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Intelligent Application of Flexible AC Transmission System Components in an Evolving Power Grid

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Intelligent Application of Flexible AC Transmission System Components in an Evolving Power Grid

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by

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ABSTRACT

The world revolves around energy and the energy sector is continually transforming and evolving. The status quo has been set by governing agencies in the United States for completely reliable power. The demand for energy efficiency continually rises for multiple reasons. Technology has improved for all sectors of the power grid, including renewable energy sources, fault protection, and SMART grid technology. The addition of new energy sources has led to the decommissioning of inefficient energy sources. The implementation of new technologies and power load on a large scale, coupled with the removal of grid stabilizers has posed different challenges that have been overcome using Flexible AC Transmission System devices or FACTS. FACTS devices increase power quality, reliability and efficiency of a power grid, if implemented correctly. With several different FACTS devices, the many power grid situations and FACTS combinations must be methodically tested and planned. ETAP and MATLAB/SIMULINK simulate designed power systems accurately with the additional functionality to model FACTS. The simulation of the IEEE nine bus model with potentially problematic variations applied show that FACTS components are required. The simulation show that the power factor and energy efficiency increased with FACTS. The avoidance of blackouts with fault recovery was made plausible, with less overshoot and quicker convergence time. Finally, combining FACTS can increase the revitalization of the power grid through the replacement of polluting generation to renewable generation.

ACKNOWLEDGEMENTS

I am very grateful to the University of Arkansas Electrical Engineering Graduate program. This thesis and course work has brought new energy and opportunities into my life. I would like to thank my professors and committee members who have helped me gain knowledge to solve larger problems.

I would specifically like to thank my family. My dad who taught me to work hard and my mother who always believed in me. This endeavor would not have been possible without the loving support, patience and encouragement from my wonderful wife. Thank you all.

TABLE OF CONTENTS

CHAPTER 1 – THESIS OVERVIEW

1.1   Motivation for This Study

In our modern society, lives revolve around power. Emerging technologies increase power consumption and energy dependence. The development of everything from electric vehicles to smart homes to massive data centers widens the spectrum of energy use. The urbanization of large cities and manufacturing demands have increased centralized load centers. At the same time, increased variability of power generation has been integrated into the power grid. These conditions combined increase the potential for power system problems. These problems range from momentary power interruptions, to incredible system damage and extended blackouts. With the high dependence on power, unreliable energy is not an option.

In addition to the customer driven demand for dependable energy, many national governments mandate specific energy reliability standards. In the United States, the standards are set by the North American Electrical Reliability Corporation or NERC. NERC provides additional guidance for standards in the bulk electric system for reliability and security [1]. NERC continually assess the requirements and constantly revises requirements for energy reliability. Any utility in the North America is required to follow these requirements, which is made more difficult as the power system transforms. NERC is governed by the Federal Energy Regulatory Commission or FERC. FERC is a federal entity that enforces the standards set by NERC. The maximum daily fine is $1,000,000 per offense per day [2]. This gives companies millions of reasons to ensure grid stability and reliability.

With the high monetary and customer demand in mind, it is crucial to identify solutions to maintain high reliability in the specific power system. Among many other solutions, one method to ensure grid reliability is through the planned installation of flexible alternating current

transmission systems or FACTS. FACTS is defined by IEEE as alternating current transmission systems incorporating power-electronics based and other static controllers to enhance control ability and power transfer ability [3]. As mentioned, the control ability enhancement provides greater system reliability through quick voltage regulation and dampening transient faults and other oscillations in the power system [4]. FACTS provide load flow control of the network surrounding the device. The transmission power transfer is also increased through the improved power factor of the line. FACTS devices need to be optimally installed and coordinated in a power system to deliver reliable, quality and economical power to all.

1.2 Purpose of This Study

The main objective within this research is to show by example the important role FACTS can have in the variety of different situations. A basic understanding of power transmission systems, load flow studies and transient analysis is expected background knowledge. The three specific objectives of this paper are outlined below:

- Identify several different industry used FACTS with their specific advantages and disadvantages. Identify the equations and software tools needed to correctly implement them into a power system.

- Identify locations/situations that could benefit from FACTS installation.

- Illustrate power and necessity of various FACTS combinations within specified situations.

1.3 Outline of This Study

The rest of this paper will be structured as described below:

- Chapter 2 provides a description of FACTS components. These sections describe typical physical layouts and applications, along with characteristic functionality. The relevant advantages and disadvantages are also discussed.

- Chapter 3 gives certain equations that will prove relevant background information for the results and conclusions made.

- Chapter 4 describes the power simulation software used in this thesis. The software advantages and disadvantages are discussed to give a background as to why these programs were chosen.

- Chapter 5 describes the various cases that will be examined. It gives the background information for these model variations and makes connections between what will be modeled and the real power systems situations.

- Chapter 6 provides the models, simulation results and analysis for the different cases provided in chapter 5. The models show which FACTS were selected and how the model was configured to result in the optimal solution.

- Chapter 7 provides conclusions made about the topics discussed in this paper. The best solution will be provided based on the simulation and other information from the paper. This chapter will also contain the future work that will be done regarding this topic.

CHAPTER 2 – FACTS DEVICES

2.1   Shunt Capacitor

The shunt capacitor one of the simplest applications of FACTS. The shunt capacitor is installed in parallel with the transmission line. The configuration can be in a delta, wye-grounded or a wye-ungrounded, depending on the protection application. Typically, several of these capacitors can be installed in together to form a capacitor bank, combining for a larger kVAR rating as shown in Fig. 2.1. The capacitor is typically installed on medium voltage lines and uses fuses, circuit switchers or circuit breakers as protection devices [5].
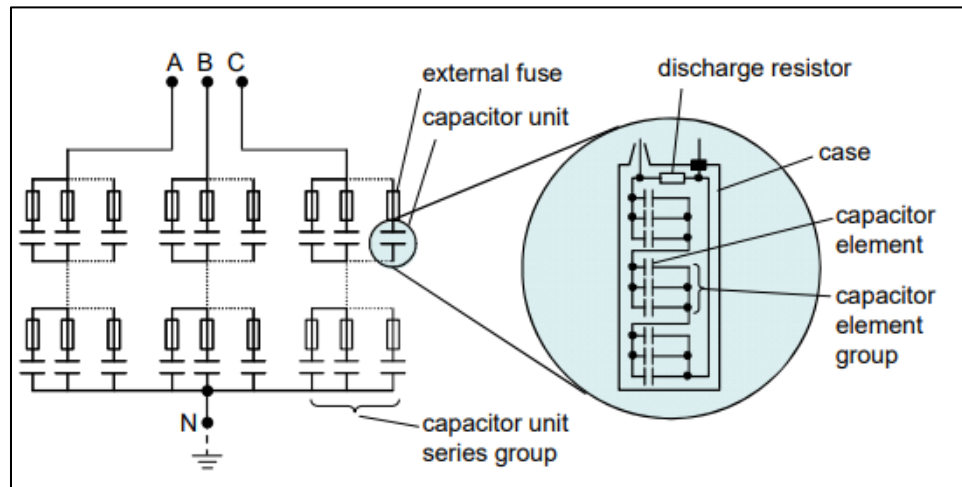
Fig. 2.1 Typical three phase capacitor bank layout [6].

The shunt capacitor could be installed for several reasons. The main purpose of a shunt capacitor is the power factor correction it provides. The reduction of reactive power transfer reduces the overall power loss and increases power transfer capability. This reduction aids in the voltage stability of an area. If there is a steady sag in the voltage, a capacitor can be installed to maintain a certain voltage level. The capacitor bank is also relatively inexpensive in comparison to other FACTS and easy to maintain. While there are several options that can vary cost significantly, Fig. 2.2 shows the dramatically reduced price of the capacitor application over other

FACTS. Fig. 2.2 will be used throughout the paper to determine cost efficiency of the implemented

FACTS.

FACTS Controllers	Cost (US $)
Shunt Capacitor	8/kVar
Series Capacitor	20/kVar
SVC	40/ kVar controlled portions
TCSC	40/ kVar controlled portions
STATCOM	50/ kVar
UPFC Series Portions	50/ kVar through power
UPFC Shunt Portions	50/ kVar controlled

Fig. 2.2 Cost comparison of various FACTS devices [7].

An important aspect to examine while planning the installation of a capacitor bank is the characteristic graph of the device. The diagram below shows the terminal characteristic of the shunt capacitor. It is linear with a slope equal to the admittance of the capacitor. This V-I terminal characteristic graph will be useful to compare the shunt capacitor to other types of more advanced FACTS.

Fig. 2.3 Shunt capacitor V-I terminal characteristic graph [7].

As aforementioned, there are many benefits and certain electrical locations to install a shunt capacitor bank. However, the simplicity of the capacitor banks limits its potential. The capacitor banks protection devices have a delayed response time to extend the life of the capacitor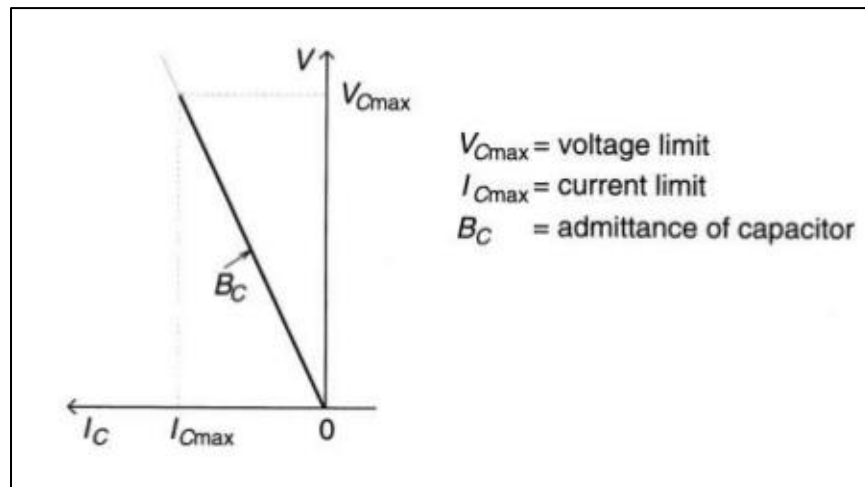s [8]. During the switching of capacitor banks with either circuit switchers or breakers, transients can take place of both high magnitude and frequency [9]. This can be mitigated, but typically the capacitor won't react to sub cycle or even several seconds of voltage fluctuations. This causes a larger problem with shunt capacitor installation for power stability. The reactive power delivered by the capacitor bank is proportional to the terminal voltage squared as seen. Therefore, as the voltage drops and reactive power is required to maintain a stable voltage, the reactive power drops at a squared rate of the voltage [10]. This exponential decay can cause a greater issue than benefit if not applied in a well-designed manner. The FACTS below boast a greater efficiency through either an independence from the system voltage or faster switching time to maintain better voltage stability.

2.2   Synchronous Condenser

A synchronous condenser can be used to provide or absorb reactive power from the network to which it is connected. The basic definition consists of a motor that doesn't provide any torque to move a load. A synchronous condenser is a generic name for several different application types. The motor can be a decommissioned generator that spins freely within its housing. Typically, special regulators and control devices must be installed to control variables which in turn control VAR output [11]. A hydropower generator can also be used to provide VARs to the system. Standalone synchronous condensers can also be installed. These condensers have self-cooling methods installed to increase efficiency, maximize capacity, and increase longevity of the condenser [12]. These are connected at various points on the grid that require voltage stability or

power factor correction. Applications can include at the receiving end of a long transmission line, near HVDC conversion sites to reduce harmonic effects, and in smaller industrial factories to provide vars and short circuit capacity for the motors [13].

The output of the VAR can be directly controlled by the motor field current [14]. Fig.2.4 shows the condenser's armature current (Ia) with respect to field excitation current (If). A synchronous condenser operates at near 0 pu real power. The stability limit is the lowest field excitation that will keep the motor spinning at the correct frequency. The normal excitation will result in a unity power factor, which is also a minimum for armature current. An under excited synchronous condenser will have a leading power factor and will absorb vars from the system [14].
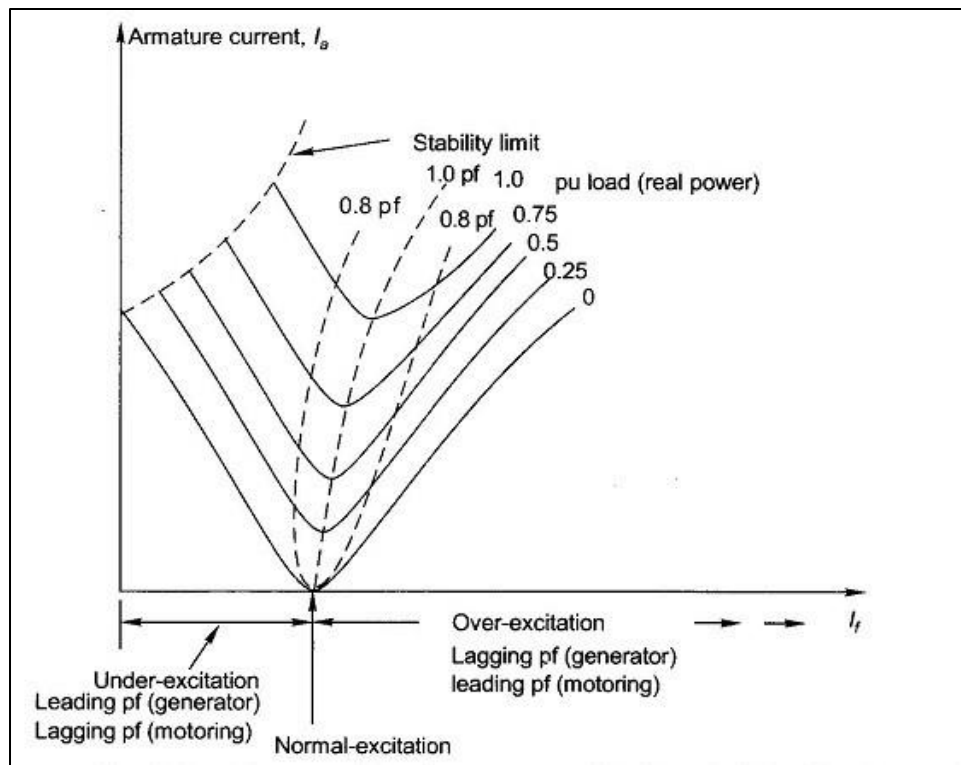

Fig. 2.4 Relationship between armature and field current in synchronous condenser [14].

With this background of synchronous condensers, advantages and disadvantages can be discussed. This device has a better response than fixed capacitors to harmonics and voltage stability. As the voltage drops on the system a capacitor bank voltage will also drop at an exponential rate, while voltage on a condenser can simply decrease current to maintain the constant voltage. Another benefit is the added stability. The condenser has real inertia, which can ride through variations such as harmonics, sudden increase or decrease in load and remote faults on the power system. The condenser can also act as a flywheel and absorb an excess or provide real power momentarily back onto the grid. The synchronous condenser, applied in an appropriate location, can benefit the overall grid.

While the synchronous condenser has many benefits, it also has many detriments. The first use of voltage regulation and stability through synchronous condensers was in the 1950's. Since then, the basic concept has remained the same, but the control sensitivity has drastically improved. However, even with drastic improvements, the reaction time can be up to 0.5 seconds or 30 cycles. During those 30 cycles, the factor which the condenser is trying to correct will exponentially decay, potentially past a critical point and beyond recovery for the simple synchronous condenser. Load curtailment, low power quality or even blackouts could occur because of this slow response time. The condenser is much less efficient than other FACTS as well. Generally, the synchronous condenser consumes approximately three percent of the real power provided [15]. This can be up to 20% less efficient than an SVC for real power consumed. This can amount to a substantial amount of lost energy and revenue [15]. In addition, using a hydro generator as a synchronous condenser can be harmful for the machine. The windings can have large physical stress placed upon them through harmonic periods. Based on the losses, poor response time and potential

damage to the generator units, a better option for power stability might be a SVC or STACOM device.

2.3   SVC Overview

There are many devices in the FACTS category. One of the capable technologies is the Static Var compensator. By definition, the SVC has no moving parts, unlike its predecessor the synchronous condenser. The SVC compensates for VAR unbalance on the power grid that it is connected to. The compensation provides voltage regulation and voltage stability for the surrounding network. The voltage regulation is the ability to maintain a set voltage, typically within ranges set by regulatory councils. Voltage stability is the ability to resist variation of voltage during a sudden change in load or a fault condition [7]. An SVC has the capability to compensate for both these conditions. In addition, an SVC can correct the power factor of the node to which it is connected. This can lead to increased efficiency of transmission lines and increase the capacity of the transmission line. The increased capacity can reduce the stress on the power grid and reduce the probability of rolling blackouts. The best method to understand how a SVC functions is by recognizing the different apparatus within a SVC and how each functions to contribute to the overall purpose.

