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Simulation of Power System Response to Reactive Power Compensation

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Pierre Alexandre Bohême

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Dedication

This dissertation is dedicated to my family, Daniel Bohême, Maria Esther Conejo, Serge Bohême, and Olivos for giving me the basis and understanding of whom I am, and for believing in me. To the rest of my family in Costa Rica, for sculpting me.

A mi querida familia,

Aqui y Arriba.

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Abstract

The demand of power in the United States has doubled in the last decade. The constant increase in power flow has saturated the existing infrastructure. Modern advances in technology are changing the way utility industry increases the transmission of power throughout the country. Distributed Energy Resources are constantly improving their reliability and power capabilities.

This thesis will simulate the response of the power system to reactive power injection. The testing will take place in the Reactive Power Laboratory at Oak Ridge National Laboratory. The facility is an initiative by the U.S. Department of Energy to facilitate the development of new resource technologies.

The simulation will include the use of a synchronous motor and an inverter as reactive power compensation devices. The model will be compared to actual measured data from which it will be used in planned contingency cases to study the response of the power system.

Table of Contents

CHAPTER 1	1
INTRODUCTION	1
1.1 U.S. Power Grid	2
1.2 Reactive Power	6
1.3 Power Quality and Restrictions.....	8
1.3.1 Harmonics.....	8
1.3.2 Voltage collapse	8
1.3.3 Blackouts	11
1.4 Reactive Power Compensation Devices.....	13
1.5 Thesis Outline.....	14
CHAPTER 2	16
REACTIVE POWER COMPENSATION LABORATORY	16
2.1 Overview	16
2.2 Equipment.....	19
2.3 ORNL Power Network	22
2.4 Test Scenarios.....	24
2.5 Leading Technologies	26
2.6 Economics and Market.....	30
2.7 Summary.....	35
CHAPTER 3	36
REACTIVE POWER COMPENSATION	36
3.1 Overview	36
3.2 Power Flow Solutions	36
3.3 The Gauss-Seidel Method.....	41
3.4 Newton-Raphson Method.....	43
3.5 Synchronous Condenser.....	46
3.5.1 Steady State	47
3.5.2 Transient analysis.....	49
3.6 Inverters	51
3.7 Summary.....	54
CHAPTER 4	55
SOFTWARE MODELING AND SIMULATIONS	55
4.1 Overview	55
4.2 SKM Model Version.....	55
4.2 Power World Simulator	59
4.3 Control System.....	60
4.4 Summary.....	64
CHAPTER 5	65

EXPERIMENTAL RESULTS	65
5.1 Test Scenarios Set up	65
5.2 Test Case 1A Synchronous Condenser VAR Injection.....	68
5.3 Test Case 1B Inverter VAR Injection.....	70
5.4 Model Assumptions	75
5.5 Summary.....	76
CHAPTER 6	77
CONCLUSIONS AND FUTURE WORK.....	77
6.1 Overview	77
6.2 Conclusions	77
6.3 Future Work	79
BIBLIOGRAPHY / LIST OF REFERENCES.....	80
APPENDICES	84
VITA	86

List of Tables

Table 2.1 Synchronous Motor Nameplate Data. Motor built by Electric Machinery.....	21
Table 2.2 Synchronous Motor Nameplate Data. Motor built by General Electric	21
Table 2.3 Inverters Nameplate Data. Programmable Inverters by Powerex	21
Table 2.4 Power Supplies Data. 6.6 kW and 150 kW Magna Power Electronics for Synchronous Motor and Inverters respectively.....	21
Table 2.5 Reactive Power Compensation Devices and Performance Characteristics.....	33
Table 4.1 Bus types with input variables needed.....	58

List of Figures

Figure 1.1 North American Electric Reliability Council Regions and Interconnections in the Contiguous United States, 2006 [1]	3
Figure 1.2 NERC - Summer Internal Demand and Capacity Resources. [6]	4
Figure 1.3 U.S. Electric Power Industry Net Summer Capacity, 2004. Net Electric Power Generation by Fuel Type. [3]	5
Figure 1.4 Power Triangle Relationships.	7
Figure 1.5 One Line Representation of an Electrical Power Layout. [9]	10
Figure 1.6 Operational Limits of the System for Voltage Collapse [9].	10
Figure 1.7 NERC Model, 2001. Predictions on Power System Failures Affecting from 10 Thousand to 10 Million Customers. [12]	12
Figure 2.1 Reactive Power Laboratory Layout [31].	17
Figure 2.2 ORNL Main Substation and 13.8 kV Feeders.	22
Figure 2.3 One-Line Diagram of 3000 Substation.....	24
Figure 2.4 (A) Investment Costs for SVC/STATCOM. (B) Investment Cost for SC, TCSC and UPFC. [22]	34
Figure 3.1 Reactive Power Dependence on Real Power Production for a Synchronous Generator. [30]	47
Figure 3.2 Equivalent One-Phase Circuit for the Synchronous Machine showing the Voltages and Currents as Phasor Quantities. [20]	48

Figure 3.3 Equivalent One-Phase Circuit for the Salient-Pole Synchronous Machine showing the Voltages in d and q-Axis [9].	50
Figure 3.4 Single-Phase H-Bridge Inverter [7].....	53
Figure 4.1 SKM One Line Simulation	57
Figure 4.2 (A) One-line Voltage profile. (B) Voltage Profile Equivalence.	58
Figure 4.3 Closed-Loop Feedback Control for the Synchronous Condenser [8]	63
Figure 4.4 Inverter Fixed-Frequency current control [8]	63
Figure 5.1 PowerNet 3000 Substation Snapshot.....	66
Figure 5.2 Measured Synchronous Motor Inrush Current at Startup.....	67
Figure 5.3 Measured Synchronous Motor Voltage at Startup	67
Figure 5.4 SKM Simulated Voltage and Current.....	68
Figure 5.5 Voltage and Current magnitude Comparison Between SKM Simulated Data and Real Time Data Measured at the Synchronous Condensers' Terminals.....	69
Figure 5.6 Voltage and Current Comparison at the Substation	69
Figure 5.7 Real and Reactive Power Comparison at the Substation.....	70
Figure 5.8 Load Current measured by Inverter's Control System.	71
Figure 5.9 Utility Current Tracked by the Inverter.	71
Figure 5.10 Inverter Compensating Current	72
Figure 5.11 Inverter System Voltage	72
Figure 5.12 Real and Reactive Power injected by Inverter.	73
Figure 5.13 Voltage and Current Measured Data in Contrast with SKM Simulation from Inverter.....	74
Figure 5.14 Substation Voltage and Current Profile.	74

Figure 5.15 Comparison of Measured Reactive Power and SKM.....	75
Figure 5.16 Comparison of Different Reactive Power Compensation Devices	76

Chapter 1

INTRODUCTION

The power industry began with Thomas Edison's Pearl Street electricity generating station in September of 1882. The requirements of higher efficiencies and profit led to a centralized generating station 20 miles away from its diverse loads. This topology was seized by industries across the nation to conform the first utilities. However, this ability of having generators isolated from their loads brought difficulties in the areas of stability, reliability, efficiency, control, and economy. Utilities, in their struggle to thwart some of these issues, made agreements including interconnections to help each other in case of contingencies.

The changing structure of the power industry has led to a de-regulation system in which utilities, transmission, and generation compete to provide the cheapest service. Consumers are able to buy directly from the generating companies across state lines, and thus a competing market exists. The problem with this structure is that the power grid was planned for providing power locally with few interconnections to provide for excess generation as well as contingencies. Moreover, power cannot be delivered to a specific location within a grid, mainly because it is delivered in a parallel manner. The stability of the system then relies on a small base load and the economic interactions performed in weekly and sometimes even daily basis. The system becomes less predictable, reliable and more congested. Cooperation between the many parties involved can make the system unstable especially during system contingencies.

Power companies charge residential customers for watts consumed, and thus generators are run to produce the maximum real power while still maintaining a profit margin. The transmission lines consume reactive power as they inherently produce inductive losses. Large motor loads such as air conditioning units, compressors, and water pumps consume large amounts of reactive power while starting because of their inductive nature. This creates sags in voltage and can contribute to the destabilization of the power grid. The flow of this reactive power is controlled by generation, transmission and distribution companies through the use of capacitors, phase shifting transformers, static VAR compensators (STC), and flexible AC transmission systems (FACTS). Several proposals have been made for greater system stability including direct involvement of government agencies like the Federal Power Commission now Federal Energy Regulatory Commission (FERC) to control and regulate regional and overall grids.

In this thesis, the use of Distributed Energy Resources (DER) for reactive power compensation will be analyzed. A comparison of Static and Dynamic compensators will be made. Different equipment configurations and possibilities will be studied according to their cost, efficiency, reaction time, dependability, maintenance and ease of control.

1.1 U.S. Power Grid

An electric power system is typically comprised of generating plants, transmission lines and distribution or sub-transmission lines. Transmission lines are normally high in voltage ranging from 115 kilovolts (kV) up to 765 kV. Subtransmission systems are in the range of 69 kV to 138 kV, and distribution systems deliver power to

the customers, operating from 0 to 69 kV. Transmission lines are simple conductors with physical limitations. As they carry large amounts of power through extensive territory, they may overheat because of their resistive and inductive characteristics and subsequently increase the $I^2 (R + jX)$ losses. For this reason, it has been designed to operate at high voltage levels to keep losses at a minimum. The transmission system is then one of the key factors in maintaining a constant, reliable, power flow.

The U.S. power system has evolved into a complex network of three major power grids, The Eastern Interconnected System, the Western Interconnected System, and the Texas Interconnected System. These three bulk systems are further subdivided into 8 regions according to the North American Electric Reliability Council (NERC) as seen in Figure 1.1. [1]

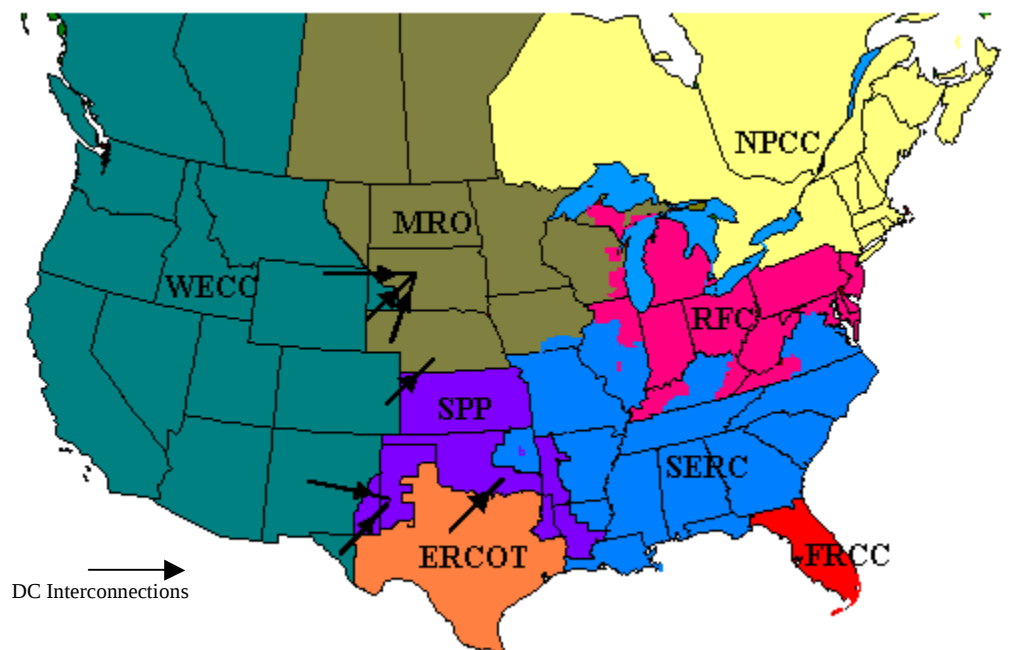


Figure 1.1 North American Electric Reliability Council Regions and Interconnections in the Contiguous United States, 2006 [1]

Each region maintains the stability of the system by making utilities operate at certain conditions and keeping interconnections. These high voltage interconnections are designed to transfer electrical energy from one part of the network to another. Although in essence they exist to aid one another, in reality the transfers are restricted because of inadequate transmission capability and the adversity in the execution of contractual arrangements.

In the last ten years, power demand has increased 2% yearly, as seen in Figure 1.2 [6]. The projections of demand after 2005 report a higher yearly increase for the next ten years. In order to keep up with demand, existing power generating facilities have been upgraded, more efficient ones have been built, and other means of power production, such as Distributed Energy Resources, have started to make an impact.

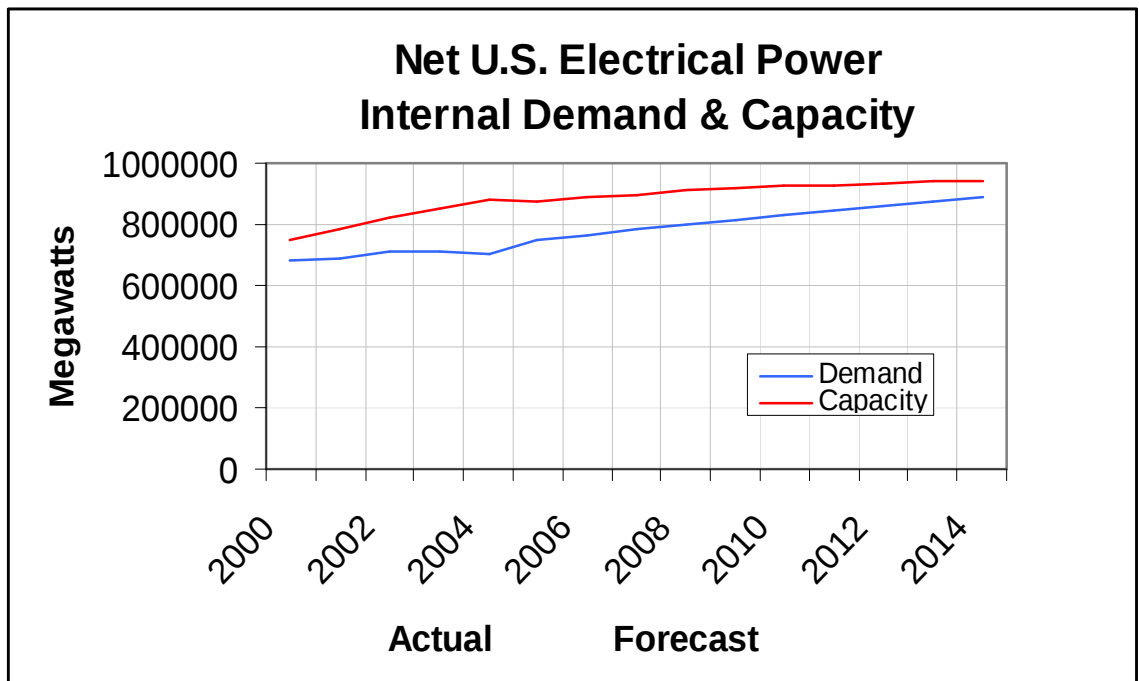


Figure 1.2 NERC - Summer Internal Demand and Capacity Resources. [6]

Greater capacity of generation however, is not enough to offset the constant growth of demand. Of the 963 Giga-watts of net production in 2004, only 1.9% pertained to DER as seen in Figure 1.3[3]. NERC and DOE are investing in new venues to maintain a constant growth of the system. Other options include load commitment and load shedding to reduce the strain in the system at peak demand.

The problem now lies in the promotion of transmission lines because the existing infrastructure is working at its limit. New transmission lines are expensive to install, not to mention the amount of time it would take to upgrade the existing lines. There are many constraints on the transmission system including thermal restrictions, voltage limits, operation, stability, optimal power flow, and preventive operation for security purposes.

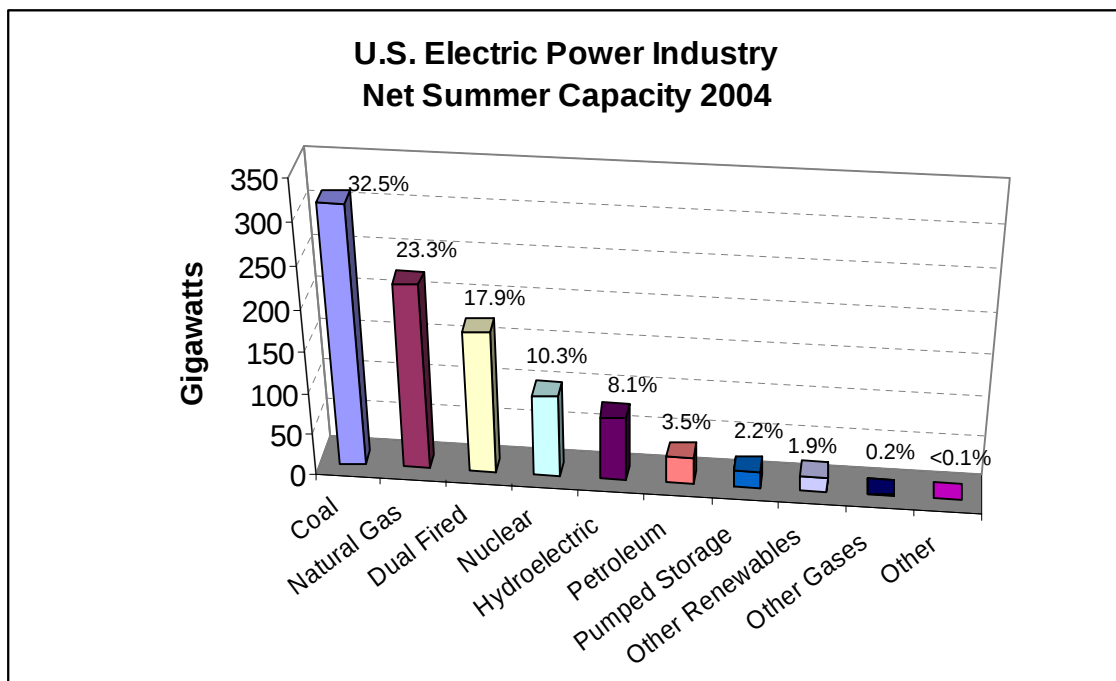


Figure 1.3 U.S. Electric Power Industry Net Summer Capacity, 2004. Net Electric Power Generation by Fuel Type. [3]

The leading technique used to transmit more power is to raise the voltage within the system. Voltage regulation in a system is complicated; it involves the increase in voltage of generators, transformer settings, replacements, breakers and other protective equipment. Coordination of interconnections between utilities must also be considered to prevent reactive power flows and thus voltage fluctuations. To control these fluctuations, reactive power is inserted or extracted, having a direct impact on voltage and system stability. There are many technologies used to manipulate the reactive power flow, but before these are presented, a better understanding of reactive power phenomena and its limitations must be discussed.

