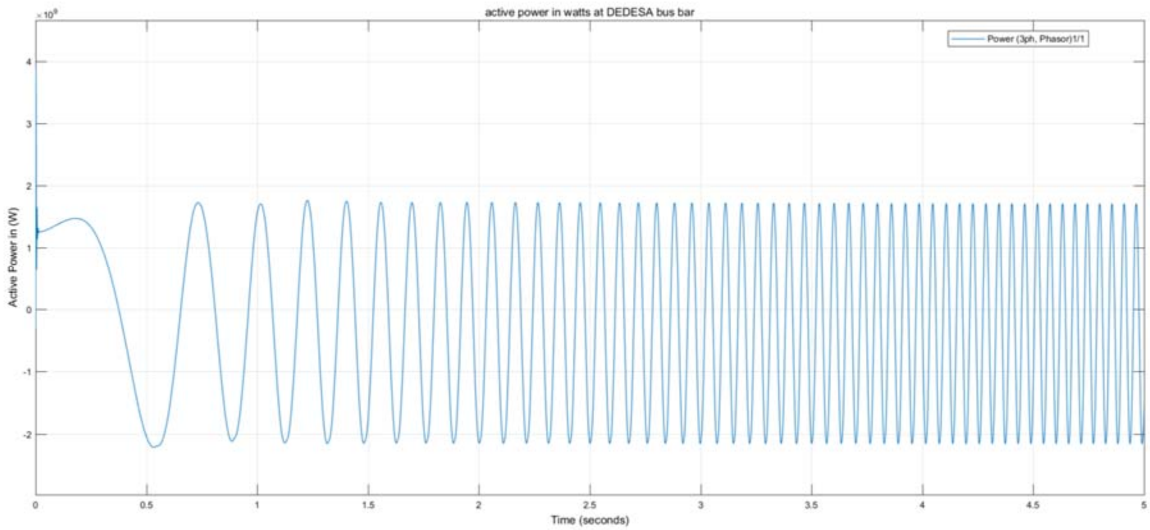

Figure 4.5: Graph showing Active power vs. time at DEDESA bus bar

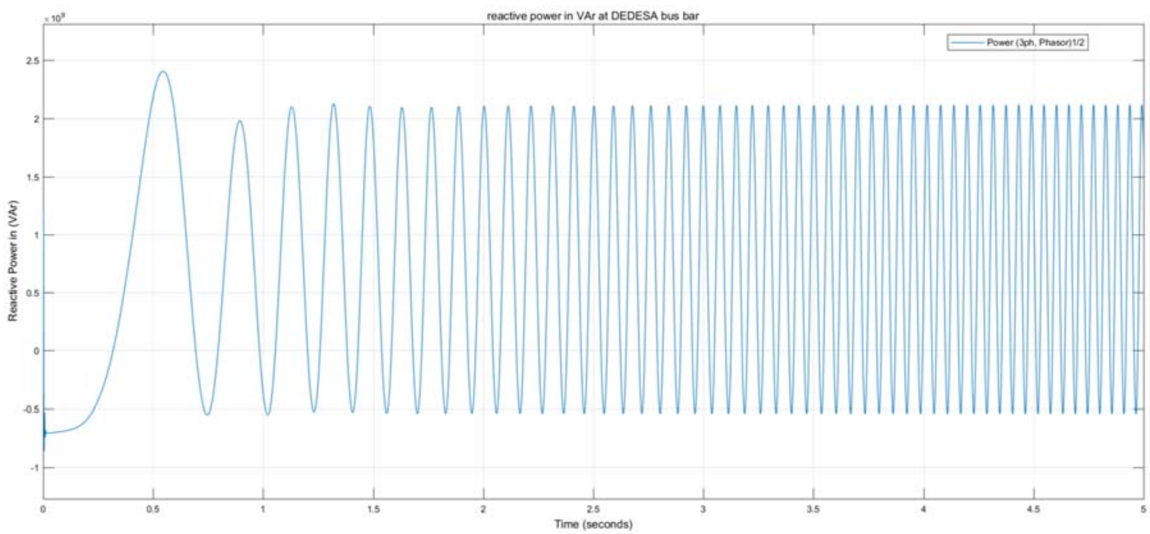

Figure 4.6: Graph showing Reactive Power vs. time at DEDESA bus bar

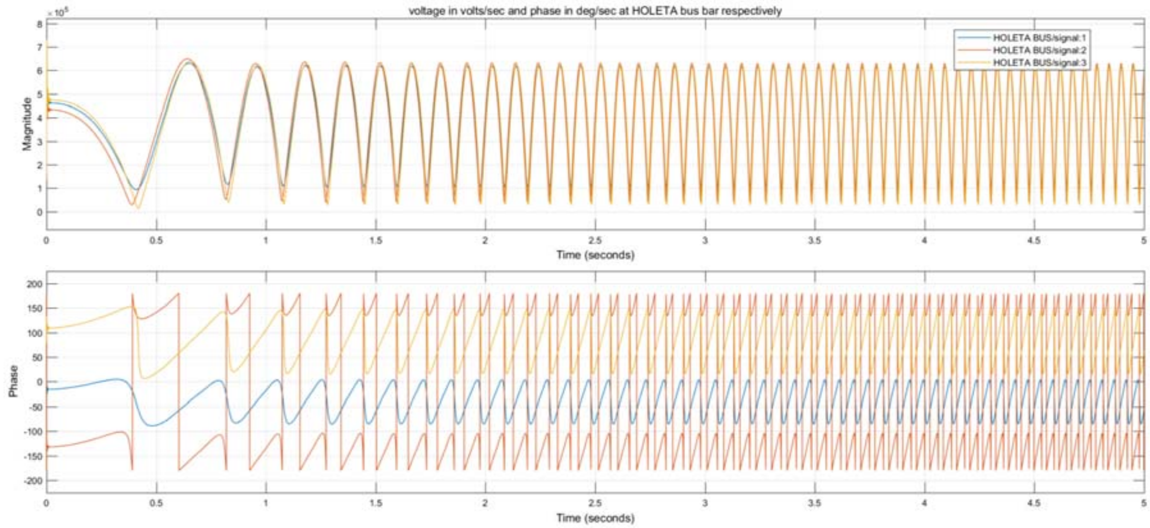

Figure 4.7: Graph showing Voltage magnitude and phase vs. time at HOLETA 500 kV Bus bar

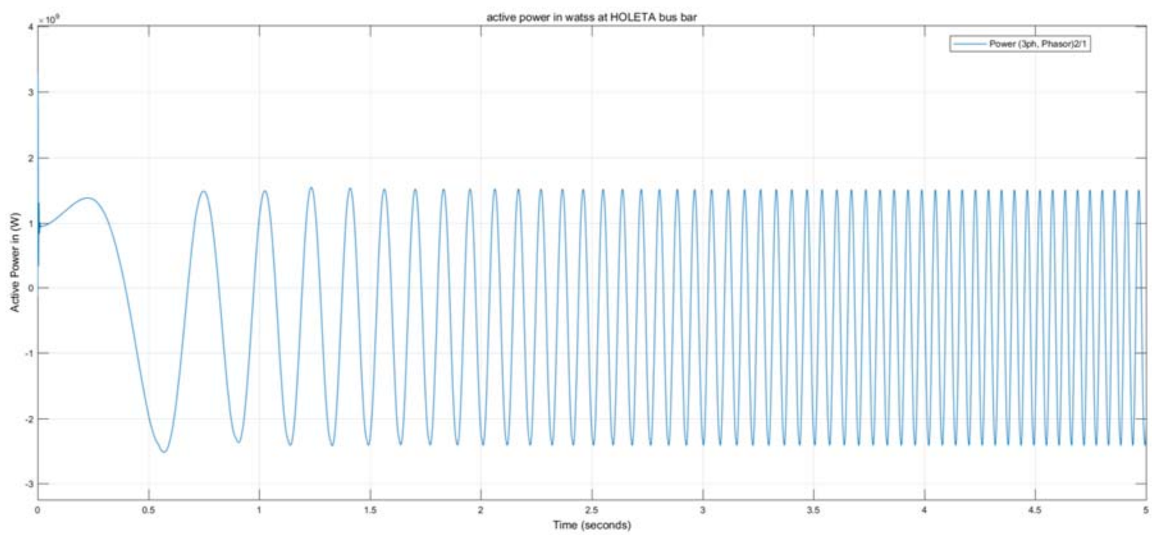

Figure 4.8: Graph showing Active power vs. time at HOLETA 500 kV bus bar

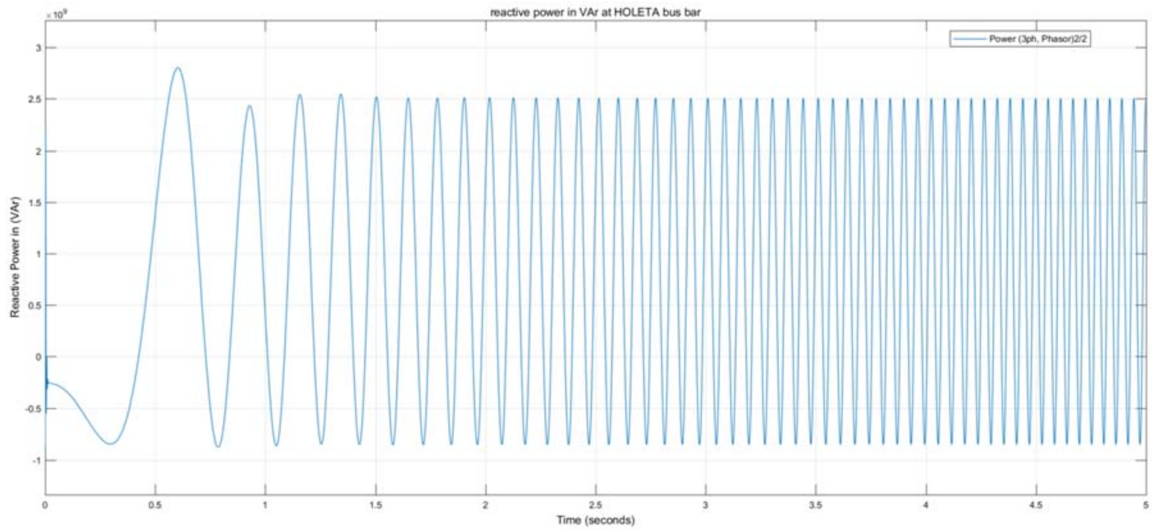

Figure 4.9: Graph showing Reactive power vs. time at HOLETA 500 kV bus bar

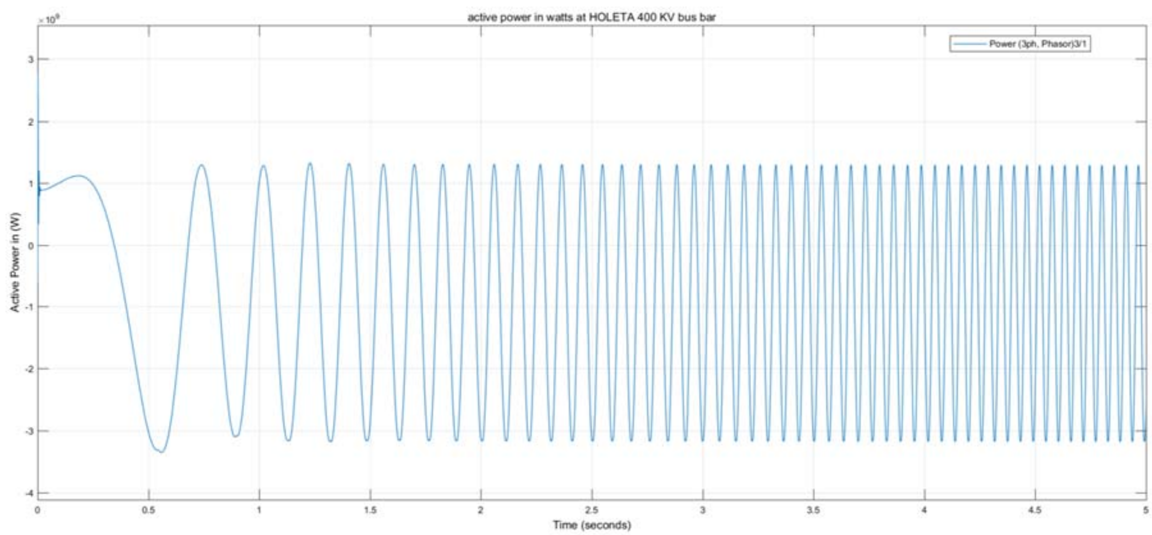

Figure 4.10: Graph showing voltage magnitude and phase vs. time at HOLETA 400 kV bus bar

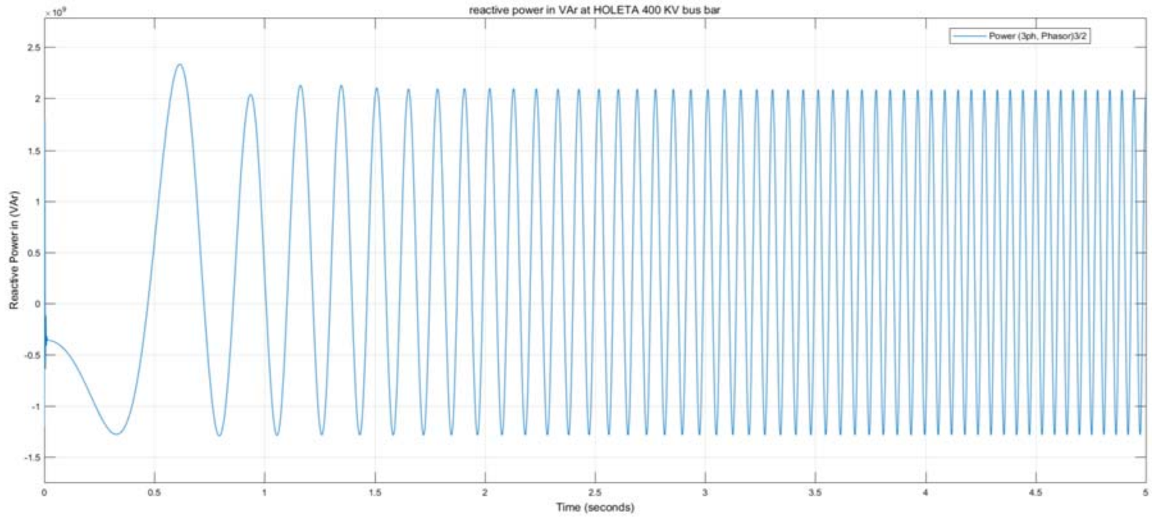

Figure 4.11: Graph showing Active power vs. time at HOLETA 400 kV bus bar

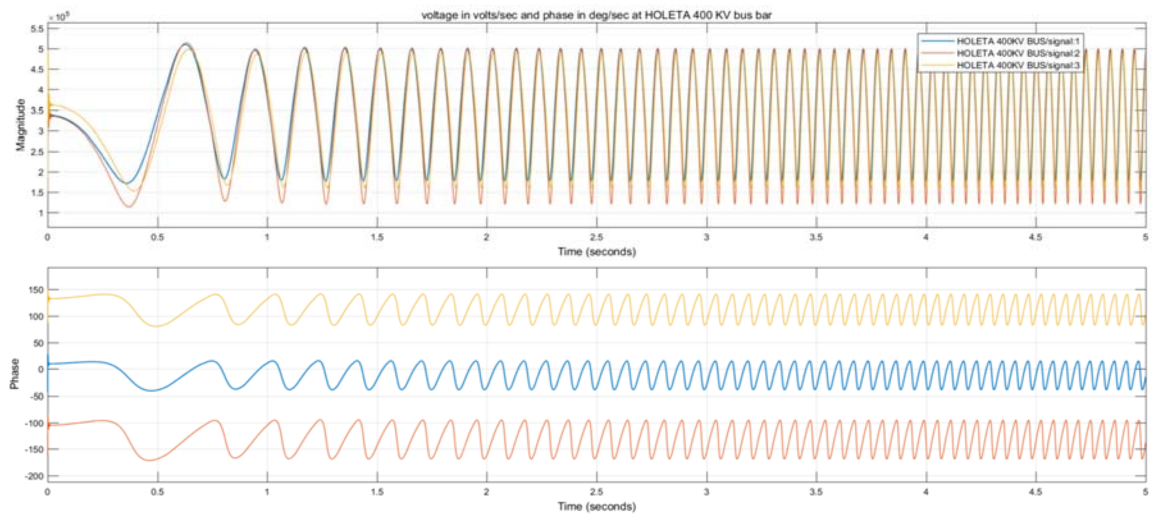

Figure 4.12: Graph showing reactive power vs. time at HOLETA 400 kV bus bar

Table 4.1: Active, reactive, apparent power and voltages in all the buses without SVCs

BUS	P(MW)	Q(MVAr)	S(MVA)	V(kV)
GERD	1243	1320	1813	568.6
DEDESA	1409	1211	1857.9	468.4
HOLETA	1465	1424	2043	435
HOLETA 400kV	1861	1247	2240	362.8

As can be seen in the above Table 4.1, the total power transferred to HOLETA 400 kV bus bar is 31.8% of the total power produced in the power plant. The active power transferred is 29.3%. The voltage deviates by 9.3%.

4.3. Stability analysis under different loading conditions without SVCs

The power flow is done using Mat Lab Simulink software and the plotting of PV and QV curve is done using Microsoft Excel. Increase the value of real power (P) loading from 25 % to 125% by a step of 25 % in order to plot PV curve while maintaining constant reactive power of load (Q), 2005 MVAr. Similarly, increase the values of Q with similar pattern by keeping constant real Power (P),4140MW.Then taking the reading of the values of P, Q and voltages at the 400 kV HOLOTA substation bus bar, plotting will be made by Microsoft EXCEL.

Table 4.2: Recorded value of P and Q for PV and QV curve at 400 kV bus bar at HOLETA 500/400 kV substation without SVCs

PV curve		QV curve	
P(MW)	V(kV)	Q(MVAr)	V(kV)
648	444	314	401.4
1296	418.5	628	387.8
1943	390.9	941	375
2591	362.8	1255	362.8
3239	335.3	1569	351.4

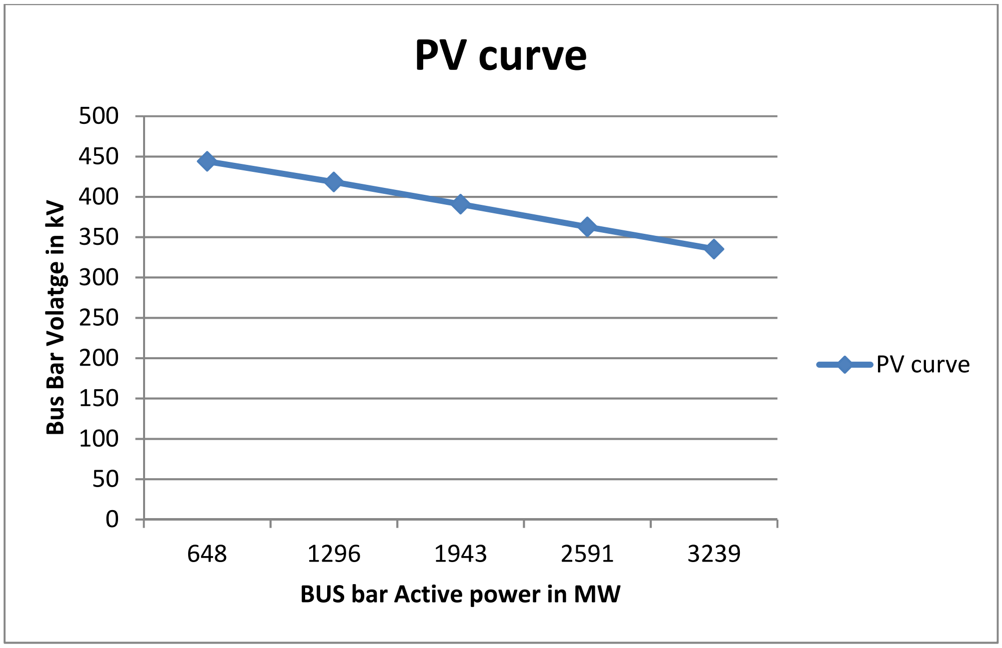

Figure 4.13: PV curve at 400 kV bus bar in HOLETA 500/400 kV substation (without SVCs)

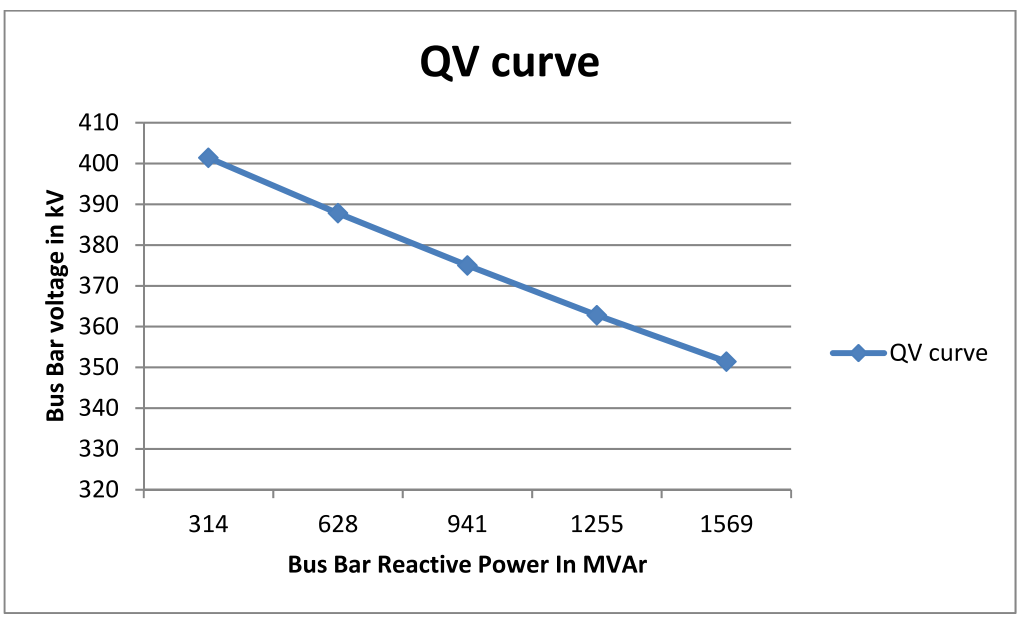

Figure 4.14: QV curve at 400 kV bus bar in HOLETA 500/400 kV substation (without SVCs)

It can be seen from Table 4.2, Figure 4.13 and Figure 4.14 that in the PV curve for 125% loading, the bus bar voltage is lowered to 335.3 kV. Similarly in the QV curve for a loading of 125% reactive load, the bus bar voltage is lowered to 351.4 kV.

4.4. System Analysis under normal operating conditions with SVCs

In this part of simulation, an attempt has been made to study the effect of SVCs on the voltage stability and power transfer capacity. The SVCs are in fixed susceptance mode, B_{ref}=0.The total rating of the SVC is - 450MVAr to + 450 MVAr. The SVCs are configured for voltage regulation mode. The SVC supports the voltage by injecting reactive power to the line when the voltage is below the reference voltage, Vref. The selected SVC reference voltage corresponds to the bus voltage with the SVC out of service. In steady state the SVC will therefore be floating and waiting for the voltage compensation when voltage departs from its reference set point.

4.4.1. SVCs installed at HOLETA 500/400 kV Substation

This is the current real scenario where the SVCs are installed, HOLETA 500/400 kV substation. The SVCs are connected to 33 kV bus bar .There are three SVC transformers of rating 400/33 kV and 315 MVA each. System load of 2591MW+j1255MVAr is connected to the 400kV bus bar at this substation [15].This value is taken from the current system peak load of 2591 MW and power factor 0.9.