2.3.1   Physical Layout

The SVC can be connected in many different configurations. A generic connection layout is outlined in Fig. 2.5 and Fig. 2.6.
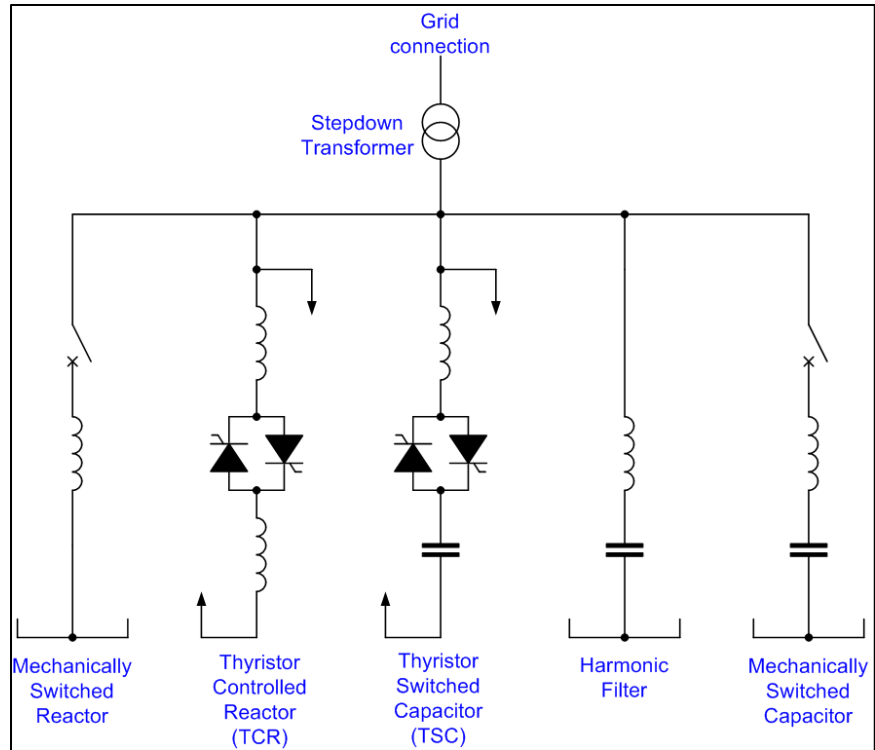
Fig. 2.5 One-line diagram of typical SVC [16].
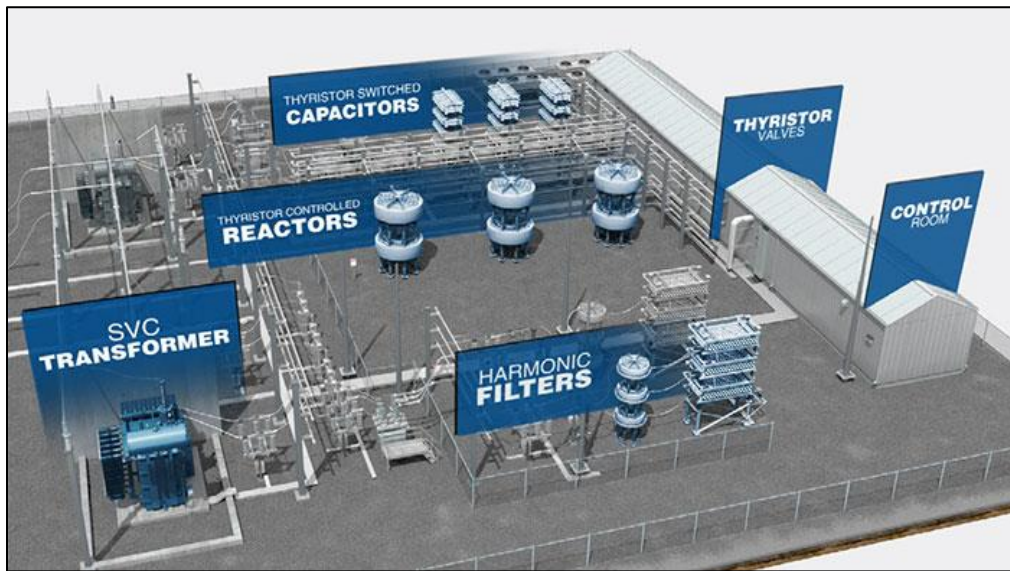
Fig. 2.6 Physical layout of SVC [17].

As shown in Fig. 2.6, the typical layout includes several different components to provide the desired functionality. The layout above includes a stepdown transformer, thyristor controller

10

reactor (TCR), thyristor switched capacitor (TSC), mechanical switched reactors and capacitors (MSR and MSC), harmonic filters, and thyristor valves in the control house. Each of these will be further discussed below.

The SVC can be connected to a high voltage bus or through a stepdown transformer. If installed, the stepdown transformer(s) then reduces the voltage to a manageable level for electrical clearance purposes. A unique configuration would be to install separate power transformers based on the harmonic that would pass through it instead of harmonic filters. For example, a configuration could have a 1st, 3rd, 5th and 7th harmonic power transformer to convert the voltage with elimination of those harmonics. This non-standard solution would cost much more than a more standard approach. A more common approach is a single power transformer with harmonic filters, with a similar capacity of the SVC. The filter's bandwidth would span the fifth, seventh and eleventh harmonics. The third and ninth harmonics are typically eliminated based on the delta connection of the compensation devices, shown in Fig. 2.7.
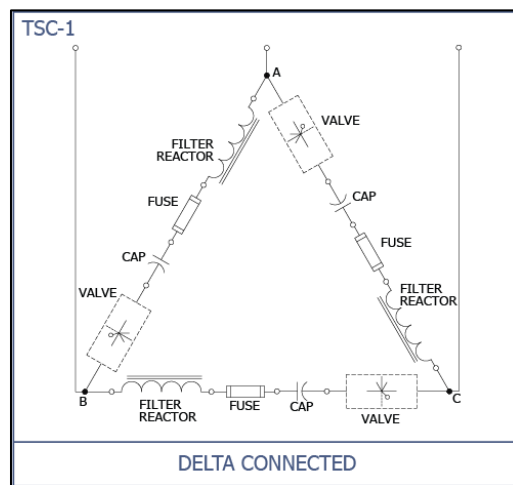
Fig. 2.7 Three phase connection diagram of a thyristor switched capacitor [18].

The high current secondary side of the transformer has special requirements as well. While the voltage is low enough to no require corona connections, the current requires unique bus

configurations. The unique configurations allow high ampacity flow and reduce deflection in the case of a short circuit. A solution for this is to install multiple conductors per phase to reduce load carried by any single conductor. This could be applied in two six-inch schedule 80 tubing per phase, transposed to maintain a balanced system.

The layout around the reactors must also be designed in a unique manner. The magnetic field created by the reactor could create a current and a change on anything that conducts electricity within its proximity. Therefore, the fence enclosing the TCRs should be of a non-metallic material [19]. The grounding for the reactor should also be separated from the overall ground grid of the SVC station. This would prevent unwanted loop currents and possible damage to the expensive equipment.

The control house holds the controls for the protection devices in the SVC station. It also houses the thyristors that control and switch the passive reactors and capacitors in the station. The thyristors have cooling pumps dedicated to keeping the thyristors within an optimal operating temperature range. These components function together to complete the designed purpose of the SVC.

2.3.2   SVC Main Components and Functionality

TSC – The TSC is a bank of thyristor switched capacitors. The capacitors are in series with bi-directional thyristor valves and dampening reactors. The thyristor capacitor series is connected in a delta configuration between the three phases.

TCR – The TCR is the reactor in series with a bidirectional thyristor switch. The thyristors alternate on half cycles, full ampacity at 90 degrees. The phases are also in a delta configuration to remove the triplen harmonics [20].

MSC/MCR – The MSC is a mechanically switched capacitor and the MCR is a mechanically controlled reactor. These may produce/absorb the constant bulk reactive power required from the SVC by the power system. Special breakers can be installed on the upstream side of these devices to avoid tripping due to switching transients [20].

The SVC must be able to reactor to the transients on the power system. Fig. 2.8 shows the IEEE defined parameters of 5% for the stabilization voltage range.
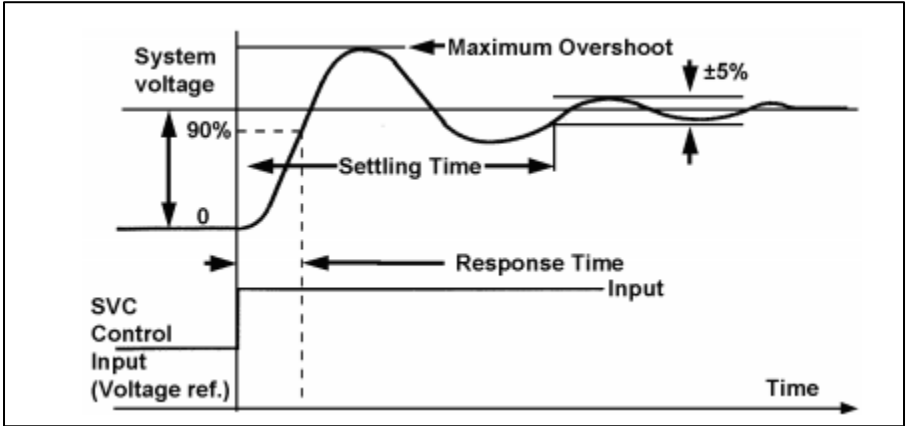
Fig. 2.8 IEEE definitions of response and settling time and stabilization voltage [21].

Similar to the shunt capacitor and synchronous condenser, the SVC also has a V-I characteristic graph. The SVC V-I terminal characteristic curve in Fig. 2.9.

13
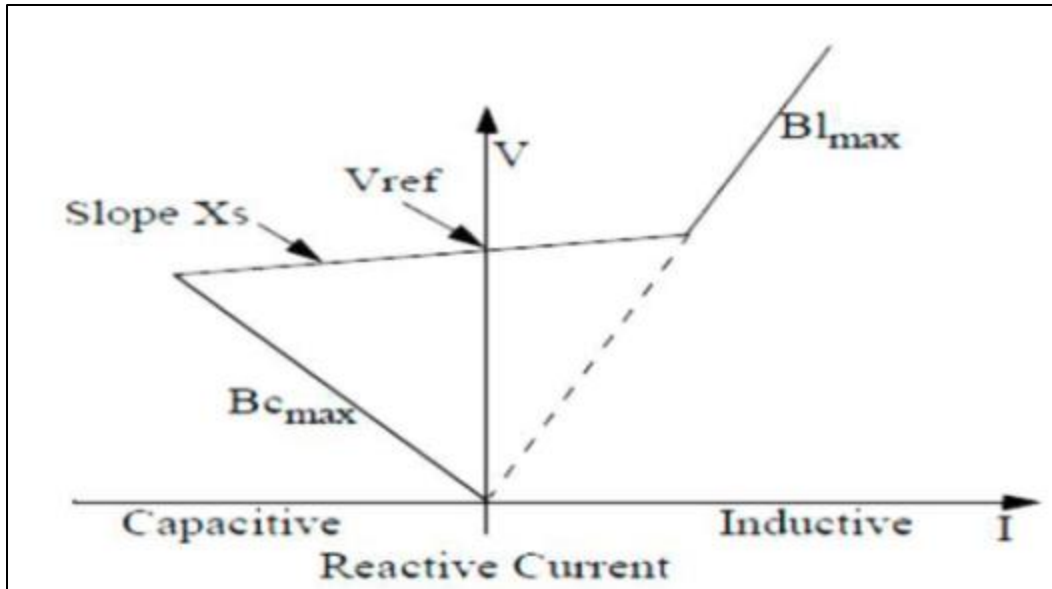
Fig. 2.9 STATCOM V-I terminal characteristic graph [22].

This characteristic curve shows the inductive and capacitive performance of the SVC. The capacitive portion is identical to the shunt capacitor, because at a certain low voltage, the SVC will simply act as a capacitor. The same is true for an overvoltage and an inductor. The center area with the slope of the droop reactance, X_S, is the voltage regulating mode. In this area, the susceptance is required to be within the maximum and minimum values to regulate the voltage to V_{ref} [22]. This characteristic graph will also be compared to the V-I graph of the STATCOM in section 2.4.3.

2.4   STATCOM

One of the most versatile and powerful FACTS is the Static Synchronous Compensator (STATCOM). This device, like the SVC has no moving parts, but can provide dynamic reactive power in adverse power network conditions. The synchronous compensation is provided through the device to absorb or provide reactive power. This system can be extremely beneficial where grid stability or reliability is a concern. The reactive power from the STATCOM can provide balance for the continuously variable transmission load. While the STATCOM's main purpose is to provide balancing power to the grid, it can also provide many other features. It can provide real

power for short durations of time. It can correct power factor; reducing the costly transmission of reactive power to the load center and increasing the overall capacity of the transmission line. These benefits stem from the effective installation of the developing STATCOM technology [23].

2.4.1 STATCOM: Emerging Technology

STATCOM is a proven and yet continuously improving technology. The components and technologies for STATCOM have been used for several decades. The STATCOM functions based on voltage source converter principles. Pulse width modulation is used to control the switch device on and off to convert DC to AC synchronous power as shown in Fig. 2.10.
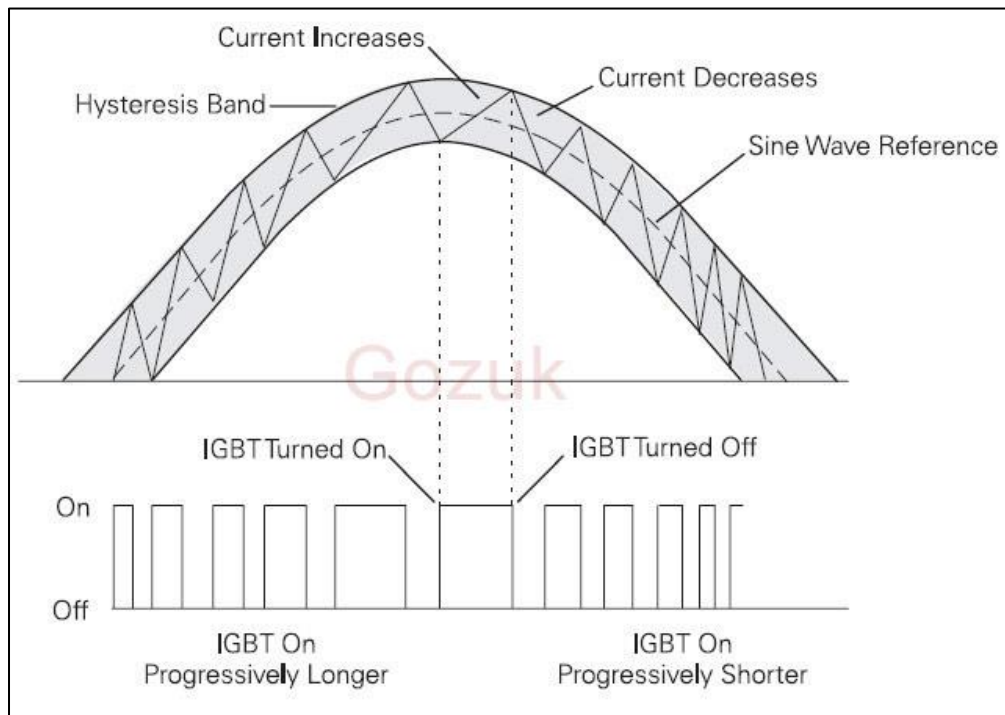
Fig. 2.10 Example of sine wave manipulation with IGBT technology [24].

Early forms of power conversion utilized mercury arc valves to rectify AC into DC. Thyristor valves quickly replaced the mercury-based devices because of higher reliability and lower cost [25]. The thyristors valves are used in the SVC. The Gate Turn-Off Thyristor was then implemented into pulse width modulation or PWM [26]. The technology was further developed

for the power industry. Today, PWM can control different devices used in STATCOM including Integrated Gate Commutated Thyristor (IGCT) and Integrated Gate Bipolar Transistor (IGBT). These devices can reach high power limits. The initial IGCT based STATCOM reached a power rating 10MVA. Currently, a STATCOM is being built by Siemens to provide a dynamic range of 2000 MVAR with an additional 1250MVAR mechanically switched reactive components [26]. Modularization has been critical to develop STATCOM into higher power and voltage solutions. These advanced switching devices minimize or eliminate the need for harmonic filtering because of the speed of the switching device [27].

2.4.2 STATCOM Circuit

As mentioned, there are several devices that can be used for the switching in a STATCOM station. The surrounding circuit is shown in the following block diagram.
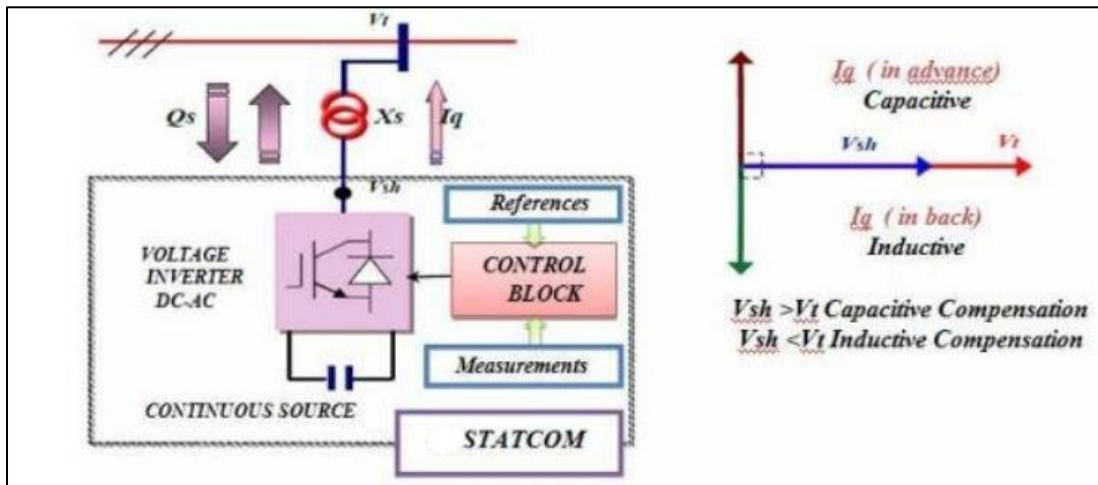
Fig. 2.11 Block diagram of STATCOM device [28].

The STATCOM typically connects to the transmission gird via a coupling or stepdown transformer. The transformer connects via high ampacity bus to the STATCOM. The STATCOM control house contains the power transistors, the continuous voltage sources and the intelligence for controlling the transistors. Typical voltage sources can include capacitors, or batteries

16

depending on the application. A battery storage system can be beneficial to transmit real power back onto the grid. Another continuous voltage source that has been used are multiple flywheels [29]. At times it may be necessary to install a smoothing reactor to minimize the harmonic content in the voltage.