1.2 Reactive Power

Reactive power is an AC characteristic in which electric power moves back and forth between the magnetic field of an inductor and the electrical field of a capacitor. Unlike a resistor, inductors and capacitors store energy momentarily and thus reactive power oscillates between the two. Reactive power occurs when the voltage and current are not in phase, and unlike real power it does not perform work. It is calculated as the square root of the difference between the square of the apparent power (volt-amperes) and the square of real power (watts). Their relation can be better appreciated by the Power Triangle, as seen in Figure 1.4.

The angle between the voltage and the current is known as the power angle, it has a direct impact on how much power can be used for work, and how much is used in magnetic or electric fields. This angle determines the power factor, and has a direct impact on system

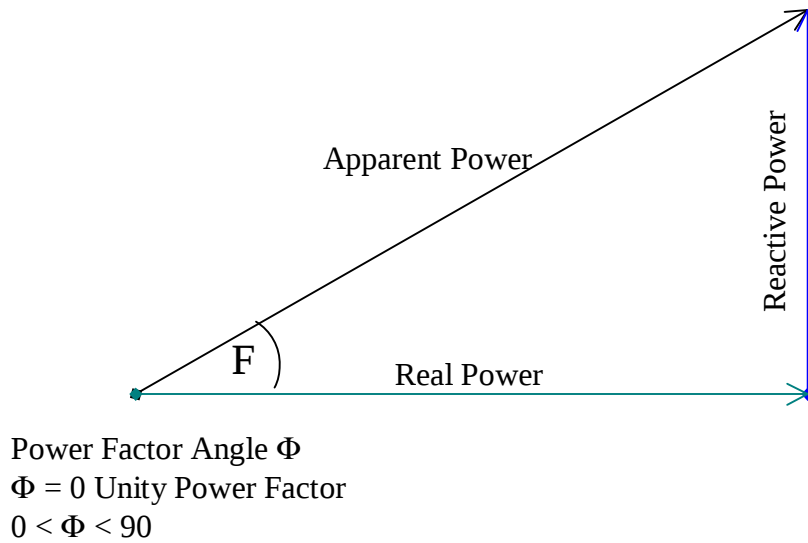


Figure 1.4 Power Triangle Relationships.

voltage and stability. The power factor determines whether reactive power needs to be injected or absorbed. In normal operations, the ideal power factor is unity, in which only real power is being delivered. This task is complicated by non-periodic loads including starting currents of large motors and non-linear loads such as power electronics that draw reactive power. When the power factor is lagging, the current is delayed in comparison with the voltage, the opposite happens when power factor is leading.

Reactive power is needed to maintain the voltage at a constant level. Transmission lines absorb reactive power because of inherent properties. Motors also need large amounts of reactive power to produce the magnetic fields needed for operation. Since generators are normally far from these motors or other loads, long transmission lines absorb large amounts of reactive power making it unreasonable to send reactive power directly from the generators. Moreover, electricity producers charge for real power. An efficient

economy dictates having reactive power compensators next to the loads to minimize the losses.

1.3 Power Quality and Restrictions

The electric power system needs to be stable, reliable, and to certain extent, predictable. The stability of the system depends on the frequency being kept at a constant 60 cycles. This is maintained by mutual agreements between the generating and consuming parts to keep a strict control over their equipment. Large loads that need special starting techniques and equipment that uses switching devices and power electronics induce harmonics and voltage distortions into the system.

1.3.1 Harmonics

Harmonics are voltage or current waveforms that operate at a different sinusoidal frequency. These are normally a multiple of the fundamental frequency. The rapid change in voltage and current waveforms at industrial sites such as paper mills, water pump stations, steel mills, and arc furnaces destabilize the system, and since they are non periodical, they cannot be predicted. Since most industrial sites work at voltages of 69kV and below, they are required to maintain a Voltage Total Harmonic Distortion (THD) of 5.0% or less. This however, is unacceptable at higher levels, and thus THD is kept at 1.5% or below in transmission levels.

1.3.2 Voltage collapse

Voltage must also be kept at a level throughout the system. Loads and end consumer devices have strict operating limits with a margin of tolerance (normally 10%). If the voltage fluctuates beyond these limits, the operation may be impaired causing

equipment damage and ultimately failure. Moreover, these system step levels at generation, transmission, and distribution rely on frequency and voltage set points for operation and stability. Any deviation from the tolerated values can ultimately cause a blackout. Hence voltage, and the variables that influence it must be controlled.

When large motors start, they require great amounts of reactive power to induce the magnetic field; this has a direct impact on the system voltage creating momentary sags. As the motor reaches a defined speed, the power requirement drops, and the voltage oscillates until reaching the set point. To counteract these fluctuations, reactive power compensators, such as capacitors are used. The control of these on a local basis can be predicted and dealt with. But the rapid growth of the consumer side and the inadequacy of the transmission lines can jeopardize the integrity and stability of the system.

The basic model of the electric system can be seen in Figure 1.5 [9]. In this one-line representation, the supply voltage must be higher than the receiving end in order to keep a balanced unity power factor. If the voltage at the terminals keeps changing in an uncontrolled manner, it can increase or decrease to a point at which voltage collapse is inevitable.

Once voltage deviates from its normal operation, it has a finite time and value to which the system can recover to stabilize, as shown in Figure 1.6 [9]. If the system cannot recover from either voltage fluctuations or frequency instability, then the generators must be disconnected from the grid to prevent damage. This in course gives way to local blackouts that can escalate in a domino effect leaving millions of people without electric power.

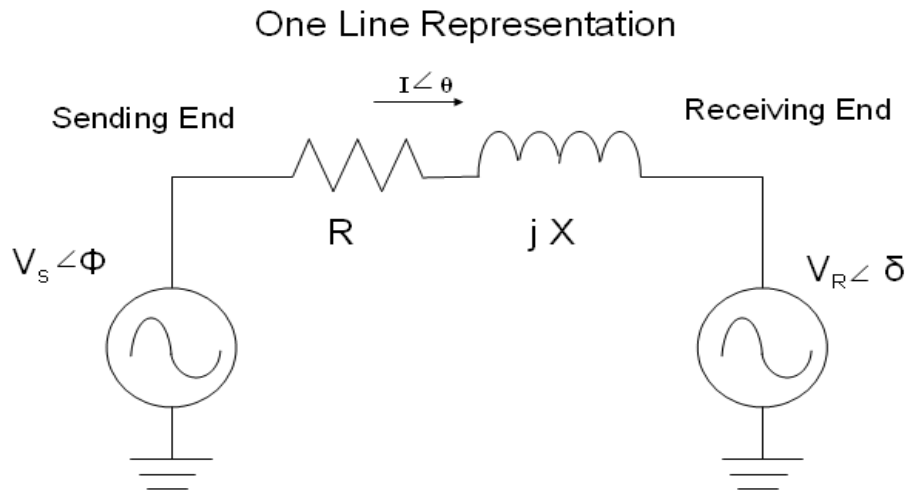


Figure 1.5 One Line Representation of an Electrical Power Layout. [9].

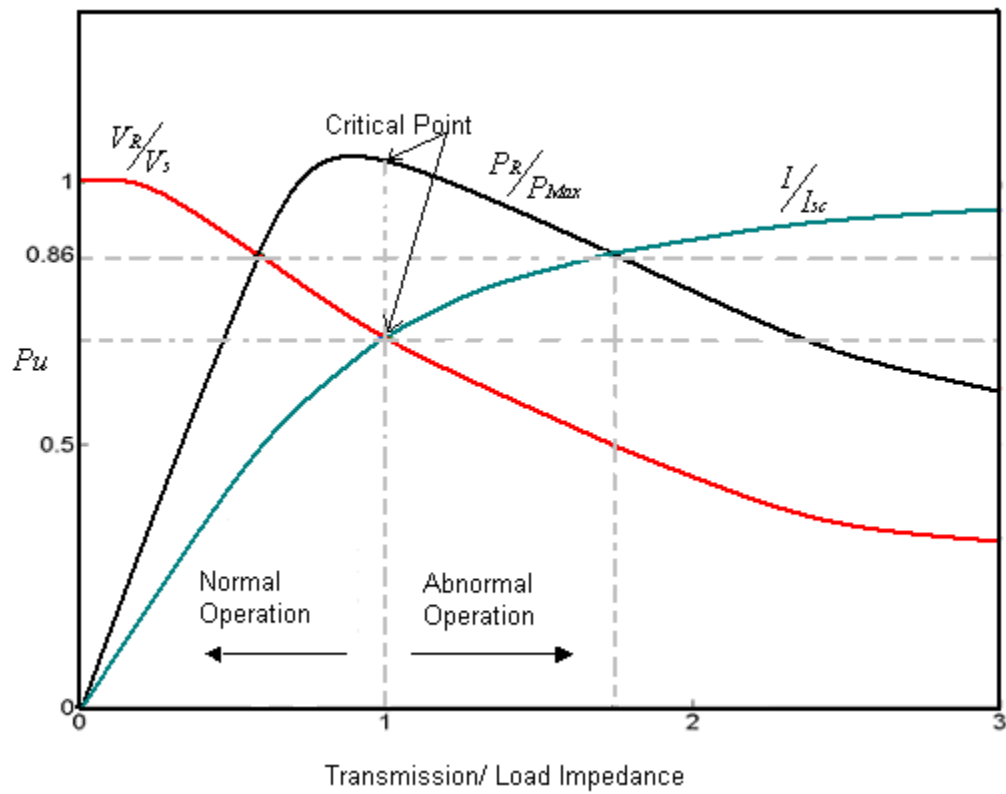


Figure 1.6 Operational Limits of the System for Voltage Collapse [9].

1.3.3 Blackouts

At the turn of the millennium, recent blackouts around the world have created an impact on electric system control, operation and to a point, predictability. Although each blackout has different root causes, they all have common consequences that spiral towards chaos. The electric system grids around the world are generating more while the transmission and contingency systems are left behind. The recent blackouts in August 14, 2003 in United States and Canada, August 28, 2003 in London, September 23, 2003 in Italy and May 25, 2005 in Moscow, Russia have left the world with great concerns over the nature of these blackouts, the main causes, and possible solutions.

The common existing model shows that a contingency affecting a population of 10 million people or more should happen once every ten years, as seen in Figure 1.7 [12]. While the model is accurate in the United States, it leaves much to be desired in Europe. Since the U.S. electric power system is turning towards deregulation, a broader study should be made on the way to control power exchange between regions. Europe is a model of what the future power system will be, where power will be delivered by the cheapest source. The control of this power, however, can give way to the problems being faced by Europe at this moment.

Each system is different, and blackouts have many causes, from natural effects such as ice storms, lightning, and earthquakes, to human factors such as tree trimming, poor maintenance, and system overloads. Although there is no direct control over natural occurring events, contingency plans should be readily available. Blackouts originate from frequency instability, voltage collapse, and load mismanagement, which to an extent can be controlled by reactive power.

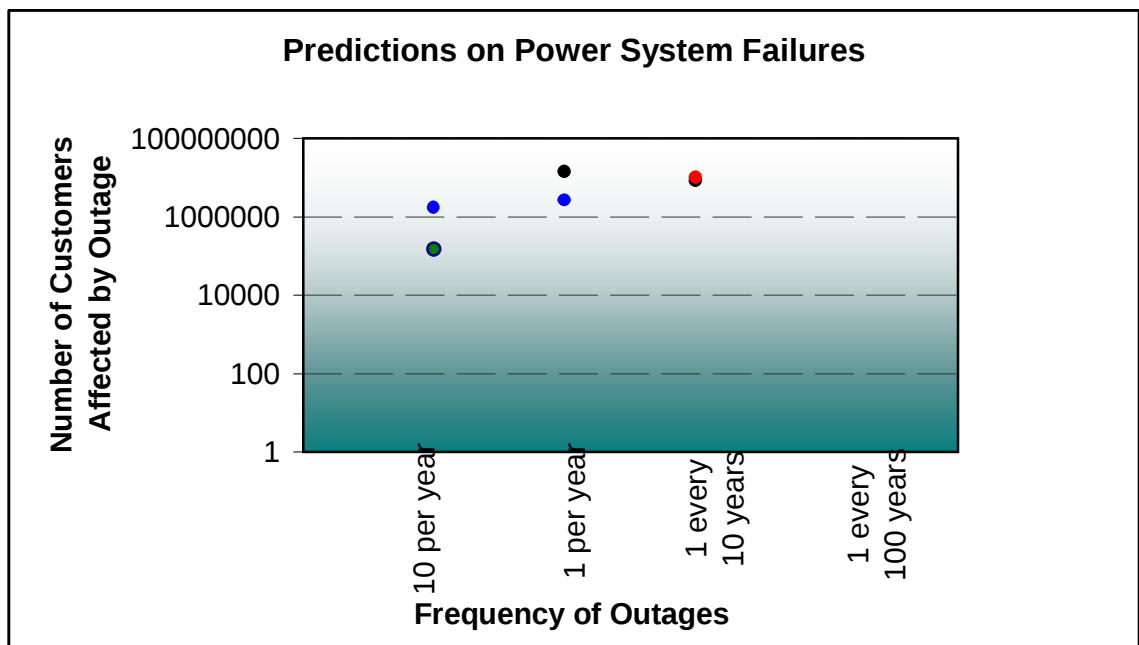


Figure 1.7 NERC Model, 2001. Predictions on Power System Failures Affecting from 10 Thousand to 10 Million Customers. [12]

Local reactive power consumption is generally compensated by capacitors. Industry uses series and shunt capacitor configurations to eliminate voltage fluctuations and harmonics. Utilities in general use capacitors to increase the power transmission or distribution capability as well as to improve static and dynamic stability. The placing of capacitors along different paths helps improve and optimize voltage and power flow in the lines. In doing so, the system can be operated closer to its thermal limit, reducing losses and voltage drops.

Capacitors however are restricted to injecting reactive power. If the voltage rises, and there is no load to consume the reactive power, the capacitor output will only contribute to the increase of voltage. Moreover, capacitors can be dangerous in short circuit scenarios because they produce high over-voltages. For this reason, reactors and

special capacitive configurations are constantly developed to assure proper system stability and reliability.

1.4 Reactive Power Compensation Devices

Power electronics based compensators use devices such as Thyristors to control the flow of reactive power. A typical Static Var Compensator (SVC) will use a Thyristor Controlled Reactor (TCR) a Thyristor Switched Capacitor (TSC) or Reactor (TSR) and AC Filters (ACF) to adjust the output of the power. The TCR controls the current amplitude through the reactors. This is done by constantly changing the thyristor firing angle from 90 to 180 degrees and thus supplying a controlled flow of reactive power. TSCs control capacitors by switching them on and off. The effective bank switching gives a stepwise control of capacitive power. TCR working in conjunction with TSC can give a smooth linear compensation. Finally, AC Filters are used to absorb harmonics generated by the TCR, while adding capacitive power used to compensate non-active power.

The application of SVCs is somewhat limited because they are used mainly in substations or the transmission side of a transformer. This in turn with their slow reaction times make SVCs an improper solution. Rolling mills and furnaces have fast cycle-to-cycle variation, high inrush currents and voltage variations. The need for fast compensation response time and proximity to the loads, make Dynamic VAR Compensators an ideal solution.

Dynamic var compensators have derived from static var compensators and static synchronous compensators. The principle is to use inverters to control the magnitude of

the voltage output. In doing so, reactive power can be either injected or absorbed. In the synchronous condenser, the field is overexcited to provide reactive power or used as a motor to absorb it. There are many different systems used to compensate reactive power. The most relevant will be discussed in Chapter 2.

1.5 Thesis Outline

The purpose of this thesis is to simulate the power system response to different reactive power compensation devices. A synchronous condenser and an inverter will be simulated using a commercial power flow solution program. This simulation in turn will be compared to real-time measured data. The information gathered will then be analyzed and used to enhance the existing program for future simulations. The reason for the simulations is to use them in lieu of tests to predict the system behavior. Tests will be conducted after response can be predicted, and thus equipment malfunction and damage can be minimized.

Chapter 1. A brief review of the U.S. power grid and its constraints has been presented in this chapter. The electrical system has much vulnerability that needs to be controlled and taken into consideration for future planning and optimization. Some of the power quality issues and system limits have been introduced. The primary focus of this Thesis is to conduct research in the area of reactive power compensation. Two methods have been discussed, static var compensation, such as capacitors and SVCs, and dynamic var compensation, such as synchronous condensers and STATCOMS.

Chapter 2 will give an insight of DOE's plan to encourage the use of DER for reactive power compensation. A description of the lab, its equipment, the distribution layout, and the test cases will be given. It will conclude with a comparison with other leading technologies.

In Chapter 3 reactive power will be analyzed using $p-q$ model theory. The synchronous condenser and inverters will be modeled accordingly, and the analysis tools for power flows, including Newton-Raphson and Current Injection methods will be scrutinized in detail. Finally, different operation points of large loads will be discussed.

Chapter 4 will compare different software packages available to ease the formulation of load flows. Assumptions of the model will be thoroughly investigated as well as the control system.

In Chapter 5, the simulations are compared with real time data taken from different meters throughout the system. Different test scenarios are evaluated and discussed. Several alternatives to reactive power injection are analyzed for ease of control, economic impact, and speed response.