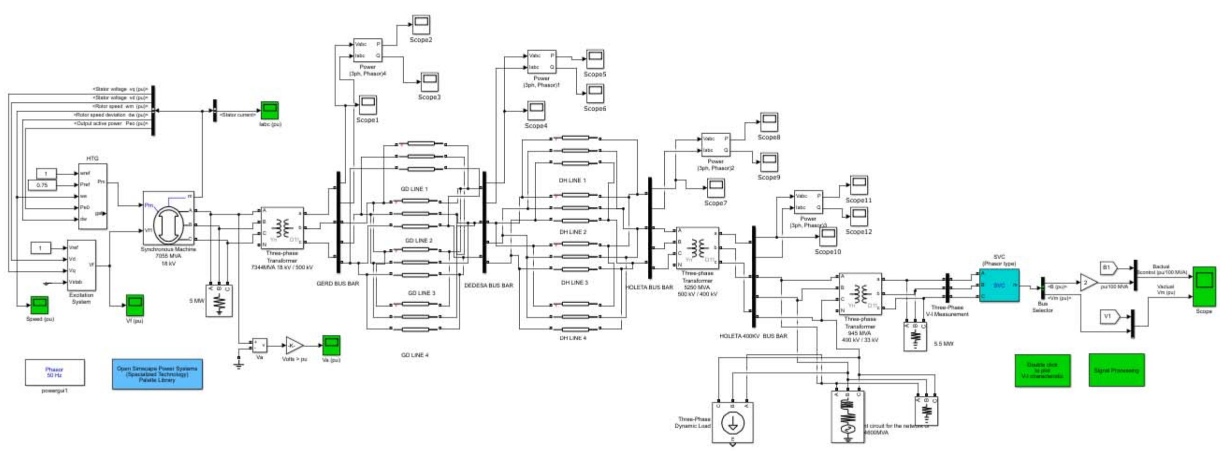

Figure 4.15: Model of the test systems with SVCs at HOLETA 500/400 kV substation

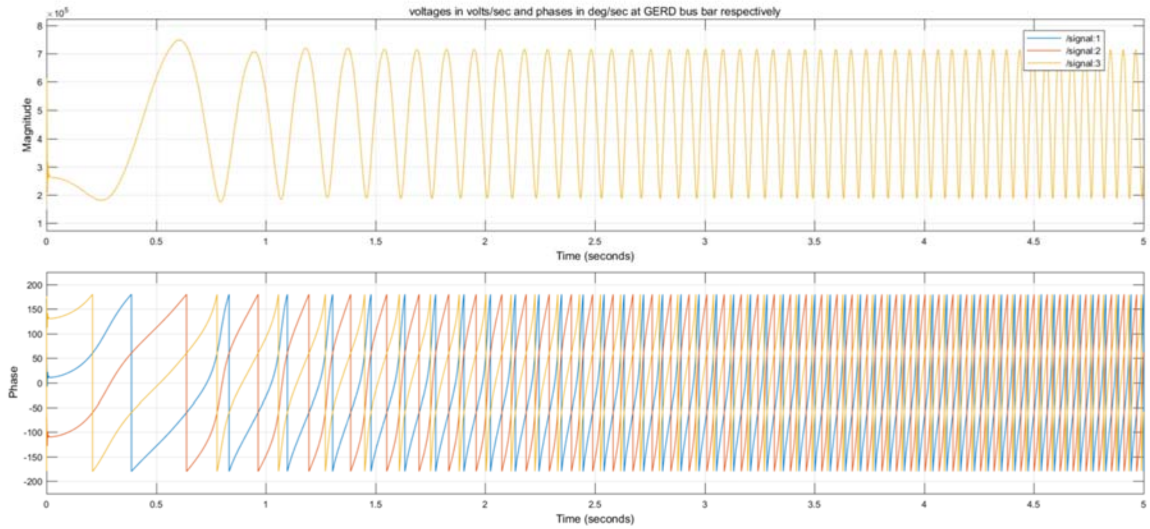

Figure 4.16: Graph showing voltage magnitude and phase vs. time at GERD bus bar

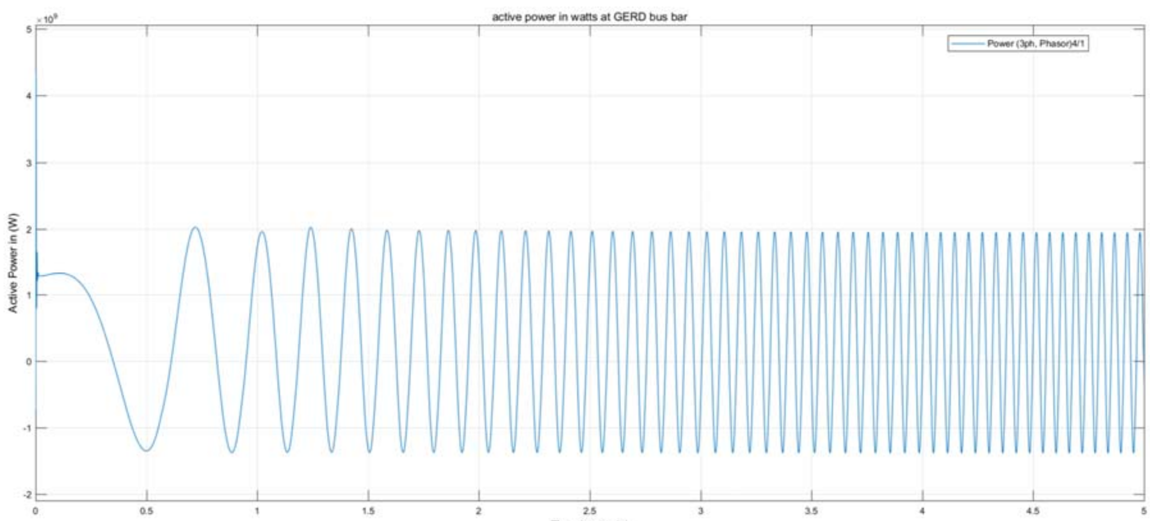

Figure 4.17: Graph showing active power vs. time at GERD bus bar

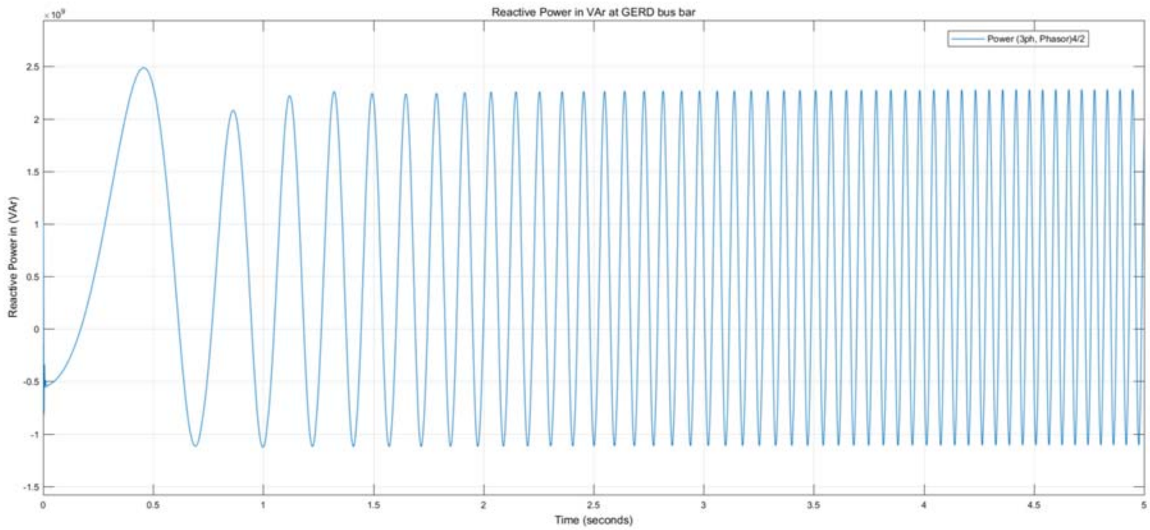

Figure 4.18: Graph showing Reactive power vs. time at GERD bus bar

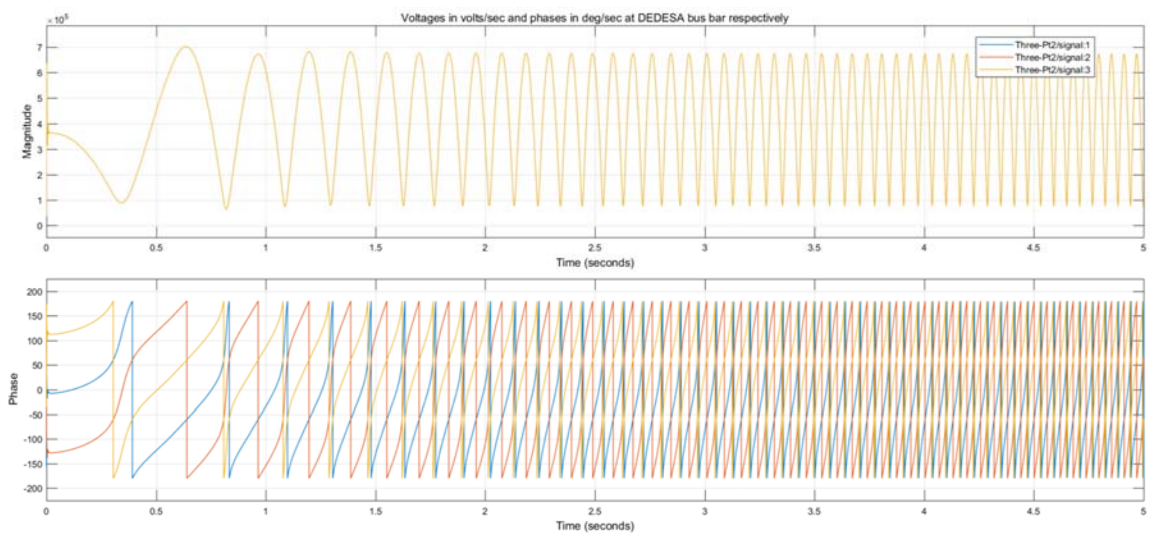

Figure 4.19: Graph showing voltage magnitude and phase vs. time at DEDESA bus Bar

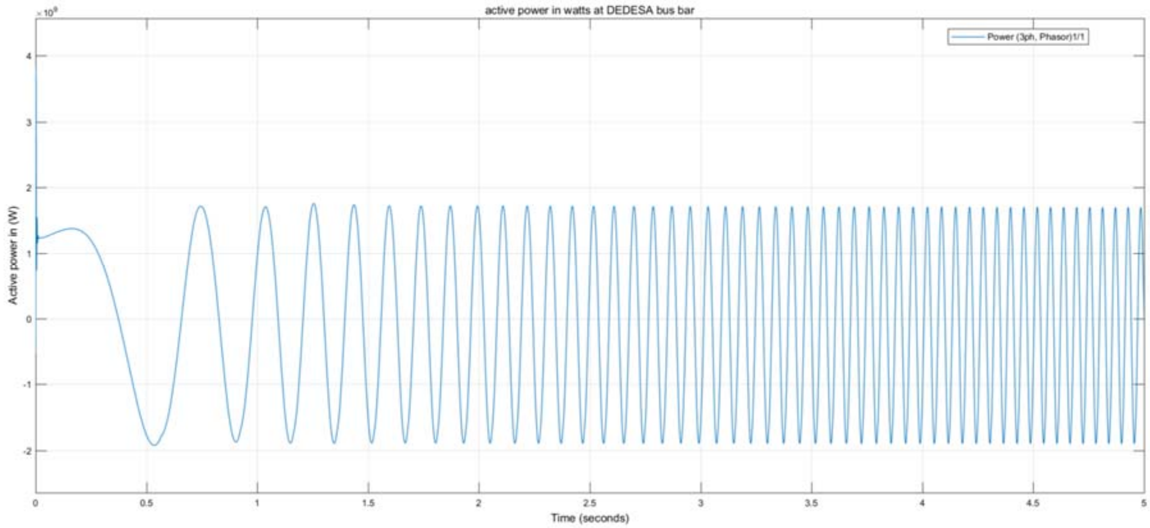

Figure 4.20: Graph showing Active power vs. time at DEDESA bus bar

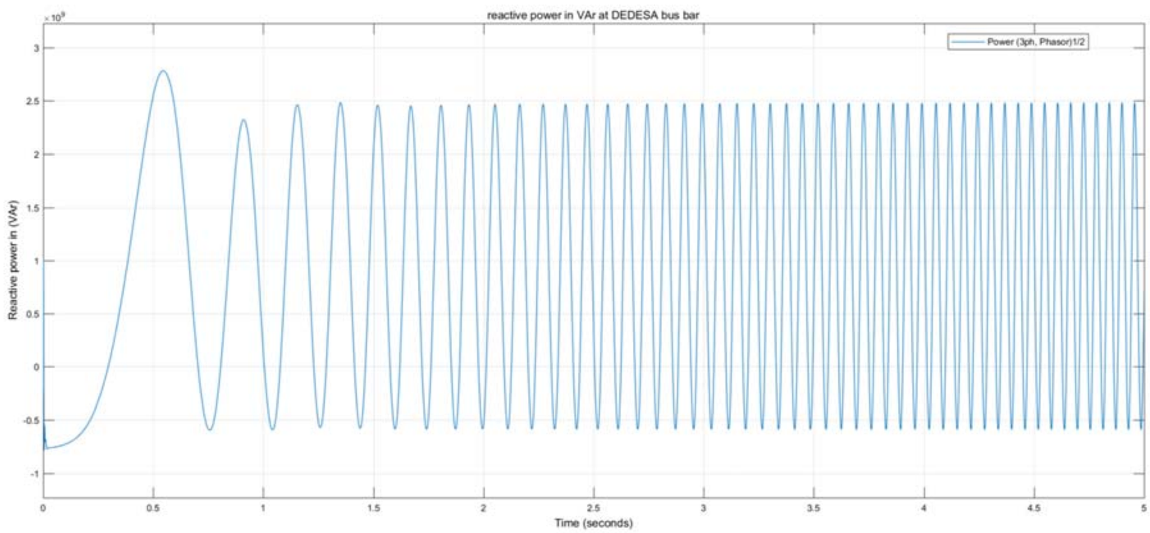

Figure 4.21: Graph showing reactive Power vs. time at DEDESA bus bar

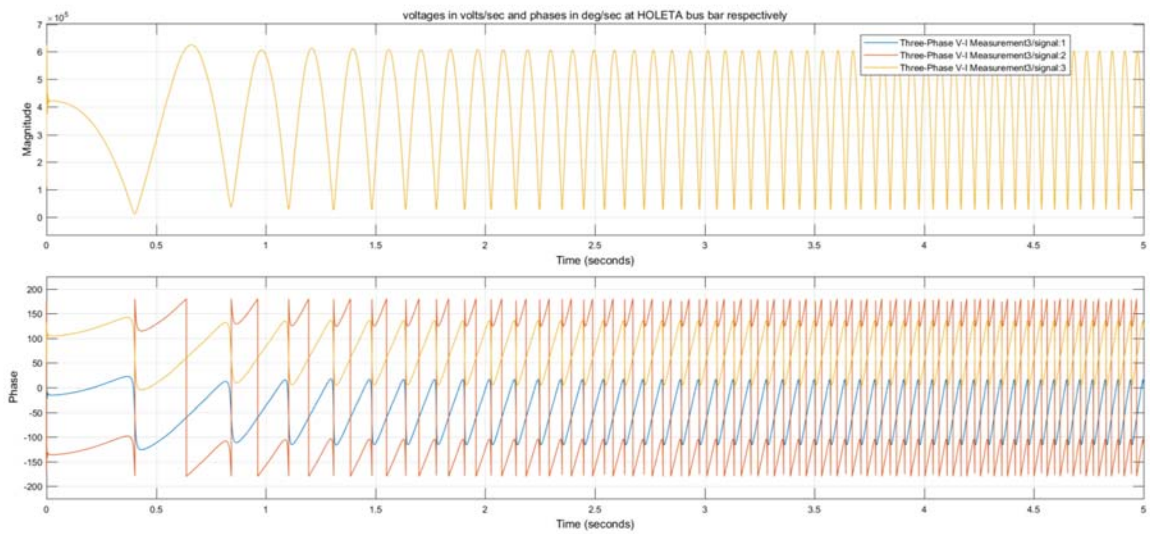

Figure 4.22: Graph showing voltage magnitude and phase vs. time at HOLETA 500kV bus bar

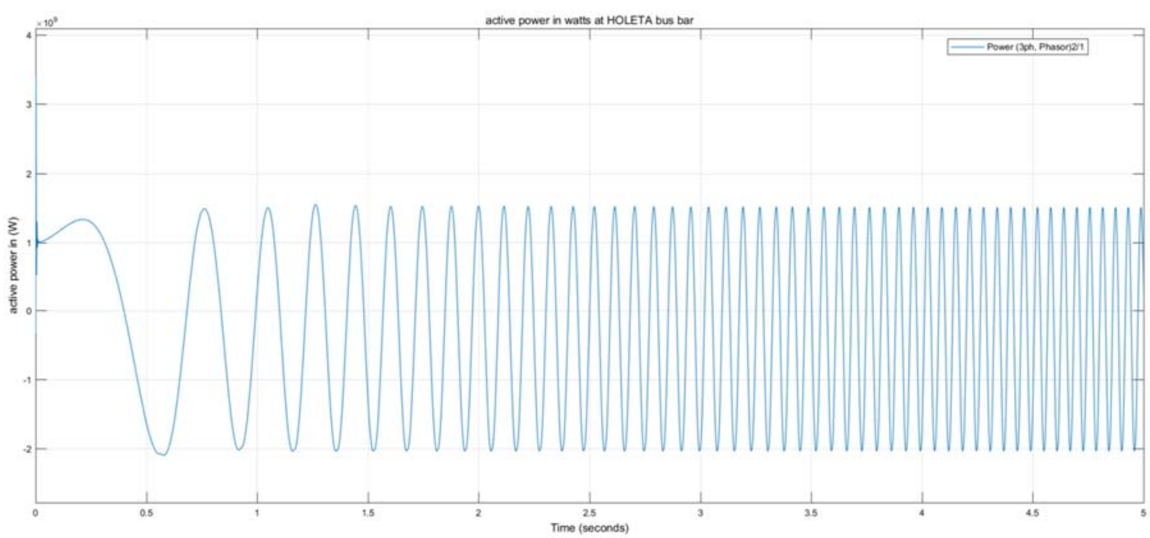

Figure 4.23: Graph showing Active Power vs. time at HOLETA 500kV bus bar

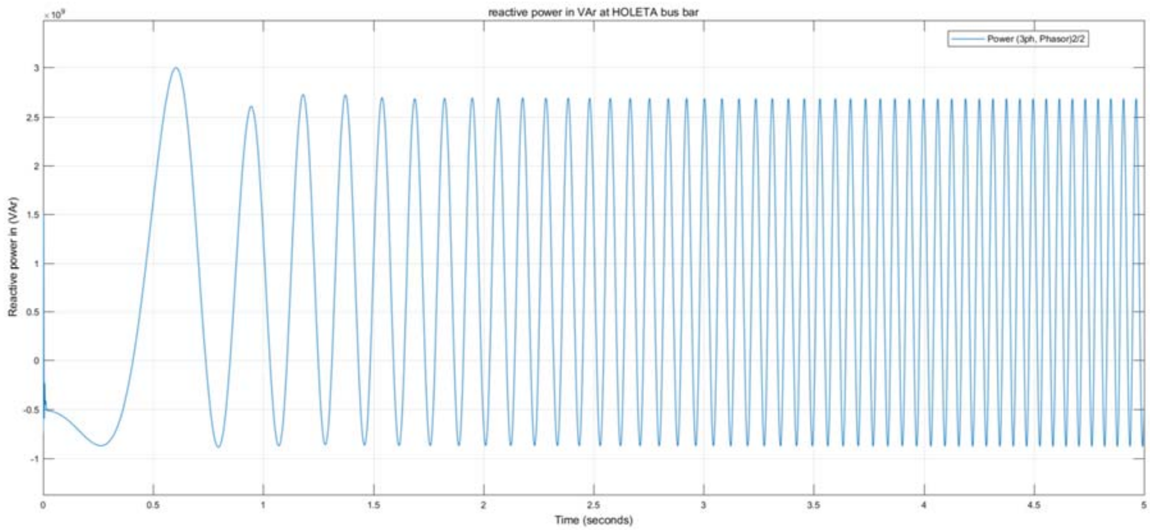

Figure 4.24: Graph showing Reactive power vs. time at HOLETA 500 kV bus Bar

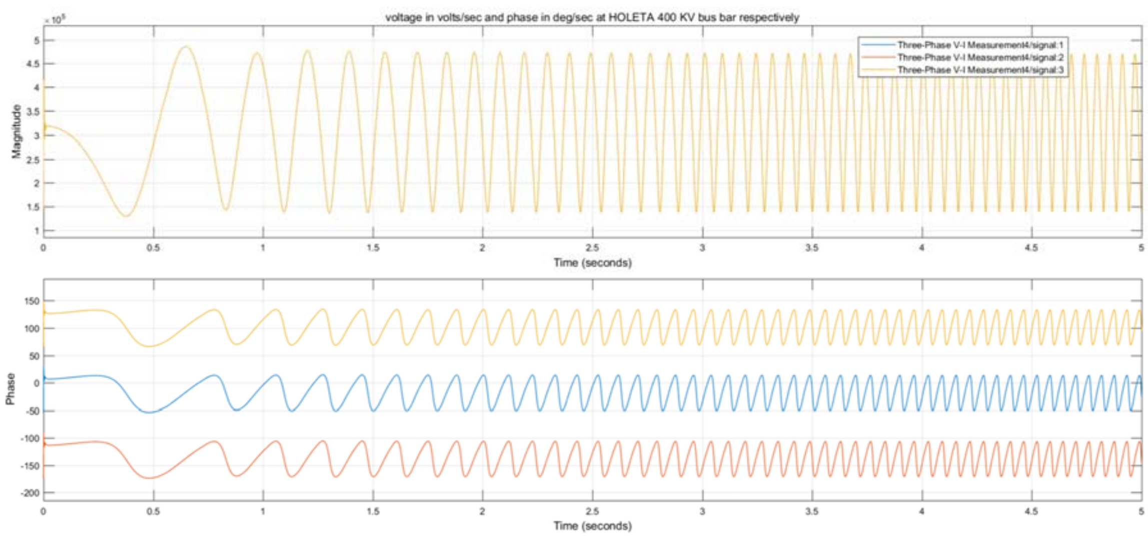

Figure 4.25: Graph showing voltage magnitude and phase vs. time at HOLETA 400 kV bus bar