2.4.3 Functionality

The STATCOM shown in Fig. 2.11 controls the current magnitude and angle from the DC source to the grid. The switches turn on and off to create an AC current. The control can be seen in the graph of Fig. 2.10. The angle of the current is a function of the ratio of the transmission line voltage to the STATCOM voltage. If the voltage on the transmission line (Vt) is less than the output voltage of the STATCOM bus(Vsh), the current Iq will lead Vt by 90 degrees. The current will lag Vt if Vt is greater than Vsh. The power delivered by the STATCOM is also a function of the difference between Vsh and Vt [28]. The equations for the power transfer can be seen below.

$$(2.1)$$

$$P(\delta) = \frac{V_t V_{sh}}{X_s} \delta$$

$$Q(V_{st}) = \frac{V_t(V_t - V_{sh})}{X_s} \qquad (2.2)$$

where real power is P, reactive power is Q, transformer inductance is Xs, and the power angle between Vt and Vsh is δ. Real power is a function of the phase shift between the two voltages. The δ is typically small and can be neglected in the reactive power transfer equation. As explained previously, the reactive power transfer is a function of the voltage difference between Vt and Vsh over the transformer inductance. The graph below shows the characteristic voltage to current relationship the STATCOM.
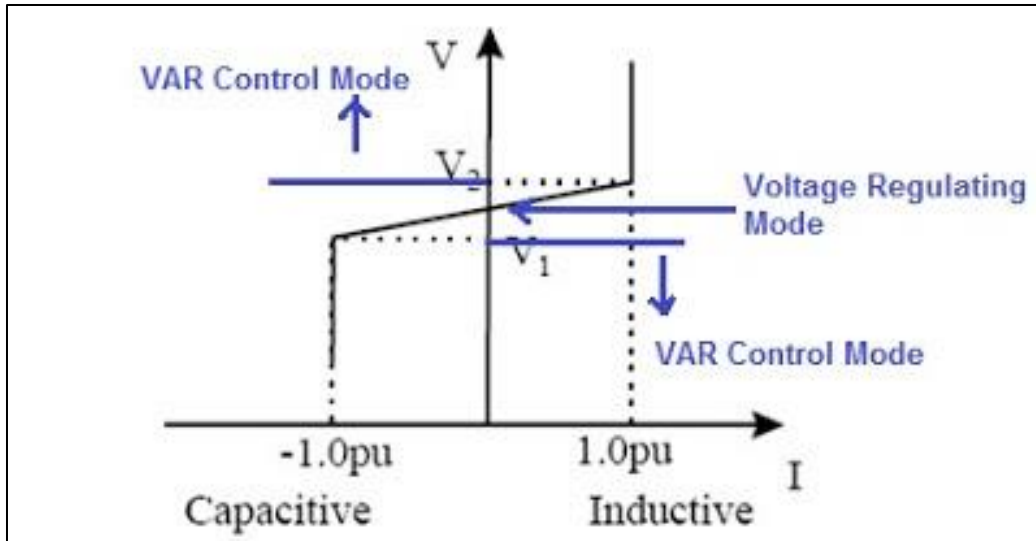
Fig. 2.12 STATCOM V-I terminal characteristic graph [30].

This graph adequately explains the inductive and capacitive zones of operation of the STACOM. As mentioned earlier, the STATCOM will have a leading current if the transmission line voltage is greater than the STATCOM voltage. STACOM functions in two different modes; voltage regulating and VAR control mode. The voltage control mode allows the STATCOM to supply or absorb reactive power to keep the transmission voltage at a specified reference voltage. This is within the range of the minimum and maximum susceptance of the STATCOM, which is referenced at -1.0 and 1.0 pu current. The maximum susceptance is referenced at the minimum current. After the current reaches this point, it operates in the VAR control mode. The VAR control mode doesn't fluctuate the current, but rather acts as a constant inductive or capacitive device [30].

2.4.4   Advantages and Disadvantages of STATCOM

The background information above allows decisions to be made about how and where it might be advantageous to install a static synchronous compensator. The characteristics of rapid VAR control make it superior over most other FACTS applications. The reaction time can be four times quicker than SVC and as great as ten times faster than a motor as a synchronous condenser

18

[31]. The dynamic response makes it more appealing than a simple shunt capacitor for power factor correction. The maintenance time is extremely low, with some estimates as low as around 1-3 man hours a year [23]. Improved STATCOM technology has become modular, and at times can be relocated as necessary. This can be beneficial if parameters change in the surrounding area. The STATCOM might be able to operate without harmonic filters and it is therefore able to mitigate unbalance in the grid. The power source for the STATCOM is also independent of the voltage of the transmission bus. This means that the STATCOM can function at full capacity (to a certain degree) even with the decrease in system voltage.

While the advantages are impressive, there are drawbacks that limit the rollout of this technology. The primary hesitation is the current cost per kvar is expensive. This is relative to the cost of synchronous condensers and SVC technology. The perspective that is important when determining whether to install STATCOM is the return on investment. If the voltage reliability is an issue; outages, FERC penalties and lost revenue will make the investment worth the investment. Another disadvantage of STATCOM is a higher real power consumption than other FACTS types [23].

CHAPTER 3 - POWER SYSTEMS ANALYSIS

The previous chapter gives a description of some of the widely used FACTS devices. This chapter will present and discuss various equations. These equations will be explained to show the relevancy and connection with the simulations preformed.

Equations 3.1 and 3.2 show general power equations for the load flow simulations. The relationship between the real power, reactive power and apparent power is defined below:

$$S = P + jQ \tag{3.1}$$

$$S = VI^* = VI\cos(\delta - \beta) + jVI\sin(\delta - \beta) \tag{3.2}$$

Where (δ - β) is the angle between voltage and current [32].

A heavily discussed topic in the paper is the power factor. The equation below gives the relationship between the real and apparent power or the difference in the angle between the voltage and current.

$$Power\ Factor = \frac{P}{S} = \cos(\delta - \beta) \tag{3.3}$$

In the following section, imaginary power equations will be defined. These equations are the basis for the FACTS devices functionality.

$$Q = \sqrt{S^2 - P^2} \tag{3.4}$$

$$X_c = \frac{V^2}{Q} = 2\pi f_c C V^2 \tag{3.5}$$

$$C = \frac{Q}{2\pi f_c V^2} \tag{3.6}$$

$$X_L = 2\pi f L \tag{3.7}$$

The transmission line model for this system will be done as medium length lines. The equations below explain the parameters and method to calculate the sending and receiving voltage and current. This medium line approximation is also used through the software to find the voltage drop and power lost through the line [32]. The KVL and KCL equations are shown in equations 3.8 and 3.9. The equations are combined in equation 3.10 and written in matrix format in equation 3.11.

$$V_S = V_R + Z\left(I_R + \frac{V_R Y}{2}\right)$$
$$= \left(1 + \frac{YZ}{2}\right) V_R + Z \tag{3.8}$$

$$I_S = I_R + \frac{V_R Y}{2} + \frac{V_S Y}{2} \tag{3.9}$$

$$I_S = I_R + \frac{V_R Y}{2} + \left((1 + \frac{YZ}{2})V_R + ZI_R\right)\frac{Y}{2}$$
$$= Y\left(1 + \frac{YZ}{4}\right) V_R + \left(1 + \frac{YZ}{2}\right) I_R \tag{3.10}$$

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} (1 + \frac{YZ}{2}) & Z \\ Y(1 + \frac{YZ}{4}) & Y(1 + \frac{YZ}{2}) \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix} \tag{3.11}$$

Where V_R and I_R are receiving end voltage and current, Vs and Is are sending end voltage and current, Z is total series impedance, and Y is total shunt admittance. With four of these known parameters, the remaining two can be derived and solved.

21

As shown above in the specific transmission line loss equation, the general equation for power loss is shown below.

$$S = I^2 Z \tag{3.12}$$

$$S = I_{real}{}^2 R + I_{imaginary}{}^2 X \tag{3.13}$$

As can be seen the resistance and reactance or inductance will remain constant because there will be no change in the transmission lines during these case studies. Variables that would affect that quantity is conductor size and type, cable arrangement, etc. It follows that the more current flowing through the line, the greater the apparent power line loss will be. The real power will remain constant at the loads as well. The reactive power can be compensated by different FACTS at the load. The reactive power compensation reduces the power lost over the transmission lines and therefor requires less power to be generated. This is typically why FACTS would be installed near load centers.

CHAPTER 4 - SIMULATION SOFTWARE

There are many power simulation programs with the capability to perform different case studies. Two of these programs with high functionality, and user-friendly interfaces are ETAP and MATLAB Simulink. These two programs can simulate the cases required to complete the research in this paper.

4.1   ETAP

ETAP is a modeling software with a wide variety of applications. The applications span from nuclear generation to distribution and microgrids. Within those sectors, it can perform harmonics, load allocation, load flow, arc flash, transients, data exchange, ground systems and much more [33]. The software provides hundreds of example models for different power components and provides typical manufacturer data for most of these components. This is extremely useful when dealing with standard equipment such as generators, transformers, power line cable, shunt capacitors and Static Var Compensators. These models have been proven accurate against published cases in books and scholarly articles. ETAP provides several examples of standard bus configurations. A simple to use bus configuration is the IEEE 9 bus standard model. This model has been validated to calculated models and will be the basis of the cases presented below in this paper.

The ETAP software simplifies the addition of components to the single line diagram. The parameters can be modified to meet design requirements. Even when shown on the single line diagram, the devices can be toggled in and out of service. This allows quick simulation of the model without redesign. The two simulation tools that will be used in this study are the power load flow and transient analysis. The power load flow analysis balances the generation with the connected load accounting for the power lines losses. This presents useful information including

magnitude and direction of real and imaginary power flow as well as per unit bus voltages. The per unit bus voltage will be used as the key indicator for the health of the power grid. The transient stability analysis allows fault simulations at different points on the single line. The timing can be matched to faults that have occurred and mitigated through line protection tripping circuit breakers to clear the fault.

One of the drawbacks to ETAP is there isn't a defined STATCOM device. STATCOM is a growing technology and will have a developed component eventually in ETAP. In the meantime, an option to create a User Defined Module (UDM) allows the creation and implementation of this device. The process utilizes transfer functions and operators to compile this device. This process was researched, and attempts were made to implement simple models. However, this was not the intent of this thesis and another software was used to simulate the STATCOM device within the power system.

4.2   MATLAB Simulink

MATLAB Simulink has numerous capabilities and several similarities to ETAP. It is sufficient to state that it also simulates load flows and transient analysis. The transient analysis and specifically per unit bus voltage will be the key indicator for the implementation of the STATCOM combinations into the model. The IEEE 9 bus model will also be the base scenario with modifications made to improve the voltage stability of several cases.

CHAPTER 5 - SIMULATED VARIATIONS

In this chapter, the various scenarios of the implementation of FACTS into power systems will be discussed. Using the IEEE 9 bus model as the base scenario, three variations will be explored. These variations will pose different problems for the overall power system. The main purpose of these variations will be to find effective mitigation strategies to keep the bus per unit voltage within five percent of the nominal voltage. This is an especially important factor at load buses. Therefore, this will be the main design parameter for the solution of these models.

5.1   Variation #1

The first variation will simulate something that is happening around the world in the power industry. In the United States, approximately 80% of the nation's population lives in urban areas. The urbanization will continue in the coming years. Forecasts project urban areas to increase by about 7% over the next twenty years [34]. This will result in tens of millions of people relocating to urban areas. The urbanization will increase the load at different areas of the power system. Therefore, the first variation to the IEEE 9 bus model is a load added to bus number five. This additional load will influence the overall power system.

5.2   Variation #2

Another situation that occurs often in real power systems is system faults. System faults can be caused from many different sources and can have varying impacts depending on the type and location. This case will use a line to ground fault on line number five. The fault will last for 13 cycles and be cleared with breakers at either side of the line. Due to the lack of redundancy within this model, a fault on this line will cause instability, regardless of the protection schemes and mitigation designed. Therefore, an additional line will be added to connect bus eight to bus

nine. This will prevent cyclical power transfer throughout the system. The line fault however will still need to be mitigated through addition of different types of FACTS [35].

5.3   Variation #3

The final variation to the IEEE 9 bus model will simulate another situation that continually happens the real power system. In the past few years, more renewable energy resources have come online. The cheap price of natural gas has increased the dependence on that source of energy as well. With new energy sources going in service, large. old coal plants are beginning to be decommissioned. The decommission of large coal generation plants has a large impact on the surrounding power grid. In Las Vegas, Nevada, for example, much of the coal generation is being replaced by an abundance of solar generation [36]. ETAP has the capability to model the specific case of replacing the spinning generator with real inertia with a solar source. However, in this example, the variation will simply remove the VAR support that would be provided from large spinning generation. The removal of VAR support will need to be mitigated through FACTS.

Within these variations, different combinations of FACTS devices will be located at strategic points throughout the model. Below, the implementation of these variations will be explained, and the results will be analyzed.

CHAPTER 6 - SIMULATED SCENARIOS DESIGN AND RESULT ANALYSIS

In this chapter, the bus model designs will be explained and the results from the power load flow and transient analysis will be examined. The scenarios will be organized in the following manner:

Results from ETAP without variations applied

- Base IEEE 9 bus model

Results from ETAP with both variations one and two applied

- Additional load on the IEEE 9 bus model

- Additional load on the IEEE 9 bus model with a shunt capacitor

- Additional load on the IEEE 9 bus model with a Static Var Compensator

- Additional load on the IEEE 9 bus model with a Shunt capacitor and SVC

Results from ETAP with variation three applied

- Decommissioned generation on the IEEE 9 bus model

- Decommissioned generation on the IEEE 9 bus model with a Shunt capacitor and SVC

Results from MATLAB Simulink with both variations one and two applied

- Base IEEE 9 bus model with STATCOM implemented

- Additional load on IEEE 9 bus model with STATCOM implemented

6.1   Base IEEE Model

This base model is one of the standard example models given by ETAP. The IEEE 9 bus standard model contains all the components for a functioning power system. The three generators are connected to individual buses. As required for an isolated power system, generator one is the swing generator. For load flow studies, a swing generator will take up the slack of the power flows

in the system, i.e., the voltage magnitude and angle of the generator terminals will remain at the specified operating values [37]. This generator will adjust the real and imaginary power production to meet the needs of the power system. Generators two and three are voltage-controlled generators. A generator can be selected as a voltage control (regulated) system, which means that the generator will adjust its var output to control the voltage. Therefore, the generator's terminal voltage magnitude, operating real power (MW), and minimum and maximum allowable reactive power supply (Max Q and Min Q) must be entered for voltage control generators. A voltage control generator means that the generator is base loaded (droop mode with fixed MW) with an Automatic Voltage Regulator (AVR) controlling the field excitation for a constant voltage operation [37]. The voltage of the generators is between 13.8kv and 18kv, depending on the generator. The low voltage buses from the generators are connected to generator step-up transformers, to connect into the 230KV system. The loads are connected to individual buses and power lines are modeled between the GSU high side bus and the load buses. Circuit breakers are placed anywhere where protection is required; specifically, at all the bus connections, with exception to the loads. ETAP has the capability to add protection schemes, i.e. differential relay (87) and line distance relay (21). However, these schemes were not within the scope of this study and were not implemented into the one-line diagram. Fig. 6.1 shows the base IEEE 9 bus. The one-line shows the labels of all the components. Fig 6.1 was taken from the load flow solution of the model. The blue percentages show the per unit voltages of the buses. The blue numbers adjacent to the lines indicate the real and imaginary flow of power at that node.
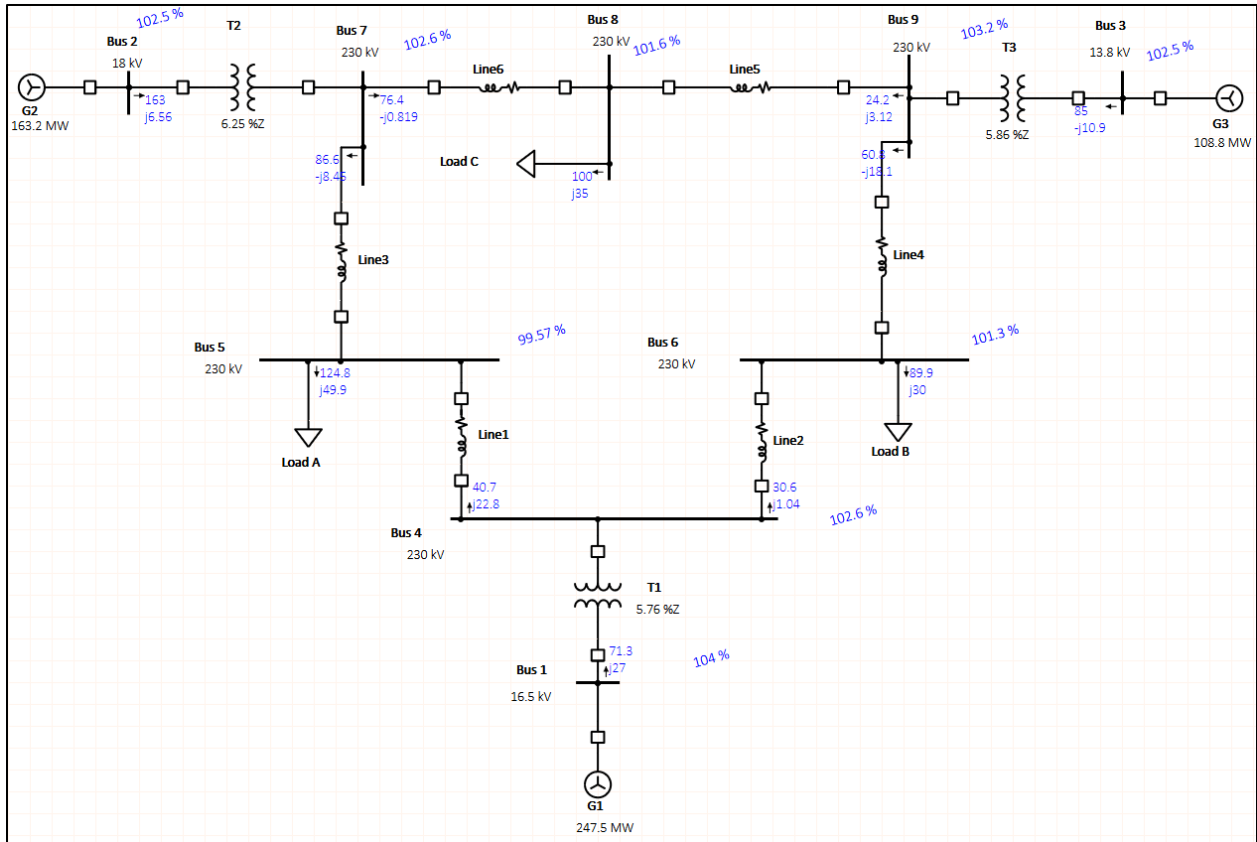
Fig. 6.1 Base IEEE 9 bus model one-line diagram with load flow results.