Chapter 6 will conclude the thesis. An overview of the ideology, simulation results and conclusions will be given. It will conclude with suggestions of future research and overall direction of reactive power compensation.

Chapter 2

REACTIVE POWER COMPENSATION LABORATORY

The Reactive Power Compensation Laboratory is a multi- year research project within Oak Ridge National Laboratory (ORNL). The objective is to integrate Distributed Energy Resources (DER) to produce and convert reactive power. The Department of Energy (DOE) is promoting through this project the interaction between electric utilities and Independent System Operators (ISO) to provide a better, cost-effective service while maintaining system stability and reliability.

In this Chapter, an overview of the Reactive Power Laboratory (RPL) and the idea behind its implementation will be discussed. Subsequent to its purpose, a brief description of the equipment and design will be given. The chapter will then move on to describe ORNL's power distribution system and the RPL's location within the grid. The chapter will then give a portrayal of data acquisition systems and simulations. Finally, it will conclude with a discussion other technologies being studied and the economic feasibility of each.

2.1 Overview

The RPL is a small facility of 2500 sq ft. Two different circuits that allow for different implementations and test scenarios service the lab. Currently the lab has a 250 hp synchronous motor, a 75 hp induction motor, 3 programmable inverters with ratings up to 300A, and two dc power supplies for excitation purposes of 6.6 and 150kW. The inverters and motors are placed on different panels and subsequent circuits as shown in

Figure 2.1[31]. The reasoning behind it is to give versatility of test scenarios for both shunt and locally. The RPL has two meters located at the DER and at the load side of the line feeders to gather data on the local impact of the current injection. Existing digital meters on each circuit and main substation relaying give access to data on a more global basis. The data acquired is then stored for future analysis by ORNL.

The main purpose behind its implementation is to test for different types of DER while providing real and reactive power. The multi year research facility has a power distribution grid and multiple loads available for a wide variety of test cases. The design of each test and control proposal is specific to the equipment in use and case. Three types of operations have been designed for both the synchronous condenser and the

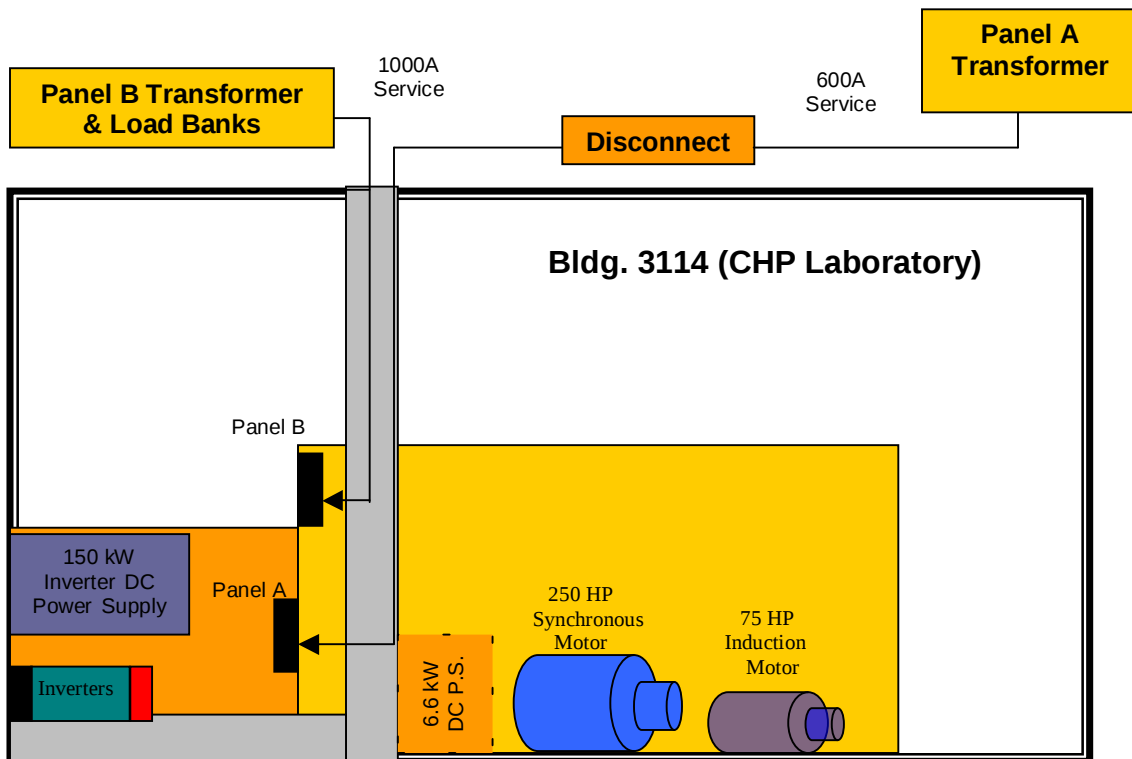


Figure 2.1 Reactive Power Laboratory Layout [31].

different inverters: forecast, immediate time response, and ancillary services. A 500 kW resistive load and a 375 kVAR inductive load both with remote control are available for test case scenarios and to control the voltage variation.

The forecast mode is simply a state in which an increase in load is known by the utility or distribution system, e.g. peak hours, and the system operator can increase the flow of reactive power before the load starts, increasing the voltage moments before the demand is needed. The immediate time response will require fast action from both equipment and control units, as such it must be able to respond to voltage swings in a manner of cycles to keep the system stable. This approach is exhaustive, requiring the interaction and synchronization of available means, in order to avoid double resources on a same location and occurrence.

Lastly, ancillary services are the provision of providing real or reactive power according to a pre-negotiated schedule or control. Contracts with other utilities and local industry include load shedding, spinning reserve utilization, and DER allocation. These can help at key moments, and even though the response needs to be fast and direct, it does not require a reaction in terms of cycles.

The last situation to be designed and studied is the use of both static and dynamic reactive compensation schemes to work together. For this, capacitors can be used to provide a base reactive power, and the synchronous condenser made to control the overall reactive power fluctuation of the system, leaving the inverters to do the immediate control of transients or fast oscillations in the system.

2.2 Equipment

The reactive power laboratory is still under development. Although tests are implemented on a continuous basis, new equipment and control methods are considered according to budgetary constraints and design feasibility. The goal is to have as many DER available as possible to make a fair comparison between each, or juxtaposition of several of these.

The start up point for the tests include two synchronous motors, an induction motor, capacitor, inductive, and resistive banks, and a combination of different size inverters. Sizeable dynamic loads, a fuel cell, and a micro-turbine are still under consideration for future tests. A description of the equipment, including nameplate data and limitations will be specified at this point.

The synchronous motor is a rotating machine that can be operated as a synchronous condenser. The mode of operation is accomplished by adjusting the field excitation current. The synchronous motor is started as a regular motor, once it achieves unity power factor or operating at a synchronous speed, the field can be overexcited by an external agent. Since the motor is not loaded, and as the field excitation is increased externally in this case by a power supply, the current becomes higher and is injected back to the grid. At this point, the current I leads the voltage V , and the synchronous motor is said to be injecting kVAR into the system, thus becoming a source of capacitance or synchronous condenser.

The lead advantage over capacitors is that the motor can be used to either inject or consume reactive power at various levels without having the need to switch on and off different units. The versatility of the synchronous condenser to be either in motoring or

generating mode can help by reducing stress on the system on a continuous base and fast speeds. The amount of kVAR that a machine can inject depends on its own physical parameters and limitations as well as those of the power supply. The nameplate data of the 250hp synchronous motor can be found in Table 2.1. The motor was built by Electric Machinery, and rebuilt by Sumter Electric in 2003. In this particular case, the data is derived from consequent transient starting tests to determine the new set points and limits. The second synchronous motor is used as a dynamic load on the system. This 500 hp synchronous motor will give an insight of impacts to be expected on the system on both transient and steady state applications. It will also be used as a synchronous condenser to see different sizing impacts. The nameplate data is shown in Table 2.2. The nameplate data helps in the proper modeling of the synchronous condenser for simulation purposes. It also serves as guidelines to operate each machine at its normal range without overheating and damaging the motors themselves. Preventive measures are in place through circuit breakers and fuses in the power supply and panels to avoid damage to equipment.

At this time, three different programmable inverters of 75 A, 150 A, and 300 A, shown in Table 2.3, are the alternate DER used to control and compensate reactive power. The three inverters, manufactured by Powerex, use Insulated Gate Bipolar Transistors (IGBT) with speeds up to 20 kHz and can operate at voltages up to 800 Volts. Inverters control reactive power by means of voltage output and phase angle variation.

The synchronous motor is excited by a small 6.6 kW dc power supply as seen in Table 2.4. With a maximum supplying capacity of 17A_{dc}, the power supply aids the synchronous condenser with the injection of up to 315 kVAR. The other power supply,

Table 2.1 Synchronous Motor Nameplate Data. Motor built by Electric Machinery



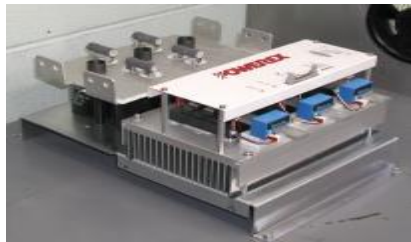
Synchronous Motor Nameplate Data			
Model	6 Pole	3- Phase	
Serial	250 Hp		
	Voltage	Current	Speed
Normal/Unity	480	315A	1200
Excitation	230 Vdc	10.6Adc	

Table 2.2 Synchronous Motor Nameplate Data. Motor built by General Electric



Synchronous Motor Nameplate Data			
Model	5TS821054A12	6 Pole	3-Phase
Serial	FD8370970	500 Hp	
	Voltage	Current	Speed
Normal/Unity	480	125A	1200
Excitation	250 Vdc	20 Adc	

Table 2.3 Inverters Nameplate Data. Programmable Inverters by Powerex



Inverters Nameplate Data			
Model	POW-R-PAKTM	3 Phase	IGBT
No.	Voltage	Current	Speed
1	Up to 800V	75 A	20 kHz
2	Up to 800V	150 A	20 kHz
3	Up to 800V	300 A	20 kHz

Table 2.4 Power Supplies Data. 6.6 kW and 150 kW Magna Power Electronics for Synchronous Motor and Inverters respectively.



Power Supplies – 3Phase		
Model	PQ-D375-17	170 mV ripple
Model	MTD-800	300 mV ripple
	Voltage	Max I
6.6 k W	375 Vdc	17 Adc
150 kW	Up to 800Vdc	180 Adc

shown in Table 2.3 has a rating of 150 kW and is especially designed for inverter application. The power supply can give a maximum of 180 A_{dc} at voltages up to 800 V_{dc}.

2.3 ORNL Power Network

The electrical power at ORNL is parallel fed by two 161 kV lines. A main 161/13.8 kV substation provides power to the entire Laboratory through 13.8 kV feeders and 2.4 kV circuits. Although the overhead 13.8 kV lines have not changed much since 1960, the demand of power has increased an average 0.5 MW per year in the last decade. The average electrical load is 26 MW with a 9 MVAR peak demand.

The main substation, as seen in Figure 2.2, supplies the power through a radial distribution system comprised of eight 13.8 kV feeders covering more than 10 square

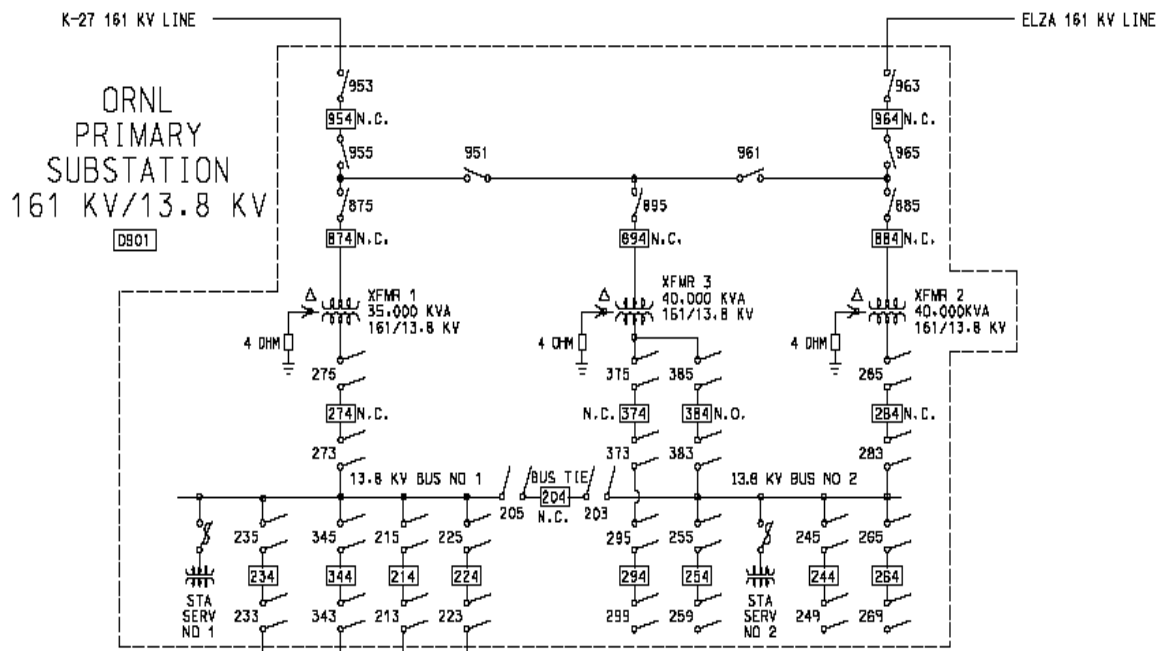


Figure 2.2 ORNL Main Substation and 13.8 kV Feeders.

miles of service area [13]. These feeders extend 22.4 miles to provide power to seven 13.8/2.4 kV substations and various facilities. The consequent substations supply thirty-eight 2.4 kV circuits that extend an extra 12 miles and thus give power to the remaining facilities.

The 2.4 kV circuits are isolated from each other with isolation switches again for contingency cases. Tiebreakers between panels and switchgear are normally open and are used mainly for maintenance issues. The transformers at each substation are mainly 5000 kVA and have an impedance of 5.5 to 5.6% to minimize power circulation between them.

The 2.4 kV substation that provides power to the Reactive Power Laboratory is number 3000. The substation feeds 10 circuits and is divided with an equal number of feeds on the east and west side, as seen in Figure 2.3. It is powered by two main 13.8/2.4 kV transformers that are protected by circuit breakers 101 North and 101 South. Each breaker is responsible for the operation of half of the circuits, with a tie between them to keep the voltages balanced. Two 900-kVAR capacitor banks on each side help regulate the power factor and voltage.

Two circuits emanating from 3000 Substation power the Reactive Power Laboratory. Circuit 2 feeds the 150 kW power supply and inverters, while circuit 4 provides power for the 6.6 kW power supply, the 250 HP synchronous motor, and will provide power in the future for the 100 HP induction motor. Circuit 2 also provides power to motor 2-5, a 500 HP synchronous motor used to drive a DC generator. The 500 HP motor will be used in the future as a load, and possibilities to use it as a parallel synchronous condenser are being studied.

two sets of data are acquired, in the morning and afternoon. ORNL is diverse in its loads, many heavy loads such as motors, accelerators, pumps and air conditioning units work at different schedules, having a wide range of impact depending on the time of day. The same tests are conducted during winter and summer for the same reasons, with the latter having a greater impact and overall strain on the power grid.

First, the synchronous condenser is tested, the software model simulates with capacitor banks in its stead to have a general idea of what kind of impact can be expected. Next, a generator replaces the capacitors, and again, the data is gathered for future analysis.

Lastly, the synchronous condenser is used, and the data compared with the previous two. The amount of kVAR injection is compared to make an assertion of which method is more economical, reliable, efficient, but more importantly, which has the quickest response time.

The second step is the actual testing of the synchronous condenser, which takes place in the reactive power lab. Meters at different locations give data on the overall impact of current injection. The importance of their locations gives information on the local and global impact of reactive power injection.

Until now, the tests have been done without placing any strain on the system. The next step is to use resistive and inductive banks to simulate a load. Again simulations are done, real tests are performed, and data is analyzed. Finally real loads are used, in this case, a 500 Hp synchronous motor. This load is located in the same circuit as the inverters (circuit 2), which is also powered by 3000 Substation. It is located 300 ft from the Reactive Power Laboratory, and since there are no significant loads on the same circuit, and an assumption of local impact can be made.

The next step is to repeat all previous tests, but now using the inverters. In these case scenarios, reactive power injection is the primary target, with harmonic distortion as a second.

Finally a global impact will be simulated, with a 300Hp synchronous motor on a different circuit and more than a mile of distribution cable (2400V) to have a greater impedance and different loads on the system. At this point, general assumptions can be made of the overall effectiveness of the dynamic simulations.

Later test case scenarios include the reduction of capacitor banks in the substation to be substituted with the dynamic reactive power compensators to measure the efficiency of the system.

2.5 Leading Technologies

The Department of Energy has been working together with power generating companies, utilities and private industry to find different DER that are economically viable, environmental friendly, and can make an overall positive impact on the grid. Power Generating and Distributing companies such as Tennessee Valley Authority, Southern California Edison, and Wisconsin Public Service are constantly investing in innovative technologies that will grant them a reliable, efficient, and cost effective system. These companies have worked in conjunction with private industry to research, build, and test leading technologies such as SuperVars [15], the “Avanti, Circuit of the Future”[16], and Real and Reactive Superconducting Magnetic Energy Storage systems (P-Q SMES [17]). Power electronics play a major role in today’s applications. In the past, semiconductor switching has been limited in voltage and current applications because of thermal

confinements. DOE currently has ongoing research and partnerships involving universities, private companies and national laboratories to relieve the economic burden on these companies, and thus assist in the development of state of the art technology. The role of power electronics has augmented with time. In today's applications, semiconductor devices are used in storage devices, variable speed drives, interconnection between AC-DC transmission systems, solid state-current limiting devices, and more to the point, interconnection of DER and voltage regulation/control devices.