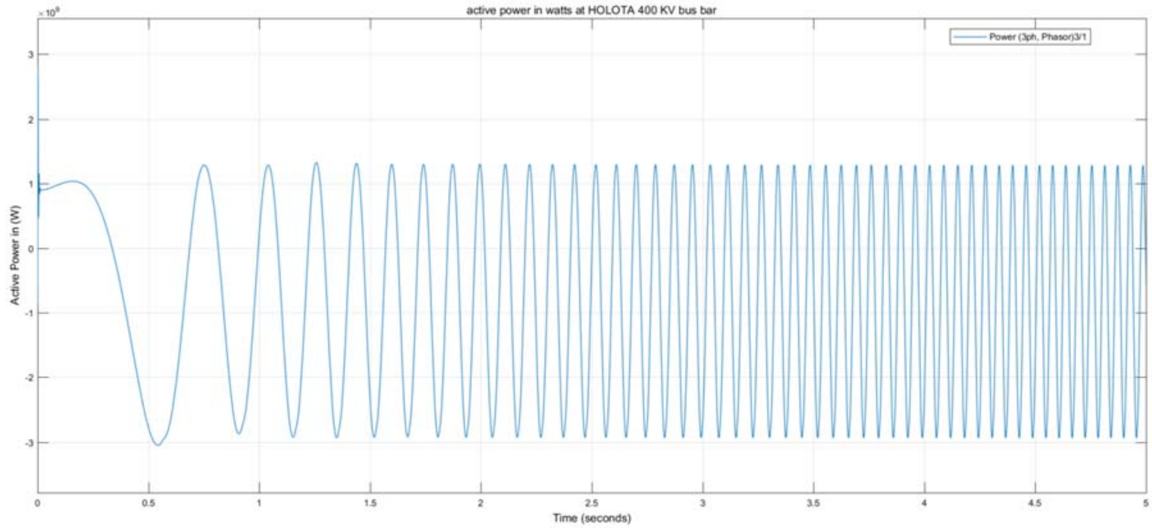

Figure 4.26: Graph showing active power vs. time at HOLETA 400 kV bus bar

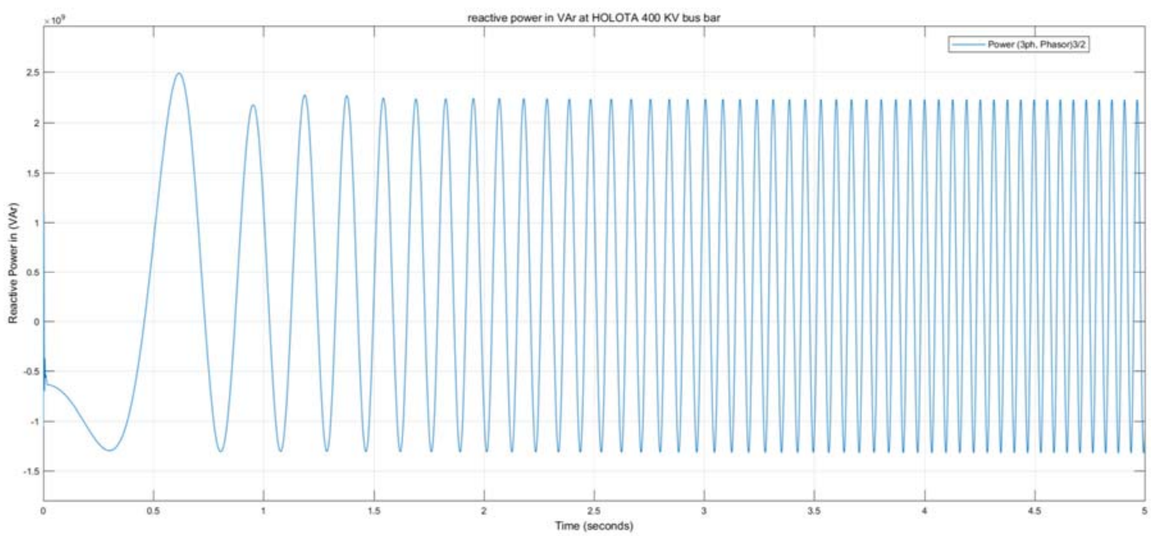

Figure 4.27: Graph showing reactive power vs. time at HOLETA 400 kV bus bar

Table 4.3: Active, reactive, apparent power and voltages in all the buses with SVCs At HOLETA 500/400 kV substation

BUS	P(MW)	Q(MVAr)	S(MVA)	V(kV)
GERD	1207	1311	1782	509.3
DEDESA	1282	1414	1908.6	467.4
HOLETA	1302	1523	2003.7	420.6
HOLETA 400kV	1695	1323	2150	338.4

A table 4.3 shows that the total power transferred is 30.5%.It is decreased by 1.3%. The actual power transferred is 26.7%.The voltage deviation is 15.4 %. Significant voltage stability margin improvement is achieved in the 500 kV network at GERD bus bar from 568.6 kV to 509.3kV.

4.4.2. SVCs installed at DEDESA substation

In this simulation, it is tried to see if there is better performance from the SVCs when they are installed at DEDESA substation. Here 500/33 kV transformers with the same capacity of 3X315 MVA are used.

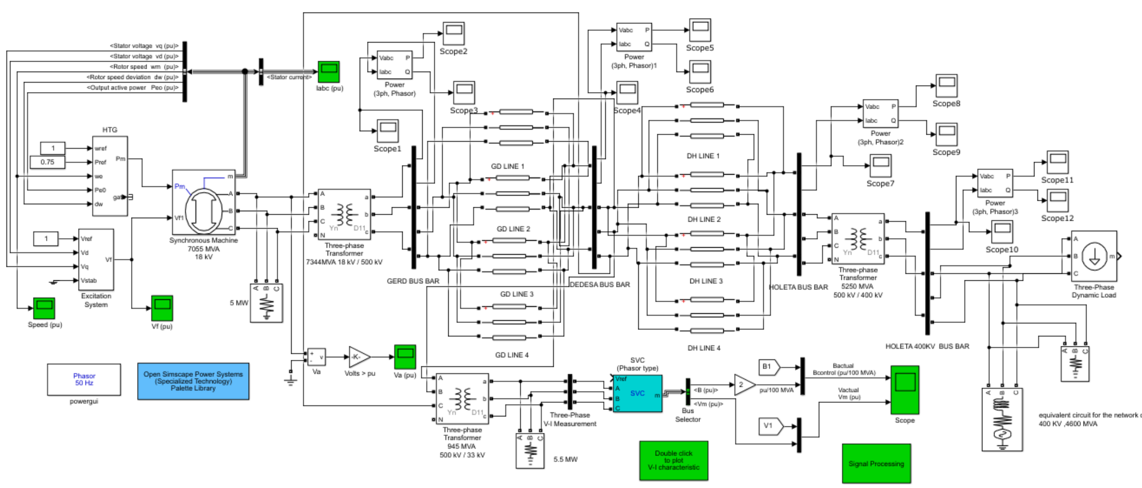

Figure 4.28: Model of the test systems with SVCs installed at DEDESA substation

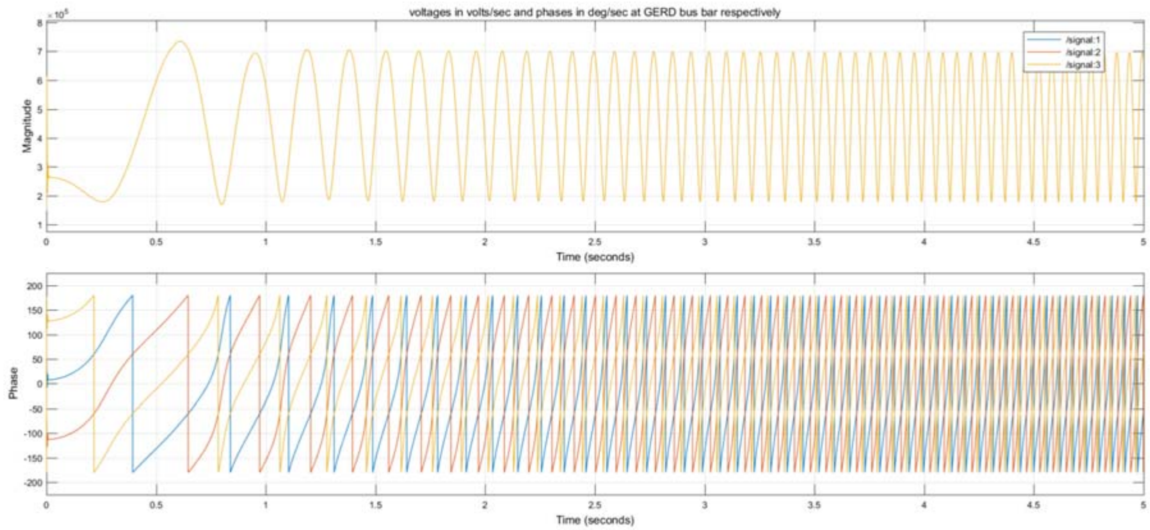

Figure 4.29: Graph showing voltage magnitude and phase vs. time at GERD bus bar

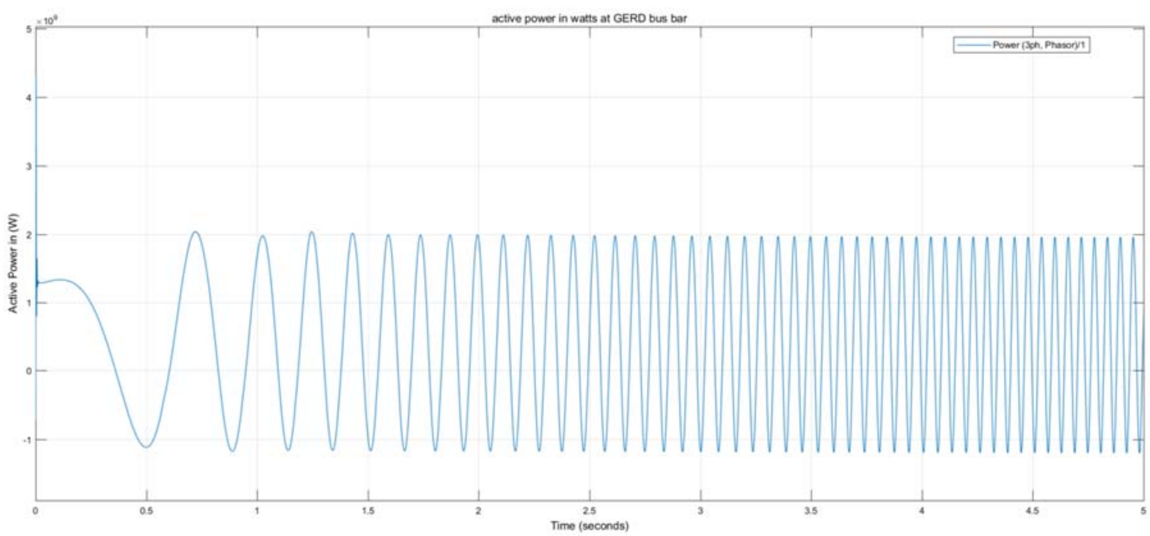

Figure 4.30: Graph showing active power vs. time at GERD bus bar

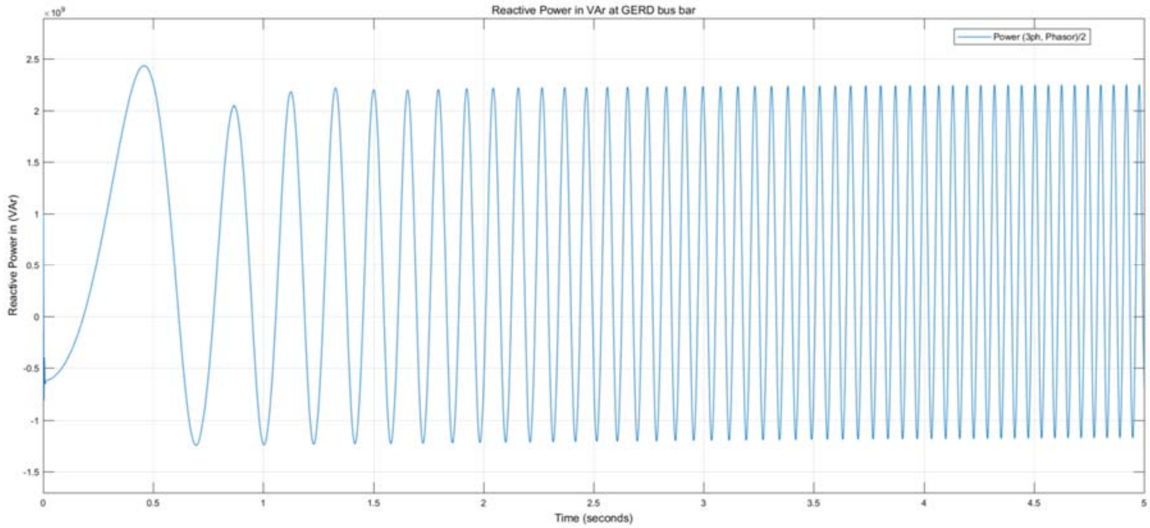

Figure 4.31: Graph showing reactive power vs. time GERD bus bar

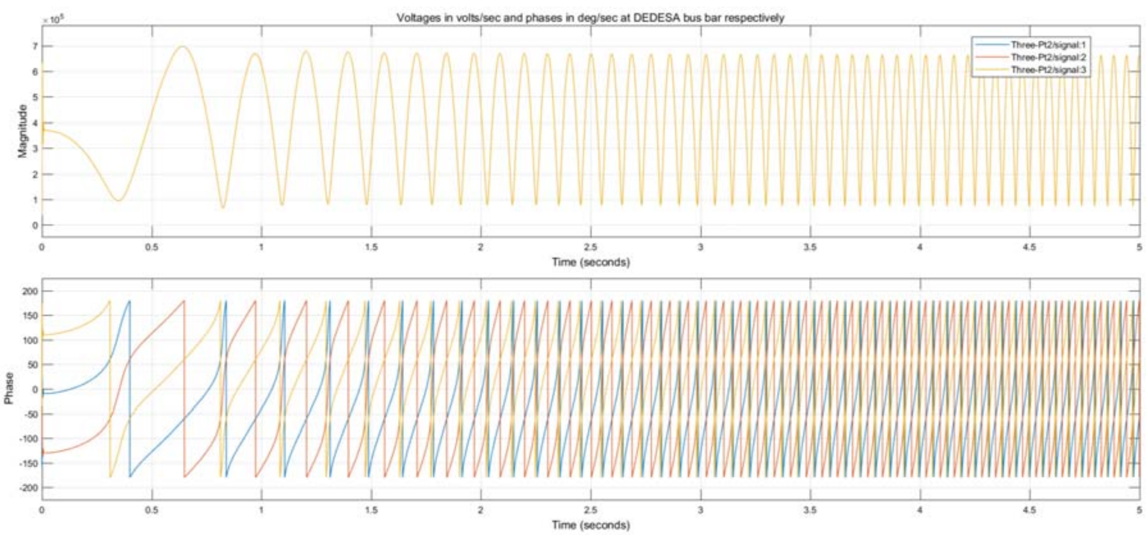

Figure 4.32: Graph Showing voltage magnitude and phase vs. time at DEDESA bus bar

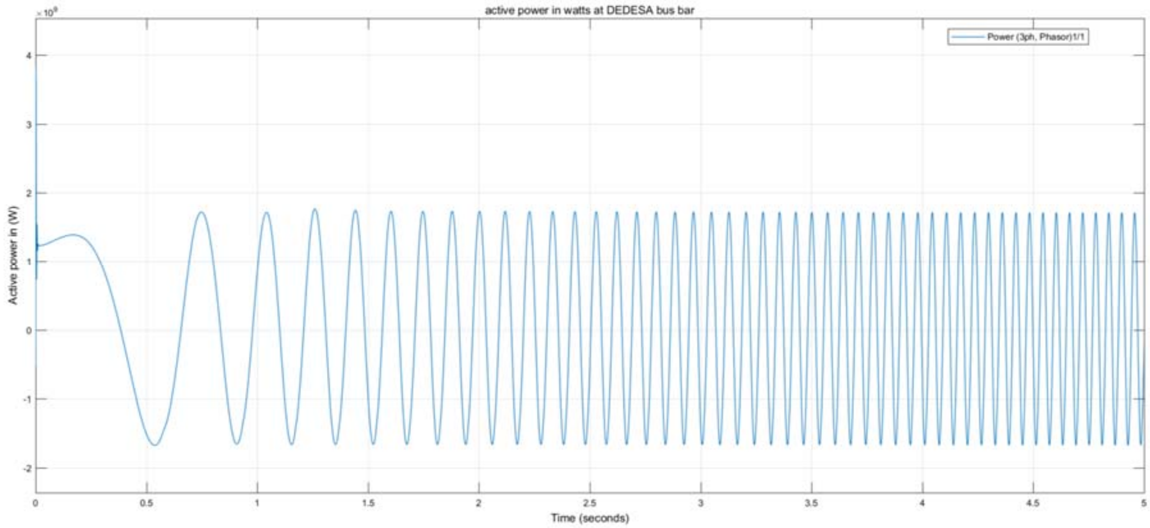

Figure 4.33: Graph showing active power vs. time at DEDESA bus bar

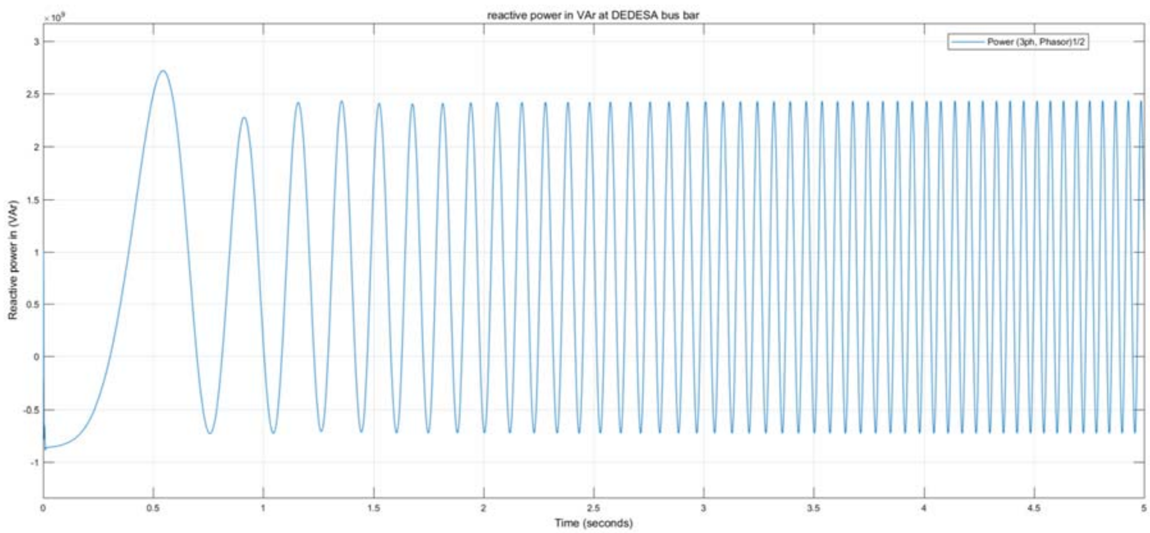

Figure 4.34: Graph showing reactive Power vs. time at DEDESA bus bar

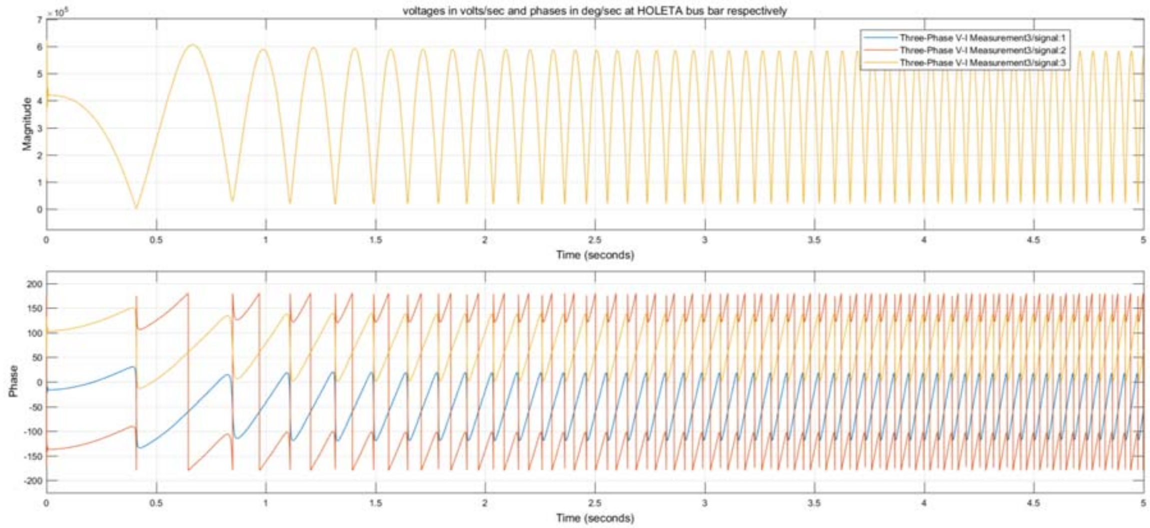

Figure 4.35: Graph showing voltage magnitude and phase vs. time at HOLETA 500 kV bus bar

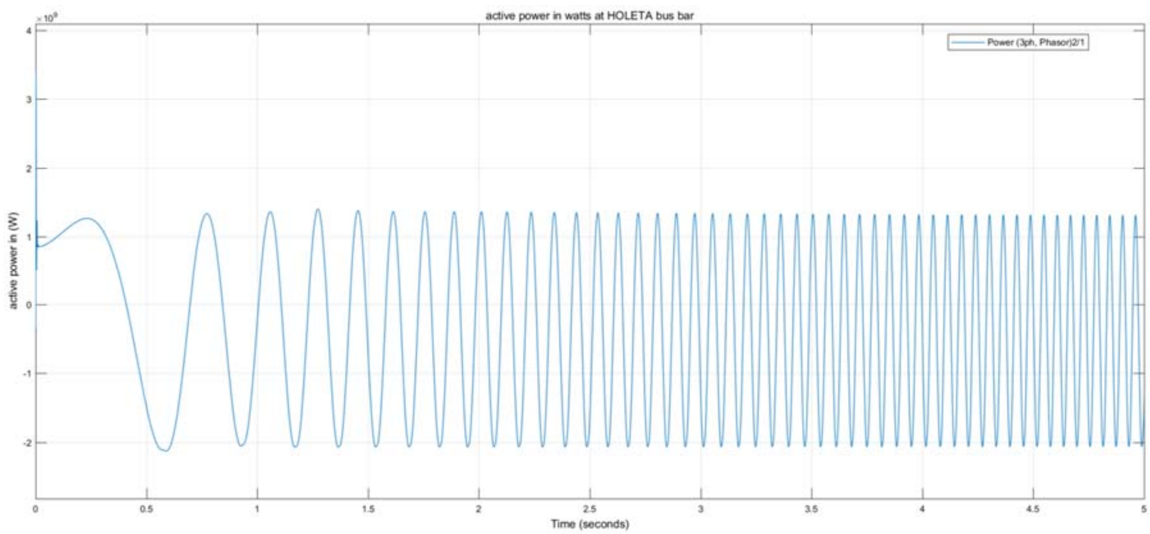

Figure 4.36: Graph showing active power vs. time at HOLETA 500 kV bus bar

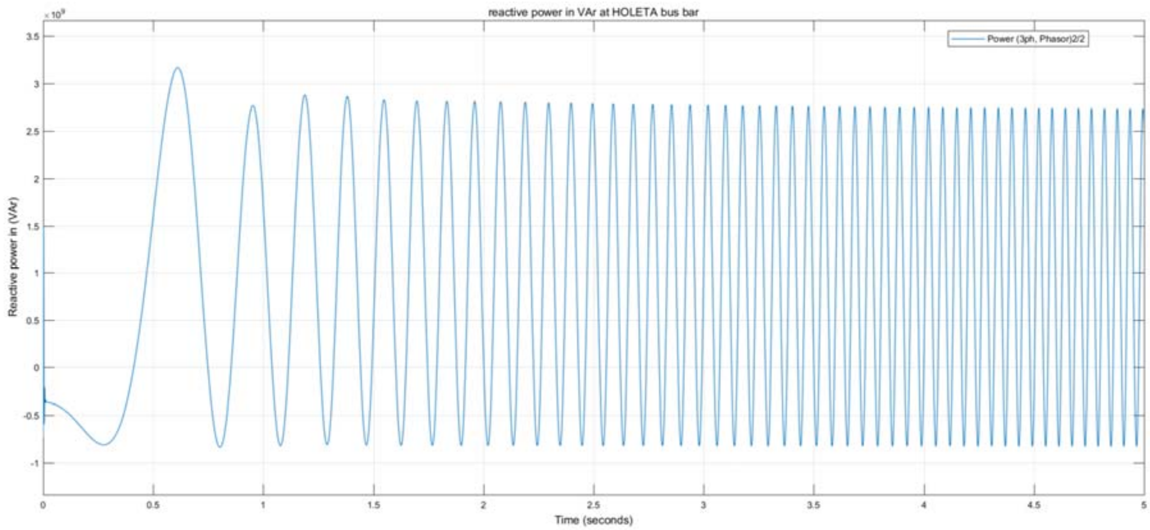

Figure 4.37: Graph showing Reactive Power vs. time at HOLETA 500 kV bus bar

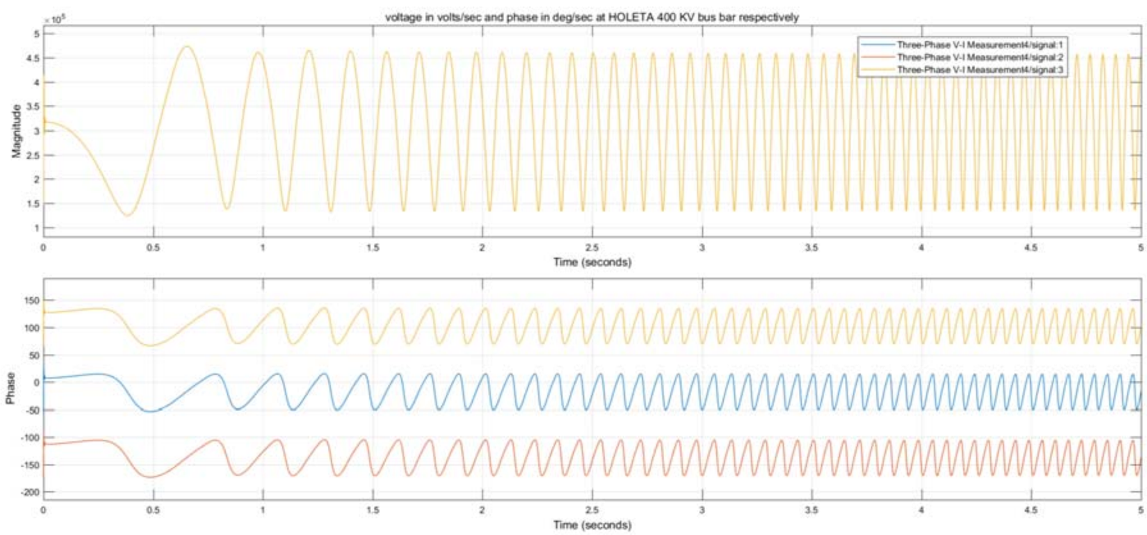

Figure 4.38: Graph showing voltage magnitude and phase vs. time at HOLETA 400 kV bus bar