6.1.1 Load Flow Analysis

The load flow above shows the voltage magnitude to be within the acceptable 5% range. The load buses are the most crucial to be within that range. Table 6.1 shows the results for different variables, organized by bus number. As a note, the MW and MVAR columns directly to the right of the power angle column represent the generation power. The MW and MVAR to the left of the empty column represent the load power on that bus. On the right of the tenth column, the information for each bus connection is shown. For example, Bus 4 in the first column is connected to both Bus 5 and Bus 6. The information of power, current and PF are shown, from Bus 4 to those two buses. It should be noted that there is a power loss between Bus 4 and Bus 5. Therefore, the magnitude of power sent from Bus 4 is greater than the power received by Bus 5.

Table 6.1 Base IEEE 9 bus model load flow study results.

BUS ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar		BUS ID	MW	Mvar	Amp	%PF
Bus 1	16.500	104.000	0.0	71.337	26.963	0.000	0.000		Bus 4	71.337	26.963	2565.9	93.5
Bus 2	18.000	102.500	9.3	163.000	6.562	0.000	0.000		Bus 7	163.000	6.562	5104.8	99.9
Bus 3	13.800	102.500	4.7	85.000	-10.885	0.000	0.000		Bus 9	85.000	-10.885	3497.7	-99.2
Bus 4	230.000	102.579	-2.2	0.000	0.000	0.000	0.000		Bus 5	40.716	22.829	114.2	87.2
									Bus 6	30.618	1.037	75.0	99.9
									Bus 1	-71.334	-23.866	184.1	94.8
Bus 5	230.000	99.570	-4.0	0.000	0.000	124.761	49.895		Bus 4	-40.460	-38.642	141.1	72.3
									Bus 7	-84.301	-11.253	214.4	99.1
Bus 6	230.000	101.266	-3.7	0.000	0.000	89.939	29.980		Bus 4	-30.453	-16.556	85.9	87.9
									Bus 9	-59.487	-13.424	151.2	97.5
Bus 7	230.000	102.573	3.7	0.000	0.000	0.000	0.000		Bus 5	86.600	-8.450	212.9	-99.5
									Bus 8	76.384	-0.819	186.9	100.0
									Bus 2	-162.984	9.269	399.5	-99.8
Bus 8	230.000	101.585	0.7	0.000	0.000	99.975	34.977		Bus 9	-24.066	-24.295	84.5	70.4
									Bus 7	-75.909	-10.683	189.4	99.0
Bus 9	230.000	103.232	2.0	0.000	0.000	0.000	0.000		Bus 6	60.842	-18.099	154.4	-95.8
									Bus 8	24.154	3.117	59.2	99.2
									Bus 3	-84.996	14.981	209.9	-98.5

The line parameters are shown in Fig. 6.2 to illustrate the cause of the power loss.

Fig. 6.2 Impedance per phase of the line between Bus 4 and Bus 5

The results in Table 6.1 have several important indicators. The per unit voltage is set to 1.04 for Bus 1 and 1.025 for Bus 2 and Bus 3. This overvoltage forces the imaginary power to the lower voltage of the load buses. The reference angle is set as generator one as zero. The real power flow direction will flow from the high to lower voltage angle. The load bus voltages for buses 5, 6, and 8 are all within 1.5% of the per unit value. The transfer of imaginary power is also relatively low, which reduces the power loss within the system.

6.1.2   Transient Analysis

The transient analysis functionality allows a user to program and model different events with in the power system. Among many things, a few options are to cause faults on power lines and buses, as well as opening circuit breakers. In order to examine the strength of the power system, a fault would be applied and cleared. Within this analysis, it is important to assign realistic settings to the fault. The first option is whether to apply a bus or line faults. Three phase bus faults typically have larger fault currents; especially buses near sources [38]. Three phase bus faults are also among the most infrequent. The most frequent source of a fault is a single phase to ground fault on a power line [38]. A line was chosen that was not adjacent to the location of additional load and the installation of the FACTS devices. Line 5 was chosen as it has load connected to it and connects to the high side bus of GSU 3. The events of the fault are as follows for all the different cases:

- The system initializes at goes to a steady state.

- At 0.2 seconds a line to ground fault is applied to the system.

- At 0.416 seconds the line circuit breakers are opened. This clears the fault on the line and the system begins to reach its new equilibrium level. The total fault time of 0.216 seconds is based on relay overcurrent settings, communication time, and breaker opening time.

With the initial testing, the power flow was cyclical, due to the limited paths the power could take to match the load requirements. In a realistic power grid system, there are multiple paths for power to flow to read the load. Therefore, to simplify the analysis, a copy of Line 5 was added as Line 11 with the same parameters and connection buses. This mitigated the cyclical load flow and the solution was able to converge.

Fig. 6.3 shows the voltage of the load buses 5, 6 and 8. The units are in per unit voltage over time. The yellow line is the nominal 1.0 per unit voltage of the buses, or 230kv.

31
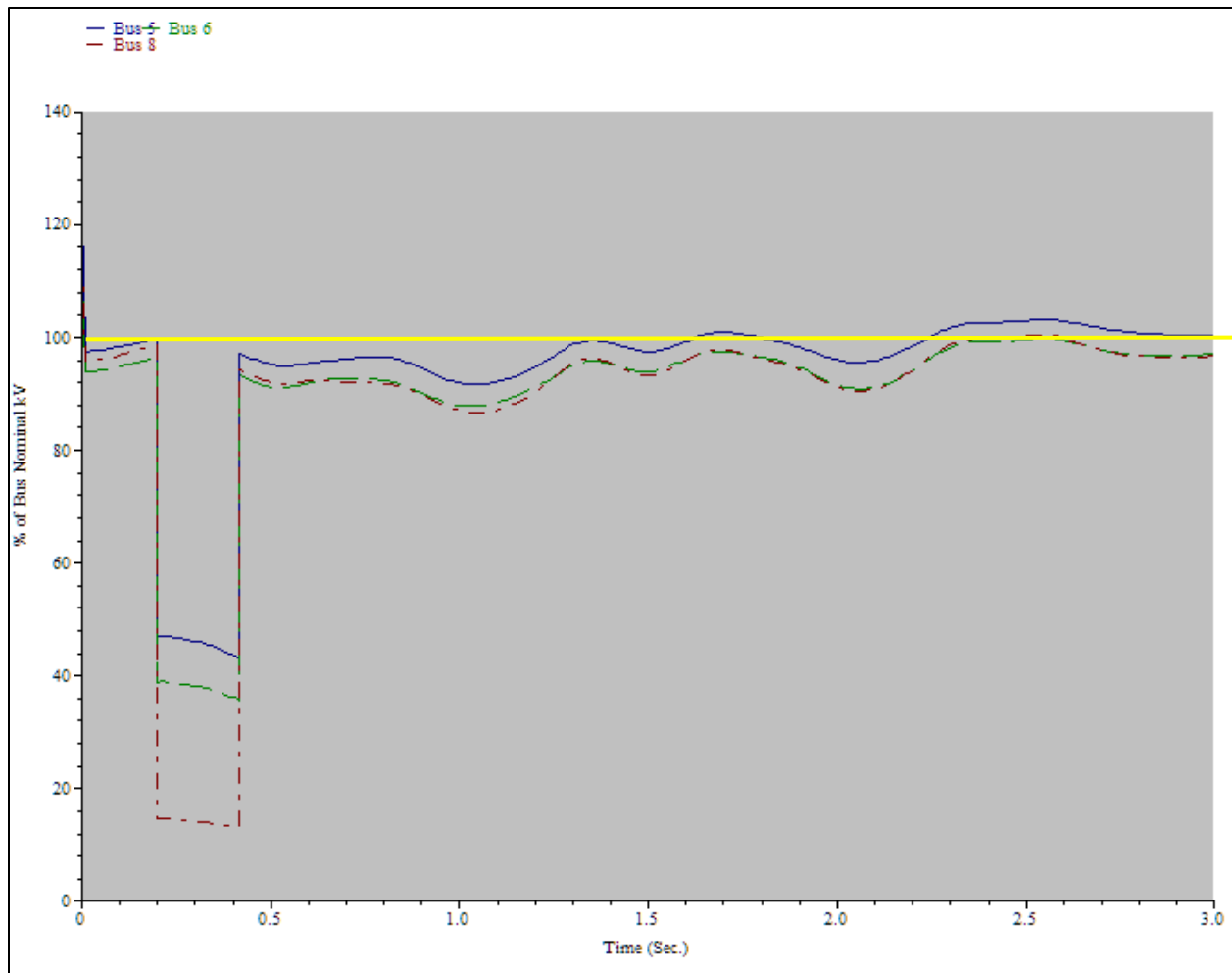
Fig. 6.3 Base IEEE 9 bus model load bus voltages during a fault on Line 5.

There are several items to be recognized and analyzed in Fig. 6.3. The first point is the initial spike in the voltage can be seen for approximately two cycles. This spike is caused by the software model initializing and then converging to a steady state. The instantaneous voltage drop can be seen at 0.2 seconds when the fault occurs. It should be noted that it affects all the buses with different severity. The proximity of the bus to the fault affects the reduction in voltage due to the high fault current. Bus 8 drops to the lowest voltage of about 0.15 p.u. The voltage continues to drop through the fault for 0.216 seconds. After the fault is cleared, the voltage immediately rises to near pre-fault conditions. The system then fluctuates for another 2.5 seconds before normalizing

at about 1.0 p.u. It is important to note that there are no large voltage swings post fault and the voltage recovers to an acceptable range.

6.2   Extra Load Simulation

As described in the various scenarios, additional load is continually being added to the existing power system. The added load is rated at 80 MW real power with 60 MVAR imaginary power. This creates a total load on Bus 5 at 205 MW and 110 MVAR. This is a significant increase in load at this bus. The purpose of such a large increase is to demonstrate what can be accomplished with the proper implementation of FACTS devices.

In Fig. 6.4 the one-line area surrounding Bus 5 is shown. This is taken from the load flow study as it presents the FACTS device and load flow information. The additional load A2 can be seen connected to Bus 5. Additional components can be seen but are commented out as they are not "In-Service" for this case.
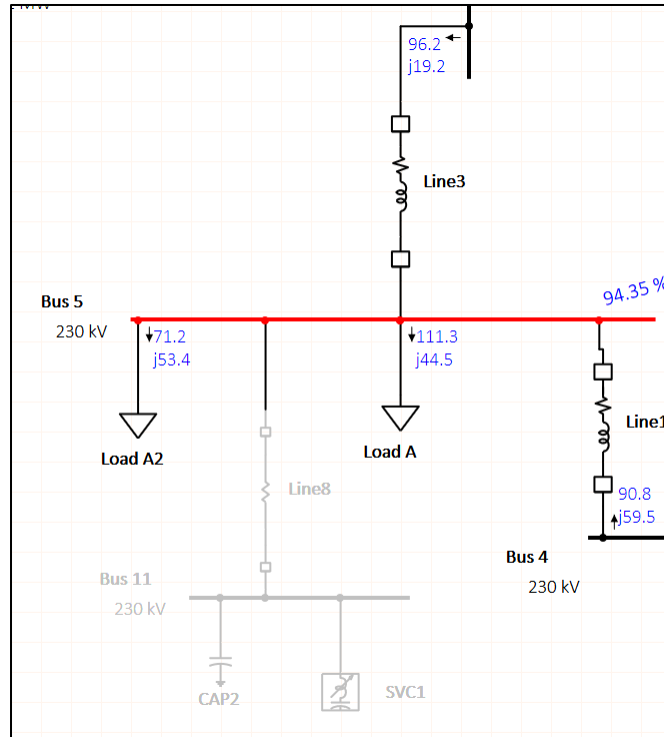
Fig. 6.4 One-line diagram of added load on Bus 5 with load flow results.

6.2.1 Load Flow Analysis

The one-line load flow in Fig 6.4 shows the bus voltage to be out of the nominal 5% range. It can also be seen that there is a mismatch between the required power and the power available for the loads. The swing generator (G1) will generate more real and imaginary power up to increase the voltage to the nominal 1.0 p.u. at all buses. The voltage-controlled generators will also increase their available imaginary power production to maintain adequate voltage at all buses. The limiting factor is the increased voltage drop over the lines and through the transformers, due to the increased current requirement. Table 6.2 shows the results of the added load on Bus 5.

Table 6.2 Additional load on Bus 5 load flow study results.

BUS ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar		BUS ID	MW	Mvar	Amp	%PF
Bus 1	16.500	104.000	0.0	129.568	62.857	0.000	0.000		Bus 4	129.568	62.857	4845.2	90.0
Bus 2	18.000	102.500	5.9	163.000	18.341	0.000	0.000		Bus 7	163.000	18.341	5132.9	99.4
Bus 3	13.800	102.500	1.2	85.000	-9.724	0.000	0.000		Bus 9	85.000	-9.724	3492.0	-99.4
Bus 4	230.000	100.767	-4.1	0.000	0.000	0.000	0.000		Bus 5	90.795	59.529	270.5	83.6
									Bus 6	38.761	-7.717	98.5	-98.1
									Bus 1	-129.557	-51.812	347.6	92.9
Bus 5	230.000	94.349	-8.3	0.000	0.000	182.485	97.911		Bus 4	-89.522	-65.473	295.1	80.7
									Bus 7	-92.963	-32.438	262.0	94.4
Bus 6	230.000	100.148	-6.1	0.000	0.000	87.964	29.321		Bus 4	-38.510	-6.868	98.0	98.4
									Bus 9	-49.454	-22.453	136.1	91.1
Bus 7	230.000	101.858	0.3	0.000	0.000	0.000	0.000		Bus 5	96.197	19.213	241.8	98.1
									Bus 8	66.787	-16.877	169.8	-97.0
									Bus 2	-162.984	-2.336	401.7	100.0
Bus 8	230.000	102.060	-2.4	0.000	0.000	100.911	35.305		Bus 9	-17.248	-19.922	64.8	65.5
									Bus 7	-66.415	4.539	163.7	-99.8
									Bus 9	-17.248	-19.922	64.8	65.5
Bus 9	230.000	103.166	-1.5	0.000	0.000	0.000	0.000		Bus 6	50.413	-10.369	125.2	-97.9
									Bus 8	17.291	-1.719	42.3	-99.5
									Bus 8	17.291	-1.719	42.3	-99.5
									Bus 3	-84.996	13.807	209.5	-98.7

As can be seen in Table 6.2, the voltage dropped to 94.349% on Bus 5. There is also an increase in voltage lag from the original model, from -4 to -8.3 degrees. There was also an increase in real and imaginary power produced by G1 of 58.26 MW and 35.89 MVAR due to the added load. It is clear from Table 6.2 though that the other two load buses, Bus 7 and Bus 8, didn't have a large variation to the bus voltage magnitude. However, due to the larger amount of real power flow, the voltage angle decreases at both buses. The overall power loss is greater as well for the system. The current loss over Line 1 and Line 3 is 44.82A. This is an increase of 16.52A over the base case. The actual power loss across just those two lines due to the increased load is 3.8 MVA. This non-billable additional load could cost up to $10,000 a day without accounting for the increased losses on the other lines in the system. A solution will be discussed in the next case model.

6.2.2 Transient Analysis

Fig. 6.5 shows the bus voltage as a percentage over time. The same fault was applied for this case as the original base case.
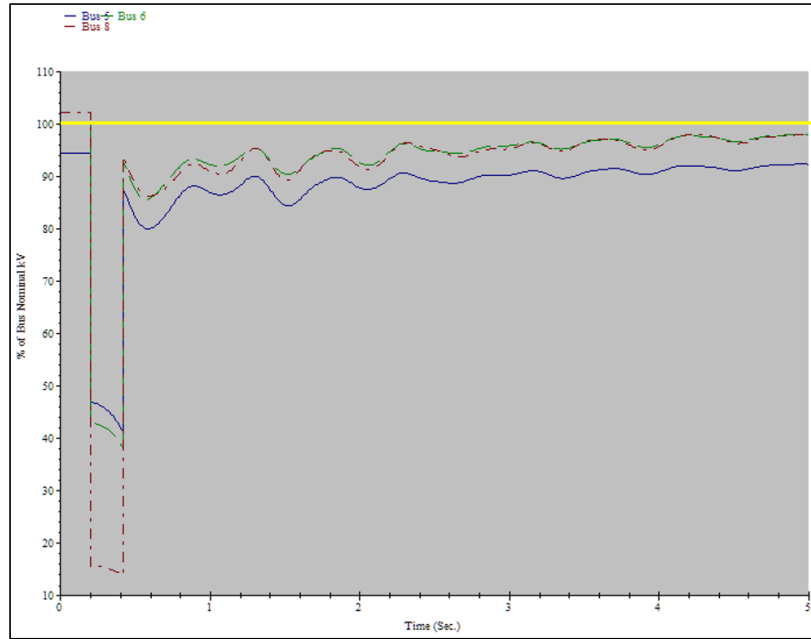
Fig. 6.5 Additional load bus on Bus 5 voltages during a fault on Line 5.