The use of inverters can convert virtually any DER into a reactive power compensation unit. Inverters connect to the grid and subsequently can inject current at any power angle with respect to the system voltage. They depend on a power supply for excitation and controls, thus DER can supply real and reactive power through inverters.

There are many DER used for generating energy through the U.S. Although all of them are potentially viable for reactive power compensation, a brief description will be given of the most promising:

Supercapacitors: These electrochemical storage devices work similar to capacitors. The most common problem is that they have low storage capabilities, high charging, and fast discharging rates. They are most commonly used for uninterruptible or backup power supplies. Supercapacitors need to be kept at lower temperatures and have stringent charging characteristics.

Another static compensating technology incorporates energy storage systems. Energy storage systems began with batteries, flywheels, and pumped hydropower storage to accrue excess power and use it for peak demand or contingency cases. The versatility of these systems made them popular for use within DER, since continuous interconnection

with the grid and with each other proved difficult to accomplish. SMES systems today are used for short-term power losses and recently for power quality issues.

D/P-Q SMES: The Dynamic SMES or Active/Reactive SMES works in conjunction with Inverters to supply active and reactive power through voltage sags and transients due to inductive loads. The system has been operational since 1998 in Australia and 2000 in Wisconsin [17]. The SMES is capable of sustaining power up to 0.8 seconds at 1.4MW with total energy storage of 0.3kWh.

Active Front-End Inverters: Active front-end induction motor drives are power converters used to start and operate these motors efficiently. They consist of the line-side converter, a dc link capacitor bank, and the load side inverter. The compensation occurs when the converter is used as an inverter and to feed reactive power back to the grid. Many Utilities such as Southern California Edison are giving incentives to the industry to use Active Front-End Inverters because of their efficiency, thus they can also be used during contingencies for reactive power compensation [18].

The most promising reactive power compensation device is the Flexible AC Transmission System (FACTS). FACTS control the voltage from the high side of the network during steady state and transient conditions incorporating power electronic devices. FACTS can be based on different equipment depending mostly on the scale and applications. The most common topologies encountered today are Thyristor based, encompassing a Tap changer, Phase angle regulator, SVC and Thyristor Controlled Series Compensator (TCSC). The Gate Turn Off (GTO) thyristor based includes the Static Compensator (STATCOM) and a Unified Power Flow Controller (UPFC). The

last configuration is the Insulated Gate Bipolar Transistor (IGBT) based, which also includes the STATCOM. [19]

Thyristor: The Thyristor based FACTS system is a series connected controller. It controls the flow of power through a transmission line by changing its reactance. The reactance in the line can be changed by different topologies, the most common are the static synchronous series compensator (SSSC), which decreases the voltage drop by having its output current being controlled independently of the lines' current. The SSSC also has the ability to compensate real power for a short time through the use of energy storage systems. The Thyristor Controlled Series Capacitor (TCSC) and Thyristor Controlled Series Reactor (TCSR) use the firing angle of the Thyristor in conjunction with capacitor/inductive banks in a controlled manner, to manage the reactive power in a transmission line. Topologies can be seen in Addendum A-1. [18]

GTO/ IGBT: These systems are comprised of a STATCOM with a controller type depending on the application. The UPFC uses different system scenarios to operate. At each scenario one variable (e.g. real power flow, reactive power flow, voltage magnitude) is measured while maintaining the others fixed. Next, the system response to each variable is analyzed to predict its behavior. Finally, limits depending on these variables are set to aid the UPFC in the challenge of maintaining a balance.

Voltage Source Converter (VSC) Its main purpose is to minimize the losses of semiconductors while producing high quality sinusoidal voltage waveforms. One such device is the Variable Frequency Transformer (VFT), consisting of a rotary transformer, drive motor and collector. It is based on a combination of hydro-generator, transformer

and drive technologies. It controls phase shift by having a rotary secondary and a drive system to control the phase angle and speed of the rotor to regulate power through it.

Synchronous Condenser: The synchronous condenser is a motor/generator used as a capacitor to inject current back to the grid. The motor has regular stator and rotor coils. The stator coils are inductive by nature and consume reactive power when connected to the grid. With the help of a power supply (exciter), the current can be controlled to stimulate the rotor and inject reactive power into the stator, thus supplying or absorbing reactive power into the network. The advantages of the synchronous condenser lie in that it can inject as well as absorb reactive power. The only problem is that its response time is slow in comparison with inverters.

SuperVAR: the Super VAR Synchronous Condenser has rotor coils made from high temperature superconductors. By changing the resistance in the condenser's rotor coils, the slow and dampened responsiveness of the synchronous condenser is overcome. Furthermore, because there is no heating in the rotor, thermal stress and losses in the field coils are minimized. The air gap is also larger because of the current density, allowing for greater current injection. The SuperVAR promises to be a candidate for replacing old static capacitors with new Dynamic Reactive Power Compensators.

2.6 Economics and Market

The electric power grid is constantly growing, requiring more generation, better quality, and more competition between power producers. The constant rise in fuel cost directly and indirectly impacts the electric generation. The profit on invested capital thus becomes a key area in the operation and maintenance of the power system.

Since de-regulation has taken place in many states, maximum efficiency, fuel conservation, and minimum losses take a major role for competing markets. Companies compete with each other to deliver power to the consumer at a minimum cost. These operational economics are normally divided into two parts, the economic dispatch and the minimum loss.

In economic dispatch, the load condition determines the power output of each generating unit, and thus lowers the cost of fuel needed. The main focus is then to coordinate the production costs of all power plants. Minimum loss models deal with the control of power flow throughout the system.

Other key factors have become variables in these calculations. Since the opening of markets for de-regulation, the economic dispatch models may now depend on daily transactions and hour-to-hour system load evaluations. Moreover, the cyclic, expected behavior of consumers is now irregular, making power flows dynamic and unpredictable. The system, however, is designed for a vertical operation mode, with power interactions at the same level occurring for contingency cases or backup. In other words, as the system's transmission lines approach the end user load, the gauge diminishes, and with it the capability of power traffic through the line. This problem makes the interaction of power delivery on a parallel basis complex if not impossible.

These problems are then addressed through the optimal power flow (OPF), in which both system operation and economics are calculated together for an efficient, reliable, and cost effective solution.

Reactive power is inherently difficult to price. In the past, the consumption of real power has been the markets' stimulant in regards to pricing and economic efficiency.

As power companies started incurring losses due to dispatch problems, reactive power became a variable. Consumers were then asked to keep a minimum power factor before incurring penalties for reactive power compensation. Manufacturers, mills, and companies with big motors in general, started using capacitor banks to increase the power factor. Power factor correction near the loads or in a plant was then addressed through ANSI/NEMA tables, Appendix A-2 [20], depending on the size of the load, original power factor, and desired correction.

This form of correction helps the system in keeping a desired stability. However, because of the constant growth of the population, small loads such as air-conditioning units make power factor correction a system wide problem. Utilities have to install compensating units near substations to lessen the burden on generation and thus further losses.

DE is then a key player. The competition between DE and generating companies is non-existent. DE is not profitable enough to compete on a regular basis. On ancillary services, however, it can become a profitable solution. Reactive power compensation is considered at the moment an ancillary service, and because DER can be close enough to the load, it can stabilize the system at the root of the problem. DER is fast enough to work through the dynamics of the system while keeping losses at a minimum and not compromising the generation of real power but enhancing its dispatch. The problem now resides in pricing these services for optimal economic dispatch.

Several methods of pricing Reactive power have been studied, at the moment none of them have been implemented on a global basis. Some variables to be considered include the initial cost of the equipment, installation, maintenance and operation costs

(e.g. control systems). A margin of these costs along with its characteristics was developed as shown in Table 2.5 [21]. The best choice for response time and voltage stability are the dynamic VAR compensators. A generator would be the optimal compensator, but from a profit point of view, reactive power dispatched means real power losses. Both the generator and distributed generation have high operating costs, moreover the opportunity cost of using them for reactive power compensation instead of real power generation is not economically advantageous. Synchronous condensers are fast and convenient, but the capital cost and maintenance make them a choice only if the equipment is already available, e.g. mill, and the use for reactive power compensation does not interrupt the normal operation.

Table 2.5 Reactive Power Compensation Devices and Performance Characteristics. [21]

Equipment Type	Speed of Response	Ability to support Voltage	Capital Cost Per (kVAR)	Operating Cost	Opportunity Cost
Generator	Fast	Excellent, additional short-term capacity	Difficult to separate	High	Yes
Synchronous Condenser	Fast	Excellent additional short-term capacity	\$30 - \$35	High	No
Capacitor	Slow, stepped	Poor, drops with V^2	\$8 - \$10	None	No
SVC	Fast	Poor, drops with V^2	\$45 - \$50	Moderate	No
STATCOM	Fast	Fair, drops with V	\$50 - \$55	Moderate	No
Distributed Generation	Fast	Fair, drops with V	Difficult to separate	High	Yes

According to the table, static var compensators are then the most expensive and have low voltage support. Recent studies by Klaus Habur and Donal O’Leary [22] show power electronics based equipment price range, shown in Figure 2.4 [22]

Power electronics are at the means for interaction between DER and the rest of the grid. Unfortunately, it also represents up to 1/3 of the total installed cost. Even though technology advancement has reduced the price by an order of 10, it is still too expensive to install equipment for short time payback. This is mainly true because the two components taken into account for pricing are the equipment costs and its infrastructure. In order to make a fair comparison with generators, an economic impact must be studied not only of the capabilities of constant var injection or absorption, but also of losses through the line, real power generation restrictions because of var injection, line thermal limits, loop flows, and voltage limits among other variables that restrict the flow of power.

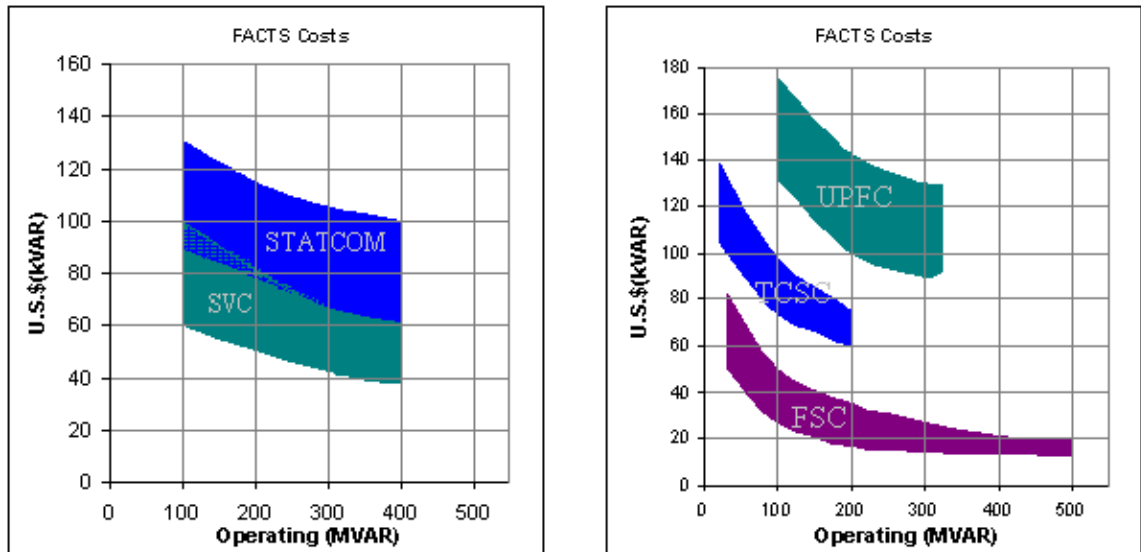


Figure 2.4 (A) Investment Costs for SVC/STATCOM. (B) Investment Cost for SC, TCSC and UPFC. [22]

2.7 Summary

In this Chapter, the Reactive Power Laboratory has been described. An overview of the equipment and location has been given. The power network at Oak Ridge National Laboratory is diverse and constitutes a sizeable distribution system adequate enough for the purposes of this research. The RPL is centrally located on the power grid with the advantage of having two voltage ranges from which to work, the 480 V system primarily on the circuit, and the 2.4kV on the substation.

The availability of a number of loads, as well as state of the art technology with real time data acquisition systems (PowerNet), make ORNL an ideal place for testing of different types of DER compensation devices as well as important test case scenarios.

Next a comparison of different technologies used today has been presented. All technologies present advantages depending on the application, size, and response time. Advances in present technologies are thrusting power electronics in all applications. Future improvements will decrease the price of power electronics making them the lead choice for high power applications.

Finally, a pricing market for reactive power is in progress. Different regions have OPF with different system requirements to properly account for reactive power compensation. DER will play a major role in the future. As technology advances, power electronics become cheaper and more reliable making the transfer from existing equipment cost-effective.

Chapter 3

REACTIVE POWER COMPENSATION

3.1 Overview

In the previous chapter, a description of the Reactive Power Laboratory, its purpose, plan, and equipment was given. Also different technologies and economic considerations were presented. In this chapter, a brief introduction to power flow solutions will be given. Next, system mathematical solutions for power flow analysis will be discussed. Later in the chapter, a model for a synchronous condenser in different states will be presented. Finally, the operation and modeling of the inverters will be discussed.

3.2 Power Flow Solutions

Voltage control is the foundation for system integrity. DER, as any other ancillary back up, depends on a strategic management system. The central control system must direct resources to meet each contingency according to its capacity, response time, and cost. Power flow from generation to load depends on many variables within the system to meet the demand and maintain stability. One such variable is transmission lines. The reactive nature of transmission lines has its roots in the geometry and configuration of the conductors themselves. This complicates the task of evaluating the reactive characteristics of the line for proper compensation. Transmission lines are inherently inductive. Their behavior however depends on the loading of the system. Independently of the systems voltage, at low line loading, the capacitive effect dominates, an excess

reactive power accumulates giving rise to the overall system voltage. Conversely if the line is heavily loaded, the inductive effect dominates, lowering the voltage and causing a voltage drop on the system. Static devices are relatively slow in reacting to these changes, creating a burden on generators that must now sacrifice the production of real power to inject reactive power and hence maintain system stability. To enhance the systems, the CIGRE report, 1999 [23] and UCTE report, 1999[24] suggest a reactive and power control on three levels:

Primary control: This first line of defense depends on the voltage regulators of generating units to detect any voltage variation across their terminals, and subsequently compensate by instigating a swift change in their excitation and thus inject reactive power.

Secondary control: The network divides itself into zones, coordinating the control of each section within itself by means of reactive power compensation devices. This is done by constantly monitoring node points within the zone.

Tertiary control: The last control system depends on the study of individual system behavior. From this study process, optimization can be performed by system simulations and calculations based on real time data. This in turn dictates the setting of reactive power compensation and voltage control devices such as capacitors, voltage regulators, and transformer tap controllers.

The electrical power system's voltage is a complex variable dependent on non-linear constants. The voltage has a limit on its operating region for overall system balance. A disturbance to this balance can lead to low efficiency, power loss, equipment overheat, damage, and ultimately failure leading to a blackout. To aid in the transmission of real power, reactive power flow must be minimized. Furthermore, in disagreement with the

order from the CIGRE report 1999[23], a generator should be the last resort when confronting reactive power compensation. In a generator, a tradeoff between real and reactive power exists. In addition, transmission lines require reactive power making the process of sending the VARs more costly both in system constraint as well as economically because of losses in the system.

Voltage control systems must be managed in a hierarchal manner depending on their speed, cost, and size. Since voltage depends on non-linear reactive power consumers, different system scenarios must be analyzed depending on load and generation patterns, and contingency plans must be put in place. These contingency plans must take into account that because the power system is composed of many devices, equipment failure is a possibility, and therefore it should be designed to withstand such non-primary equipment loss without overall system failure. Because of the system's variance through time and unpredictability, a dynamic reactive power compensation is no longer an alternate, but a necessity.

New system simulators as well as dynamic system studies must be used. Future designs of electrical power generation/distribution must take into account that reactive power reserves are needed as much as real-power reserves. The main difference remains in locating these reactive resources throughout the system. The demand of reactive power is scattered throughout the system, though reactive power compensation must be locally controlled to avoid losses throughout the system. This makes DER an ideal choice for reactive power compensation.

In order to have a basic understanding of the system configuration and operation, a visualization of the grid with all the elements involved must be made. To simplify the

system, one-line diagrams are made and solutions to system power flow are based on single-phase, balanced equations. Assuming that all phases are equally loaded, a solution can be obtained for a particular system's configuration. The importance of power simulation programs plays then a major role in the planning and design of existing and future networks.

A power flow study will provide extensive information about the system's state, weaknesses, and possible expansion opportunities. The most important information given by the power flow is the voltage and phase angle at each node. Real and reactive power may also be obtained, though the accuracy of the output depends on the system stance.

Power flow systems today are simulated through computer software that can generate an output in a manner of minutes. These commercial and private software programs vary depending on the amount of buses and components allowed within a project. Utilities and power producing companies use programs with at least 25,000 buses. Currently 100,000 bus system programs are available and can calculate load flows as well as perform state estimations based on real time data. Even though each program contains proprietary methods of calculation as well as presentation of the material, they all base the mathematical calculations on either bus self and mutual admittance or driving point and transfer impedance matrix operations. Power flow solutions base themselves on system constraints and assumptions, the single-phase representation of the voltage, phase angle, and power are shown below.