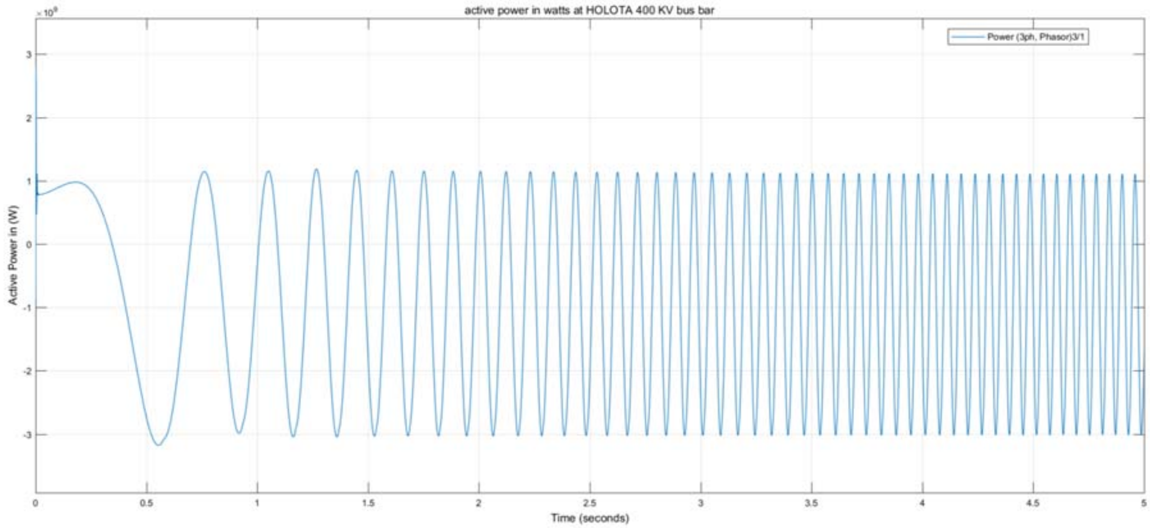

Figure 4.39: Graph showing active power vs. time at HOLETA 400 kV bus bar

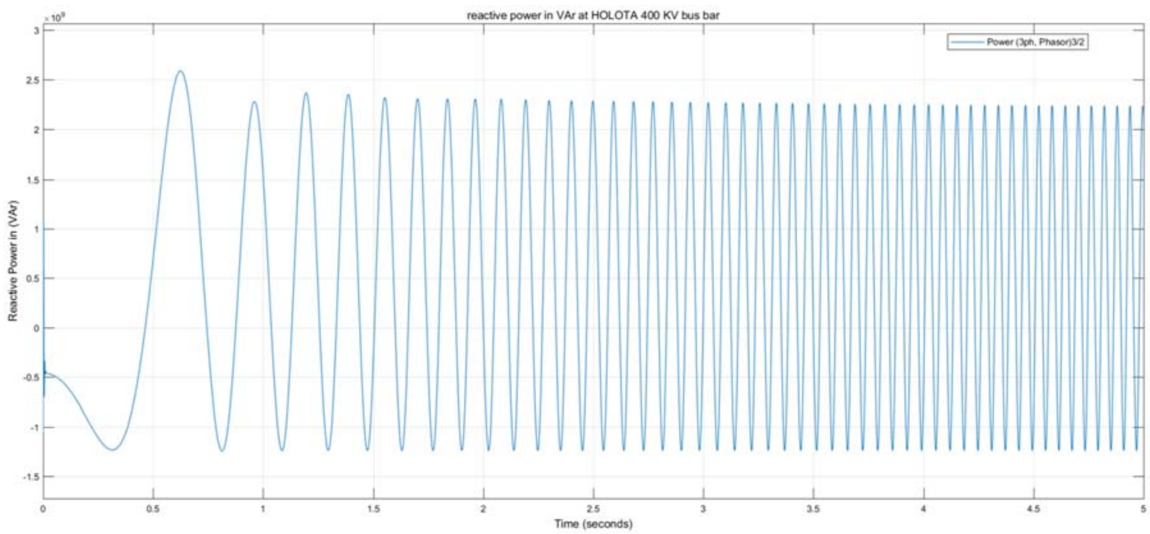

Figure 4.40: Graph showing Reactive power vs. time at HOLETA 400 kV bus bar

Table 4.4: Active, reactive, apparent power and voltages in all the buses with SVCs at DEDESA Substation

BUS	P(MW)	Q(MVAr)	S(MVA)	V(kV)
GERD	1177	1301	1754	499.4
DEDESA	1201	1385	1833	463.8
HOLETA	1277	1587	2036.98	408.4
HOLETA 400 kV	1744	1337	2197.5	330.7

When the SVCs are installed at DEDESA substation, the total power transferred is 31.2%.It increases by 0.7%.The active power transferred is 27.5%.It is increased by 0.8% than when it is installed at HOLETA 500/400 kV substation. The voltage deviation is 17.3%.It is not a better location for the SVC in terms of voltage stability.

4.4.3. SVCs installed at GERD substation

In this scenario, the simulation is run if SVCs were installed at GERD substation. The transformers size will be 3x315 MVA of 500/33 kV.

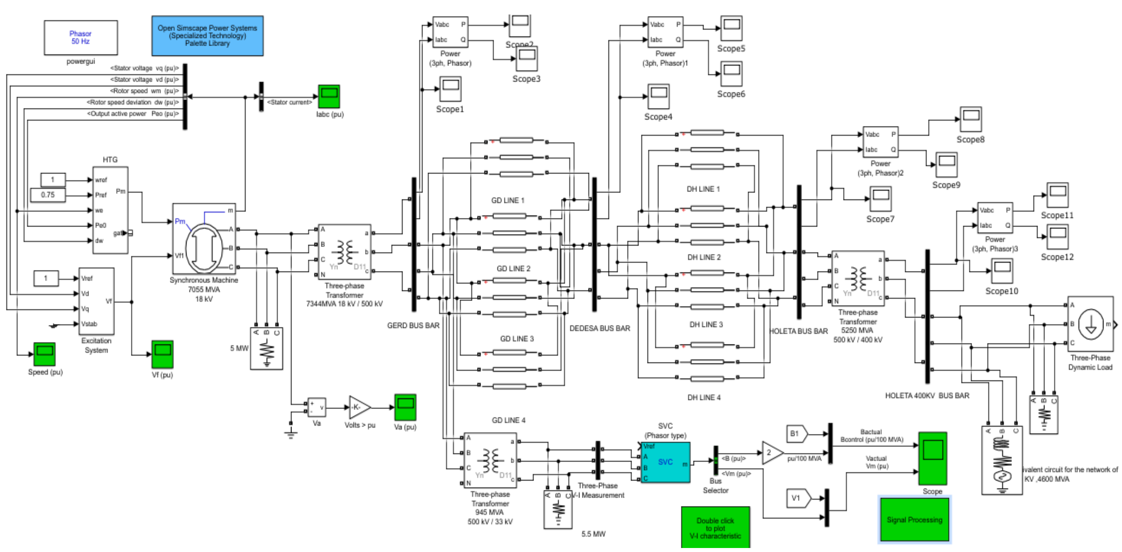

Figure 4.41: Model of the test systems with SVCs installed at GERD Substation

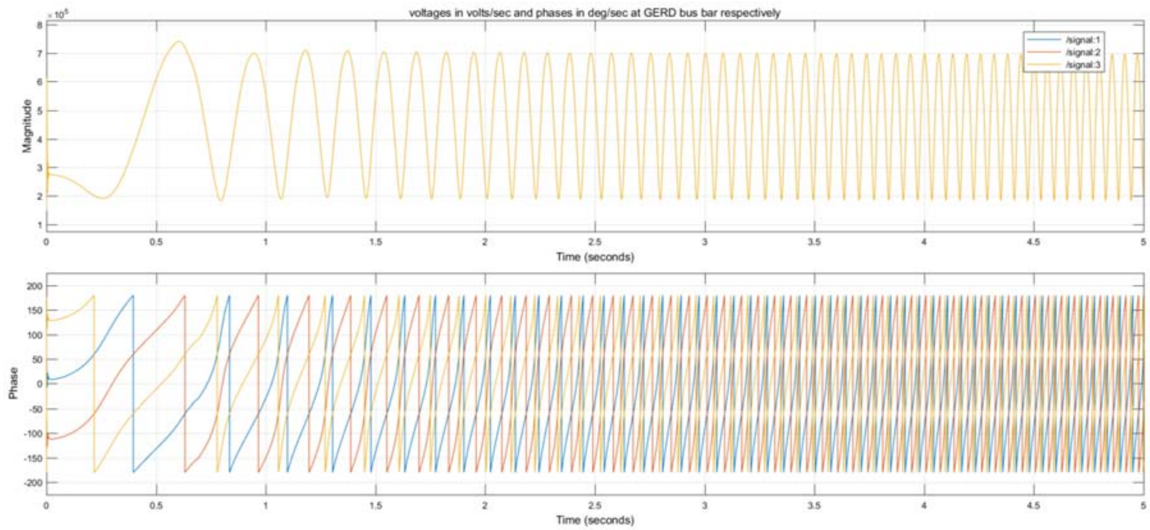

Figure 4.42: Graph showing voltage magnitude and phase vs. time at GERD bus bar

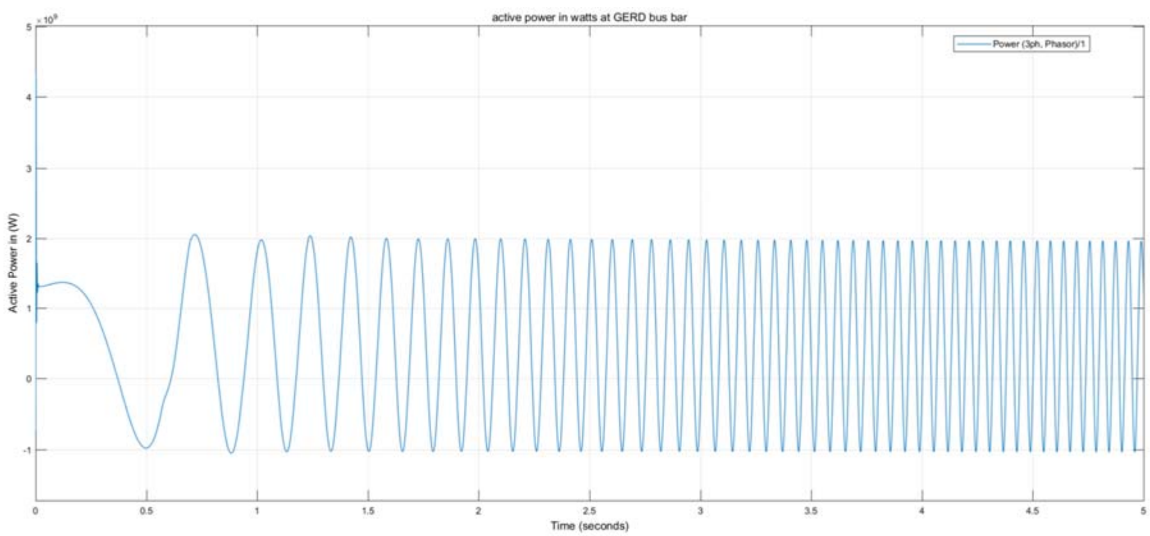

Figure 4.43: Graph showing active power vs. time at GERD bus bar

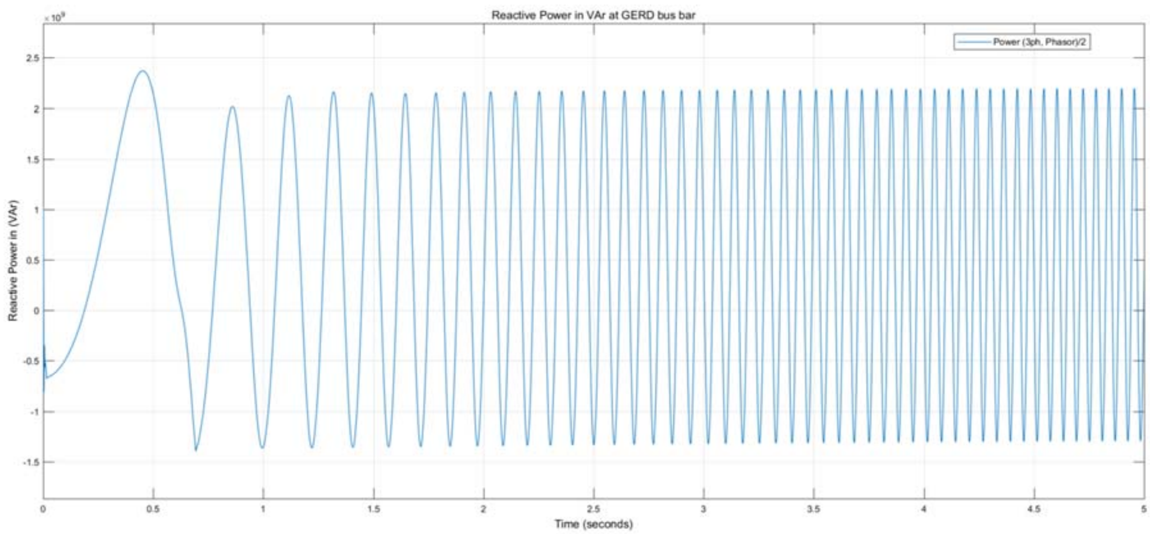

Figure 4.44: Graph showing Reactive Power vs. time at GERD bus bar

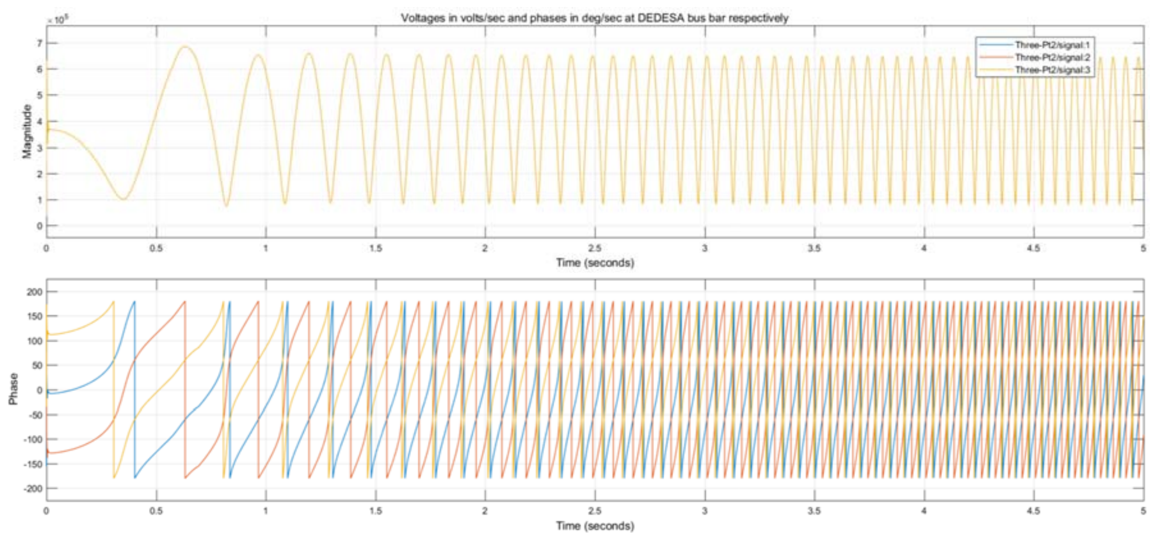

Figure 4.45: Graph showing voltage magnitude and phase vs. time at DEDESA bus bar

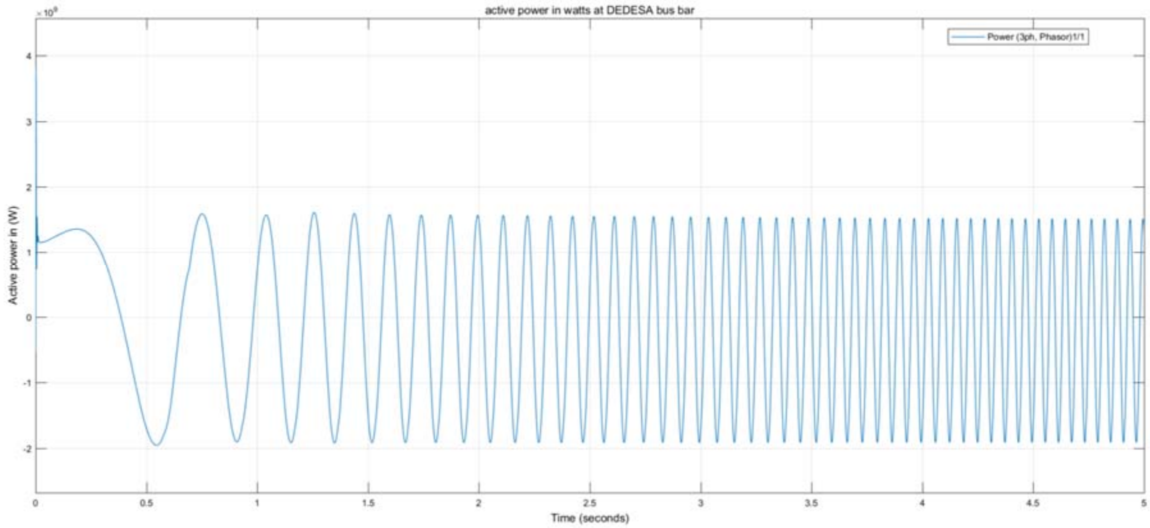

Figure 4.46: Graph showing Active power vs. time at DEDESA bus bar

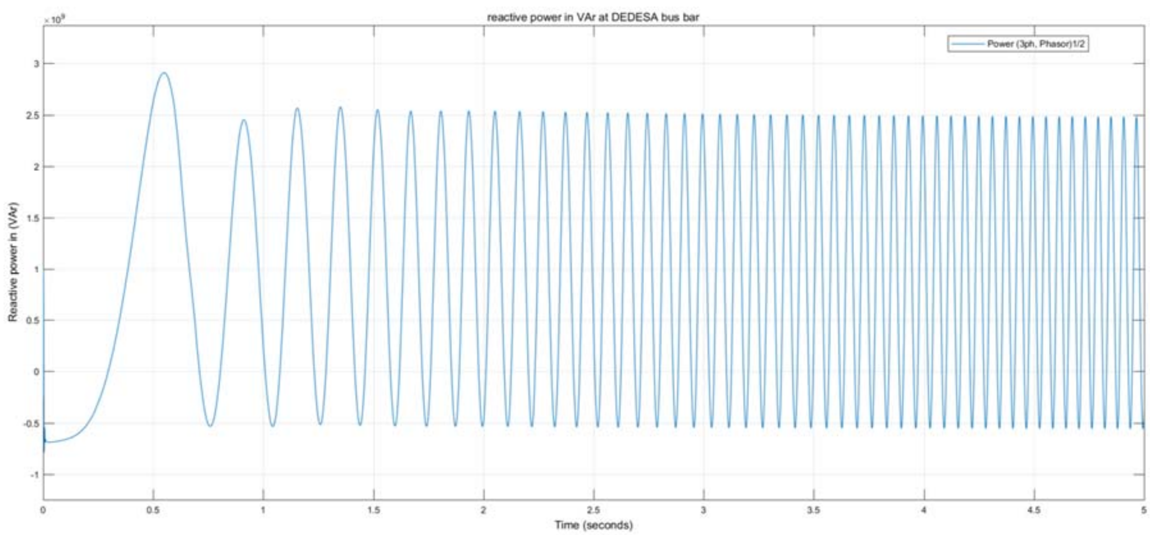

Figure 4.47: Graph showing Reactive Power vs. time at DEDESA bus bar

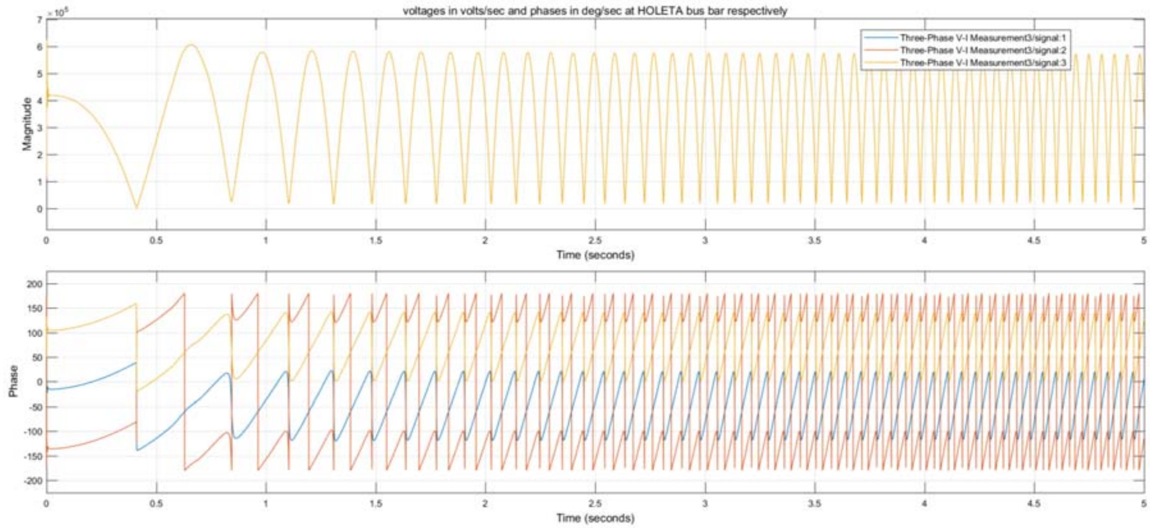

Figure 4.48: Graph showing voltage magnitude and phase vs. time at HOLETA 500kV bus bar