The initial drop after the fault is approximately the same voltage level. Interestingly, with the additional load, the rate of voltage drop increases for Bus 5. The rate is also more exponential than the Bus 6 voltage drop. The power system model state at the moment before the fault is cleared can be seen in Fig. 6.6. After the fault is cleared, the voltage spikes closer to pre-fault conditions. However, the voltage is approximately 9% lower than pre-fault conditions. All buses then immediately oscillate significantly due to lack of MVAR support reaction time. The voltage will continue to oscillate but dampen and trend in a positive direction until it reaches a new steady state. The system remains stable as it reaches the new steady state. The new steady state is less than the original voltage. Fig. 6.6 shows the transient analysis on the one-line diagram. It shows the per unit voltages and frequency of the generators at 0.403 seconds in the right before the

breakers clear the fault. This is the worst point in the transient stability study. All the bus voltages are far outside of acceptable ranges. The power transfer is shown in KW and KVAR. The real power transfer drops for all the buses, and the frequency increases up to 61.1 Hz at G2. This is a useful tool to see all these variables across the one-line diagram with respect to the time.
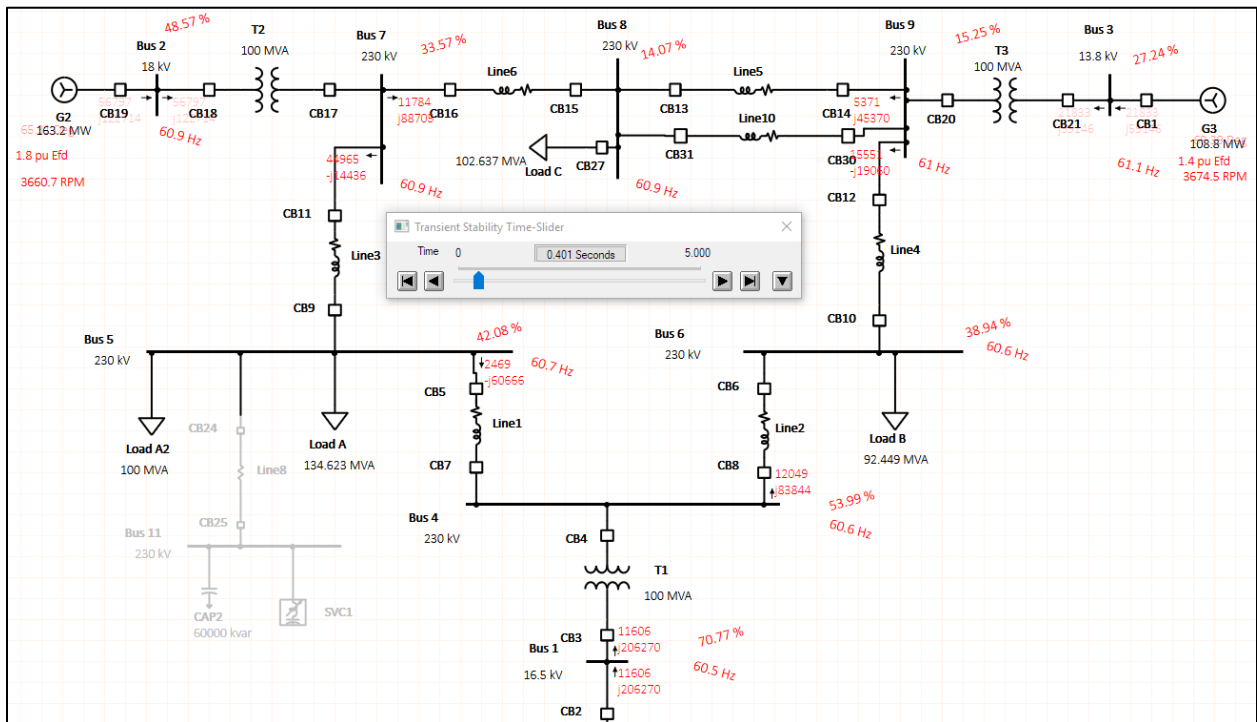
Fig. 6.6 Transient Stability response of power system and 0.401 seconds

The following case will analyze how adding a shunt capacitor to the system could be beneficial.

6.3   Added Shunt Capacitor to Bus 11 Simulation

In this case, Bus 11 was added to the model. The purpose of adding another bus to the model is to review results specifically at that node. It should be noted that at one point, a Bus 10 was added then deleted from the model. The software then defaulted the next available Bus ID as Bus 11, which is why it is not labeled as Bus 10.

At Bus 11, a shunt capacitor was added. Knowing the value of the added load was 60 MVAR inductive, the rating of the capacitor was rated for a total of 60 MVAR. The ETAP software allows a user to define the configuration of the cap bank as well. As mentioned in the shunt capacitor section above, multiple capacitor banks can be placed in parallel to increase the overall capacity of the bank. The configuration chosen here was 10 banks rated at 6 MVAR each.

The line connecting the two buses has a negligible impedance. This is because the shunt capacitors would be installed in the same substation as Bus 5. The circuit breakers were added at both ends of the line for device protection. Fig. 6.7 shows the addition of the devices described in this section.
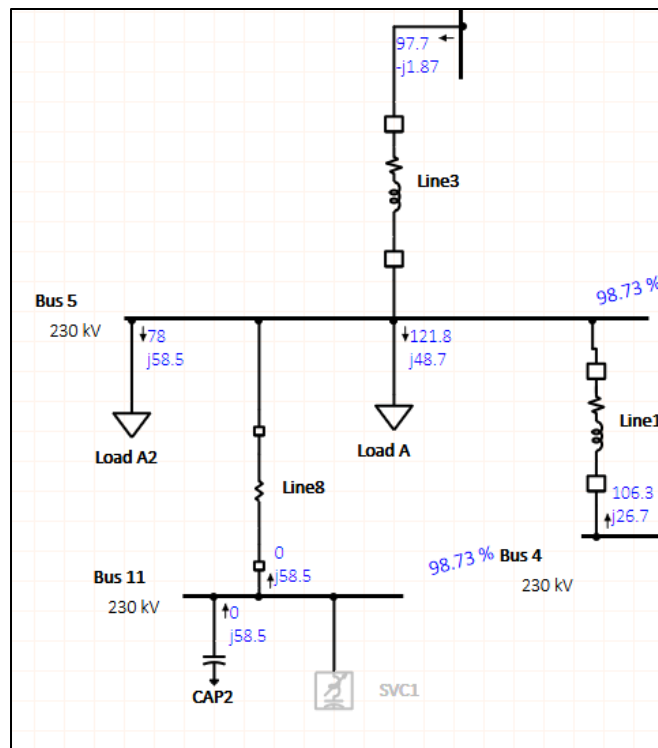
Fig. 6.7 One-line diagram of added Bus 11 and Shunt Capacitor with load flow results.

6.3.1 Load Flow Analysis

The one-line diagram load flow above shows the Bus 5 voltage within the nominal 5% range. The power flow to the load has also increased from the previous case when the extra load was added. The shunt capacitor contributes 60 MVAR to Bus 5 with reduces the flow of imaginary power from both Bus 4 and Bus 7. Table 6.3 shows the data for the load flow with the addition of the shunt capacitor.

Table 6.3 Addition of Bus 11 and shunt capacitor load flow study results.

| BUS ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar		BUS ID	MW	Mvar	Amp	%PF
Bus 1	16.500	104.000	0.0	150.012	35.085	0.000	0.000		Bus 4	150.012	35.085	5183.4	97.4
Bus 2	18.000	102.500	4.6	163.001	1.392	0.000	0.000		Bus 7	163.001	1.392	5100.9	100.0
Bus 3	13.800	102.500	0.2	85.000	-18.477	0.000	0.000		Bus 9	85.000	-18.477	3550.4	-97.7
Bus 4	230.000	102.386	-4.7	0.000	0.000	-0.014	0.000		Bus 5	106.275	26.715	268.7	97.0
									Bus 6	43.738	-4.270	107.7	-99.5
									Bus 1	-149.999	-22.445	371.8	98.9
Bus 5	230.000	98.728	-9.6	0.000	0.000	199.812	107.210		Bus 4	-105.074	-34.312	281.0	95.1
									Bus 7	-94.738	-14.414	243.6	98.9
									Bus 11	0.000	-58.485	148.7	0.0
Bus 6	230	101.3729	-6.838	0	0	90.128	30.043		Bus 4	-43.426	-10.438	110.6	97.2
									Bus 9	-46.703	-19.605	125.4	92.2
Bus 7	230	102.8864	-0.931	0	0	-0.0004	0.0003		Bus 5	97.684	-1.873	238.4	-100.0
									Bus 8	65.301	-12.542	162.2	-98.2
									Bus 2	-162.985	14.415	399.2	-99.6
Bus 8	230	102.776	-3.501	0	0	102.33	35.802		Bus 9	-18.687	-17.751	63.0	72.5
									Bus 7	-64.957	-0.301	158.7	100.0
									Bus 9	-18.687	-17.751	63.0	72.5
Bus 9	230	103.6655	-2.531	0	0	0.0016	0.0001		Bus 6	47.531	-14.413	120.3	-95.7
									Bus 8	18.732	-4.142	46.5	-97.6
									Bus 8	18.732	-4.142	46.5	-97.6
									Bus 3	-84.996	22.698	213.027	-96.614
Bus 11	230	98.72861	-9.576	0	0	-4E-05	-58.484		Bus 5	4E-05	58.484	148.698	7E-05

One of the benefits from adding the shunt capacitor is the bus voltage correction at Bus 5. The voltage is now at 98.73% of the nominal value. The additional real power generation at G1 was proportional to the real power delivered to the loads. As anticipated there was a large drop in MVAR generation of 53.47 MVAR. A critical point of cost savings was the decreased current flowing over Line 1 and Line 3. The combined current loss over the two lines is 17.65 amps. This is 27.17 A less than the case when the extra load was added. The actual power loss is therefore 6.25 MVA less than the added extra load case. This could amount to $15,000 per day saved with

the installation of the shunt capacitor, assuming a $100/MVA bulk energy cost. This cost per MVA

will be used through the remainder of the paper. Further analysis of this cost savings will be done

in the conclusion.

6.3.2 Transient Analysis

Fig 6.8 shows the bus voltage as a percentage over time. The same fault was applied for

this case as the original base case.
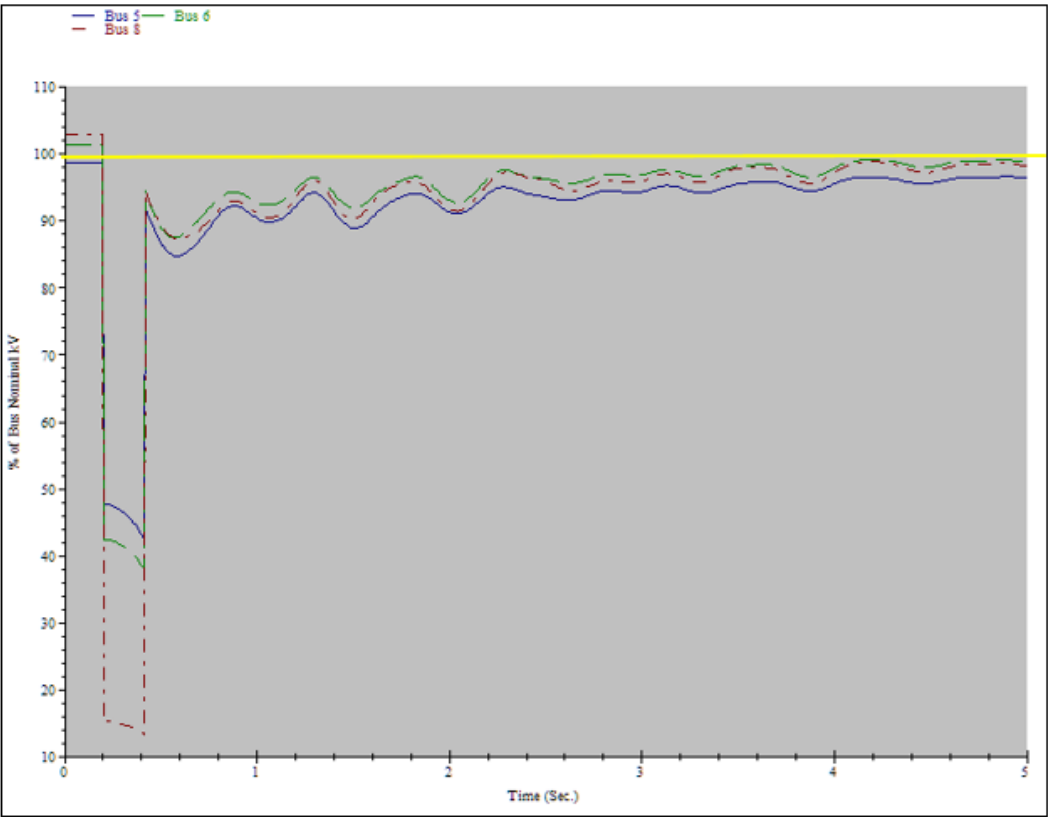
Fig. 6.8 Shunt Capacitor added to Bus 11 case during a fault on Line 5.

The initial drop after the fault is a slightly higher voltage level than the base case. The

voltage rise is shifted to a greater magnitude than the previously examined extra load case. The

first oscillation after that rise is approximately the same length and magnitude as without the

capacitor. The amplitude of the oscillations is also comparable. The important factor is the post

40

fault steady state voltage for all the load buses is within the required 5% limit. This is an important factor in the overall stability and reliability of the power system.

6.4   Added Static Var Compensator to Bus 11

In this case the shunt capacitor was taken out of service and a SVC was added to the model. The nominal value of the SVC is +/- 50 MVAR. This value was chosen because it is an industry standard. The maximum rating of the SVC is +/- 100 MVAR. This maximum capacity range gives the SVC extra versatility within the power system. Fig. 6.9 shows the load flow one-line diagram with the addition of the SVC.
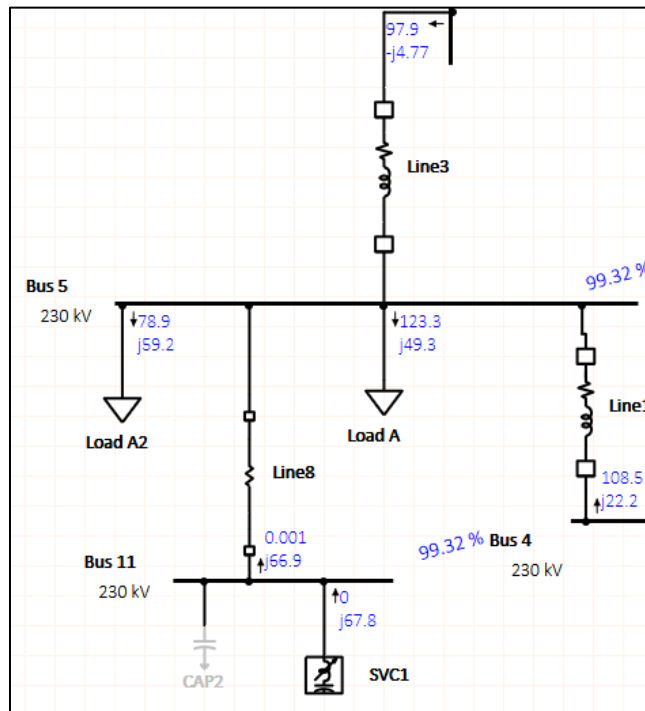
Fig. 6.9 One-line diagram showing SVC addition with load flow results.

6.4.1   Load Flow Analysis

The one-line diagram above shows the bus voltage within 0.7% of the nominal voltage. The power provided to the loads on Bus 5 have increased over the shunt capacitor addition. The

SVC is able to provide MVAR support at this bus as well as to Bus 7. The SVC contributes 66.9

MVAR to the system. Table 6.4 shows the data for the load flow with the addition of the SVC.

Table 6.4 Addition of SVC load flow study results.

BUS ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar		BUS ID	MW	Mvar	Amp	%PF
Bus 1	16.500	104.000	0.0	152.920	31.351	0.000	0.000		Bus 4	152.920	31.351	5252.0	98.0
Bus 2	18.000	102.500	4.4	163.000	-0.912	0.000	0.000		Bus 7	163.000	-0.912	5100.8	100.0
Bus 3	13.800	102.500	0.0	85.000	-19.664	0.000	0.000		Bus 9	85.000	-19.664	3561.0	-97.4
Bus 4	230.000	102.605	-4.7	0.000	0.000	0.000	0.000		Bus 5	108.485	22.167	270.9	98.0
									Bus 6	44.423	-3.793	109.1	-99.6
									Bus 1	-152.907	-18.375	376.8	99.3
Bus 5	230.000	99.324	-9.7	0.000	0.000	202.234	108.508		Bus 4	-107.273	-29.813	281.4	96.3
									Bus 7	-94.960	-11.828	241.8	99.2
									Bus 11	-0.001	-66.866	169.0	0.0
Bus 6	230.000	101.539	-6.9	0.000	0.000	90.424	30.142		Bus 4	-44.101	-10.928	112.3	97.1
									Bus 9	-46.324	-19.213	124.0	92.4
Bus 7	230.000	103.026	-1.1	0.000	0.000	0.000	0.000		Bus 5	97.888	-4.775	238.8	-99.9
									Bus 8	65.096	-11.943	161.3	-98.4
									Bus 2	-162.985	16.718	399.2	-99.5
Bus 8	230.000	102.873	-3.6	0.000	0.000	102.526	35.870		Bus 9	-18.885	-17.452	62.7	73.4
									Bus 7	-64.756	-0.965	158.0	100.0
									Bus 9	-18.885	-17.452	62.7	73.4
Bus 9	230.000	103.733	-2.7	0.000	0.000	0.000	0.000		Bus 6	47.136	-14.961	119.7	-95.3
									Bus 8	18.930	-4.474	47.1	-97.3
									Bus 8	18.930	-4.474	47.1	-97.3
									Bus 3	-84.996	23.909	213.7	-96.3
Bus 11	230.000	99.324	-9.7	0.000	0.000	-0.001	-66.866		Bus 5	0.001	66.866	169.0	0.0

The addition of the SVC corrects the voltage at Bus 5 to be the closer to the nominal voltage

than the addition of the shunt capacitor. The additional real rower generated was delivered to the

loads. The SVC power system required 4 MVAR less from the generators. By the same calculation

method as the shunt capacitor addition, the SVC addition reduced the lost current over the lines

coming into Bus 5. The total lost current was 13.5 A, which is 31.26 A less than when the extra

load was added. This could amount to 7.19 MVA and up to approximately $17,260 a day.