For the voltage, the magnitude and phase angle at any node or bus i is given

$$V_i = |V_i| \cdot (\cos d_i + j \sin d_i) = |V_i| \angle d_i \quad (3.1)$$

Admittances can be represented in the same manner in a matrix format

$$Y_{ij} = |Y_{ij}| \cdot (\cos q_{ij} + j \sin q_{ij}) = |Y_{ij}| \angle q_{ij} \quad (3.2)$$

The current injected into the network can then be expressed as follows:

$$I_i = Y_{i1}V_1 + Y_{i2}V_2 + \dots + Y_{iN}V_N = \sum_{n=1}^N Y_{in}V_n \quad (3.3)$$

For power, we divide the real and reactive net power on each node,

$$S_i = P_i + jQ_i \quad (3.4)$$

then the complex conjugate or the apparent power at node i is,

$$P_i - jQ_i = V_i^* \cdot \sum_{n=1}^N Y_{in}V_n \quad (3.5)$$

Substituting equations (3.1) and (3.2) into (3.5),

$$P_i - jQ_i = \sum_{n=1}^N |Y_{in}V_iV_n| \angle q_n + d_n - d_i \quad (3.6)$$

giving the real and reactive power identities

$$P_i = \sum_{n=1}^N |Y_{in}V_iV_n| \cos(q_{in} + d_n - d_i) \quad (3.7)$$

And

$$Q_i = \sum_{n=1}^N |Y_{in}V_iV_n| \sin(q_{in} + d_n - d_i) \quad (3.8)$$

These polar forms of the power flow equations provide the real and reactive net calculated values. On a theoretical basis, the equation would work according to the conservation of energy. Since there are losses in the system that need to be taken into account, the theoretical equations will have a disparity of ΔP_i and ΔQ_i . The power flow calculation hence depends on the quantities V_i , δ_i , P_i , and Q_i . Since the ultimate goal of

the equation is to have a balanced voltage, and a discrepancy angle of 0, two of the unknowns can be assumed. By the same reasoning, the generation and loads will have a finite value of real and reactive power associated with them, leaving two unknown constants again, at a different node. The power flow hence, depends on three types of nodes or buses: The load bus, in which the real and reactive parts are known. Second is the generation or voltage control bus, in which the voltage magnitude is maintained at a constant predetermined value. The last bus is the reference voltage angle bus, known as the slack bus. Applying equations (3.6) and (3.7) to the power flow gives

$$\sum_{i=1}^N P_i = \sum_{i=1}^N P_{gi} - \sum_{i=1}^N P_{li} = 0 \quad (3.9)$$

And

$$\sum_{i=1}^N Q_i = \sum_{i=1}^N Q_{gi} - \sum_{i=1}^N Q_{li} = 0 \quad (3.9a)$$

A complexity arises in trying to simultaneously solve the equations. Since the functions for real power P_i and reactive power Q_i are dependent on non linear functions of the state variables voltage V_i and phase angle δ_i , iteration methods are employed to solve for both sides of equation (3.5) to try to solve for the two remaining constants. This method employs the decrease in difference of ΔP and ΔQ to a tolerated value. Various methods can be used to speed up the iteration process and make it converge within a certain error margin. The two most commonly used methods will be discussed.

3.3 The Gauss-Seidel Method

The Gauss method is a scalar method in which the equations are rearranged to find possible roots to a function with no unique solution. The equation is estimated for

an initial condition, making the output the initial condition for the second estimation. For a given function $f(x) = 0$, reorganize in form $X = F(X)$, where

$$X = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \quad f = \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{bmatrix}$$

the procedure has then three basic steps:

1. Estimate an initial solution X^0 , and set initial condition $k=0$;
2. Let $k = k+1$, and compute $X^{k+1} = F(X^k)$;
3. Iterate until $|X_i^{k+1} - X_i^k| < \epsilon_i$

The Seidel Method helps accelerate the convergence process of the iterations by subtracting the previous state and multiplying the function by an acceleration factor σ .

Taking Gauss equation and subtracting the previous state,

$$X^{k+1} - X^k = F(X^k) - X^k \tag{3.10}$$

$$X^{k+1} = X^k + (F(X^k) - X^k) \sigma; \tag{3.11}$$

with $\sigma > 1$ for acceleration factor.

The difficulty in the solution takes place in the formulation of enough equations to match the number of unknown state variables. Since an initial educated guess can be made for the voltage and phase angle, a first solution can be computed. From the first iteration, new values for the voltage at each bus are obtained continuing until the difference between iteration k and $k-1$ is less than a specified tolerance value ϵ .

Applying Gauss Seidel power flow method to the power network equations yields the solution methods for single and 3 phase-balanced equations.

Rearranging equation (3.3)

$$V_n = \frac{1}{Y_{nn}} \left(\frac{S_n^*}{V_n^*} - \sum_{l=1}^n Y_{nl} V_l \right) \quad (3.12)$$

Gives the Gauss-Seidel iterative equation

$$V_n^{k+1} = \frac{1}{Y_{nn}} \left(\frac{S_n^*}{(V_n^*)^{k*}} - \sum_{l=1}^n Y_{nl} V_l^{k+1} \right) \quad (3.13)$$

3.4 Newton-Raphson Method

This power flow solution method consists of iterations performed on a Taylor's series expansion for a function with two or more variables.

Taylor Series:

$$F(x) = f(\delta) + f'(\delta)(x - \delta) + \frac{f''(\delta)(x - \delta)^2}{2!} + \dots + \frac{f^{(n)}(\delta)(x - \delta)^n}{n!} + \dots$$

The merit in this method is that it requires the evaluation of both the function and its derivative at random points. If an initial estimate is calculated close enough to the true root, then the deviance δ will be small enough where the expressions, and their partial derivatives of order greater than 1 can be neglected, hence

$$\delta = - \frac{f(x)}{f'(x)}$$

Relating back to equations (3.7) and (3.8), the bus voltages and line admittances are expressed in polar form.

$$P_i = |V_i|^2 G_{ii} \sum_{n=1}^N |Y_{in} V_i V_n| \cos(q_{in} + d_n - d_i) \quad (3.14)$$

And

$$Q_i = -|V_i|^2 B_{ii} \sum_{n=1}^N |Y_{in} V_i V_n| \cos(q_{in} + d_n - d_i) \quad (3.15)$$

The linear system of mismatch equations for the power flow can now be expressed as

$$\begin{pmatrix} \Delta P \\ \Delta Q \end{pmatrix} = \begin{pmatrix} \frac{\partial P}{\partial d} & \frac{\partial P}{\partial |V|} \\ \frac{\partial Q}{\partial d} & \frac{\partial Q}{\partial |V|} \end{pmatrix} \begin{pmatrix} \Delta d \\ \Delta |V| \end{pmatrix} \quad (3.16)$$

The partial derivatives are written in a square matrix form referred to as the Jacobian. If the derivatives of these functions are continuous, the Newton-Raphson method will converge. The method is chosen over Gauss-Seidel approach because of the fast convergence. If the first derivatives of the function are near a root, and the Jacobian has a non-singular solution, then the number of significant digits doubles each step, and the method converges quadratically.

The Newton Raphson method is similar in procedure to the Gauss-Seidel where the initial values for $\delta_i^{(0)}$ and $|V_i|^{(0)}$ are estimated. Equations (3.14) and (3.15) can be calculated to find the values for the mismatches and Jacobian matrix of equation (3.16). Corrections to the deviated values $\Delta \delta_i^{(0)}$ and $\Delta |V_i|^{(0)} / |V_i|^{(0)}$ can then be calculated. The solved corrections can then be added to the initial estimates, and hence these become the new starting values for the next iteration. The Newton Raphson iteration equation is then

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta \delta_i^{(k)} \quad (3.17)$$

And

$$|V_i|^{(k+1)} = |V_i|^{(k)} + \Delta |V_i|^{(k)} \quad (3.18)$$

Advances to these power flow methods are constantly evaluated for complicated cases in which convergence is not possible. One such method is the Decoupled-flow method. Parting from the Newton-Raphson method, and taking into account that change in the voltage angle at a bus affects principally the flow of real power throughout transmission lines, whereas change in voltage magnitude influences the reactive power, can simplify the procedure and speed up the convergence process by reevaluating the Jacobian matrix in the first iterations. This process will decrease the calculation time at an expense of greater iterations, depending on the accepted deviation.

For a fast solution of the power flow, the interaction of more than one method might be necessary. The Gauss-Seidel method is a preferred method when poor voltage distribution and reduced reactive power allocation resources are involved, because the Newton-Raphson method is prone to failure due to its need for proximity with a true root. The Newton-Raphson Fast Decoupled method fails to converge in low voltage systems, especially if the reactance value on the lines is less than its resistance. In many situations, a “soft start” with Gauss-Seidel might give a close enough guess to use Newton-Raphson and make the system converge faster.

For reactive power compensation, a special consideration must be taken into account on the megavar flow between buses. The power flow might become more complicated due to the charging megavars. The flow of megavars and compensation

devices such as capacitors will vary as the square of the voltage. This complexity leads to a further study for the simulation of compensation devices.

3.5 Synchronous Condenser

The synchronous machine is complex in nature and cannot be fully analyzed in this section. The main interest is its application and operation within an interconnected power system, with prominence in the application and behavior for reactive power compensation. Every synchronous motor has the same reactive power capabilities as a synchronous generator.

The capacity of a synchronous machine to convey reactive power depends on the real power capabilities. The two main limitations for reactive power compensation are intrinsic to the physical properties of the machine. They are manifested as heat because of the armature current and field current. These limits can be better appreciated in Figure 3.1 [30] (Rustebakke, 1983). There are two general structures for synchronous machines, the cylindrical rotor machine, known as the turbine generator, and the salient-pole machine.

In order to simulate the reaction of a synchronous machine in a network, the different modes of operation must be defined. First motor starting, at which point the machine is consuming great amounts of reactive power. Next is motoring mode; at this point the motor is consuming mainly real power. Last is the overexcited mode, or generation at which the synchronous condenser will be injecting reactive power. The main emphasis must be made on the behavior under steady state and transient conditions.

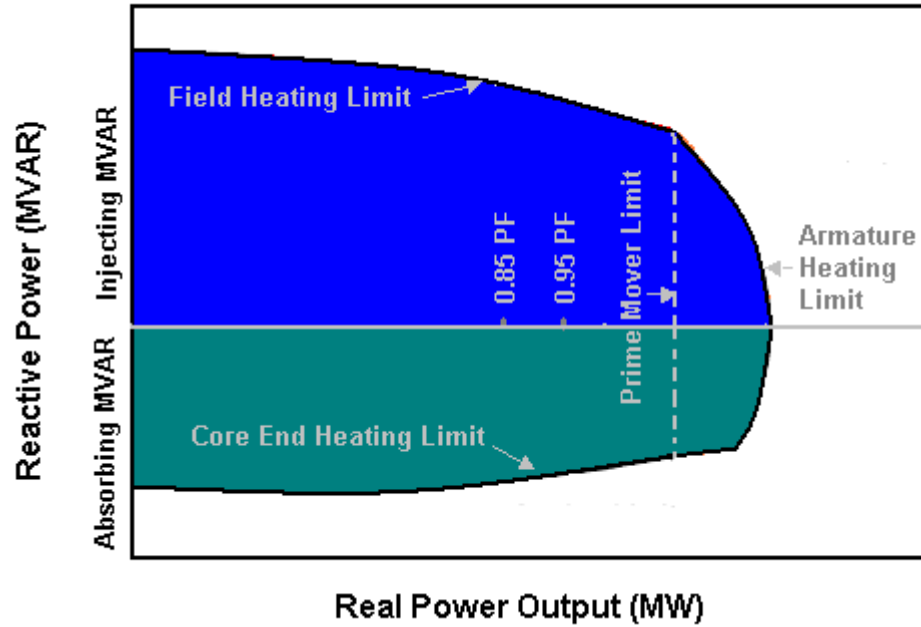


Figure 3.1 Reactive Power Dependence on Real Power Production for a Synchronous Generator. [30]

3.5.1 Steady State

From Chapter 1, Figure 1.5, a representation of the synchronous motor can be simplified. As seen in Figure 3.2 [20] the machine parameters are simplified. The voltage seen at the motor terminals is dependent on the induced emf at no load minus the losses due to armature resistance and armature self and mutual reactance. The equation thus becomes:

$$V_a = E_i + I_a R + j\omega (L_s + M_s) \quad (3.19)$$

The synchronous reactance during steady state operation can then be termed,

$$X_d = \omega (L_s + M_s) \quad (3.20)$$

The three parameters must now be determined to give an accurate description of the motor. The armature resistance is determined by measuring the dc resistance of the

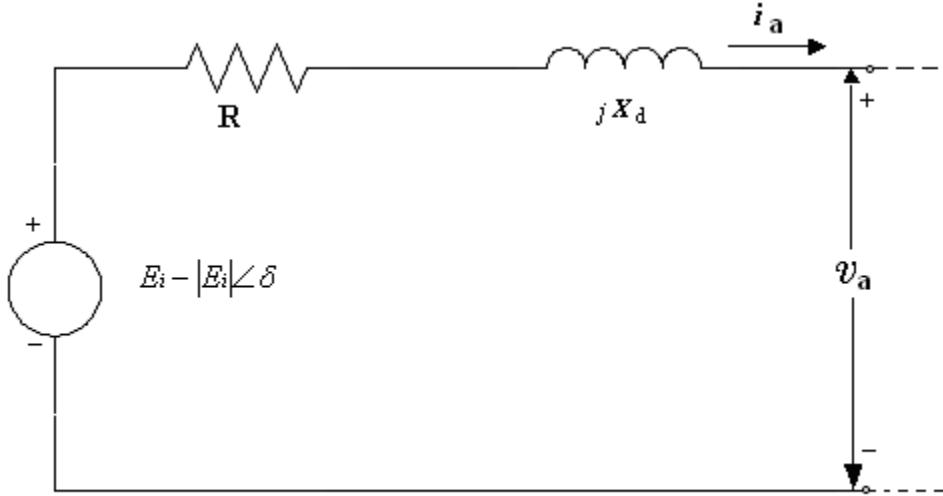


Figure 3.2 Equivalent One-Phase Circuit for the Synchronous Machine showing the Voltages and Currents as Phasor Quantities. [20]

winding. The induced emf and synchronous reactance can be determined using the open circuit test. Since the main focus is to simulate the reactive power injection characteristics, and to simplify the circuit, the resistance of the generator will be neglected. From Figure 3.2, the armature current can then be expressed in terms of the voltage and reactance as:

$$I_a = \frac{|E_i| \angle d - |V_t|}{jX_d} \quad (3.20)$$

then the real and reactive power equations for the synchronous motor steady state operation are:

$$P = \frac{|V_t| \cdot |E_i| \sin d}{X_d} \quad (3.21)$$

And

$$Q = \frac{|V_t| \cdot (|E_i| \cos d - |V_t|)}{X_d}$$

The simplified equations show that the synchronous machine, when in reactive power compensation mode and steady state operation, depends on the synchronous reactance X_d . Theoretically, the curve shows the limits as the field heating and armature heating cross each other. Test results show that the actual curve deviates from this theoretical value because of saturation in which the synchronous reactance X_d is decreased. Most manufacturers generate their own curves describing the field heating limits.

3.5.2 Transient analysis

Current flowing in a synchronous machine immediately after a fault will effect the armature current causing changes in the flux generating the voltage in the motor. The current will change slowly from its present value to the steady-state value. This difference in current gives rise to a new problem. The two-axis model of the salient pole machine relates better to this problem. Like the round rotor, the salient pole machine has three symmetrically distributed armature windings. Each field winding has constant self-inductance, and mutual inductances. The difference lies in the mutual inductances between them, since they are not constant in the salient-pole machine, they vary as a function of the rotor angular displacement. The equations are then dependent on the flux linkages of each phase $\lambda_a, \lambda_b, \lambda_c$, and between them $\lambda_{ab}, \dots$. To reduce the level of complexity, a transformation of the variables is made giving the direct-axis, quadrature-axis, and zero-sequence(d,q,0). This is done via the Park's transformation, and the corresponding matrix is conveniently orthogonal. The P-transform then defines a set of currents, voltages, and flux linkages for the stationary 0-coil, d coil, and q coil. The inductances can then be defined as

$$L_d = L_s + M_s + \frac{3}{2} L_m; \quad L_q = L_s + M_s - \frac{3}{2} L_m; \quad L_o = L_s - 2M_s \quad (3.22)$$

The d-axis winding and the field winding represent a single physical field since the two coils are coupled and therefore stationary with respect to each other. Hence they share the mutual inductance kM_f . In a fault scenario, the internal speed voltages $\omega \lambda_q$ and $\omega \lambda_d$ can be assumed as zero. From Figure 3.3[9] the d-axis transient inductance can be

estimated as:
$$L'_d = L_d - \frac{(kM_f)^2}{L_{ff}} \quad (3.23)$$

The synchronous transient reactance is then $X'_d = \omega \left[L_d - \frac{(kM_f)^2}{L_{ff}} \right]$

The sub-transient reactance can be found in a similar way to give

$$X'_d = \omega \left[L_d - k^2 \left(\frac{M_f^2 L_D + M_D^2 L_{ff} - 2M_f M_D M_r}{L_{ff} L_D - M_r^2} \right) \right] \quad (3.24)$$

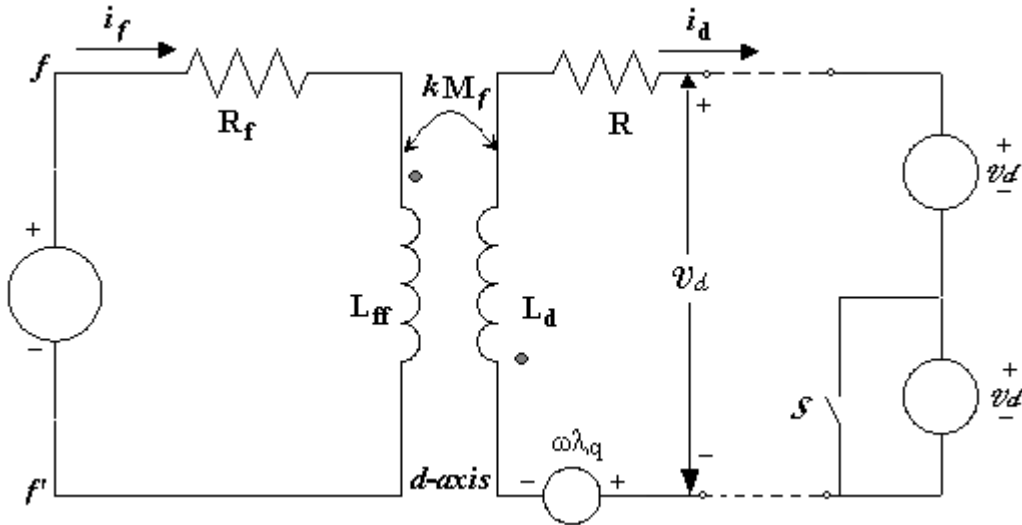


Figure 3.3 Equivalent One-Phase Circuit for the Salient-Pole Synchronous Machine showing the Voltages in d and q-Axis [9].