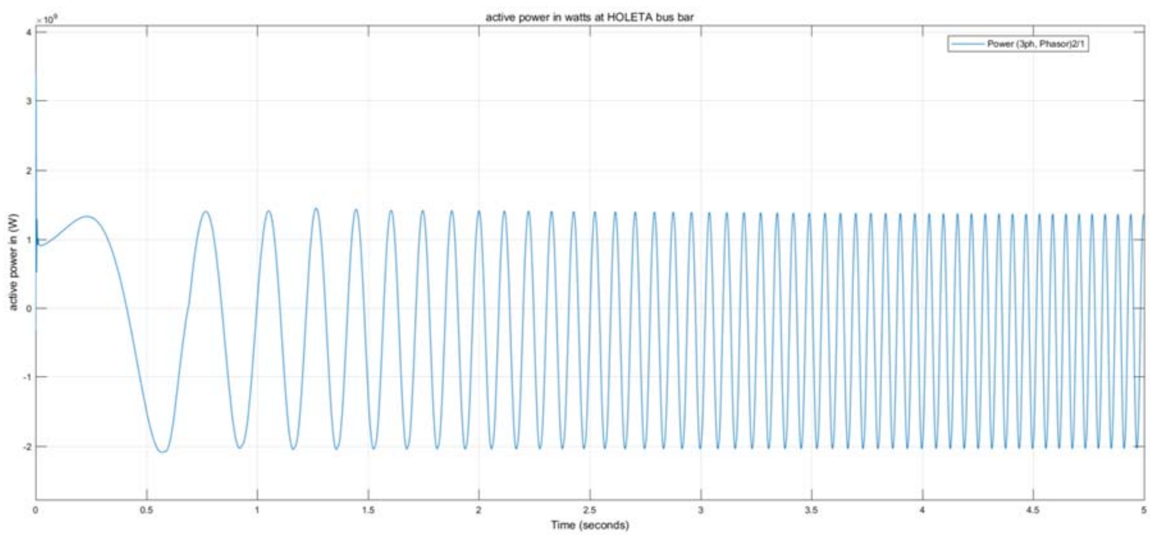

Figure 4.49: Graph showing active power vs. time at HOLETA 500 kV bus bar

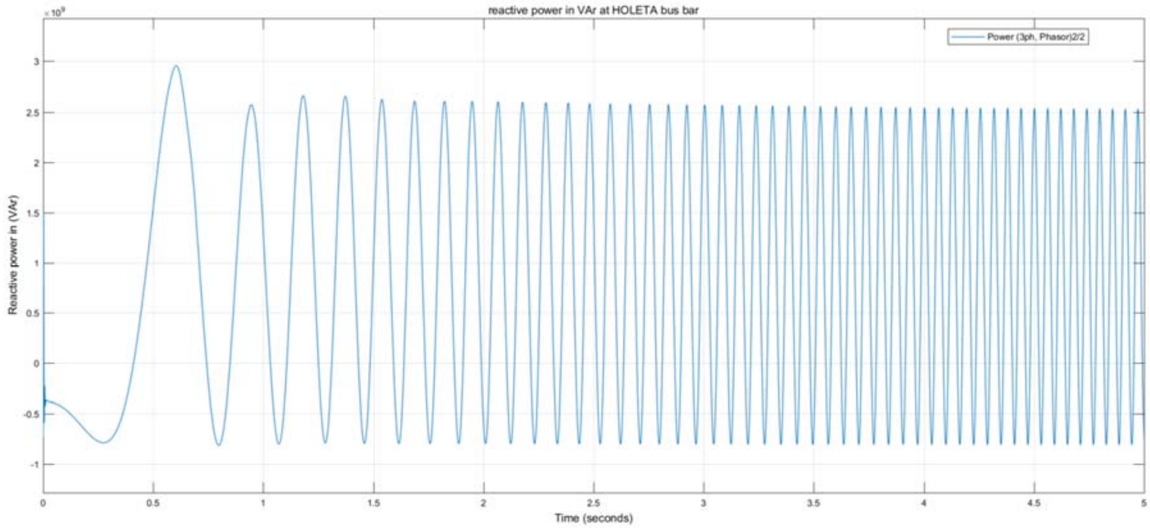

Figure 4.50: Graph showing Reactive power vs. time at HOLETA 500 kV bus bar

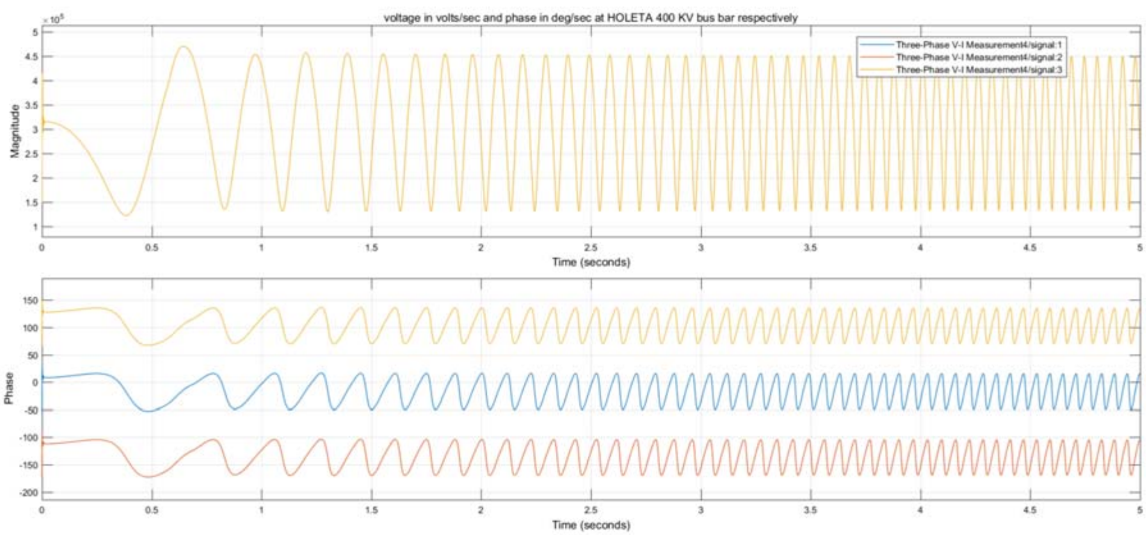

Figure 4.51: Graph showing voltage magnitude and phase vs. time at HOLETA 400 kV bus bar

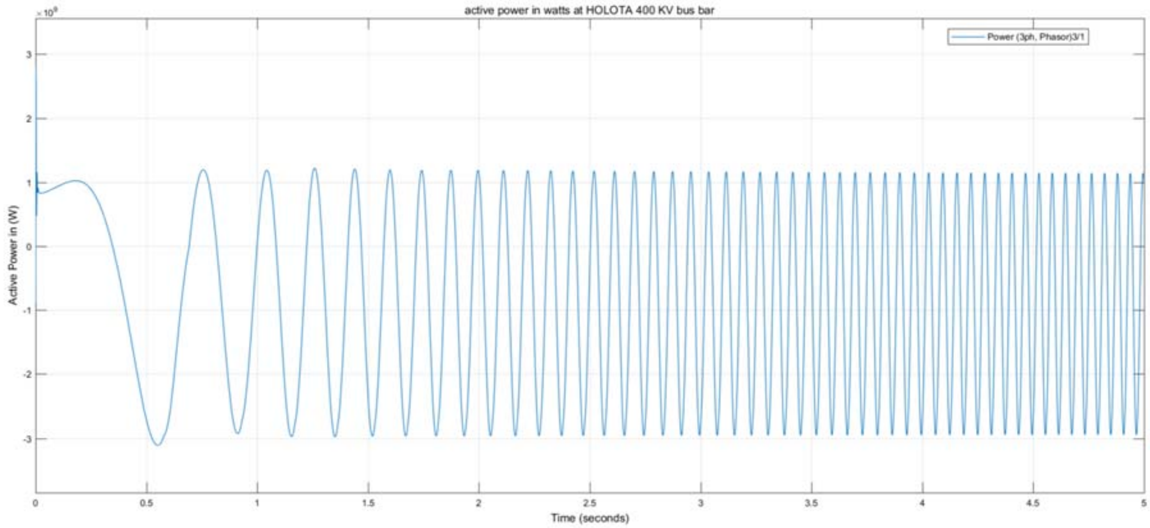

Figure 4.52: Graph showing active power vs. time at HOLETA 400 kV bus bar

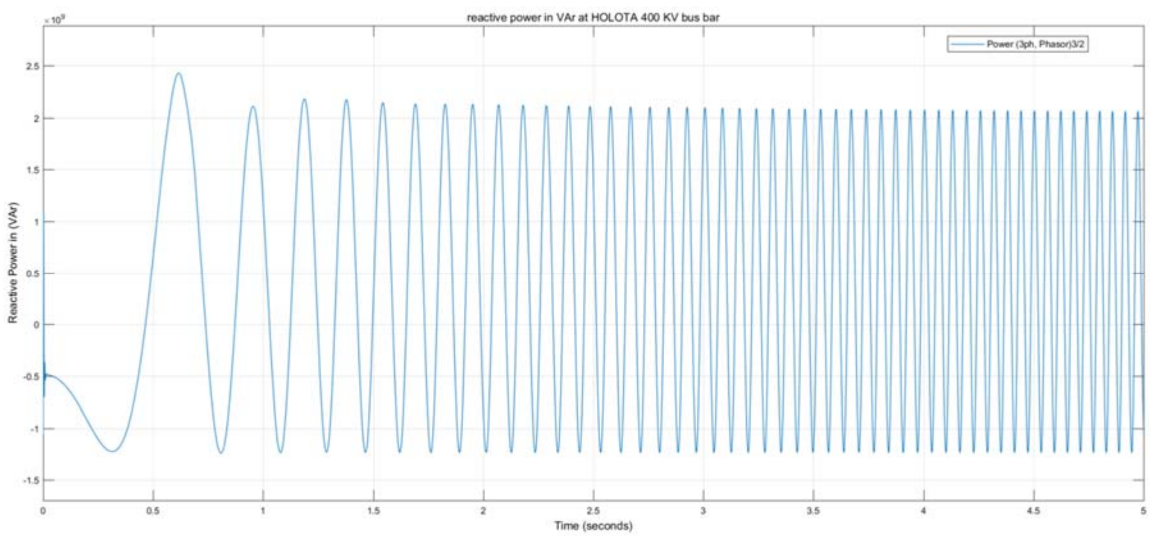

Figure 4.53: Graph showing Reactive power vs. time at HOLETA 400 kV bus bar

Table 4.5: Active, Reactive, Apparent Power and voltages in all the buses with SVCs at GERD substation

BUS	P(MW)	Q(MVAr)	S(MVA)	V(kV)
GERD	1163	1287	1734.6	502.5
DEDESA	1240	1449	1907	453.8
HOLETA	1268	1469	1925.5	402.8
HOLETA 400 kV	1695	1251	2106.7	326.1

Table 4.5 shows that the total power transferred is 29.9%.It is greater by 3.2% than when the SVCs are installed at HOLETA 500/400 kV substation. The active power transferred is 26.7%.The voltage deviation is 18.5%.This location is not advisable to put the SVC in terms of voltage stability.

Overall, as we can see from all the results above, the voltage stability at GERD bus bar is very much improved when the SVCs are in the network. But there is no improvement in power transfer.

4.4.4. Simulation involving both SVCs and Reactors

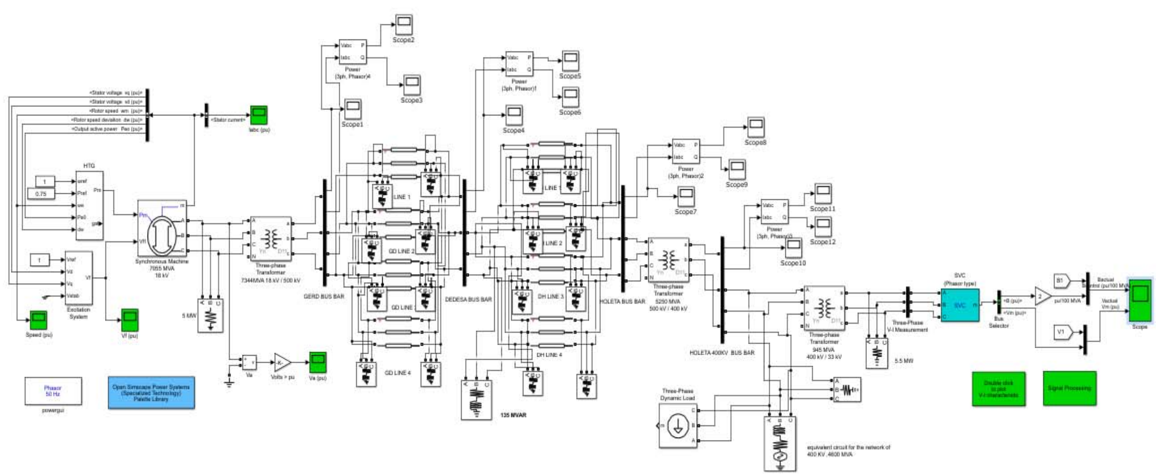

Fig4.54: Model of the test systems comprising SVCs at HOLETA 500/400 kV substation with Reactors

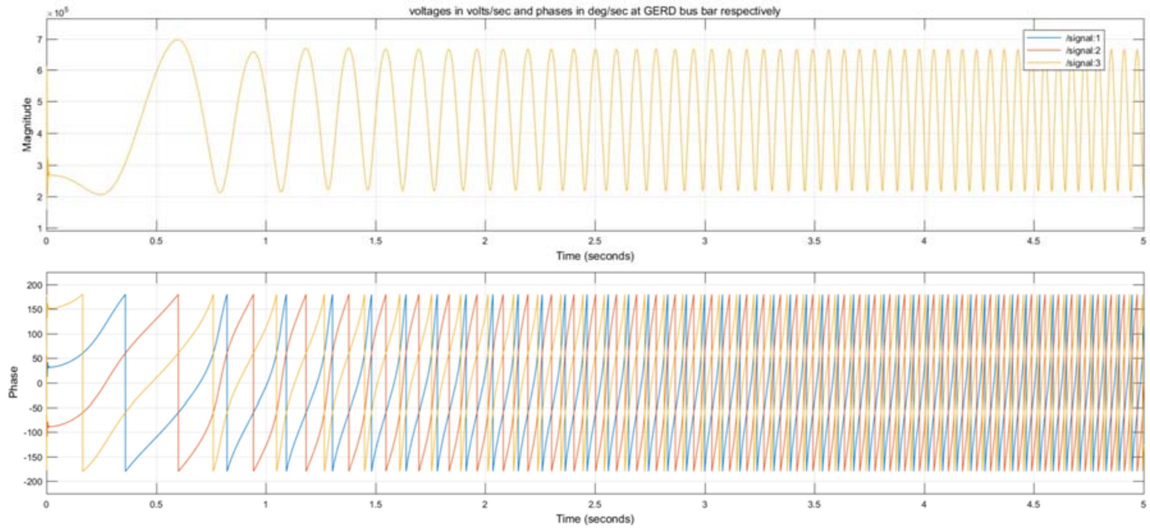

Fig 4.55: Graph showing voltage magnitude and phase vs. time at GERD bus bar with Reactors

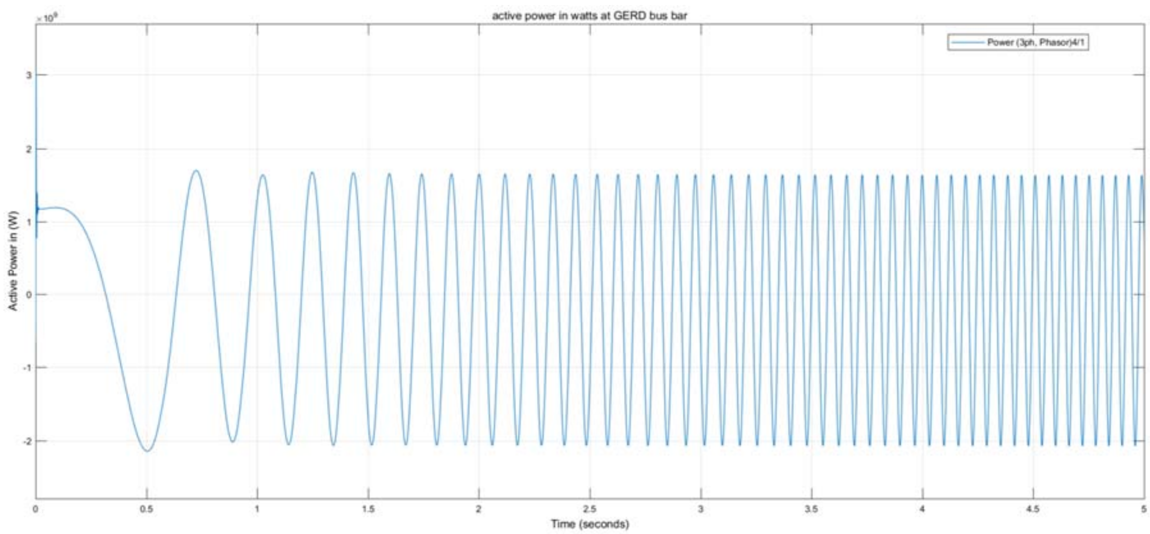

Fig 4.56: Graph showing Active power vs. time at GERD bus bar with Reactors

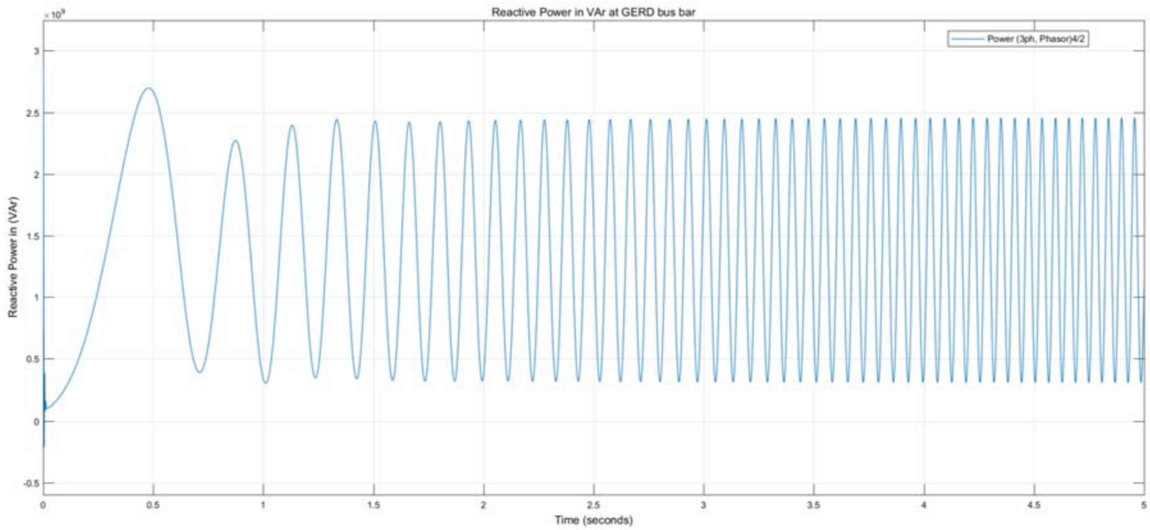

Fig 4.57: Graph showing reactive power vs. time at GERD bus bar with Reactors

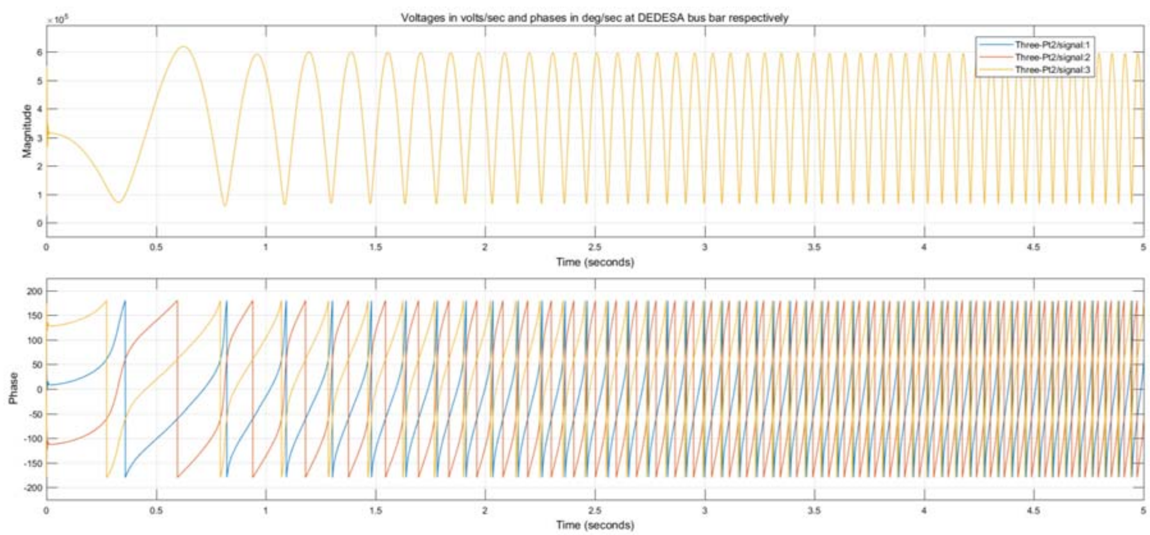

Fig 4.58: Graph showing voltage magnitude and phase vs. time at DEDESA bus bar with Reactors