6.4.2 Transient Analysis

Fig. 6.10 shows the bus voltage as a percentage over time. The same fault was applied for

this case as the original base case.
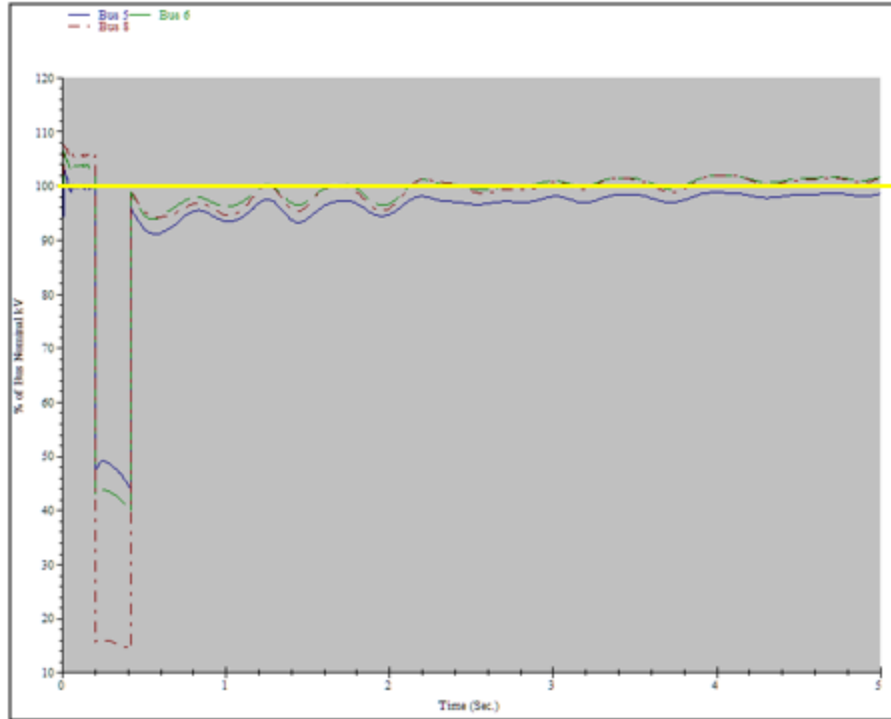
Fig. 6.10 SVC added to Bus 11 case during a fault on Line 5.

This transient analysis graph is similar in many ways to the analysis done with the shunt capacitor. However, an aspect that makes it unique is the small rise immediately after the fault is applied and the initial drop occurs. This is the SVC attempting to provide necessary MVAR support to reduce the imbalance. The first oscillation post fault is also smaller in magnitude and the voltage is at a greater per unit voltage. The voltage at all the load buses is at a steady state in the voltage range of 5% within 1.6 seconds from the fault clearing time. This is the quickest FACTS device that has been added to the model. The Bus 5 voltage also normalizes at 98.5% as can be seen in Fig. 6.11, which is closer than the shunt capacitor alone. This may seem like the optimal choice for implementation. However, due to the high cost per installed KVAR, an additional option with a shunt capacitor is explored in the section below.

43
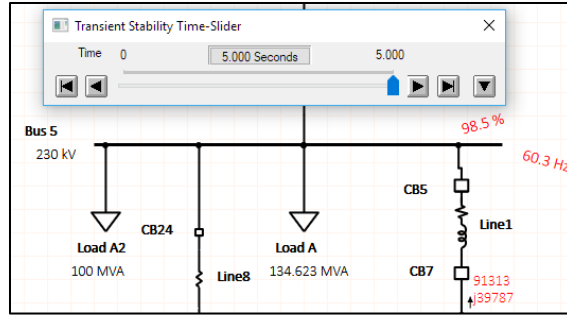
Fig. 6.11 Bus 5 voltage after 5 seconds in the transient analysis study.

6.5 Added Static Var Compensator and Shunt Capacitor to Bus 11

In this case, the previously designed shunt capacitor was placed into service. The SVC was also placed in service with a small modification. As previously explained, the Var support provided by the SVC costs more than the support from a capacitor. The SVC, however, has the ability to react to the fault conditions in the power system. As demonstrated below the two can be coupled together in order to create a cost efficient, optimal solution. The rating for the SVC was reduced to +/- 25 MVAR. As a side note, a typical SVC yard would have fixed capacitance and possibly inductive reactive support as well. The inductive reactive support would require harmonic filters. While this software is capable of modeling both devices, it would not be beneficial to the specific case to add them into the model. Fig. 6.12 shows the shunt capacitor bank and the SVC installed on Bus 11.
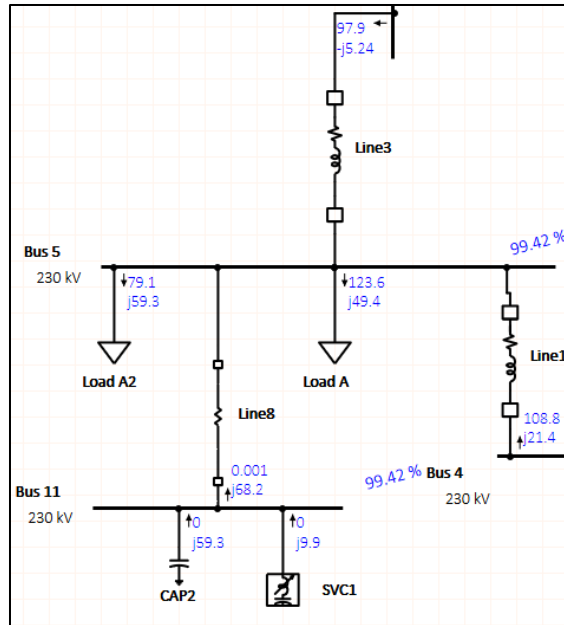
Fig. 6.12 One-line diagram showing added SVC and Shunt Capacitor at Bus 11.

6.5.1 Load Flow Analysis

The one-line diagram load flow above shows the Bus 5 voltage only .58% from the nominal range. The MVARs for the load was provided from the additional FACTS devices installed on Bus 11. The shunt capacitor provided 60 MVAR and the SVC provided almost 10 MVAR. In certain cases, settings will prevent the SVC from providing var support until an event occurs. This allows the SVC to have a greater capacity to stabilize the system through a larger event. In this case, however, no such settings prevent it from providing a constant MVAR support to the system. Table 6.5 shows the data for the load flow with the addition of the shunt capacitor and SVC.

Table 6.5 Addition of Shunt Capacitor and SVC to Bus 11 load flow study results.

BUS ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar		BUS ID	MW	Mvar	Amp	%PF
Bus 1	16.500	104.000	0.0	153.389	30.749	0.000	0.000		Bus 4	153.389	30.749	5263.5	98.0
Bus 2	18.000	102.500	4.4	163.000	-1.283	0.000	0.000		Bus 7	163.000	-1.283	5100.9	100.0
Bus 3	13.800	102.500	0.0	85.000	-19.855	0.000	0.000		Bus 9	85.000	-19.855	3562.8	-97.4
Bus 4	230.000	102.641	-4.7	0.000	0.000	0.000	0.000		Bus 5	108.843	21.432	271.3	98.1
									Bus 6	44.533	-3.716	109.3	-99.7
									Bus 1	-153.376	-17.716	377.6	99.3
Bus 5	230.000	99.420	-9.8	0.000	0.000	202.626	108.718		Bus 4	-107.629	-29.082	281.5	96.5
									Bus 7	-94.995	-11.408	241.6	99.3
									Bus 11	-0.001	-68.228	172.3	0.0
Bus 6	230.000	101.565	-7.0	0.000	0.000	90.472	30.157		Bus 4	-44.209	-11.007	112.6	97.0
									Bus 9	-46.263	-19.150	123.7	92.4
Bus 7	230.000	103.049	-1.1	0.000	0.000	0.000	0.000		Bus 5	97.921	-5.244	238.9	-99.9
									Bus 8	65.063	-11.847	161.1	-98.4
									Bus 2	-162.985	17.090	399.2	-99.5
Bus 8	230.000	102.889	-3.7	0.000	0.000	102.557	35.881		Bus 9	-18.917	-17.404	62.7	73.6
									Bus 7	-64.723	-1.073	157.9	100.0
									Bus 9	-18.917	-17.404	62.7	73.6
Bus 9	230.000	103.744	-2.7	0.000	0.000	0.000	0.000		Bus 6	47.072	-15.050	119.6	-95.3
									Bus 8	18.962	-4.528	47.2	-97.3
									Bus 8	18.962	-4.528	47.2	-97.3
									Bus 3	-84.996	24.105	213.8	-96.2
Bus 11	230.000	99.420	-9.8	0.000	0.000	-0.001	-68.228		Bus 5	0.001	68.228	172.3	0.0

The results in Table 6.5 are almost identical to the results from the case with only an SVC installed. The load Bus 5 voltage is within .6% of the nominal voltage. This voltage stability is added because of the steady output of the shunt capacitors and the variable capacity of the SVC. Again, more real power was delivered to the loads than the original extra load case. The generators provided and consumed approximately the same MVARs as in the SVC only case. The lost current across the lines that terminate at Bus 5 is 12.9 A. This is 31.9 A less than the original case, and similar to the SVC only case.

6.5.2 Transient Analysis

Fig. 6.13 shows the bus voltage as a percentage over time. The same fault was applied for this case as the original base case.
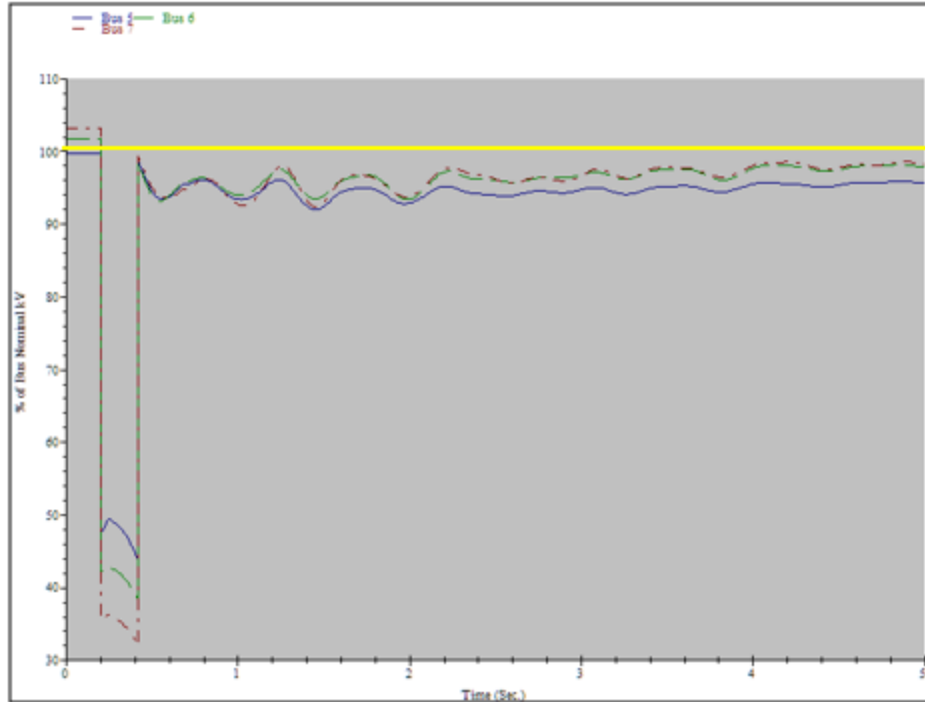
Fig. 6.13 SVC added to Bus 11 case during a fault on Line 5.

This transient analysis graph has several aspects that make it unique. The first characteristic is that the voltage on bus 8 is restricted to a 35% drop. The voltage drops to approximately 15% with the extra loads installed and no FACTS devices in service. Another unique aspect is that the voltage doesn't drop lower than 90% except during the fault. The voltage is able to rise to the nominal level right after the fault is cleared. This system stabilizes at approximately 95% of the nominal voltage at Bus 5 and 98% at both the other load buses. The SVC only simulation voltage swings have less amplitude in the reaction and stabilizes at a more nominal level. While the SVC only solution offers a slightly better response to the fault analysis, the shunt capacitor and SVC combination solution offers similar results with lower capital costs.

6.6   Decommissioned Generator 3 With SVC

This case is applicable to many situations within the power system in the United States. Due to higher environmental regulations and higher fuel costs, several types of large energy

47

generation sites are being decommissioned. The generation capacity is not only important for real power, but also grid stabilization and reactive power exchange. To model this situation, Generator 3 was removed from service. The other devices modeled previously (extra load, Bus 11 shunt capacitor and SVC) were also removed from service. The transient analysis without that generation capacity resulted in bus voltages out of the specified range. An SVC was added at Bus 3 to stabilize the grid and provide reactive support as can be seen in Fig. 6.14.

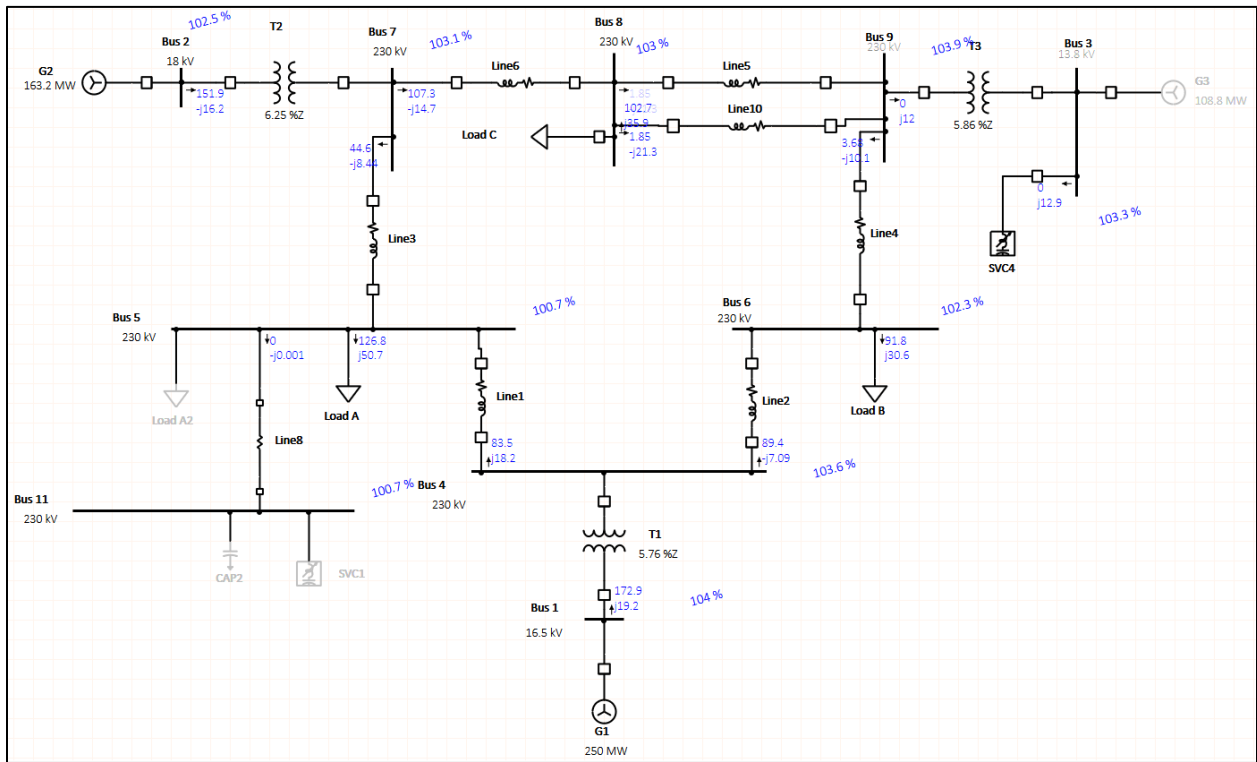Fig. 6.14 One-line diagram showing added SVC at Bus 3.

6.6.1 Load Flow

The one-line diagram above shows all the in-service devices operating during the study. As seen above as well, none of the bus voltages are out of the specified range. The chart below shows the results from the load study. The power transferred to the loads was adequate and slightly high due to the small overvoltage at the buses.

Table 6.6 Decommissioned generator 3 and addition of SVC at Bus 3 load flow study results.

BUS ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar		BUS ID	MW	Mvar	Amp	%PF
Bus 1	16.500	104.000	0.0	172.941	19.208	0.000	0.000		Bus 4	172.941	19.208	5854.4	99.4
Bus 2	18.000	102.500	0.0	151.910	-16.169	0.000	0.000		Bus 7	151.910	-16.169	4780.5	-99.4
Bus 3	13.800	103.259	-6.9	0.000	0.000	0.000	11.951		Bus 9	0.000	-11.951	484.2	0.0
Bus 4	230.000	103.574	-2.6	0.000	0.000	0.000	0.000		Bus 5	83.539	18.238	207.2	97.7
									Bus 6	89.394	-7.092	217.3	-99.7
									Bus 1	-172.933	-11.146	420.0	99.8
Bus 5	230.000	100.712	-6.4	0.000	0.000	126.783	50.704		Bus 4	-82.817	-30.467	219.9	93.9
									Bus 7	-43.966	-20.237	120.6	90.8
Bus 6	230.000	102.291	-7.1	0.000	0.000	91.769	30.590		Bus 4	-88.127	-2.795	216.4	99.9
									Bus 9	-3.642	-27.794	68.8	13.0
Bus 7	230.000	103.092	-2.6	0.000	0.000	0.000	0.000		Bus 5	44.583	-8.442	110.5	-98.3
									Bus 8	107.321	-14.668	263.7	-99.1
									Bus 2	-151.903	23.111	374.1	-98.9
Bus 8	230.000	102.956	-6.8	0.000	0.000	102.692	35.928		Bus 9	1.852	-21.306	52.1	-8.7
									Bus 7	-106.396	6.685	259.9	-99.8
									Bus 9	1.852	-21.306	52.1	-8.7
Bus 9	230.000	103.937	-6.9	0.000	0.000	0.002	0.000		Bus 6	3.678	-10.114	26.0	-34.2
									Bus 8	-1.840	-0.958	5.0	88.7
									Bus 8	-1.840	-0.958	5.0	88.7
									Bus 3	0.000	12.030	29.1	0.0

It can be seen that the power factor of Bus 3 to Bus 9 is 0 percent for this analysis. This is because the source is completely capacitive. This provides the necessary reactive support to decrease the amount compensated by the other two generators in the system.