The synchronous reactance during steady state, transient and sub-transient conditions are then stated. The synchronous reactance is part of the equivalent circuit of the motor. During normal operation, the amount of reactive power that can be either consumed or delivered will be determined by the synchronous reactance. The transient reactance will have a direct impact on stability issues while the sub transient reactance will determine the available fault current at or near the motor. The steady state reactance component is the largest, followed by the transient, and ending with sub-transient.

3.6 Inverters

The electric power demand is constantly on the rise. Although DER constitutes merely 2.9% of the net production [1], it is expected to grow in the next decade, especially when pertaining to ancillary systems. Power electronics are the key factor in the success of these Distributed Energy Resources. Moreover, power electronics are incorporated in approximately 30% of all power generated [20], integrated from generating facilities to end consumer loads. The assimilation of power electronics in power factor correction, control systems, motor drives and ancillary services make them a necessity more than a commodity.

In terms of reactive power compensation, the dependence is directly on converters, energy storage systems, and inverters to interface the DER to the grid in an economic, reliable, controllable way with minimum impact and stress on the system. A converter is normally used to supply a dc voltage to the inverter. The converter may differ in topology depending on the configuration and type of system. The most common is a diode rectifier, in which the line voltage is thus rectified and filtered to provide a constant

dc voltage. For purposes of this project, a commercially available dc power supply is used. The dc voltage is then supplied to an inverter. The inverter is a commonly used dc-to-ac converting switching device in motor drives and uninterruptible power supplies. Inverters normally accept dc voltage as an input and produce either single or three phase sinusoidal output voltages at a specified lower frequency than the switching frequency. Current source inverters are also used in motor drives where variable frequency techniques are engaged. Then, the two modes of operation are the voltage mode and current regulated modulation.

Voltage source inverters have different modes of output. The pulse-width modulated PWM inverters use a constant dc voltage as input. The main function is to modulate the switches to shape the output ac voltages as close to a sinusoidal wave as possible. Square wave inverters use a controlled dc input to control the magnitude of the ac voltage, thus the inverter controls the frequency of the output voltage. It derives its name from the output that is similar to a square wave. The last type is the single-phase with voltage cancellation. In this case, the two previous topologies are combined. The phase cancellation can be accomplished only in single-phase inverters.

Both single-phase and three-phase inverters are functional in terms of reactive power compensation. The main difference is cost and complexity versus operational versatility. The ultimate goal in the power grid is to have a balanced system. Although all compensations systems are equally sized, the requirements per phase will differ because the phases are not balanced. Under these conditions, three single-phase inverters may be a better topology. The three inverters can work as one to compensate while responding to the dynamic needs according to individual phase behavior. The system is

described in Figure 3.4 [7]. In the PWM, a sinusoidal output voltage waveform is shaped by comparing a control signal $\hat{V}_{control}$ with a triangular waveform $\hat{V}_{tri}$. The frequency of the triangular waveform f_s controls the inverter switching frequency. The control signal is used to modulate the switch duty ratio at the fundamental frequency f_1 . The amplitude modulation ratio, and the frequency modulation ratio are respectively defined as

$$m_a = \frac{\hat{V}_{control}}{\hat{V}_{tri}}; \quad m_f = \frac{f_s}{f_1} \quad (3.25)$$

The switching frequencies of the PWM are selected to be less than 6kHz and greater than 20kHz. The reasoning behind this selection is that in the higher switching frequency a better harmonic filtering can be achieved. The drawback is that switching losses are proportional to the switching frequency and thus the lower band may be chosen for certain applications. Another factor is the modulation index m_a , in the linear region

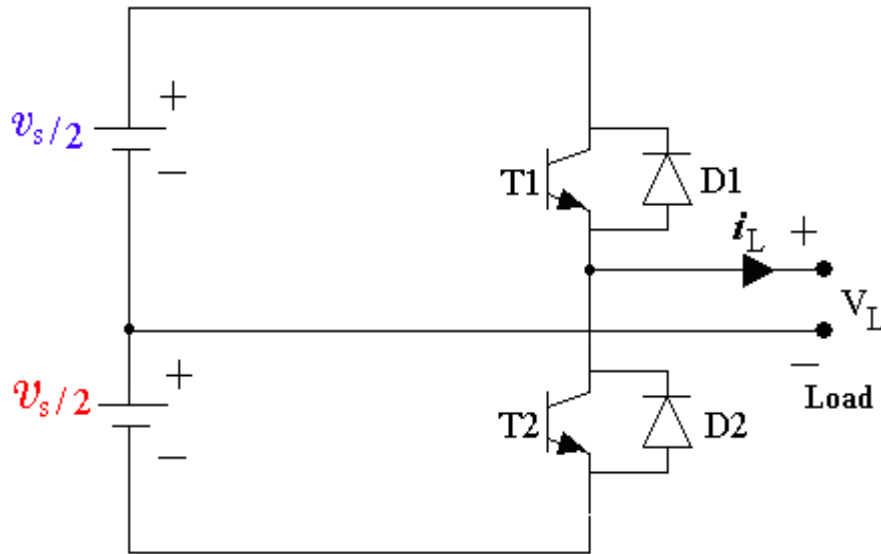


Figure 3.4 Single-Phase H-Bridge Inverter [7]

$m_a \leq 1$, the amplitude varies linearly and the harmonics are driven far into the high frequency range. In some applications, the amplitude of the fundamental frequency needs to be increased, and the modulation index is driven into the overmodulation index or $m_a > 1$. This region causes more harmonics on the output voltage. In linear modulation, the peak value of the fundamental frequency output voltage is

$$\hat{V}_{AN1} = m_a \frac{V_d}{2} \quad (3.26)$$

Each phase voltage can then be calculated by making a phase displacement of 120°. For a three phase balanced PWM inverter, the line to line rms voltage can be calculated from (3.26). An approximate value in linear modulation is $0.612m_a V_d$.

3.7 Summary

In this Chapter, a basic understanding of power flow solutions has been presented. The electrical power system is a complex, variable system with non-linear loads and power correction devices that make the system all but predictable. In order to achieve a correct model for reactive power compensation, different power flow solution calculations have to be made. More than one method may be involved to give a base state of the overall system. Reactive power compensation devices have been modeled according to their response in different scenarios.

Power flow solution methods give average output quantities. Finally, methods of gathering data and predicting the grids state have been introduced. The state estimation process is a valuable tool in power flow solution methods because of its ability to gather real time data and correct erroneous data.

Chapter 4

SOFTWARE MODELING AND SIMULATIONS

4.1 Overview

In this chapter, an overview of the commercial software packages used will be given. SKM's limits and capabilities will be discussed along with the solutions used. Next the Power World Simulator program will be presented with details on the Optimal Power Flow for economic dispatch. Finally, an overview of controls for both the synchronous condenser and the inverter will be presented.

4.2 SKM Model Version

There are many commercial available packages for performing various power flow simulations. Each program contains software packages for different studies ranging from short circuit calculations to harmonic elimination, transient motor starting, unbalanced studies, and equipment sizing. These software packages use power flow methods, like Newton-Raphson to evaluate the systems state. From the power flow, all other programs can make certain assumptions and make calculations.

Certain assumptions must be made while modeling a power system. In many cases the data is not available because the equipment is inaccessible and the nameplate data might be lost. In this case, curve fitting might be used on equipment like transformers to find their equivalent impedance. Tables are used and approximations are made according to their size and classification. On protective equipment, if the data is

not attainable, then equipment data with similar rating at different locations is used in lieu of it.

Finally, for non-motor loads, an average of the consumption is made. This data is obtained monthly from meters, and a 12-month average is made. Different case scenarios are managed by using the highest value of the summer months, and the lowest value throughout the year. Since summer is the main concern of reactive power compensation, the highest values are used for most of the simulations. Nonetheless, each case scenario has been pre-determined and a system base state has been setup. This is done with real time data taken before and after each test to make the simulations as close as possible to the real conditions.

The simulations have been done using SKM version 5.2. The model of ORNL's power grid has been an ongoing effort for 2 years. The average data used had been collected between the years 2004 –2005. Even though the lab's model is an averaged constant kVA load, the direct contributing loads have been accurately modeled through nameplate information and real time data.

The software package is modeled through one line equivalent diagrams, which are similar in view to ordinary drawings as seen in Figure 4.1. The equipment is modeled by its equivalent impedance. SKM is a CAD-based – user-friendly program. The license available to ORNL has a maximum of two thousand buses or nodes, but the equipment devices are unlimited. Certain rules that need to be followed include an impedance branch, e.g. cables/feeders, between devices. No loops are allowed because of convergence issues.

Table 4.1 Bus types with input variables needed.

Bus Type	Node	Variables
I	Load Bus	P, jQ
II	Generation Bus, Class A	$-P, + - Q$
II	Generation Bus, Class B	$- P, V$
III	Slack (Swing) Bus	$V,$

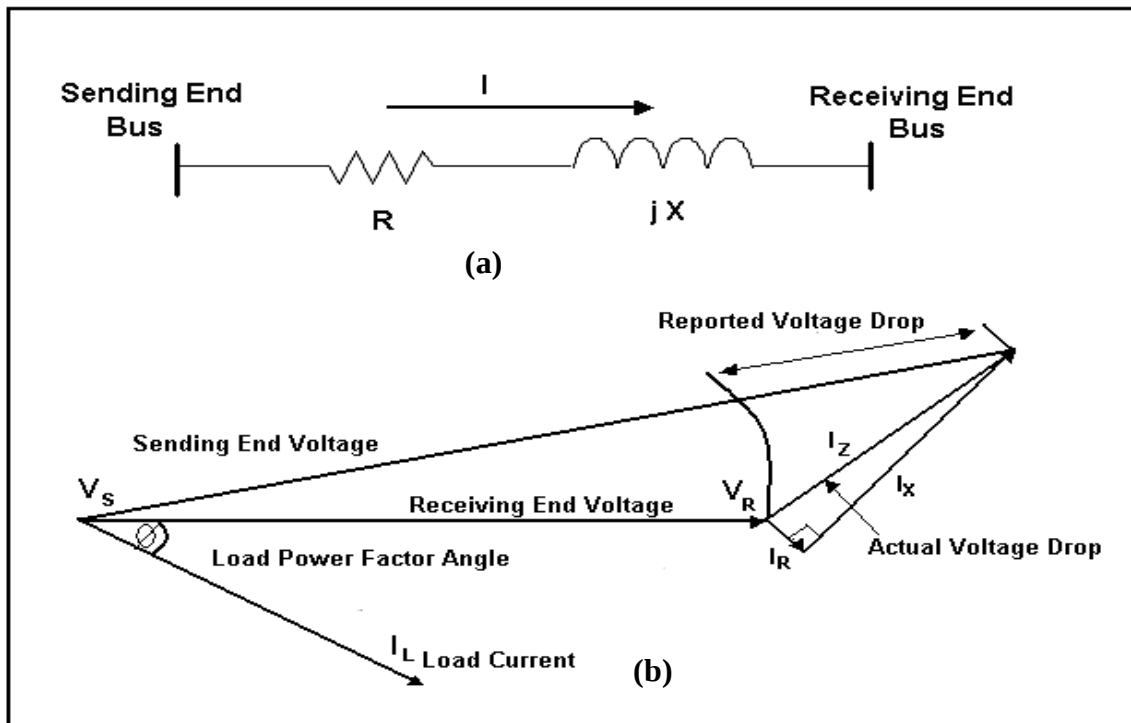


Figure 4.2 (A) One-line Voltage profile. (B) Voltage Profile Equivalence.

4.2 Power World Simulator

Power World Simulator is another commercially available power flow solution software. The program has a capability to calculate up to 100,000 buses. It is designed for high voltage power systems, normally relating to power generation and transmission. The difference lies in that the program has a package with an optimal power flow (OPF). In this program, the simulator solves the power flow equations using either of the solutions mentioned in Chapter 3, but at the same it uses linear programming to find an economic solution.

Its mode of operation uses an algorithm to minimize an objective function by changing system controls. The two objective functions used are minimum cost and minimum control change, each trying to minimize generation costs by different approaches. The various equality and inequality constraints are then linearized with the introduction of slack variables to make the problem initially feasible. The linear problem then calculates the optimal solution to the linear problem while solving the power flow. Although it is mainly used for large systems and high voltage applications, its application can be focused to distribution grid analysis.

This valuable tool can then be used to find the best location for different DER throughout a grid. It can also pinpoint the best resources to be used for reactive power compensation. The integration of an OPF with control systems can therefore determine the best economic dispatch solution while maintaining system stability and reliability.

4.3 Control System

The electric power system is an endless interaction of dynamic events. Although the system is constantly referred to as in steady state, it should be referenced to as stable. Power system stability implies its successful operation while keeping a fixed voltage and frequency throughout the entire structure. Moreover, it states that if the system suffers a perturbation, it can return to its original state in the shortest time possible without a suspension of service [9].

Faults on the network, failures in devices, changes in the demand and losses, make the operating state dynamic. Such events make steady state operation impossible. Consequently, power system operators try to study the overall equilibrium as the grid changes from one state to another. The importance is not only impressed on the new state but in the transition from one status to another.

DER is viewed as an outside power source that may impact the grid in a negative way. The interaction of micro-grids within a system helps with stability as long as its operation is reliable and to a point, self-sufficient. The contribution made by DER is not enough to make them an important, competitive source. It is however large enough to make a disturbance on a local basis. For this reason, a stringent control system must be part of the DER. In addition, contingency cases must be analyzed in advance to predict and resolve any DER system failure.

The power grid is vast and normally modeled as an infinite impedance bus system. On a global basis, local fluctuations are not perceived unless they involve the closing of transmission lines, or large equipment failure up to a generator. In order to

understand the system behavior, simulations must include impact on the network before, during and after a transient.

This project encompasses the control of reactive power. Its interaction within the network must be stable, reliable and predictable. Although an overall system behavior is taken into account, a control system for scattered DER would be too complex to model. There is a need to manage the activities of each individual compensator. A possible scenario would include various DER trying to compensate a single load. This would give part to overcompensation, and in turn instigate the devices to absorb reactive power. The result would create a constant overshoot transient response. Other cases may result in equipment failure, and worst-case scenarios may involve instability or even voltage collapse.

The best solution would involve a centralized control system that can monitor the grid's condition and find the optimum response in accordance with economic and ergonomic considerations. Location of the reactive power compensation equipment may depend on availability as well as load size and distribution. Even though the compensation device nearest to the load is the most desired, economics and system behavior might dictate otherwise. Problems arise with this design because of its complexity and re-formulation time after a new resource is added, but mainly because of the cost. The advantage of DER over generators is its ability to compete on a small case, ancillary cases. A complex control system would increase the price too much to remain competitive.

The reactive power laboratory has several milestones throughout the year. The control system design will encompass a feasible management of an inverter and a synchronous condenser working in parallel to compensate a load. In order to take this leap, each

compensator's control will be designed independently of the other. A centralized controller will then direct the secondary control systems.

For the synchronous motor, a closed feedback control system is designed as seen in Figure 4.3.[8] A d-Space controller is used with Matlab software to control the excitation level to the synchronous condenser. The 6.6kW dc power supply has been operated manually to predict the system's response, and to locate desired output magnitudes. These predetermined levels are then set as limits in the software to control the power supply. The current, power and voltage is measured through power meters and converted to digital data. The data is then collected and analyzed by Matlab through an interface, and consequently a new state is commanded to the power supply. For the inverter, the two modes of operation were mentioned in chapter 3. The current mode is chosen because of its applications in instantaneous var control. In the current switch mode, the ac current can be quickly controlled in magnitude and angle with respect to the ac voltage phases.

The closed loop control of the inverter is shown in Figure 4.4 [8]. The fixed frequency control works by comparing the actual phase current i_A with a reference current i_A^* . The error between these is amplified through a proportional integral gain controller. The voltage output is then compared with a fixed-frequency waveform. The switching is controlled by a limit set within a tolerance band.