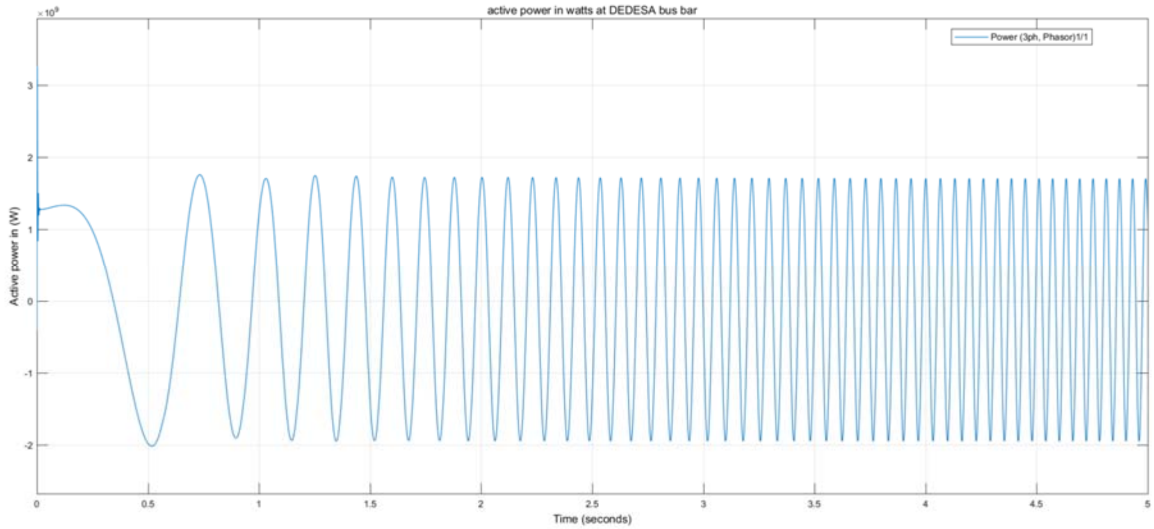

Fig 4.59: Graph showing active power vs. time at DEDESA bus bar with Reactors

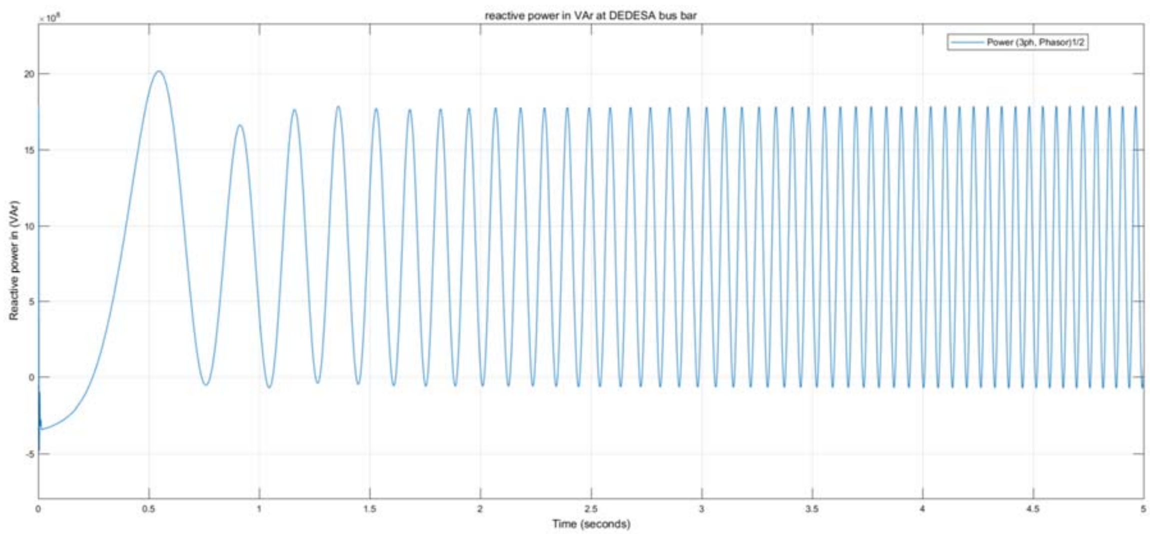

Fig 4: 60: Graph showing reactive power vs. time at DEDESA bus bar with Reactors

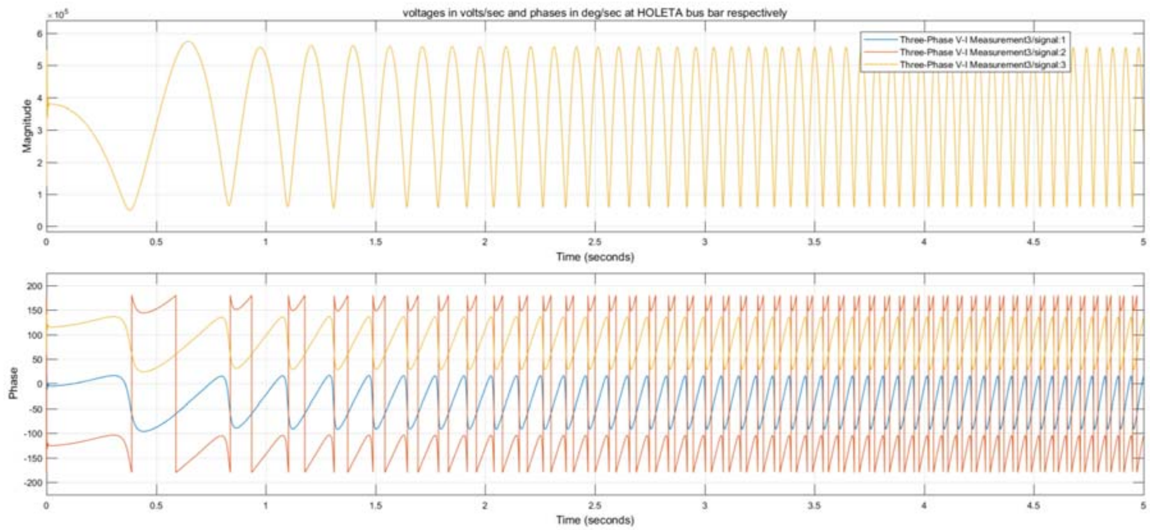

Fig 4.61: Graph showing voltage magnitude and phase vs. time at HOLETA 500 kV bus bar with Reactors

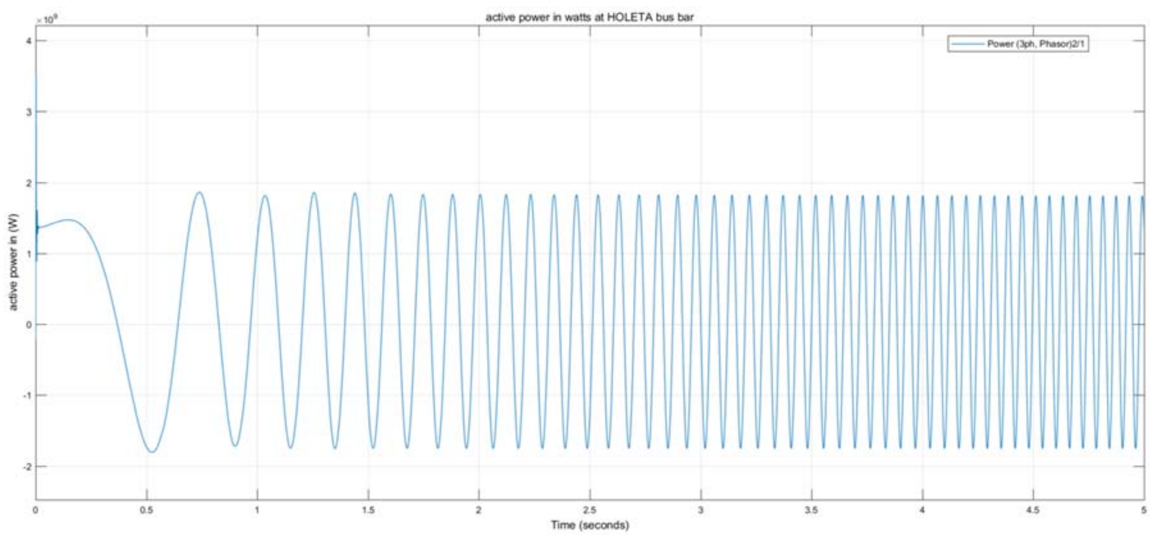

Fig 4.62: Graph showing active power vs. time at HOLETA 500 kV bus bar with Reactors

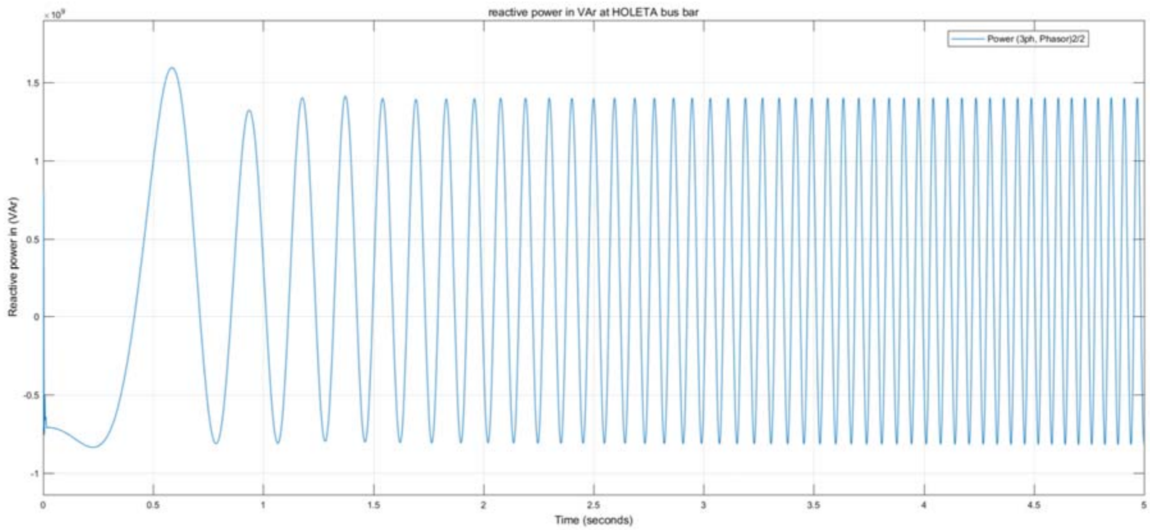

Fig 4.63: Graph showing reactive power vs. time at HOLETA 500 kV bus bar with Reactors

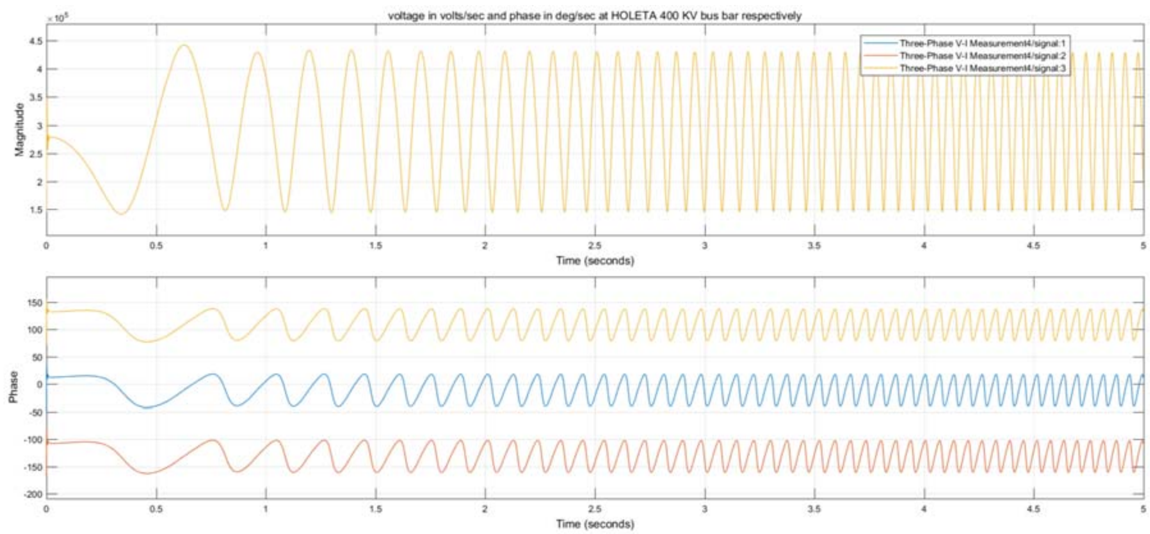

Fig 4.64: Graph showing voltage magnitude and phase vs. time at HOLETA 400 kV bus bar with Reactors

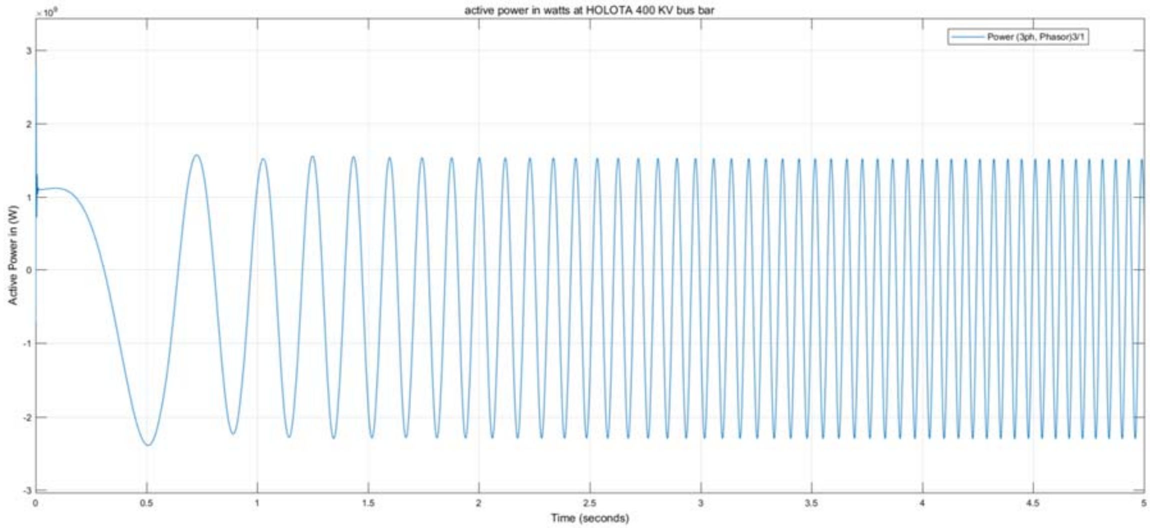

Fig 4.65: Graph showing active power vs. time at HOLETA 400 kV bus bar with Reactors

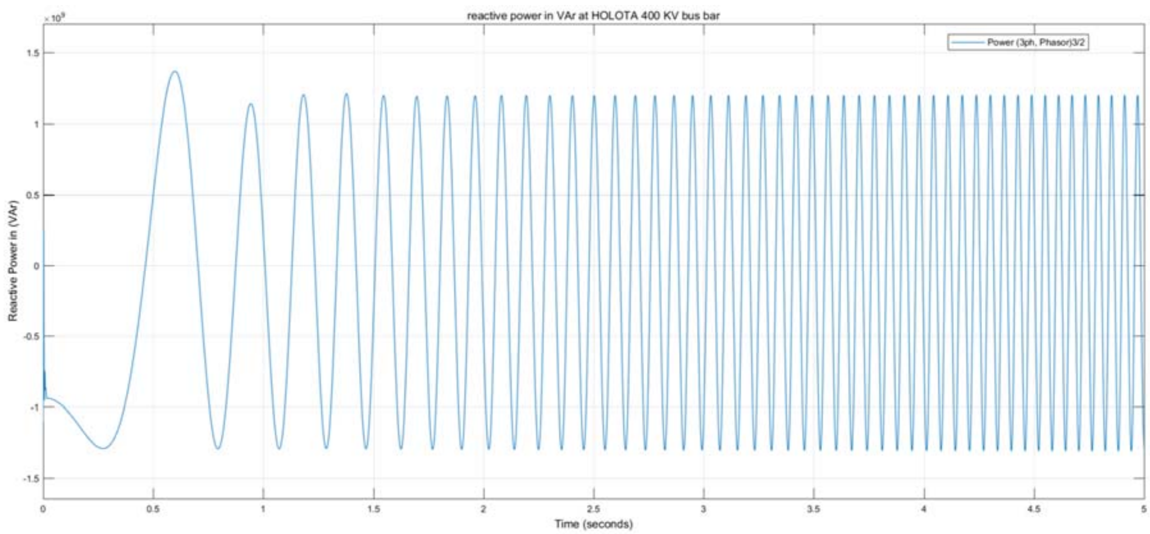

Fig 4.66: Graph showing reactive power vs. time at HOLETA 400 kV bus bar with Reactors

Table 4.6: Active, Reactive, Apparent Power and voltages in all the buses with SVCs at HOLETA 500/400 kV substation with Reactors

BUS	P(MW)	Q(MVAr)	S(MVA)	V(kV)
GERD	1316	1553	2035.6	484.3
DEDESA	1297	1055	1671.9	413.8
HOLETA	1271	836.9	1521.8	389.9
HOLETA 400 kV	1387	904.3	1655.8	314.1

When the SVCs installed at HOLETA 500/400 kV substation are used with reactors at HOLETA 500/400 kV substation, DEDESA substation and GERD substation, the total power transferred is 23.5%.It is decreased by 7%.The active power transferred is 21.8%.It is decreased by 4.9% than when the SVC are used alone. The voltage deviation is 21.5%.

From the above result, the study understands that the reactors and the SVCs at HOLETA 500/400 kV substation should not be used together.

4.4.5. Network simulation involving only Reactors

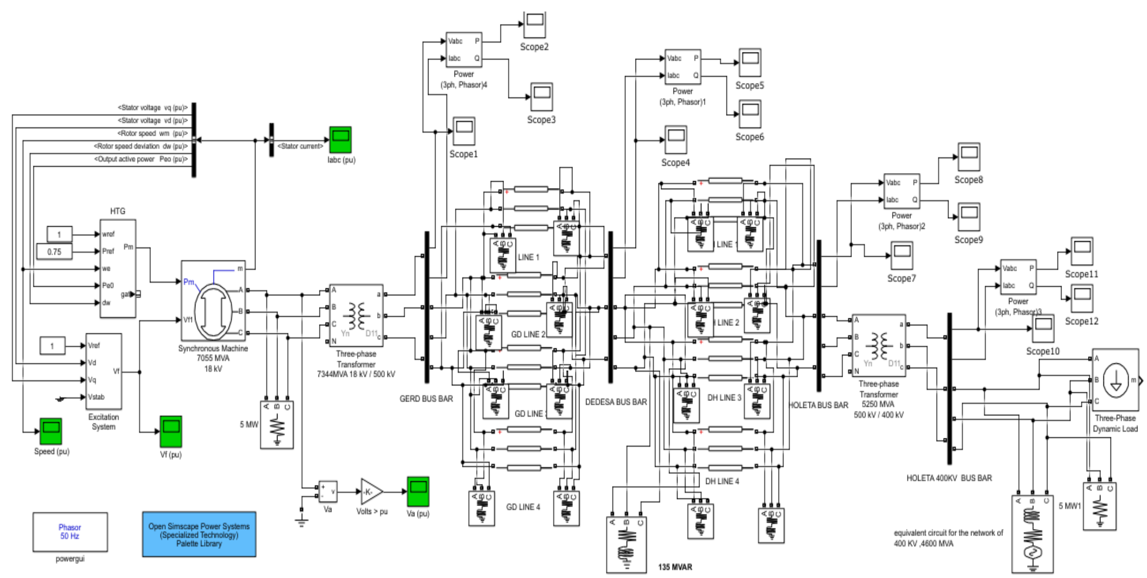

Fig 4.67: Model of the test systems with Reactors only in the network

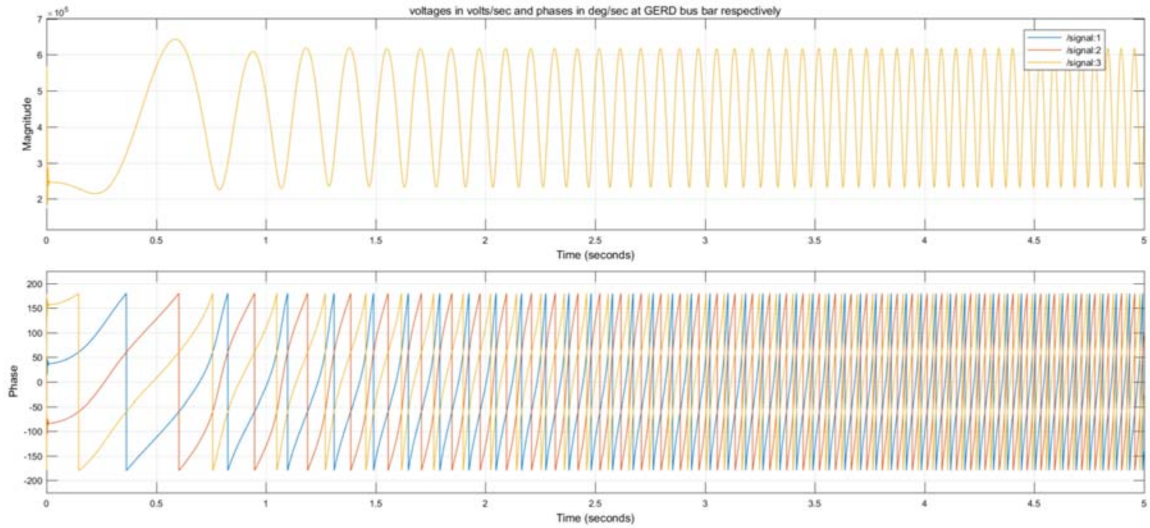

Fig 4.68: Graph showing Voltage magnitude and phase vs. time at GERD bus bar with Reactors only

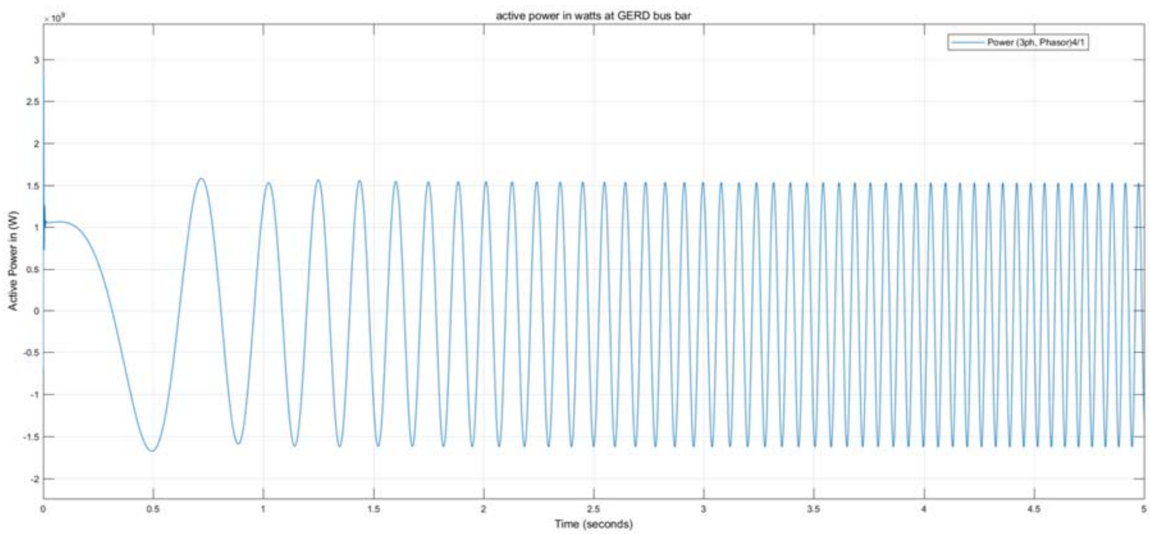

Fig 4.69: Graph showing active power vs. time at GERD bus bar with Reactors only

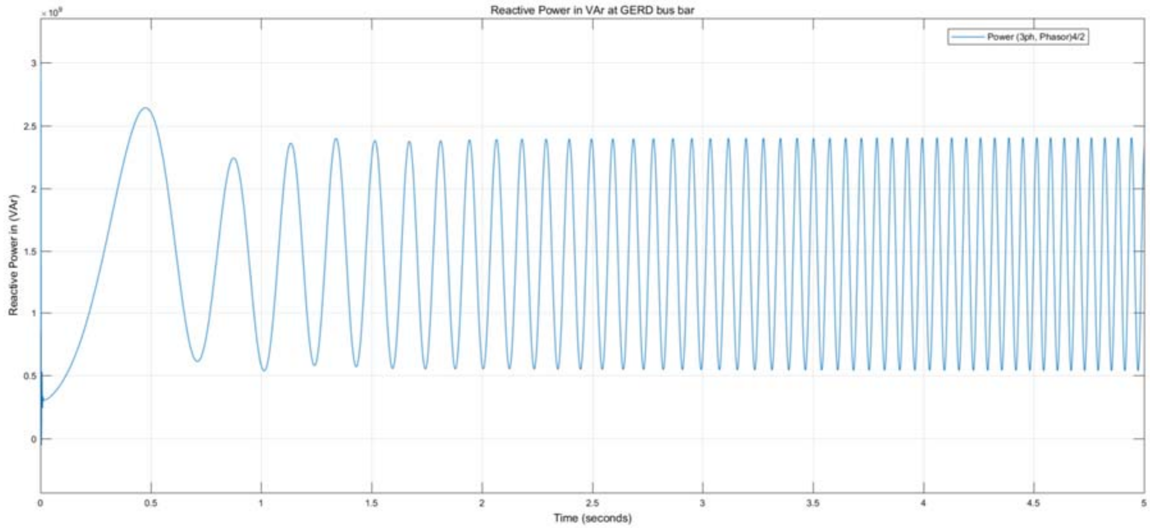

Fig 4.70: Graph showing reactive power vs. time at GERD bus bar with Reactors only