6.6.2 Transient Analysis

Fig. 6.15 shows the bus voltage as a percentage over time. The same fault was applied for this case as the original base case.
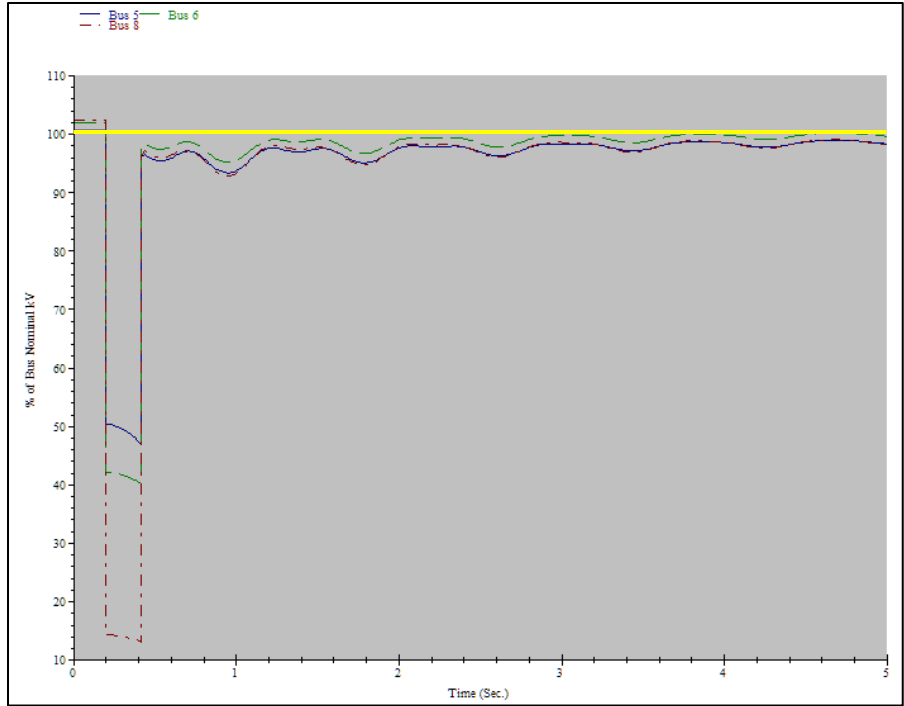
Fig. 6.15 SVC added to Bus 3 with decommissioned generator 3 during a fault on Line 5.

This transient analysis proves the results to be very similar to the other initial base case analysis. This should be compared with the original base case transient analysis in section 6.1.2. The voltage for all three load buses normalizes within the nominal range in about 3.5 seconds. It seems that the amplitude of the voltage swings is also smaller than the original case as well. The voltage of Bus 6 is higher because of the larger transmission of power through the bus. The voltage at Bus 5 and Bus 8 are nearly identical post fault. With the SVC installed, the system will return to an adequate voltage range after the fault has been cleared. Without the installation of the SVC on Bus 3, none of the load buses can normalize within the required voltage range.

6.7   Shunt Capacitor & Svc with Extra Load and Decommissioned Generator

This case represents all the variations presented in chapter 5 applied to the IEEE 9 bus base case presented in section 6.1. The first variation is an increased in load of 80MW and 60MVAR on Bus 5. The second variation is the fault applied to Line 5. The third variation is the

decommissioning of Generator 3. Without the addition of FACTS in the power system, the extra load and loss of a generator would cause the power system to collapse during the fault. The FACTS in this case have been selected to mitigate voltage drop and transients, thereby increasing the reliability of the power system. The shunt capacitor and SVC are both in-service on Bus 11 as demonstrated in section 6.5. The SVC is also in-service on Bus 3 as previously described in section 6.6. The explanation of these results will be minimal to avoid repetition, as the results are mostly similar to previously discussed cases. This case is presented to provide final results of cases modeled with the installation of an SVC.
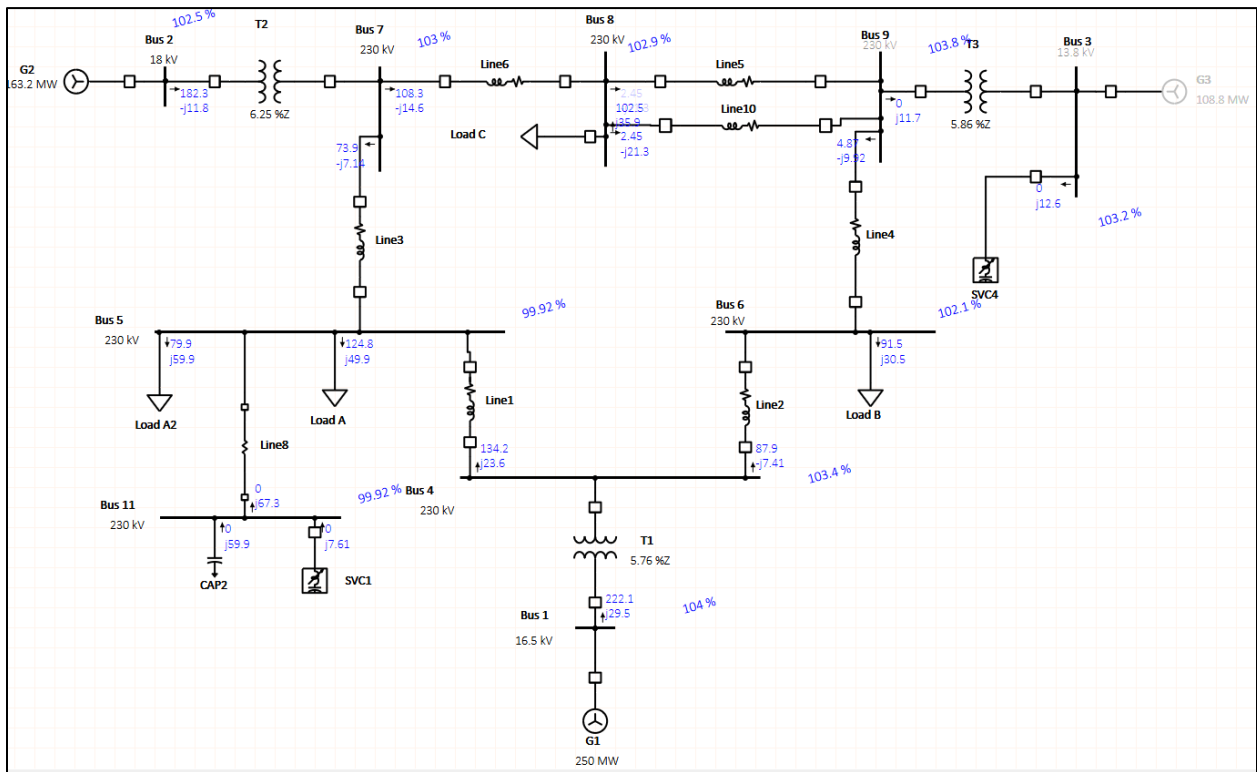

Fig. 6.16 One-line diagram showing all variations implemented.

6.7.1 Load Flow Analysis

The one-line diagram load flow above shows the Bus 5 voltage only .22% from the nominal range. The other bus voltages are also within nominal range during steady state. There is a greater

amount of power flowing through Line 6 in this case, which may impact the transient analysis. Table 6.7 shows the data for the load flow with the addition of the shunt capacitor and SVC at Bus 11 and the replacement of Generator 3 with another SVC.

Table 6.7 Load flow study results of case with all the variations implemented.

BUS ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar		BUS ID	MW	Mvar	Amp	%PF
Bus 1	16.500	104.000	0.0	222.105	29.538	0.000	0.000		Bus 4	222.105	29.538	7538.5	99.1
Bus 2	18.000	102.500	0.0	182.272	-11.800	0.000	0.000		Bus 7	182.272	-11.800	5715.7	-99.8
Bus 3	13.800	103.178	-7.5	0.000	0.000	0.000	11.633		Bus 9	0.000	-11.633	471.7	0.0
Bus 4	230.000	103.359	-3.4	0.000	0.000	0.000	0.000		Bus 5	134.230	23.583	331.0	98.5
									Bus 6	87.862	-7.412	214.1	-99.6
									Bus 1	-222.091	-16.170	540.8	99.7
Bus 5	230.000	99.924	-9.6	0.000	0.000	204.688	109.824		Bus 4	-132.441	-26.569	339.3	98.0
									Bus 7	-72.246	-15.953	185.9	97.6
									Bus 11	0.000	-67.302	169.1	0.0
Bus 6	230.000	102.121	-7.8	0.000	0.000	91.465	30.488		Bus 4	-86.633	-2.619	213.0	100.0
									Bus 9	-4.831	-27.870	69.5	17.1
Bus 7	230.000	103.004	-3.1	0.000	0.000	0.000	0.000		Bus 5	73.919	-7.143	181.0	-99.5
									Bus 8	108.343	-14.581	266.4	-99.1
									Bus 2	-182.262	21.724	447.3	-99.3
Bus 8	230.000	102.860	-7.3	0.000	0.000	102.500	35.860		Bus 9	2.449	-21.324	52.4	-11.4
									Bus 7	-107.399	6.788	262.6	-99.8
									Bus 9	2.449	-21.324	52.4	-11.4
Bus 9	230.000	103.839	-7.5	0.000	0.000	0.002	0.000		Bus 6	4.872	-9.919	26.7	-44.1
									Bus 8	-2.437	-0.894	6.3	93.9
									Bus 8	-2.437	-0.894	6.3	93.9
									Bus 3	0.000	11.708	28.3	0.0
Bus 11	230.000	99.925	-9.6	0.000	0.000	0.000	-67.301		Bus 5	0.000	67.301	169.1	0.0

These results follow the results from most other cases, particularly with regards to the per unit voltage. The correct amount of power is delivered to all the loads. The voltage angle however is about 3.5 degrees lagging the SVC and shunt capacitor case in section 6.5. The lagging voltage angle indicates that the power flow had to travel further than the case where the generation was a single bus away. The real power generation increased by 3 MW in comparison to the SVC and shunt capacitor case as well. This is because more power had to be transferred through a longer distance and resulted in greater power loss. The average power factor is also greater on the generation buses.

6.7.2   Transient Analysis

Fig. 6.17 shows the bus voltage as a percentage over time. The same fault was applied for this case as the original base case.
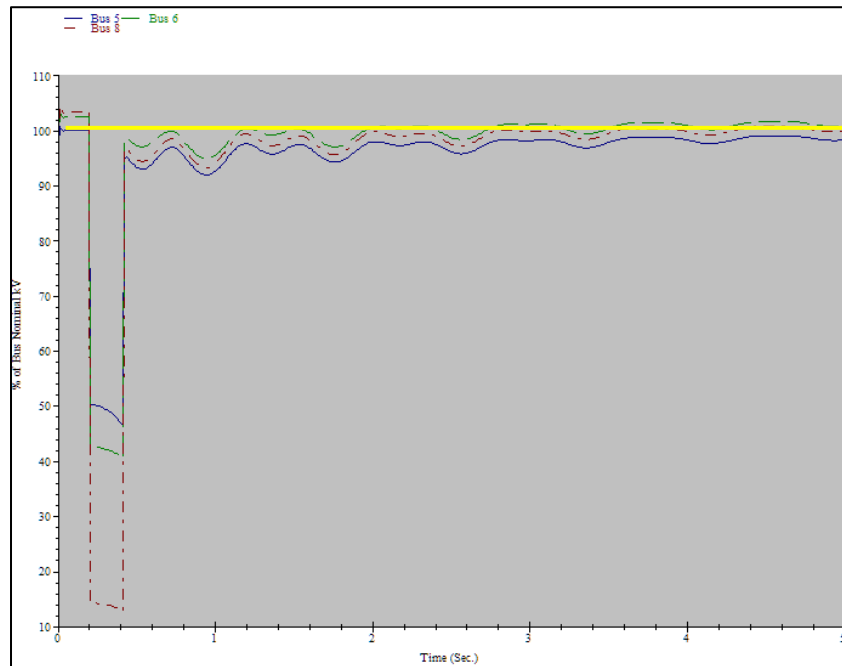

Fig. 6.17 All variants implemented during a fault on Line 5.

As expected, the voltage dropped to approximately .15 per unit after the fault was applied. Once the fault was cleared, the voltage rose for all the load buses. The wavelength of the voltage oscillations is shorter than the oscillation wavelengths of the previous case in section 6.6. The amplitude of the waves appears to be greater. The common factor is the removed generation, but the difference is the additional SVC and shunt capacitor is installed with the additional load in this case. The shunt capacitor must decrease the wavelength and the extra load must cause the greater variation in the loads provided. The steady state after the event stabilizes to an approximately normal level.

6.8   Added STACOM To IEEE 9 Bus Model

This case was done in the MATLAB Simulink software. The original code for this model was developed from the MathWorks website [39] [40]. This model started as the exact same model as the original IEEE 9 bus base case demonstrated in section 6.1. The components parameters from the Simulink version matched those of the ETAP version. The results matched from both programs. The model in Simulink was upgraded for the addition of the STATCOM devices and modeling tests. The STATCOM was added to Bus 5, the same location as the SVC in section 6.5. The STATCOM was sized for +/-50 MVAR, which will remain constant in this case and section 6.9. An additional line was also added between Bus 8 and Bus 9, to aid with the transient analysis. The additional load was added as well, but as can be seen in Fig. 6.18, was not placed in service in this simulation. The additional components shown in Fig. 6.18 are CCVTs to measure bus voltages, fault banks to simulate faults, and other simulation tools.
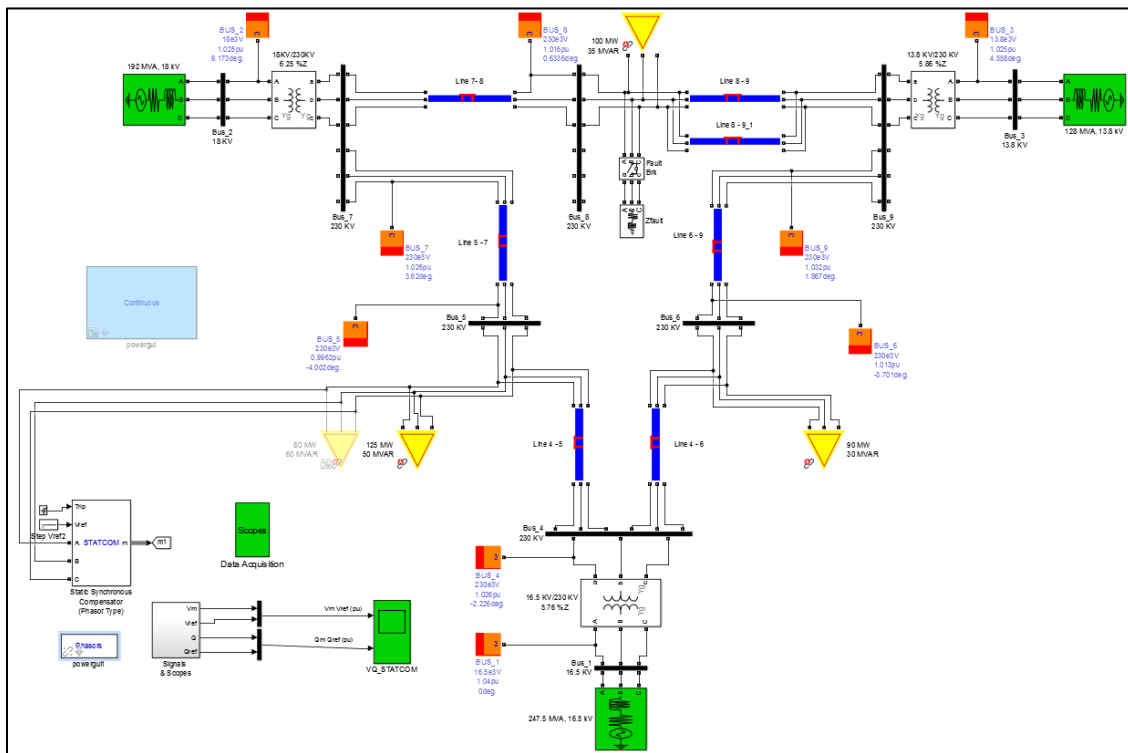

Fig. 6.18 One-line diagram of IEEE 9 bus model with added STATCOM on Bus 5.

6.8.1 Load Flow Analysis

In MATLAB, the power load flow results can be easily found and analyzed in the results report. The results are very uniform and meet all required criteria. The purpose of the load flow report in Table 6.8 is to show the base values of the model with the STATCOM added and no other additional loads added. This will be useful for the comparison to the load flow study completed in section 6.9.1.

Table 6.8 Load flow study results of case with all the variations implemented.

Block type	Bus type	Bus ID	P (MW)	Q (Mv...	V_LF (pu)	Vangle_LF (deg)	P_LF (MW)	Q_LF (Mvar)	Block Name
Vsrc	swing	BUS_1	0.00	0.00	1.0400	0.00	72.15	22.91	247.5 MVA, 16.5 kV
Bus	–	BUS_4	0.00	0.00	1.0282	-2.22	0.00	0.00	Load Flow Bus1
RLC load	PQ	BUS_5	125.00	50.00	0.9998	-3.91	125.00	50.00	125 MW 50 MVAR/Three-Phase Par...
RLC load	PQ	BUS_6	90.00	30.00	1.0170	-3.79	90.00	30.00	90 MW 30 MVAR/Three-Phase Para...
Bus	–	BUS_7	0.00	0.00	1.0321	3.77	0.00	0.00	Load Flow Bus4
Bus	–	BUS_9	0.00	0.00	1.0384	1.52	0.00	0.00	Load Flow Bus5
RLC load	PQ	BUS_8	100.00	35.00	1.0305	0.87	100.00	35.00	100 MW 35 MVAR/Three-Phase ...
Vsrc	PV	BUS_2	163.00	0.00	1.0250	9.29	163.00	-3.59	192 MVA, 18 kV
Vsrc	PV	BUS_3	85.00	0.00	1.0250	4.20	85.00	-21.32	128 MVA, 13.8 kV
RLC load	Z	*1*	300.00	300...	3.930...	85.15	0.00	0.00	Zfault

The voltage at Bus 5 where the STATCOM was installed, was measured as 0.9998, which is a near perfect voltage measurement. The voltage angle at all the load buses was approximately -4 or less, which indicates how much the voltage was lagging at these buses. This is the same as compared to the original base case. This result makes sense because there is no additional power to the loads from the generation buses.