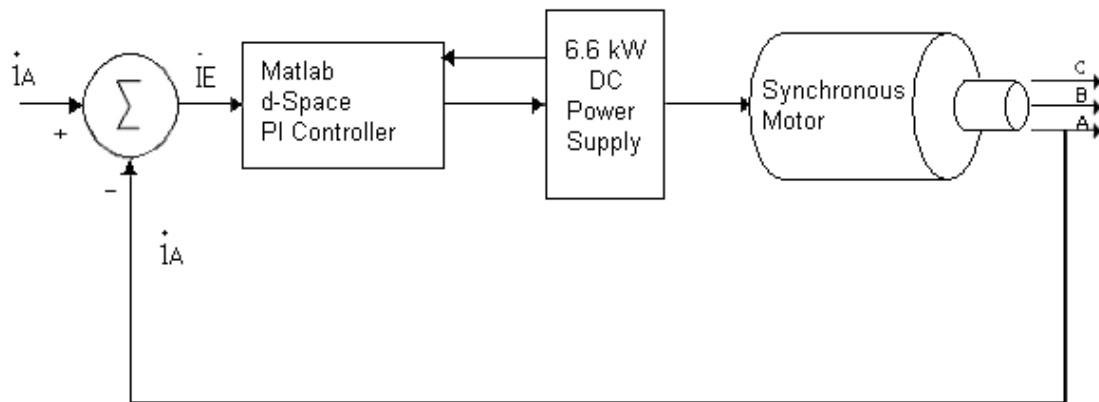


Figure 4.3 Closed-Loop Feedback Control for the Synchronous Condenser [8]

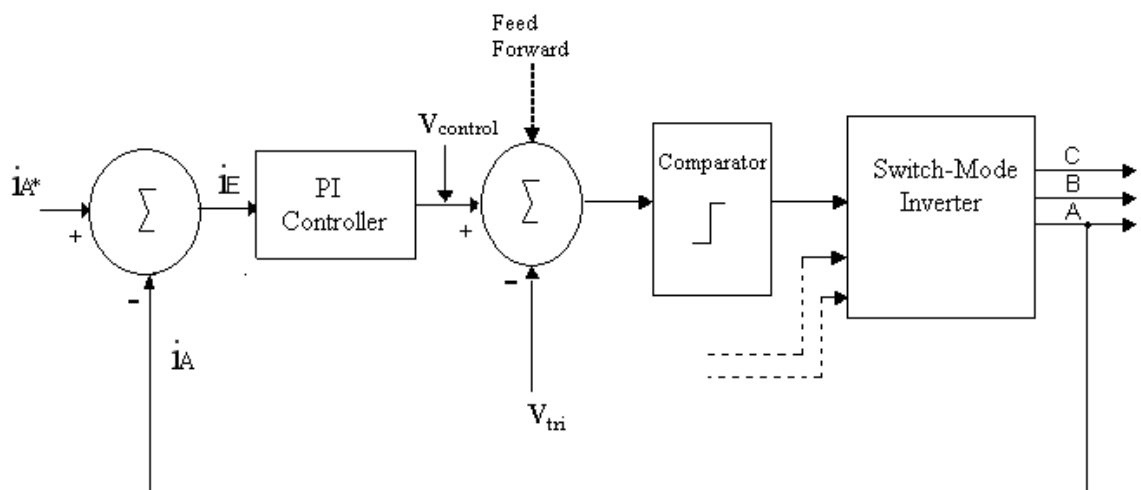


Figure 4.4 Inverter Fixed-Frequency current control [8]

4.4 Summary

In this chapter, an overview of the simulation packages has been given. Each simulation software package has different modes of operation and requirements. SKM is a commercially available software used normally by Industry on a distribution level. Power World Simulator is used for Generation and Transmission level studies. Its ability to perform economic dispatch studies makes the software a powerful tool in the design and operation of power systems. Lastly, the control for the electric power grid is too complex for one system to manage. Instead, each region is responsible for the stable and reliable operation of the power system within its customers and neighboring power systems. The control of DER can become expensive and therefore a reliable intelligent system must be designed to manage the interactions of it within the network. In reactive power compensation, different devices have individual control systems designed for their particular operation. The operation of each device in conjunction with the others needs to be addressed for a proper system operation.

Chapter 5

EXPERIMENTAL RESULTS

In Chapter 3, different approaches for power flow solutions were presented. An overview of instantaneous reactive power and state estimators predict discrepancies between the real time data and the simulations. In this chapter, a comparison between such data will be presented.

Since the reactive power compensation is an ongoing effort, data comparison will only be available for the non-loaded synchronous condenser and inverters. Many variables have a direct impact on the system behavior. Although these variables are modeled to have a minimum effect on the system, the dynamic behavior makes them unpredictable. The tests were conducted during different conditions and long time frames involving both summer and wintertime conditions. Discrepancies throughout the system will be observed, especially the current magnitude around feeders that do not contribute directly to the tests.

5.1 Test Scenarios Set up

Before each test, a system state was recorded in order to start simulations at the same levels and as close to the real conditions as possible. Data was obtained at the 3000 Substation through the PowerNet, a SCADA system maintained by Cuttler Hammer for the electrical power distribution grid at ORNL, as seen in Figure 5.1.

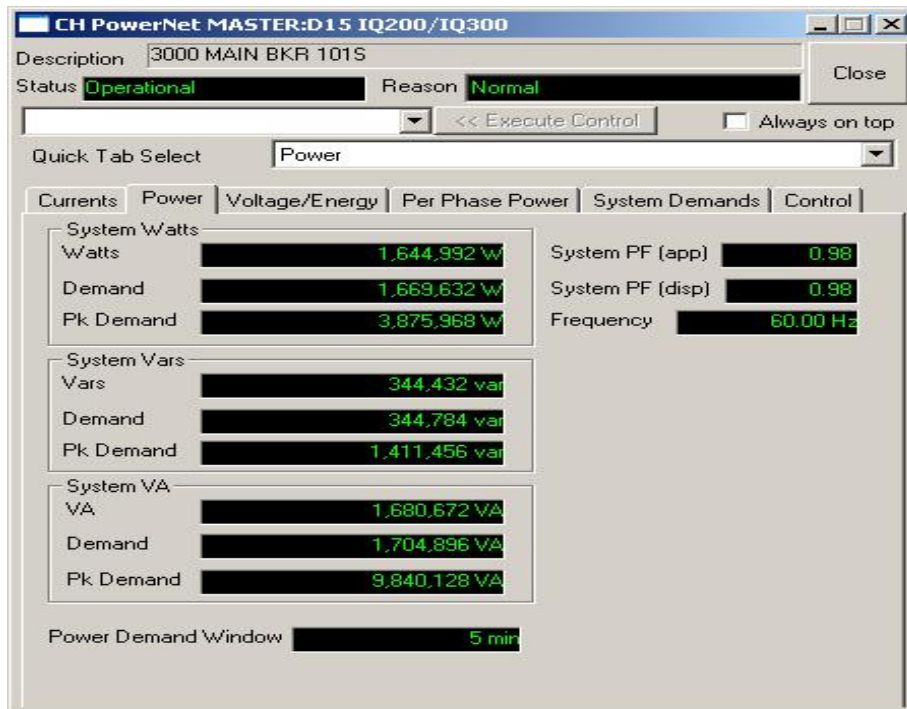


Figure 5.1 PowerNet 3000 Substation Snapshot.

Metering for the motor, inverters and panels was done through Dranetz power meters and Node Link. The motor data for the current and voltage at startup are seen in Figures 5.2 and 5.3. The voltage immediately rises to the pre-determined profile as the circuit is closed. At the same time, the inrush current peaks lowering the voltage while the motor starts building momentum. At different time intervals, the motor's behavior to the settings is seen. The motor is started as a normal induction machine. It is then synchronized with the power system, while requiring a minimum amount of current to maintain its current speed. Finally it is run again as an induction machine and then turned off. The respective simulation of these events can be seen in Figure 5.4.

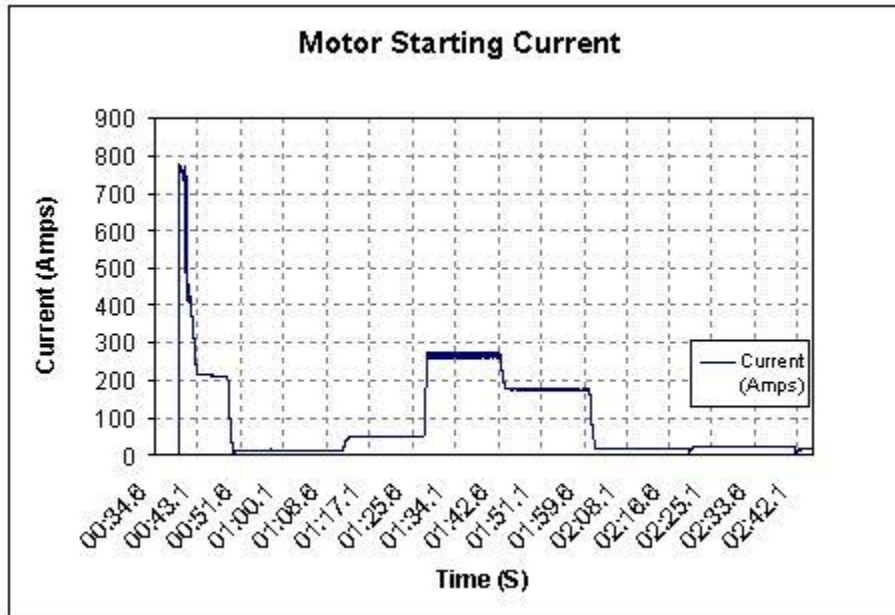


Figure 5.2 Measured Synchronous Motor Inrush Current at Startup

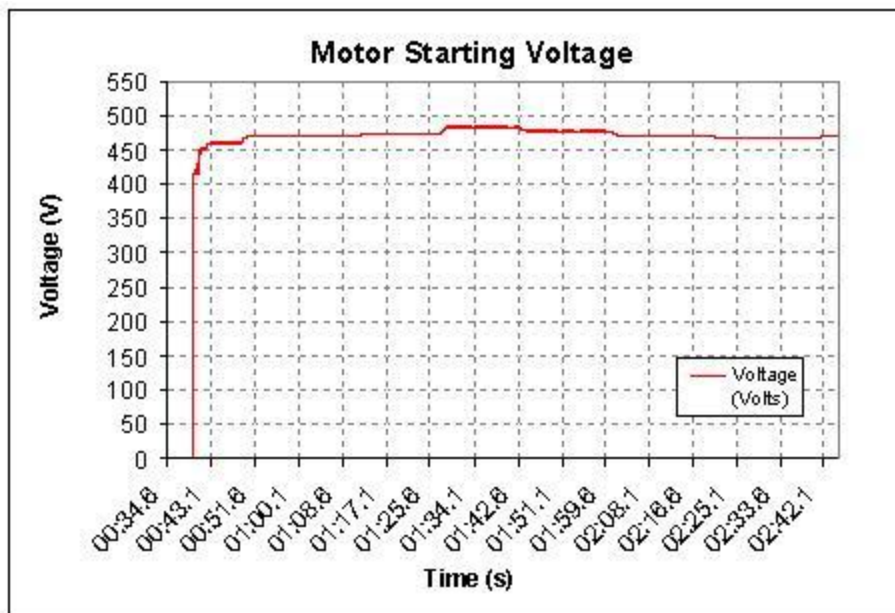


Figure 5.3 Measured Synchronous Motor Voltage at Startup

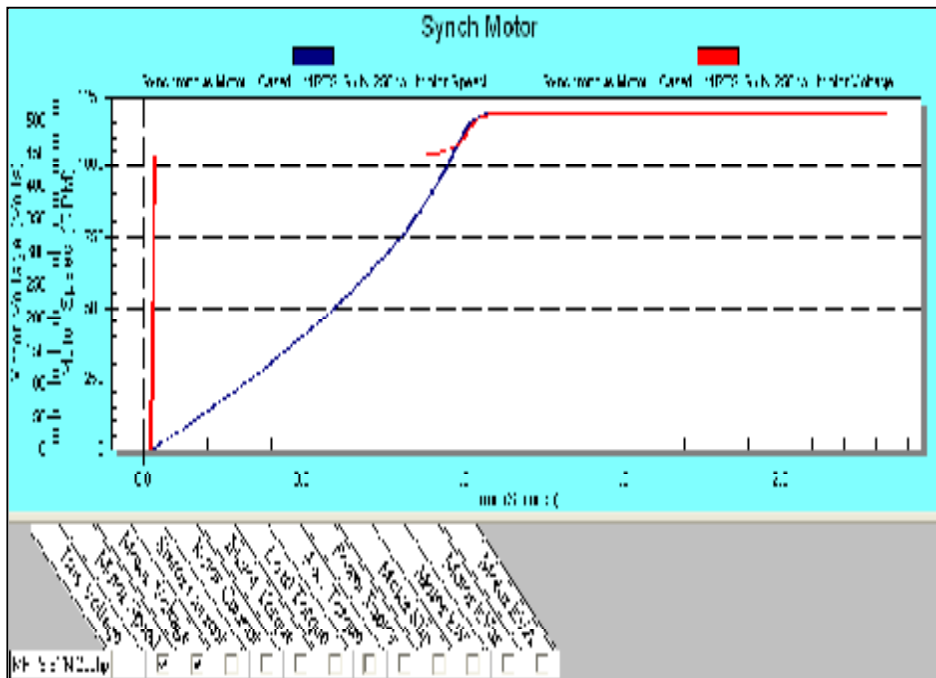


Figure 5.4 SKM Simulated Voltage and Current

5.2 Test Case 1A Synchronous Condenser VAR Injection

The first test was done during July and August of 2005. The condenser was started as an induction motor, then run in unity power factor and finally overexcited in a sequential manner from 0 to 300+ kVAR. The main concern was the voltage profile at different locations. The voltage and current magnitudes at the panels and synchronous condensers' terminals match on both simulation and real time data, as seen in Figure 5.5. The reactive power injected was used as a reference. At the substation, the simulated voltage is close to the real value. The current, however, differs from the actual data because of changes in the different circuits. Since the simulation data was static, and state estimation was not available, the model did not make the necessary changes, as seen in Figures 5.6 and 5.7.

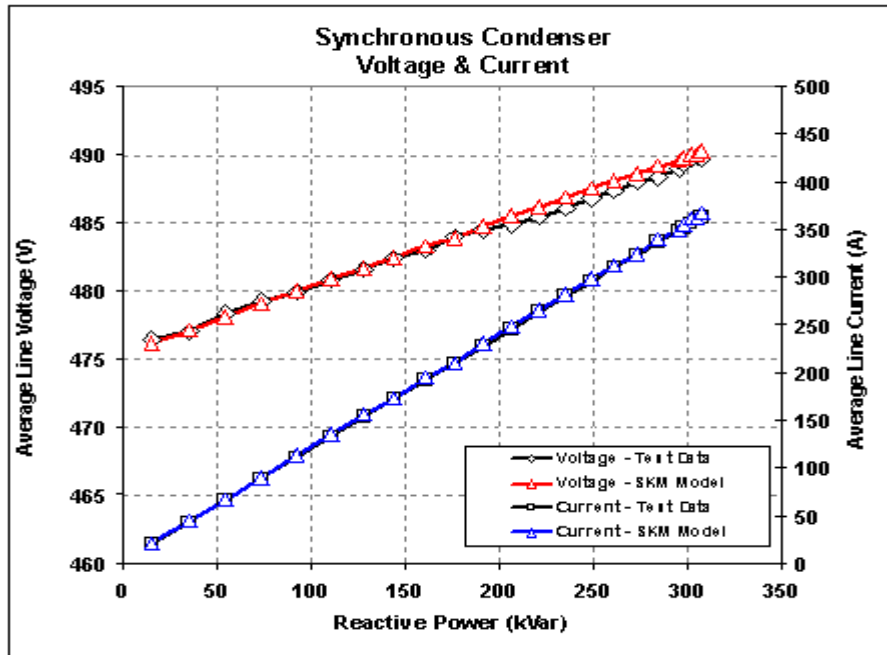


Figure 5.5 Voltage and Current magnitude Comparison Between SKM Simulated Data and Real Time Data Measured at the Synchronous Condensers' Terminals.

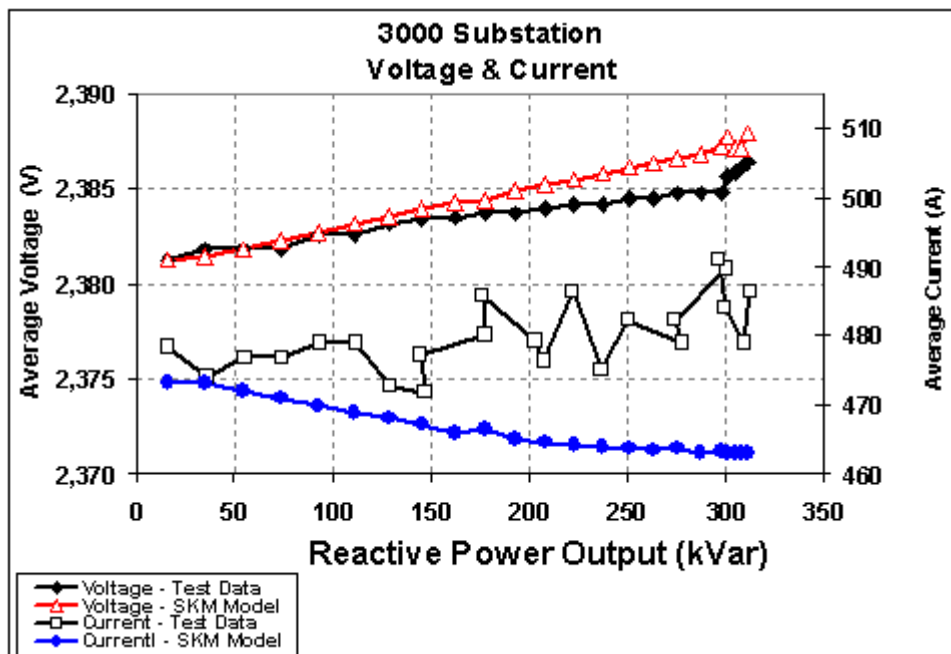


Figure 5.6 Voltage and Current Comparison at the Substation

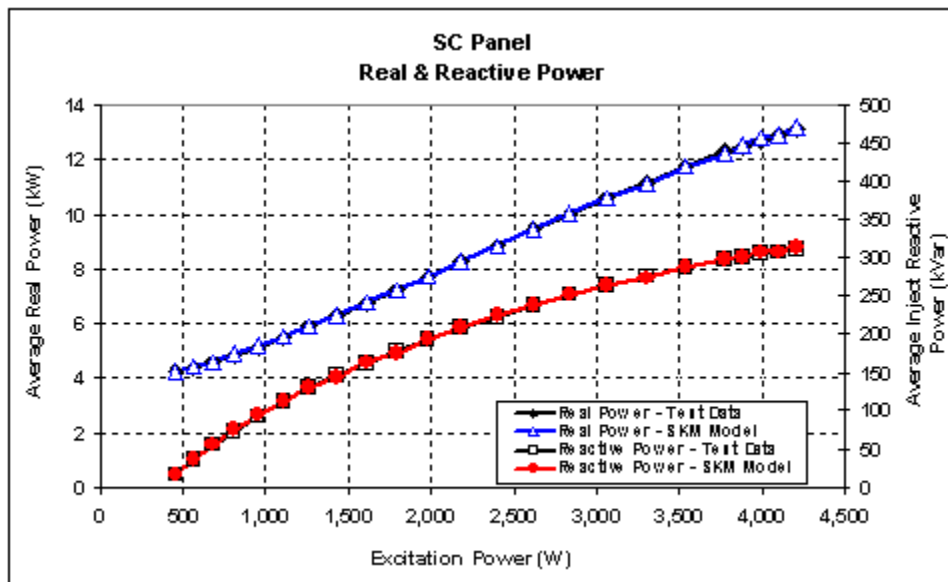


Figure 5.7 Real and Reactive Power Comparison at the Substation

5.3 Test Case 1B Inverter VAR Injection

In the case of the motor, the parameters were measured directly from the motor. The inverter case was different. During the simulations, nameplate data was available for the inverters, but no tests could be conducted as the equipment was not ready. The real data on the inverters is shown below. The mode of operation and control can be seen in Figures 5.8 and 5.9. The inverter tracks the load current and system voltage and attempts to inject reactive power to control the voltage at the point of common coupling. In Figure 5.10, the load is using a current of 65 Amps. The utility provides the power as seen in Figure 5.11 until the inverter begins to compensate a limited amount as seen in Figure 5.12