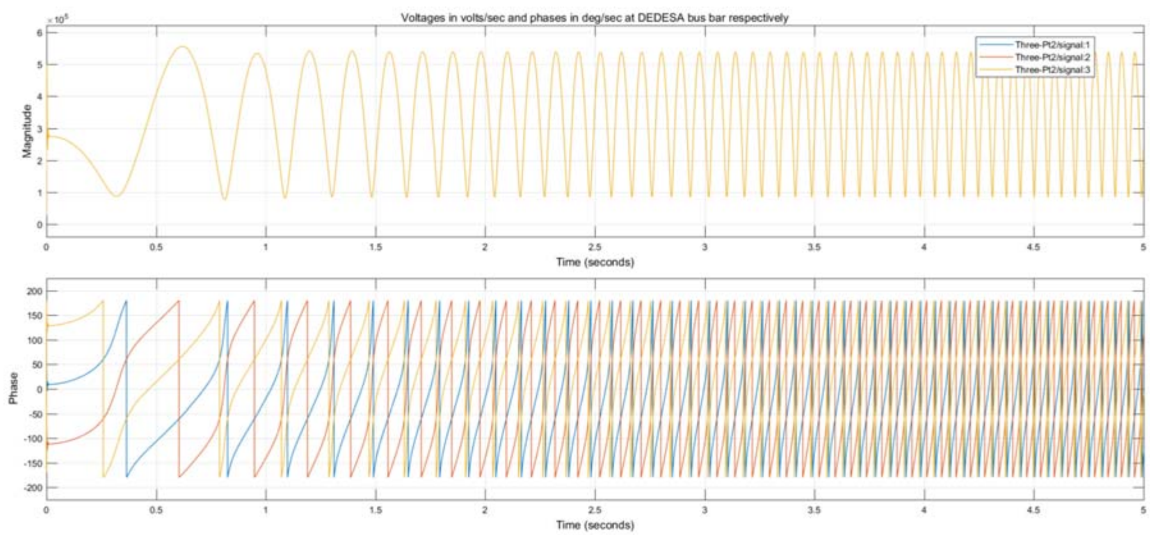

Fig 4.71: Graph showing voltage magnitude and phase at DEDESA bus bar with Reactors only

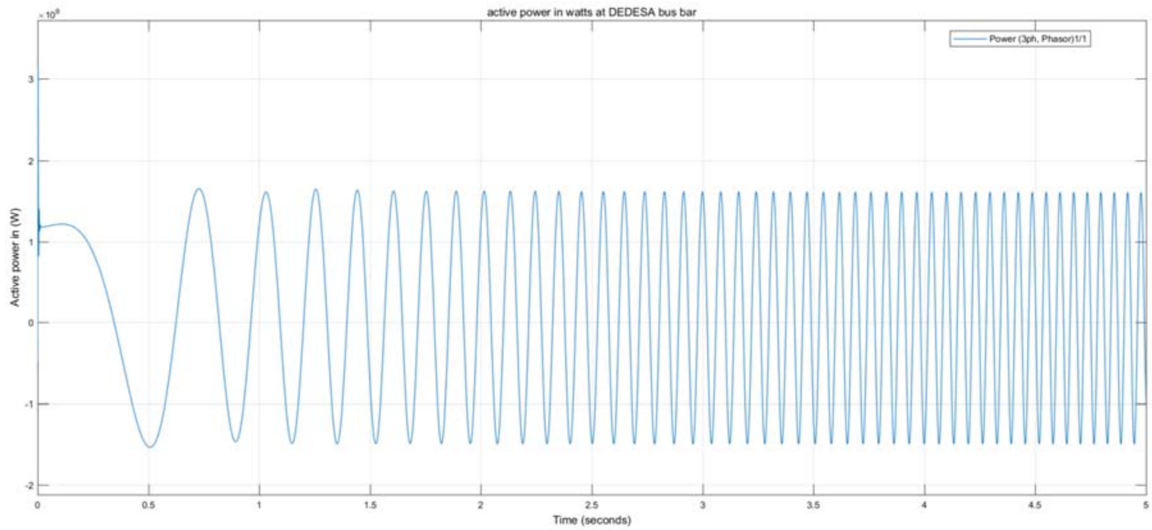

Fig 4.72: Graph showing active power vs. time at DEDESA bus bar with Reactors only

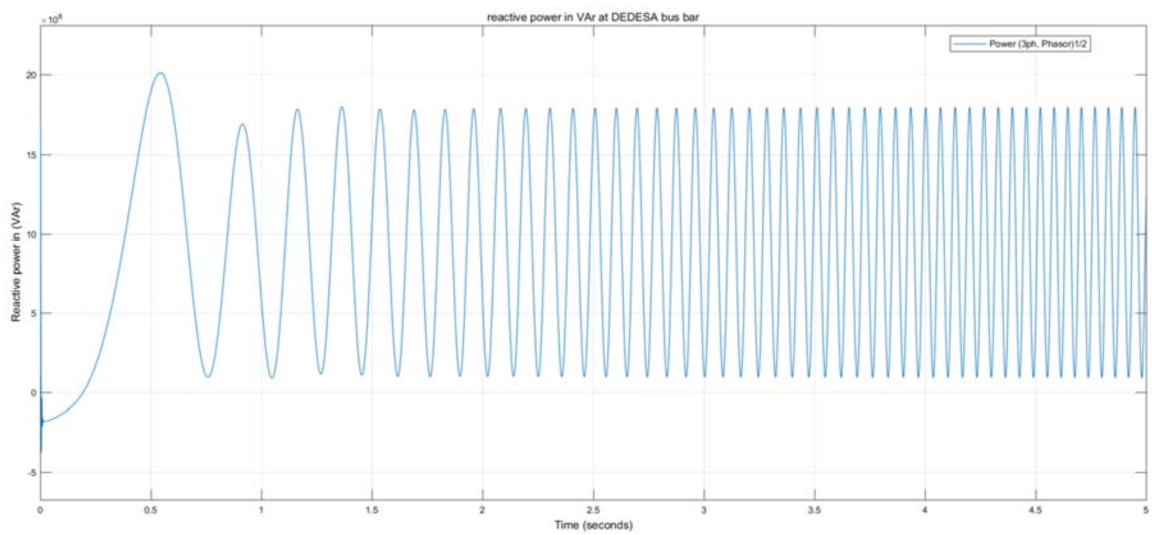

Fig 4.73: Graph showing reactive power vs. time DEDESA bus bar with Reactors only

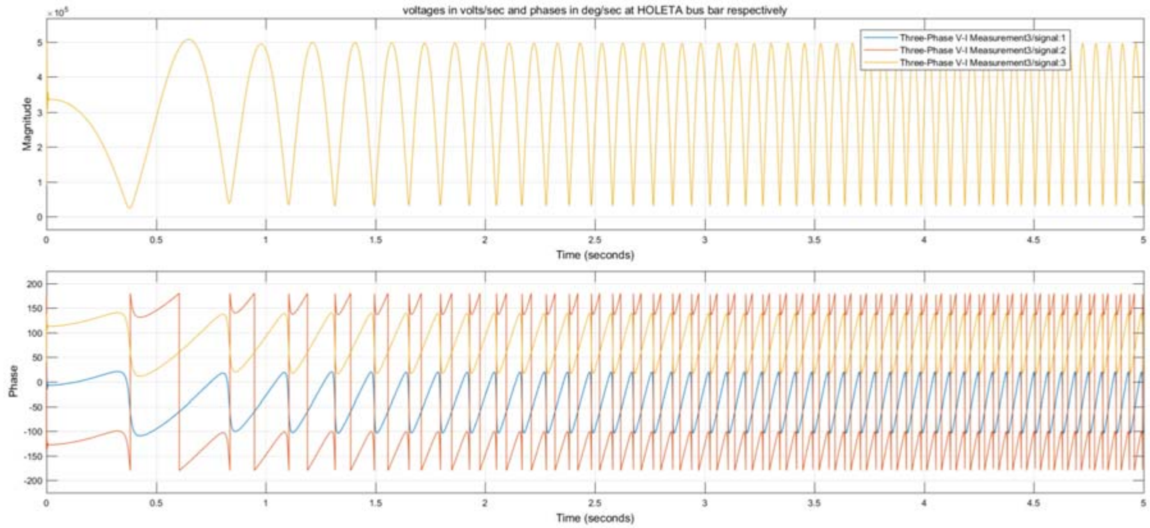

Fig 4.74: Graph showing voltage magnitude and phase vs. time at HOLETA 500 kV bus bar with Reactors only

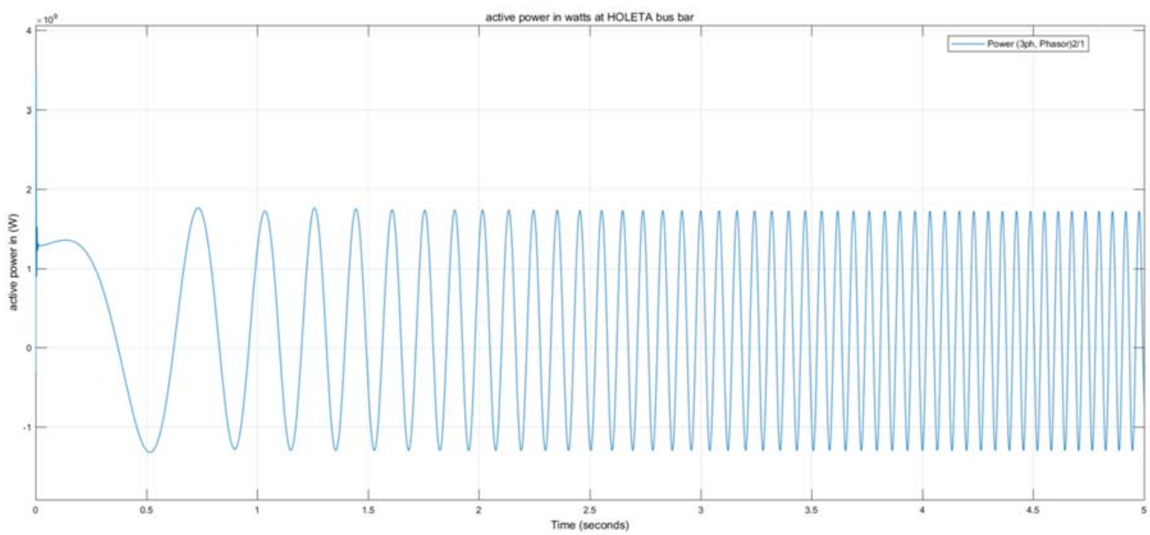

Fig 4.75: Graph showing active power vs. time at HOLETA 500 kV bus bar with Reactors only

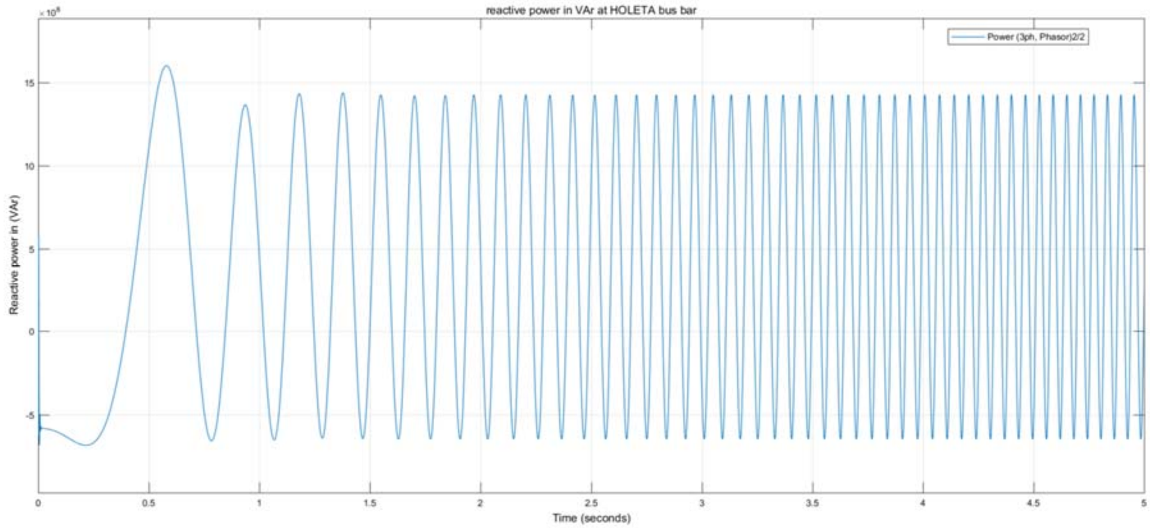

Fig 4.76: Graph showing reactive power at HOLETA 500 kV bus bar with Reactors only

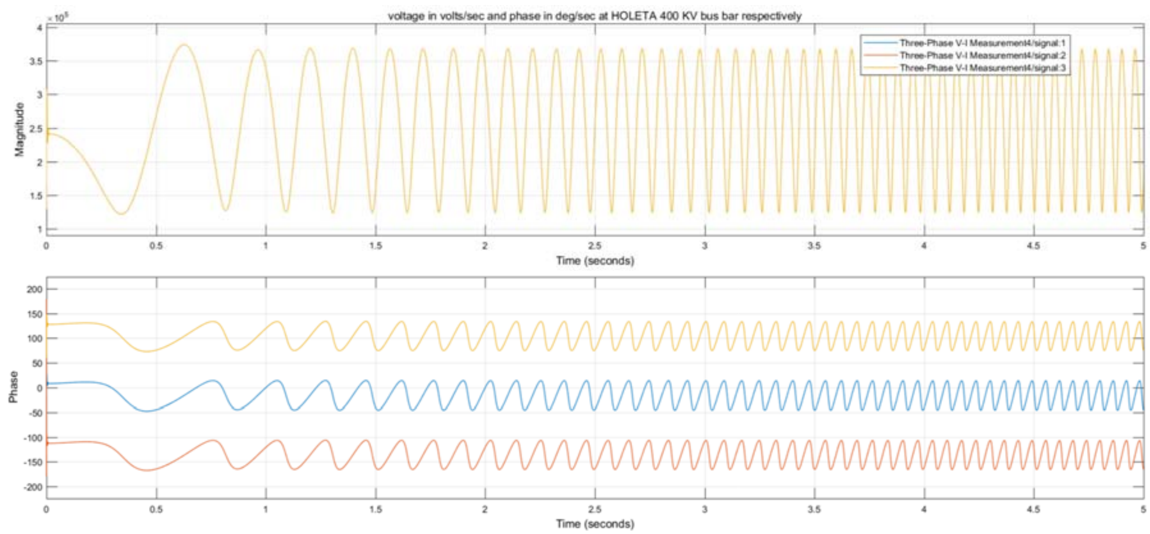

Fig 4.77: Graph showing voltage magnitude and phase vs. time at HOLETA 400 kV bus bar with Reactors only

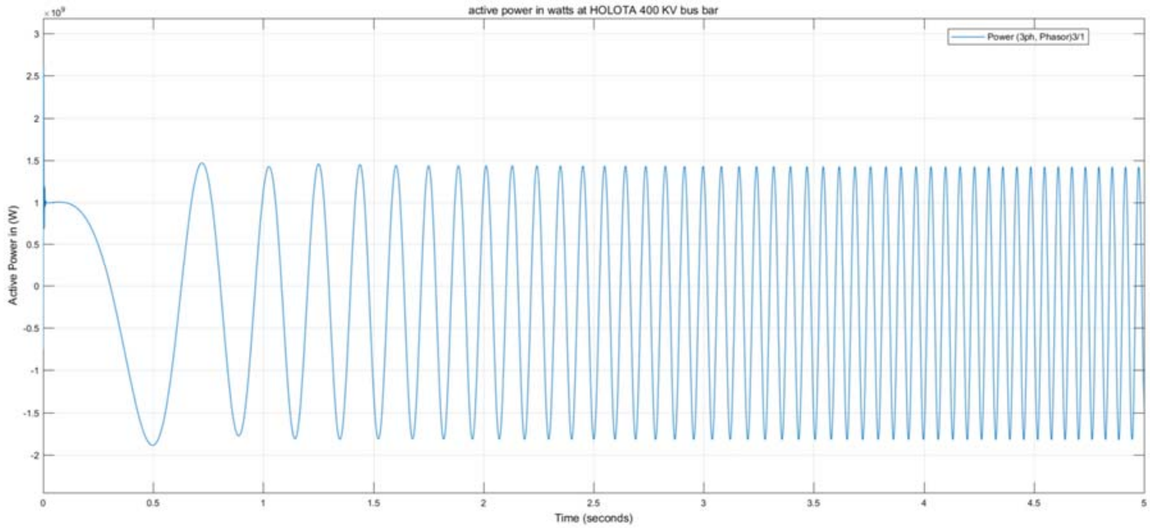

Fig 4.78: Graph showing active power vs. time at HOLETA 400 kV bus bar with Reactors only

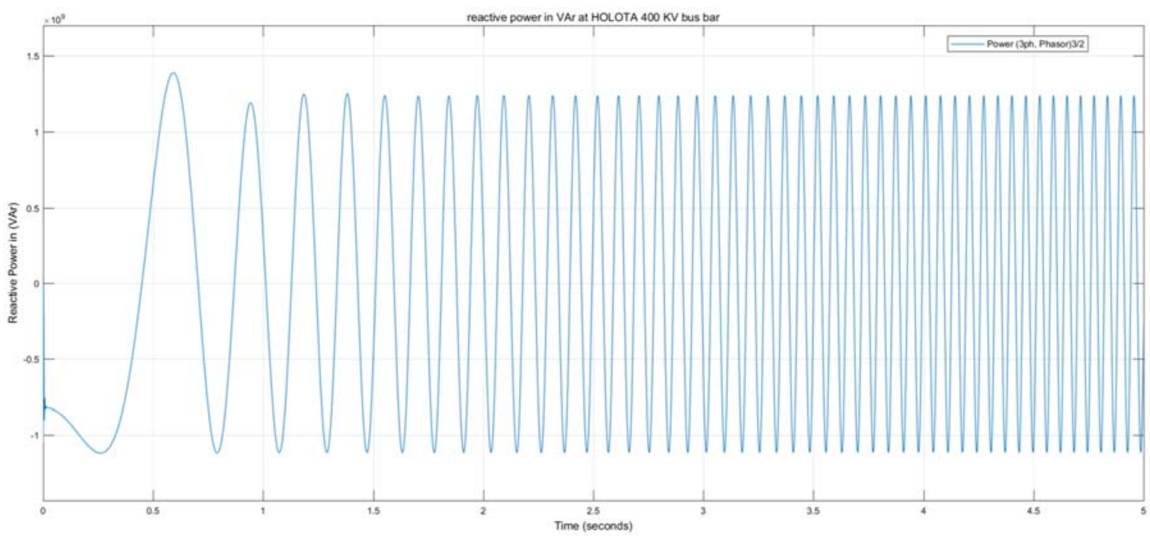

Fig 4.79: Graph showing reactive power vs. time HOLETA 400 kV bus bar with Reactors only

Table 4.7: Active, Reactive, Apparent Power and voltages in all the buses with Reactors only

BUS	P(MW)	Q(MVAr)	S(MVA)	V(kV)
GERD	1108	1597	1943.7	456.1
DEDESA	1098	1094	1549.98	376.9
HOLETA	1098	823.4	1372.44	346.6
HOLETA 400 kV	1150	845.5	1427.4	270.1

Simulation result shown in Table 4.7 above is found when the network is working with reactors only. The total power transferred to the 400 kV bus bar at HOLETA 500/400 kV substation is 20.2%. This number is smaller by 6.5% than when the SVCs are used alone and by 3.3% when both SVCs and Reactors are used together. The actual power transferred is 18%. A number which is smaller by 8.7% than when the SVCs are used alone. It is also decreased by 3.8% when both SVCs and Reactors used together. The voltage deviation is 32.5%.In this circumstances; it is better the reactors not involved in the system.

4.5. Voltage Stability analysis of GERD-DEDESA-HOLETA Network under different loading conditions with SVCs at HOLETA 500/400 kV substation

Table 4.8: Recorded value of P and Q for PV and QV curve at 400 kV bus bar at HOLETA 500/400 kV substation with SVCs

PV curve		QV curve	
P(MW)	V(kV)	Q(MVAr)	V(kV)
648	425.6	314	366.2
1296	396.3	628	356.7
1943	367.2	941	347.4
2591	338.4	1255	338.4
3239	311.6	1569	329.8

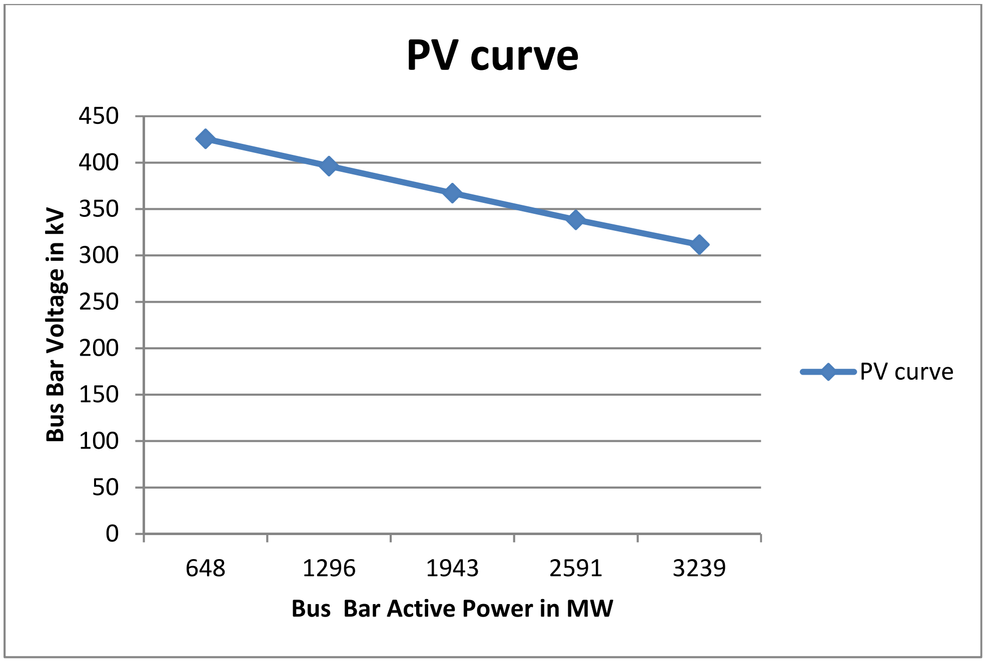

Figure 4.80: PV curve at 400 kV bus bar in HOLETA 500/400 kV substation (with SVCs)

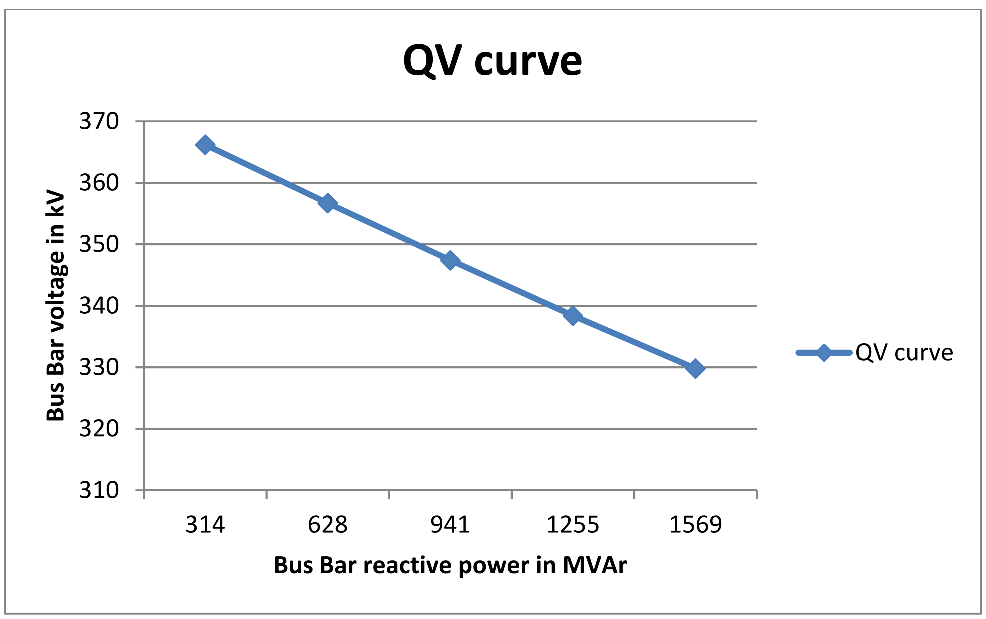

Figure 4.81: QV curve at 400 kV bus bar in HOLETA 500/400 kV substation (with SVCs)

As can be seen from Table 4.8, Figure 4.80 and Figure 4.81, in the PV curve for 125% active power loading the bus bar voltage is 311.6 kV, which is lower by 23.7 kV than without SVCs condition. In the QV curve, for a similar 125% reactive power loading, the bus bar voltage is 329.8 kV. This value is lower by 21.6 kV than the previous condition. Both curve analysis depicts that voltage stability margin is not improved at the 400 kV bus bar when the SVCs are operated in the network.