6.8.2 Transient Analysis

Fig. 6.19 and Fig. 6.20 show the transient analysis for a fault applied on Line 5. The top graph in each screen shows the bus voltage as a per unit over time. The lower graph in the screen shows the current in kA with respect to time. The same fault was applied for this case as the original ETAP base case. The graphs shown below only span one and a half seconds to show the complete

operation of the STATCOM. The scale, therefore, does not match the graphs from ETAP as those
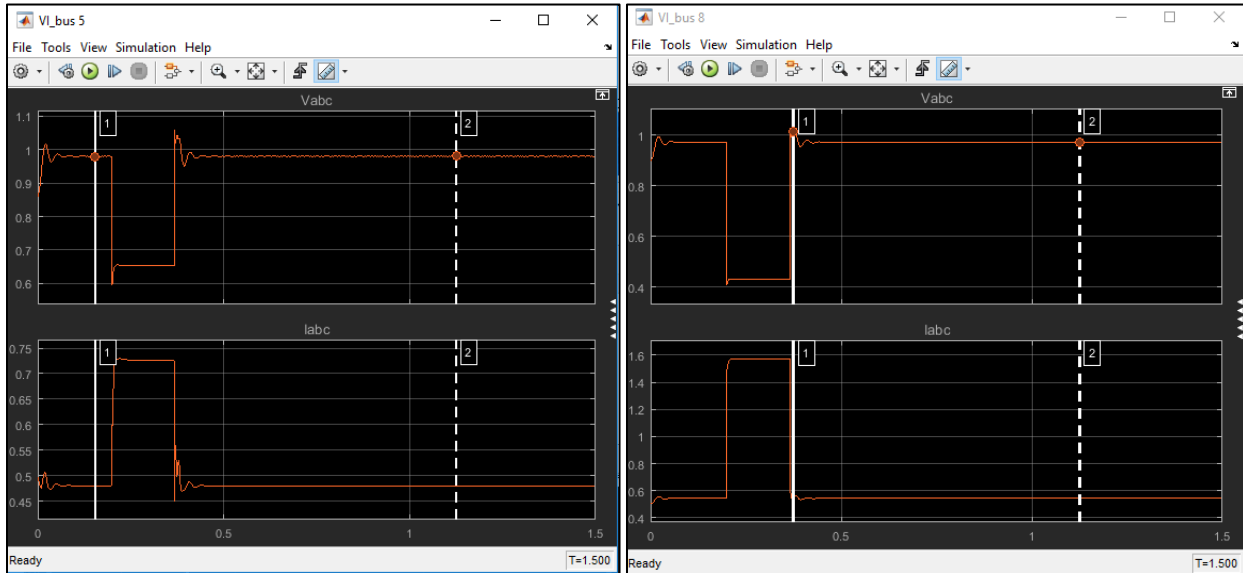
devices required more time to stabilize.

Fig. 6.19 (Left) Bus 5 voltage and current during a fault on Line 5. Fig. 6.20 (Right) Bus 8 voltage

and current during a fault on Line 5.

The transient analysis above shows several similarities to the results from the ETAP

testing. The general waveform is approximately the same. The initialization of the model takes a

few cycles to stabilize. When the fault is applied at 0.2 seconds the voltage drops on both buses,

then when the fault is cleared the voltage returns to a new equilibrium point. The voltages also

normalize at .97 and .99 per unit for Bus 5 and Bus 8 respectively. The STATCOM device allows

much greater control of the power system. The voltage drop during the fault is much less with the

STATCOM, because of the quicker reaction time. The STATCOM even stabilizes the system

during the fault. It should be recognized that the higher current delivered because of the additional

STATCOM device, might require station upgrades for fault current ratings. The voltage rise after

the fault is cleared is almost instantaneous. The voltage slightly overshoots the nominal voltage,

but the rapid response from the STATCOM can dampen out the oscillations. The pulse width

modulation that controls the IGBTs can consume or produce the correct current to dampen out the variations in the power delivered to the bus and rest of the system. The system stabilizes in about 0.1 seconds after the fault is cleared. This is an incredible difference compared to the best SVC case modeled previously. While the new voltage doesn't stabilize at one per unit, the voltage is well within the required parameters and provides an excellent solution to the fault response.

6.9   Added STATCOM to Model with Extra Load

This case is similar to the case presented in section 6.8. A load was added to Bus 5. The load demand from the system is 80 MW and 60 MVAR inductive. This extra load represents the variation explained in section 5.1. This addition demonstrates the effect of load growth in a metropolis. In order to offset the highly inductive load, a series of shunt capacitor banks was also installed at Bus 5. This will reduce the amount of transmitted power from the generators. The model is shown in Fig. 6.21.
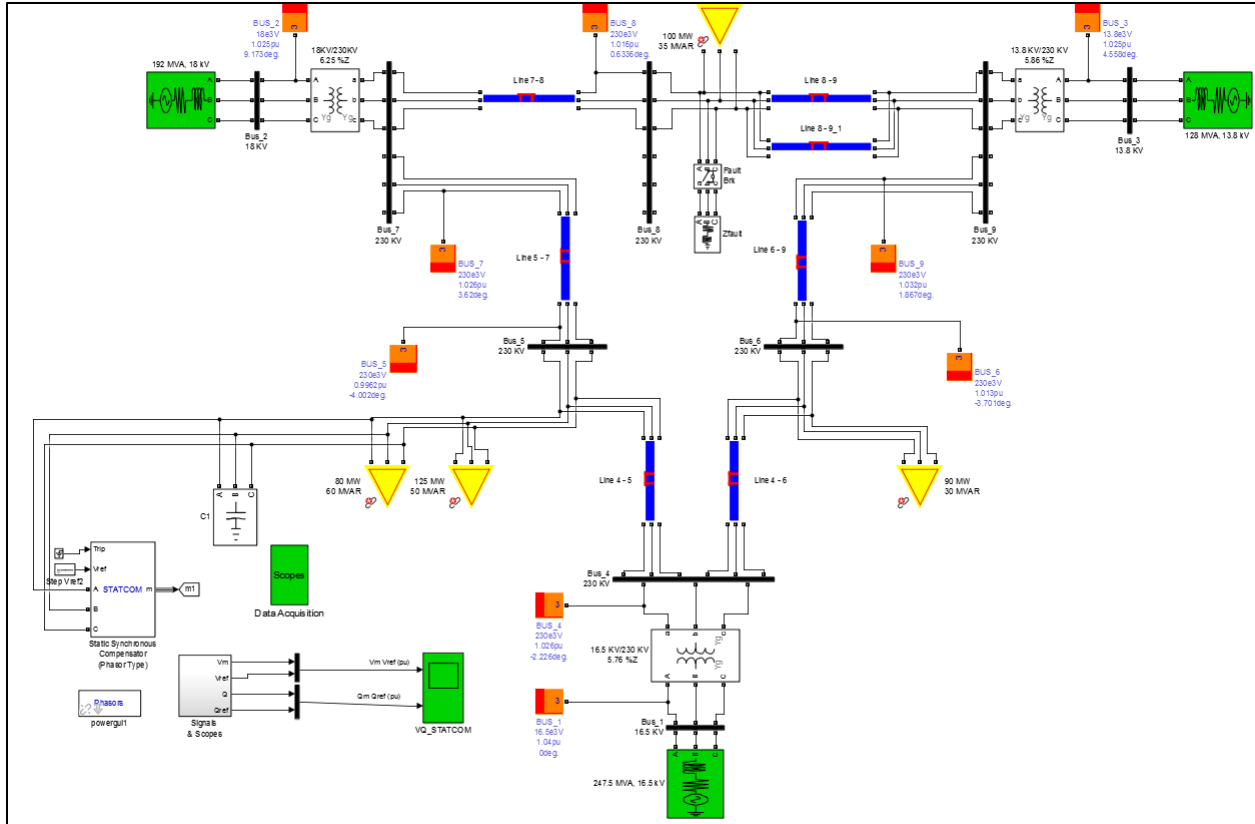
Fig. 6.21 One-line diagram with added STATCOM, load and shunt capacitor on Bus 5.

6.9.1   Load Flow Analysis

The results of the load flow from the previously described configuration are shown in Table 6.9.

Table 6.9 Load flow study results of case with all the variations implemented.

	Block type	...	Bus ID	Vbase ...	Vref (pu)	...	P (MW)	Q (Mv...	...	...	V_LF (pu)	Vangle_LF (deg)	P_LF (MW)	Q_LF (Mvar)	Block Name
1	Vsrc		..BUS_1	16.50	1.0400..		0.00	0.00.	..		1.0400	0.00	154.01	35.68	247.5 MVA, 16.5 kV
2	Bus	-	BUS_4	230.00	1..		0.00	0.00.	..		1.0328	−1.89	0.00	0.00	Load Flow Bus1
3	RLC load Z		BUS_5	230.00	1..		0.00	−60.00.	..		0.9920	−6.88	0.00	−59.05	C1
4	RLC load	..BUS_5	230.00	1..	125.00	50.00.			..		0.9920	−6.88	125.00	50.00	125 MW 50 MVAR/Three-Phase Par...
5	RLC load	..BUS_5	230.00	1..	80.00	60.00.			..		0.9920	−6.88	80.00	60.00	80 MW 60 MVAR/Three-Phase Para...
6	RLC load	..BUS_6	230.00	1..	90.00	30.00.			..		1.0207	−3.99	90.00	30.00	90 MW 30 MVAR/Three-Phase Para...
7	Bus	-	BUS_7	230.00	1..		0.00	0.00.	..		1.0294	1.84	0.00	0.00	Load Flow Bus4
8	Bus	-	BUS_9	230.00	1..		0.00	0.00.	..		1.0383	0.30	0.00	0.00	Load Flow Bus5
9	RLC load	..BUS_8	230.00	1..	100.00	35.00.			..		1.0294	−0.65	100.00	35.00	100 MW 35 MVAR/Three-Phase ...
10	Vsrc		..BUS_2	18.00	1.0250..		163.00	0.00.	..		1.0250	4.60	163.00	−10.04	192 MVA, 18 kV
11	Vsrc		..BUS_3	13.80	1.0250..		85.00	0.00.	..		1.0250	2.98	85.00	−21.15	128 MVA, 13.8 kV
12	RLC load Z		*1*	500.00		1..	300.00	300.	...	..	3.926...	83.63	0.00	0.00	Zfault

The results from Table 6.9 are very similar to the results found from the configuration in section 6.8. The voltage at Bus 5, where the extra load was installed, remains at a steady 0.992 per

58

unit value. The other load buses also remain within the nominal range. The voltage angle of Bus 5 increased from -3.91 to -6.88 degrees. This is due to the larger load on the particular bus. The other load bus angles are approximately the same as the original case due to the constant load. It is difficult to glean the power lost in the system without the exact currents at each of the buses. However, the total generation from the generators was 409 MVA. This does not consider the 60 MVAR shunt capacitor banks or the STATCOM, both of which provide MVAR support for the load flow analysis. The total consumed power for the system was 435.44 MVA. The real power lost would be the difference between real power generated and consumed. This result would between 402 MW (generated) and 395 MW (consumed) or a total of 7 MW lost throughout the power system. Without the current loss on the buses, a dollar amount cannot be assigned to the system, but the loss across the system should be equal to or less then the SVC example given in section 6.5.

6.9.2   Transient Analysis

Fig. 6.22 and Fig. 6.23 show the voltage and current response to a fault on Line 5. The same fault was applied to this case as the original base case.
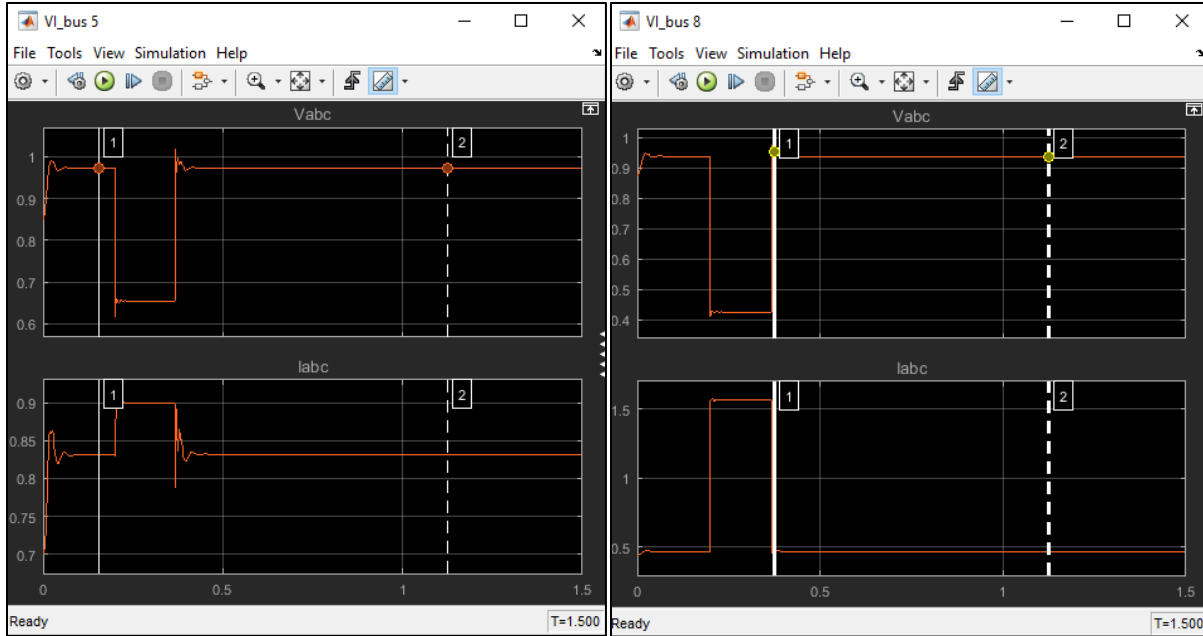
Fig. 6.22 (Left) Bus 5 voltage and current during a fault on Line 5. Fig. 23 (Right) Bus 8 voltage and current during a fault on Line 5.

The results from the fault on Line 5 for this case is nearly identical to the results from section 6.8. Therefore, only the differences will be analyzed here. The first difference is the per unit voltage on both Bus 5 and Bus 8 are slightly lower in this case. The current at Bus 5 increased due to the additional load as well. It appears the voltage for both the buses recovered in less time in this case, even with the additional load. The STACOM device coupled with the capacitor must have reduced the number of oscillations and the amplitude of the fewer oscillations. The current at Bus 5 had a larger post fault transient than the previous case. This is due to the large current swing provided by the STATCOM device. The waveforms responded nearly perfectly to the event. The final voltage normalized slightly lower than the case in section 6.8, but still well within nominal range. This solution is the most robust and precise of all the different cases explored. The cost is also the highest for this configuration. Referencing Fig. 2.2, the cost of the capacitor banks would be the product of 60 MVAR and $8/kVAR to total $480,000. The STATCOM would be an

60

even larger addition to the price. The cost would be the product of 50 MVAR and $50/kVAR to total $2,500,000. This three-million-dollar infrastructure addition would need to be strategically placed and systematically programed to break even and have a return on investment. The conclusion will compare the different cases overall feasibility and determine the best solution for all the variants implemented.

CHAPTER 7 - CONCLUSION AND FUTURE WORK

7.1   Conclusion

Power systems transform. Faults happen. The reaction to these events depends on the foresight of the planners, engineers and utilities. These people must work coherently to design the best solution with respect to required reliability standards, quality standards and the overall cost. The demand for the correct solution to prevent catastrophic failures depends on the informed consumer of energy and the governing energy reliability corporations. The information, research and results presented in this paper are solutions for a significant amount of power system failures. FACTS provide a method to ensure reliable, quality power to consumers. It is crucial to look at all the aspects of the power system, model different cases and variations when planning the feasibility of the FACTS components. It is also crucial to know the components strengths and disadvantages. How will this component affect the system in situation A? B? What about the combination of A, B and C with the combination of these components. The attempt was made throughout this paper to describe examples of functional results in differing situations.

The first objective of this paper was to identify the various commonly used industry FACTS, as seen in Chapter 2. The equations and theories were explained to implement them into power systems appropriately in Chapter 3. The tools to simulate the power system models were described in Chapter 4.

The second objective for this paper was to identify some of the typical locations and situations that would require FACTS. This was done through the variations presented in Chapter 5. This aspect of the paper took additional research to create models that would fail and could be solved with the implementation of FACTS. The situations modeled are definitely not inclusive but start the process for FACTS implementation in individual power systems.

The third and final objective of the paper was to illustrate the power of various FACTS components and coordinated combinations. The functional solutions were presented throughout Chapter 6. The combinations may differ in size and layout, but generally the concepts presented will function in a majority of different cases. Many combination trials were simulated and failed to meet standard criteria to be recorded in this paper. The principle of exploiting the advantages of different FACTS may lead to the best solution.

As a final conclusion to this thesis, the best choice will be selected for the variations presented above. The specific situation of an additional load center with a fault on a line in the system posed a common power system transformation. The two best solutions simulated installed a shunt capacitor with either a SVC or STACOM component. Both of the solutions cost significantly more than the addition of shunt capacitor banks in normal loading conditions. The necessity for the SVC arises when the fault is applied. As seen in the simulations, both the SVC and STATCOM normalize within required limitations. The STATCOM stabilizes much more rapidly than the SVC, but is a much larger size than the SVC as well. The cost difference between the two devices, at the current time, validates the choice for a SVC and Shunt capacitor installation at the additionally loaded bus. Additional components should be added to the installation as described in chapter 2, such as step-down transformers, harmonic filters, etc. This design would be the best solution to the variants applied in this particular power system.

7.2   Future Work

This thesis formulated solutions to several unique situations and analyzed the results. While the system solutions and analysis are complete for the cases examined, other cases should be explored to expand of the FACTS solutions. A larger, more integrated model should be used to verify the results and functionality of the FACTS and locations selected. The more developed

model could simulate more accurately installed power systems. With the developed system, ETAP should be used to design and coordinate protection devices. The protection schemes would be simple, but also reflective of industry standard designs. The simulation of the protection schemes would align the model even more closely with the actual power system. The many other result variables could also be examined to verify overall system functionality. In this paper, bus voltage was chosen as a simple yet encompassing variable of system health. The other system variables could include harmonics, frequency, volts/hertz, and current. As a final expansion of the model, load growth data could be requested from a utility to implement FACTS to meet the transforming grid.

The other future work for this area of study will be to develop the STATCOM device as a user defined module in ETAP. This would give a better comparison between the STATCOM and the other models simulated in ETAP. This UDM would require several levels of systems control, and an increased understanding of the software functionality. The implementation of block level transfer functions would require a block diagram example, testing and expected results data. This would be the most probable direction of future work within this topic of FACTS study.

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