4.6. Analysis of Results

The overall results at 400 kV bus bar HOLETA 500/400 kV substations are summarized in the table 4.9 as follows.

Table 4.9: Active, Reactive, Apparent Power and voltages at HOLETA 400kV bus bar

Scenarios	P(MW)	Q(MVAr)	S(MVA)	V(kV)	p.f.
Without SVC	1861	1247	2240	362.8	0.83
With SVC	1695	1323	2150	338.4	0.79
SVC with Reactors	1387	904.3	1655.8	314.1	0.84
Reactors only	1150	845.5	1427.4	270.1	0.81

As can be seen in the above table, the voltage at HOLETA 400 kV bus bar is good when the system is without SVCs and reactors on the system. But the voltage at GERD bus bar is 13.7% above the nominal value. The best power factor is achieved when the SVCs are working with the reactors. The voltage at HOLETA 400 kV bus bar is good when the system is working without SVCs but the problem is the voltage at GERD bus bar. It becomes over voltage.

Table 4.10: Voltages in kV at all bus bars for different peak loads

Bus Location/Name	Peak loads							
	2591 MW		3000 MW		3500 MW		4200 MW	
	Without SVC	With SVC	Without SVC	With SVC	Without SVC	With SVC	Without SVC	With SVC
GERD	568.6	509.3	552.7	494.4	537.2	477.8	519.7	461.7
DEDESA	468.4	467.4	444.9	447.8	419.2	426	389.6	403.6
HOLETA	435	420.6	411.2	399.4	384.6	376.3	354.3	351.7
HOLETA 400 kV	362.8	338.4	338.8	316.8	312.6	293.3	282.6	267.9

Table 4.11: Reactive Power in MVAr at all bus bars for different peak loads

Bus Location/Name	Peak loads							
	2591 MW		3000 MW		3500 MW		4200 MW	
	Without SVC	With SVC	Without SVC	With SVC	Without SVC	With SVC	Without SVC	With SVC
GERD	1320	1311	1281	1285	1258	1270	1253	1271
DEDESA	1211	1414	1205	1399	1202	1378	1193	1360
HOLETA	1424	1523	1377	1468	1321	1399	1248	1328
HOLETA 400 kV	1247	1323	1208	1273	1157	1210	1088	1139

As can be seen from the table 4.10 and 4.11, the bus bar voltages decreases as the peak load increases from 2591 MW to 4200 MW. For example at HOLETA 400 kV bus bar, the voltage decreases from 362.8 kV to 282.6 kV when the SVCs are not working. From the simulation results, it is observed that the system is experiencing both over voltage at GERD bus bar and under voltage on the other bus bars. The probable reason is that GERD bus bar is very far away from the load center, HOLETA 400 kV bus bar and has no any load connection on it. Series capacitor compensation is usually applied for long transmission lines. They reduce net transmission line inductive reactance. They are connected in series mainly for boosting the receiving end voltage. The simulation also depicts that while the SVCs are used, reactive power of the system increases and system voltage reduces. As a result voltages of GERD bus bar comes to normal but the other bus bars need additional capacitive compensation.

CHAPTER FIVE

5. Conclusions ,Recommendations and Future works

5.1. Conclusions

This thesis studies the impact of SVCs installed at HOLETA 500/400 kV substation. HOLETA 500/400 kV substation is the focus because it is the main gateway of GERD power to the main grid through Sululta, Gelan and Sebeta II 400 kV substations.

Since the energy which is coming from this dam is more than the total current capacity, it is not easy for evacuation. Given the existing problem of grid capacity, this big amount of energy coming from one dam to the grid will add problem for sure. When the system is getting most of its power from a single source and face some fault either in transmission line or substation, black out will be imminent unless the system is dynamically controllable. There will be also network congestion which ultimately leads to power failure in the system.

The GERD was initially designed to generate 5250 MW then it was raised to 6000 MW at sometimes. After many design reviewing currently it is said to produce 6450 MW of power. But while this all design reviewing and modification made, the power transmission project was going on. So the study understands these two tasks should have gone in parallel but only the design of the dam was in continuous amendment. That is why the study so interested to see if it is possible to evacuate all the power by the installed SVCs at HOLETA 500/400 kV substations.

The total capacity in the dam is 7055 MVA. In HOLETA 500/400 kV substation there is a total autotransformer capacity of 5250MVA. The study made on 2008 G.C, the Ethiopian grid loss is 20% [9].

By considering the grid loss as 20%, power factor 0.9 and avoiding equipment loss, the total active power available at HOLETA 500/400 kV substation is calculated to be 5080MW.

The detailed models of the SVCs are implemented and tested with MATLAB/simulink simscape environment. The model is applicable for voltage stability and better range of power transfer capability study. The SVCs are simulated for the other two substations as well i.e. DEDESA and GERD substations. Simulation is also made for SVCs with the compensation devices. All the parameters like active power, reactive power, and voltage are measured in the respective substation bus bars.

The effect of SVCs on the GEDR-DEDESA-HOLETA 500/400 kV system is analyzed and the conclusions of the thesis are as follows:

1. The best location of SVCs in terms of voltage stability is at HOLETA 500/400 kV substation. At HOLETA 400 kV bus bar, the voltage is 338.4 kV when the SVCs are at HOLETA 500/400 kV substation. It is 330.7 kV when they are installed at DEDESA substation. The Value is further decreased to 326.1 kV when the SVCs are installed at GERD substation.
2. The Voltage stability in the 500 kV network is better when the SVCs are used in the system. The voltage at GERD bus bar improved from 568.6 kV to 509.3 kV. Simulation with compensation devices 90 MVAr for each line at HOLETA 500/400 kV Substation, 135MVAr for each line to both direction and one 135 MVAr for bus bar at DEDESA substation, and 135 MVAr for each line at GERD substation is used. Voltage deviation further worsened by 24.3 kV to 314.1kV and the total apparent power transferred is decreased by 494.2MVA at HOLETA 400 kV bus bar. When the system is simulated with compensation devices only, the voltage deviation is further increased by 68.3kV to 270.1 kV. The total apparent power transferred is decreased by 722.6 MVA.
3. The simulation result shows that the reactive power in the HOLETA 400 kV bus bar is always lower than the active power. Voltage deviates by 9.3% at HOLETA 400 kV bus bar when the system is working without SVCs. When the system is working with SVCs, the voltage deviation is 15.4%. Using SVCs didn't improve the voltage stability at HOLETA 400 kV bus bar during full load working. But the voltage stability at GERD bus bar is improved by 11.84 % during operation of SVCs.
4. The PV and QV curve analysis shows that better voltage stability is not attained when the SVCs are used in the network at HOLETA 400 kV bus bar for full load loading. For 125% loading of the system i.e. 3239 MW active power the voltage will be 335.3kV and 1569MVAr at 351.4kV.But when the SVCs are used in the network, for 3239MW of active power, the bus bar voltage will be 311.6kV and 329.8 kV for 1569MVAr.The PV and QV curve Study also shows that SVCs improve over voltage problem. During 50% loading in the absence of SVCs, the voltage at HOLETA 400 kV bus bar is 418.5 kV. But when the SVCs are present it is 396.3 kV which is very good for the system. Since the system is facing both over voltage and under voltage problem, the SVCs are helpful in controlling the over voltage problem.
5. The impact of the SVCs on the GERD bus bar is visible. The reactive power is reduced by 9 MVAr and the voltage improved by 59.3 kV.

5.2. Recommendations

1. The total apparent power generated at GERD power plant which is 7055 MVA, is greater than the current generating capacity of the country and the system is not capable of transferring this whole power. It is only possible to transfer 31% of the power generated at GERD. It is recommended to go for other additional FACTS device for better power transfer.
2. In addition when the system voltage deteriorates, SVC will struggle to rectify the voltage stability. Therefore additional support for the SVCs is mandatory.
3. In the GERD-DEDESA-HOLETA 500/400 kV system, the reactive power greater than the active power resulting in the system voltage to deviate by around 9.3% from the nominal voltage. Series capacitive compensation devices should be installed to rectify this voltage stability problem as they reduce system inductive reactance and boost receiving end voltage.

5.3. Suggestions for Future work

1. The impact of the installed SVCs on the distance protection relays and protection system of nearby substation should be studied. The Substations are Sululta 400 kV substation, Gelan 400 kV substation and Sebeta II 400 kV substation where all are connected by double 400 kV transmission lines.
2. Study on power transfer and voltage stability should be made after the energization of GERD power plant as well by taking real voltage and reactive power data’s from the GERD-DEDESA-HOLETA 500/400 kV system.

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Appendices

Appendix A

Network and equipment data

500 kV transmission line conductor electrical data

No	Characteristics of conductor	explanation
1	Material of the conductor	Aluminum and steel
2	Actual area (total) in mm2	454.5
3	Standard overall diameter of conductor in mm	27.72
4	Resistance per km(ohm/km)	0.07173
5	Current carrying capacity	566 A at 65 deg. Centigrade,705 A at 75 deg. Centigrade

Data of 500/400 KV auto transformers

No	Type of transformer	Total capacity
1	500/400 kV(single phase types of capacity 250 MVA)	7*750 MVA=5250 MVA

Data of HOLETA 500/400 kV substation SVCs

No	Name of equipment	Capacity	Quantity
1	Static Var Compensator(SVC)	-450 to +450MVAr (total)	three
2	SVC transformer	400/33 kV, 315 MVA (each)	three

500 kV Transmission line length data

No	Transmission line name	Transmission line length	Voltage level
1	GERD-Dedesa(4 transmission lines)	345 km	500/400 kV
2	Dedesa-Holeta(4 transmission lines)	275 km	500/400 kV

Data of Step up transformer at GERD

No of units(3 single phase transformers for each unit plus one spare)	3x(16+1)
Continuous rated power output	153 MVA
Nominal frequency	50 Hz
Rated power factor	0.9
Type	Single phase ,outdoor installation
Insulation type	Mineral oil
Cooling medium	Mineral oil
Cooling class	ONAN/ONAF
Rated voltage	
HV winding	500 kV
MV winding	18 kV
Winding connection	YNd11

Thyristor controlled reactor (TCR) data sheet (three in numbers) at HOLETA 500/400 kV substation

Rated voltage	33 kV
Rated capacity	150 MVAr
Rated current	2624 A
Rated frequency	50 Hz

Thyristor switched capacitor (TSC) data sheet (three in numbers)
At HOLETA 500/400 kV substation

Rated voltage	33 kV
Rated capacity	150 MVAr
Rated current	2624 A
Rated frequency	50 Hz

Data sheet of filter capacitor device (three for each TSC)

Rated voltage	33 kV
Rated capacity	50 MVAr
Rated current	875 A
Rated frequency	50 Hz
Tuning frequency	150 Hz

Data sheet of SVC transformer at HOLETA 500/400 kV substation (three in number)

Rated power	315 MVA
Rated voltage	400 ± 5%/33 kV
Type of cooling	ONAN/ONAF
Connection type	YNd11
Rated frequency	50 Hz
Number of phase	Three phase
Working condition	Outdoor

Data sheet of power transformer at HOLETA 500/400 kV substation (21 + 1 spare)

Rated power	250/250/25 MVA
Rated voltage	500/400/20 kV
Connection symbol	YNaOd11
Number of phase	Single –phase
Rated frequency	50 Hz
Working condition	Outdoor
HV-MV impedance(impedance at rated frequency)	12.93%

GERD substation shunt Reactor datasheet

Designation	Technical parameter
Shunt reactor type	Oil immersed with conservator
Type of cooling	ONAN
Number of phases	Single phase
Rated frequency	50 Hz
Rated capacity	45MVAr X 3
Rated voltage	500/400 kV
Rated current	156 A
Rated reactance	1850.5 Ω
Winding connection	star

DEDESA substation shunt Reactor datasheet

Description	Technical data
Installation	outdoor
Rated Voltage	500/400 kV
Method of cooling	ONAN
Number of phases	3 phase
Frequency	50 Hz
Rated power for DEDESA substation on GERD line bay	135 MVAr
Rated power for DEDESA substation on Holeta line bay	135 MVAr
Rated power for DEDESA bus bar reactor	135 MVAr

HOLETA substation shunt Reactor datasheet

Description	Technical data
Installation	outdoor
Rated Voltage	500/400 kV
Method of cooling	ONAN
Number of phases	3 phase
Frequency	50 Hz
Rated power	90 MVAr

SVCs cost in USD at HOLETA 500kV substation

no	supply	Sea transport	Local transport	Civil work	Erection ,test and commissioning	insurance
1	17,696,535.00	1,238,757.00	176,965.00	884,827.00	884,827.00	88,483.00
						20,970,394.00

Appendix B

HOLETA 500/400/230/33 kV Substation voltage profile

400 kV bus bar 2 daily reports on 2017-09-08 at HOLETA 500/400 kV substation

Time	Urs(kV)	Ust(kV)	Utr(kV)
00:00	0.00	0.00	0.00
01:00	0.00	0.00	0.00
02:00	0.00	0.00	0.00
03:00	0.00	0.00	0.00
04:00	0.00	0.00	0.00
05:00	0.00	0.00	0.00
06:00	0.00	0.00	0.00
07:00	0.00	0.00	0.00
08:00	0.00	0.00	0.00
09:00	0.00	0.00	0.00
10:00	0.00	0.00	0.00
11:00	0.00	0.00	0.00
12:00	397.28	397.28	395.34
13:00	407.42	407.63	405.30
14:00	396.12	396.36	394.48
15:00	402.82	403.19	400.63
16:00	396.71	396.75	394.78
17:00	397.86	397.84	395.75
18:00	396.45	396.61	394.58
19:00	396.06	396.20	394.14
20:00	396.34	396.33	394.39
21:00	404.76	405.36	402.73
22:00	404.72	404.88	402.16
23:00	395.89	396.94	394.25

400 kV bus bar 2 daily reports on 2017-09-14 at HOLETA 500/400 kV substation

Time	Urs(kV)	Ust(kV)	Utr(kV)
00:00	396.47	397.05	394.03
01:00	398.55	399.13	396.10
02:00	397.93	398.43	395.63
03:00	398.53	399.29	396.27
04:00	398.88	399.87	397.01
05:00	398.67	399.43	396.10
06:00	396.26	397.24	394.35
07:00	396.20	396.29	394.56
08:00	395.94	396.31	394.29
09:00	394.85	395.18	393.29
10:00	395.23	395.36	393.42
11:00	394.72	394.95	393.10
12:00	396.98	396.82	395.09
13:00	394.76	394.40	392.87
14:00	395.69	395.82	394.37
15:00	396.73	396.75	394.32
16:00	395.85	396.15	394.03
17:00	396.33	395.97	394.40
18:00	396.04	396.06	394.03
19:00	395.67	395.83	394.30
20:00	396.06	395.83	393.44
21:00	398.41	398.09	396.22
22:00	400.93	401.35	398.87
23:00	398.11	399.29	396.29

400 kV bus bar 2 daily reports on 2017-09-21 at HOLETA 500/400 kV substation

Time	Urs(kV)	Ust(kV)	Utr(kV)
00:00	395.43	395.96	393.21
01:00	395.96	397.33	393.95
02:00	396.13	397.10	393.89
03:00	394.42	396.50	392.96
04:00	395.23	395.76	393.10
05:00	395.60	396.24	393.10
06:00	396.12	397.14	394.40
07:00	395.62	395.71	393.33
08:00	395.94	396.49	393.96
09:00	395.57	395.96	393.63
10:00	395.96	396.50	394.07
11:00	395.41	395.15	392.89
12:00	395.55	396.15	393.91
13:00	395.90	396.27	393.54
14:00	395.80	396.04	393.93
15:00	395.45	395.53	393.96
16:00	396.01	396.42	394.35
17:00	395.32	395.96	393.10
18:00	395.30	395.66	393.03
19:00	395.78	396.12	393.96
20:00	395.43	395.90	393.24
21:00	396.10	397.47	394.49
22:00	395.53	396.54	393.58
23:00	395.30	396.19	394.09

400 kV bus bar 2 daily reports on 2017-09-30 at HOLETA 500/400 kV substation

Time	Urs(kV)	Ust(kV)	Utr(kV)
00:00	402.36	403.65	400.3
01:00	395.94	397.03	394.07
02:00	395.02	396.56	392.80
03:00	394.58	396.31	393.03
04:00	395.27	395.50	392.09
05:00	395.20	395.99	392.31
06:00	394.72	396.61	393.08
07:00	395.64	396.59	393.56
08:00	395.62	395.89	393.77
09:00	396.15	396.80	394.12
10:00	395.78	396.87	394.21
11:00	394.58	395.71	393.65
12:00	395.55	395.80	393.98
13:00	395.37	396.17	393.35
14:00	396.27	396.31	394.05
15:00	395.94	396.12	393.42
16:00	395.87	396.20	394.11
17:00	395.13	395.59	393.88
18:00	395.13	395.67	393.93
19:00	396.40	396.43	394.26
20:00	395.94	396.31	393.61
21:00	394.93	395.99	391.97
22:00	395.64	396.45	393.38
23:00	395.43	396.71	392.80

Appendix C

Gebereguracha 400/230/66/33 kV substation voltage profile

Maximum and Minimum voltage in a day through the month of June/2017

Date (June/2017)	400kV bus bar Voltage in kV	
	max	min
1	408	402
2	411	402
3	410	403
4	412	402
5	404	395
6	410	401
7	409	405
8	410	402
9	410	402
10	411	401
11	407	400
12	409	403
13	407	403
14	410	403
15	411	400
16	409	400
17	408	400
18	409	403
19	409	404
20	408	402
21	405	400
22	407	400
23	404	396
24	407	392
25	-	-
26	410	401
27	406	400

Maximum and Minimum voltage in a day through the month of July/2017

Date (July/2017)	400kV bus bar Voltage in kV	
	max	min
1	-	-
2	-	-
3	-	-
4	409	392
5	409	391
6	404	397
7	410	399
8	411	402
9	413	405
10	409	400
11	412	402
12	409	403
13	411	402
14	407	401
15	404	397
16	414	409
17	415	399
18	407	399
19	409	401
20	407	400
21	412	399
22	412	402
23	416	406
24	412	401
25	411	402
26	410	403
27	410	399
28	408	398
29	407	398
30	413	406
31	412	399

Maximum and Minimum voltage in a day through the month of August/2017

Date (August/2017)	400kV bus bar Voltage in kV	
	max	min
1	409	403
2	411	404
3	413	404
4	412	400
5	408	402
6	412	408
7	409	401
8	412	400
9	412	400
10	411	402
11	400	400
12	413	399
13	413	401
14	411	403
15	410	401
16	410	399
17	413	399
18	408	401
19	408	398
20	417	406
21	411	401
22	413	402
23	408	403
24	411	403
25	414	400
26	413	399
27	412	404
28	412	399
29	418	397
30	-	-
31	409	405

Maximum and Minimum voltage in a day through the month of October/2017

Date (October /2017)	400kV bus bar Voltage in kV	
	max	min
1	402	395
2	409	402
3	408	401
4	400	393
5	412	402
6	411	399
7	408	401
8	411	403
9	399	392
10	400	392
11	401	392
12	398	392
13	399	394
14	399	394
15	405	395
16	400	392
17	400	392
18	398	392
19	402	395
20	400	392
21	399	393
22	403	398
23	403	396
24	401	395
25	404	392
26	400	395
27	402	394
28	408	394
29	405	394
30	409	402
31	402	395

Maximum and Minimum voltage in a day through the month of November/2017

Date (November /2017)	400kV bus bar Voltage in kV	
	max	min
1	412	400
2	410	402
3	408	398
4	411	404
5	411	402
6	410	402
7	410	399
8	412	401
9	410	404
10	410	405
11	403	398
12	412	399
13	410	400
14	413	406
15	411	405
16	412	401
17	410	403
18	411	406
19	403	396
20	412	402
21	410	405
22	411	401
23	408	399
24	411	402
25	408	400
26	409	402
27	409	401
28	399	393
29	408	401
30	411	404

Maximum and Minimum voltage in a day through the month of December/2017

Date (December /2017)	400kV bus bar Voltage in kV	
	max	min
1	409	399
2	405	398
3	400	392
4	411	401
5	408	402
6	400	391
7	409	401
8	412	401
9	409	398
10	402	395
11	410	401
12	410	402
13	409	402
14	409	404
15	408	398
16	405	398
17	408	400
18	404	398
19	409	386
20	399	395
21	407	402
22	410	400
23	410	403
24	410	401
25	411	401
26	408	401
27	408	398
28	412	402
29	409	401
30	408	403
31	413	407

Maximum and Minimum voltage in a day through the month of January /2018

Date (January /2018)	400kV bus bar Voltage in kV	
	max	min
1	406	399
2	407	399
3	408	399
4	409	403
5	406	400
6	410	402
7	414	401
8	406	398
9	409	401
10	407	401
11	410	403
12	410	403
13	397	392
14	404	397
15	411	393
16	407	401
17	409	401
18	410	402
19	410	402
20	410	395
21	411	402
22	408	398
23	409	403
24	410	402
25	409	401
26	406	396
27	406	400
28	409	403
29	408	401
30	409	401
31	405	399

Maximum and Minimum voltage in a day through the month of October /2018

Date (October /2018)	400kV bus bar Voltage in kV	
	max	min
1	406	402
2	407	404
3	407	401
4	406	405
5	407	404
6	407	405
7	403	401
8	407	402
9	406	405
10	407	401
11	406	405
12	407	406
13	407	402
14	404	402
15	407	406
16	407	405
17	408	406
18	407	403
19	406	402
20	407	406
21	404	402
22	407	404
23	407	406
24	407	405
25	407	404
26	407	405
27	406	405
28	403	400
29	407	405
30	406	404
31	406	405

Maximum and Minimum voltage in a day through the month of November /2018

Date (November /2018)	400kV bus bar Voltage in kV	
	max	min
1	406	405
2	407	405
3	406	405
4	403	402
5	407	405
6	407	406
7	407	405
8	407	405
9	406	405
10	407	405
11	403	402
12	407	405
13	407	405
14	407	402
15	406	402
16	407	405
17	406	405
18	404	402
19	406	405
20	406	405
21	406	405
22	406	402
23	406	405
24	406	405
25	403	401
26	406	404
27	407	405
28	406	405
29	406	404
30	407	405