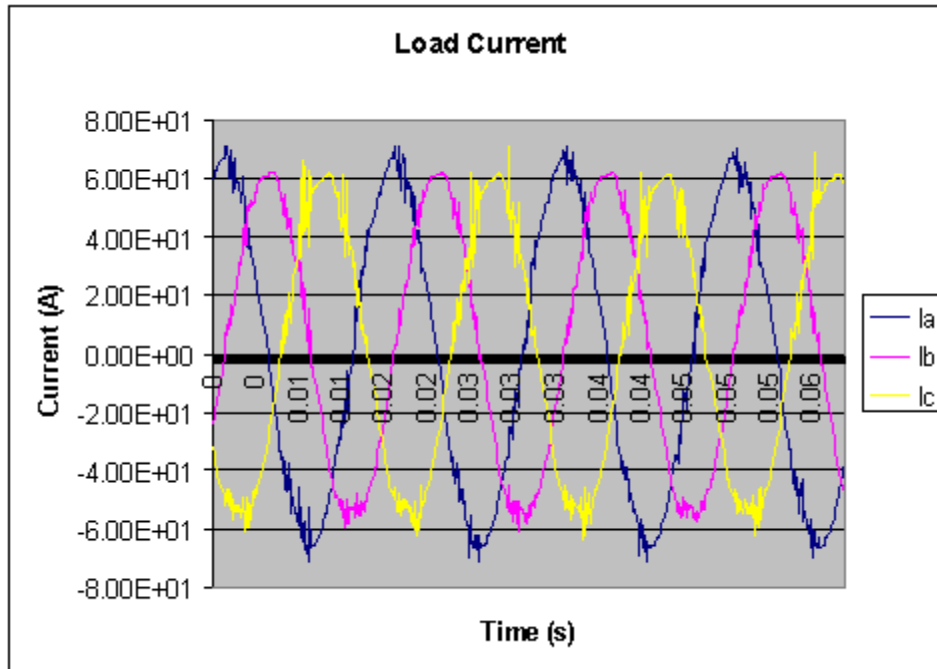


Figure 5.8 Load Current measured by Inverter's Control System.

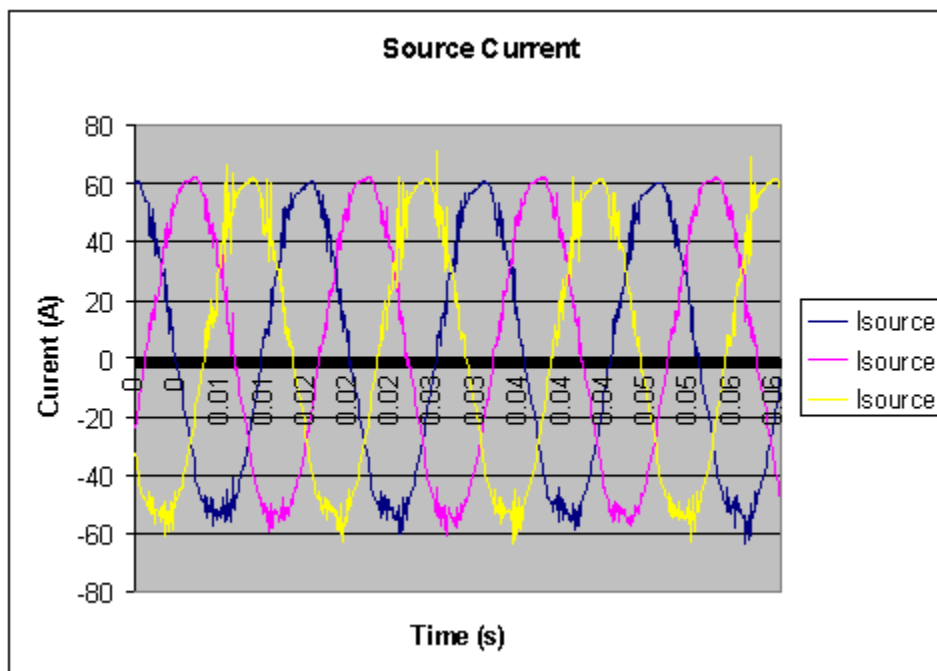


Figure 5.9 Utility Current Tracked by the Inverter.

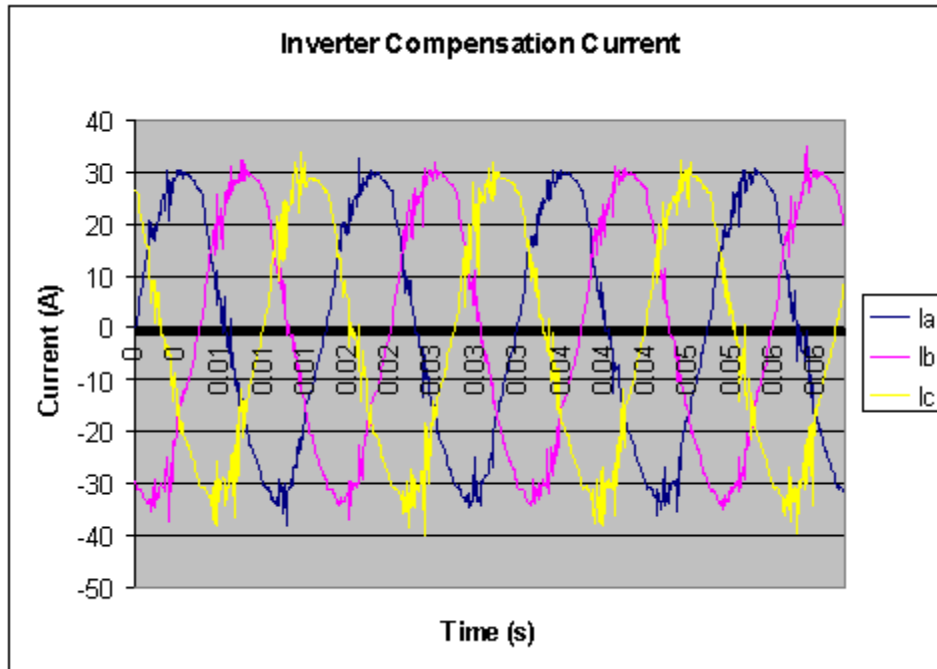


Figure 5.10 Inverter Compensating Current

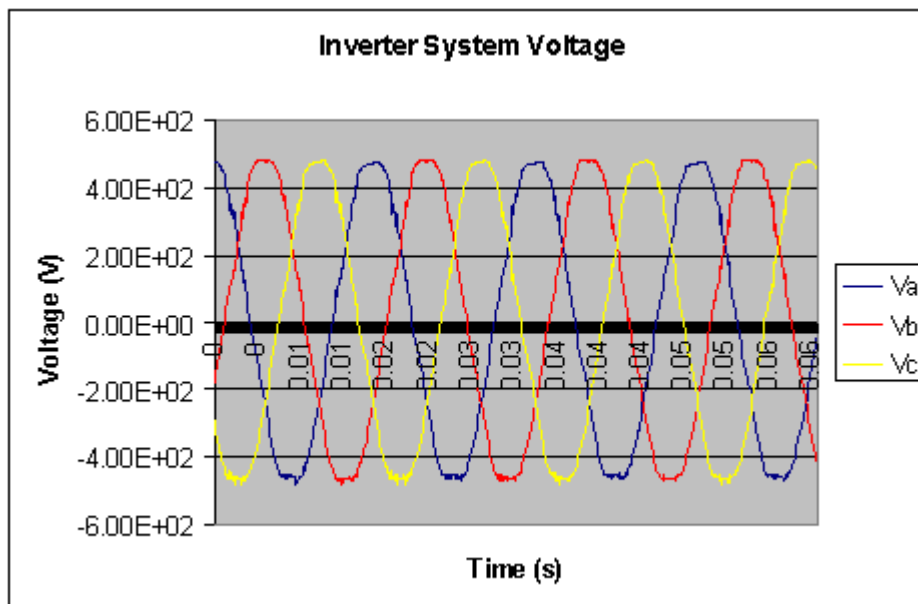


Figure 5.11 Inverter System Voltage

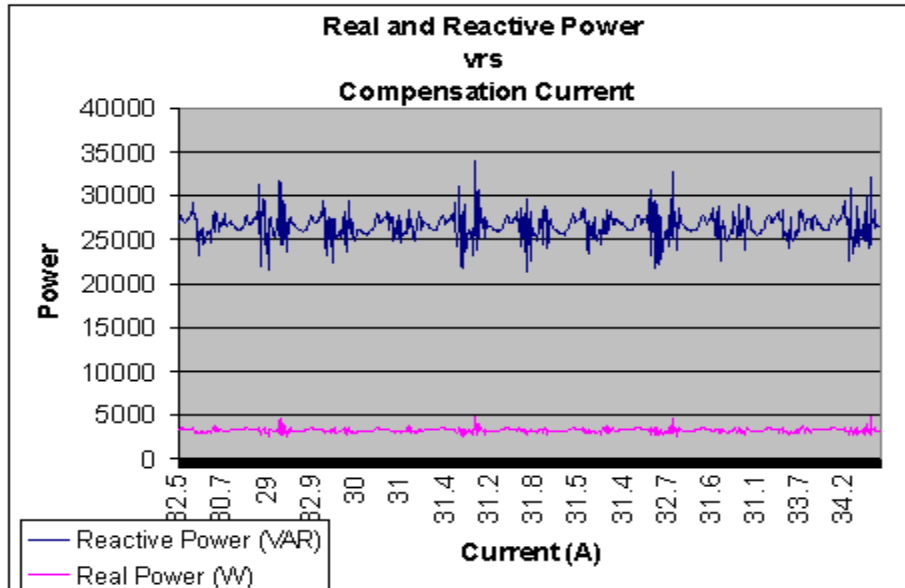


Figure 5.12 Real and Reactive Power injected by Inverter.

The simulation on SKM was done using the existing data from the tests for a starting point. The injection of current was done through steps of 20 Amps leaving all other parameters free. In contrast with the synchronous condenser, the voltage profile did not increase significantly. The control system of the inverter thus, maintains the voltage at a stable margin. Figure 5.13 shows a comparison between the simulated data and the information measured from the inverter's panel. The increasing current does not create a big impact on the system, seen in Figure 5.14. This could be because of the rigidity of the substation with voltage regulators to aid in the control. Even though the voltage profile at the substation remains steady, the utility current decreases as the inverter injects more current into the system. In reality, the substation would see dynamic changes that would make the current fluctuate depending on the system loading. The reactive power injection can be seen in Figure 5.15. The system clearly shows a decrease in the reactive power at the substation while the inverter injects more current.

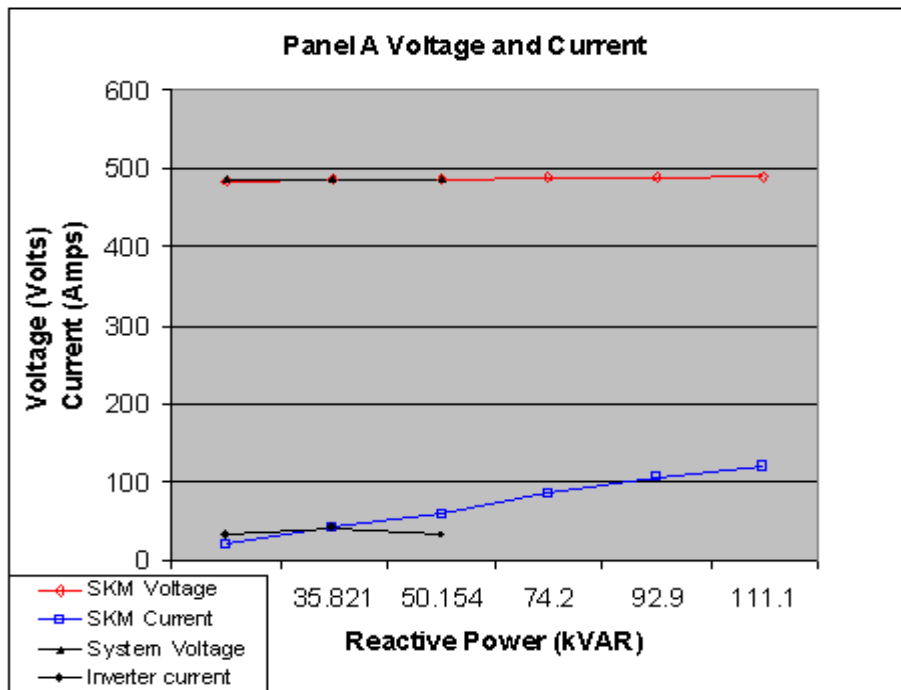


Figure 5.13 Voltage and Current Measured Data in Contrast with SKM Simulation from Inverter

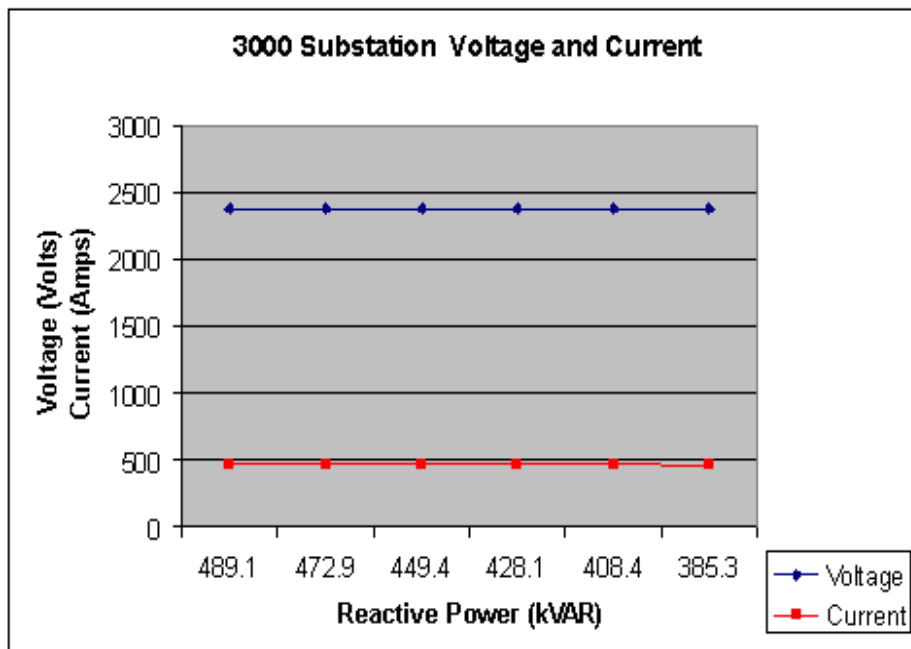


Figure 5.14 Substation Voltage and Current Profile.

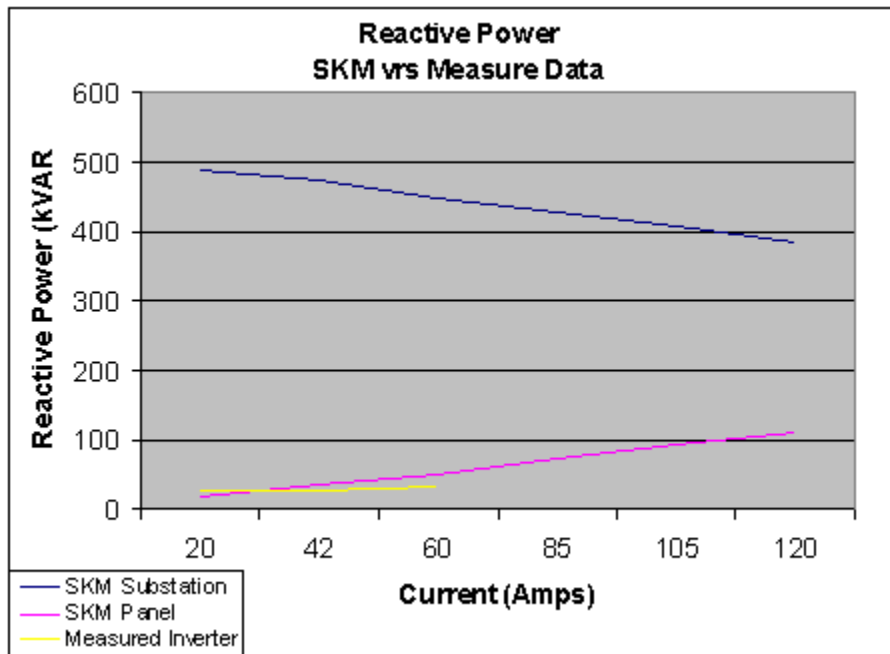


Figure 5.15 Comparison of Measured Reactive Power and SKM

5.4 Model Assumptions

The system was modeled through averaged data. All loads were modeled as constant kVA. Furthermore, motors were assumed to be running at a constant speed and not demanding inrush currents. For this reason, the model is limited in its ability to predict the system's behavior. Since the power grid is dynamic, and because of the great demand during the months of summer, a better model with either state estimators or instantaneous calculations is needed.

Equipment was calibrated on a normal basis. In order to compare values given by SKM, different compensation devices were used and matched against actual measured data. The results can be seen in Figure 5.16.

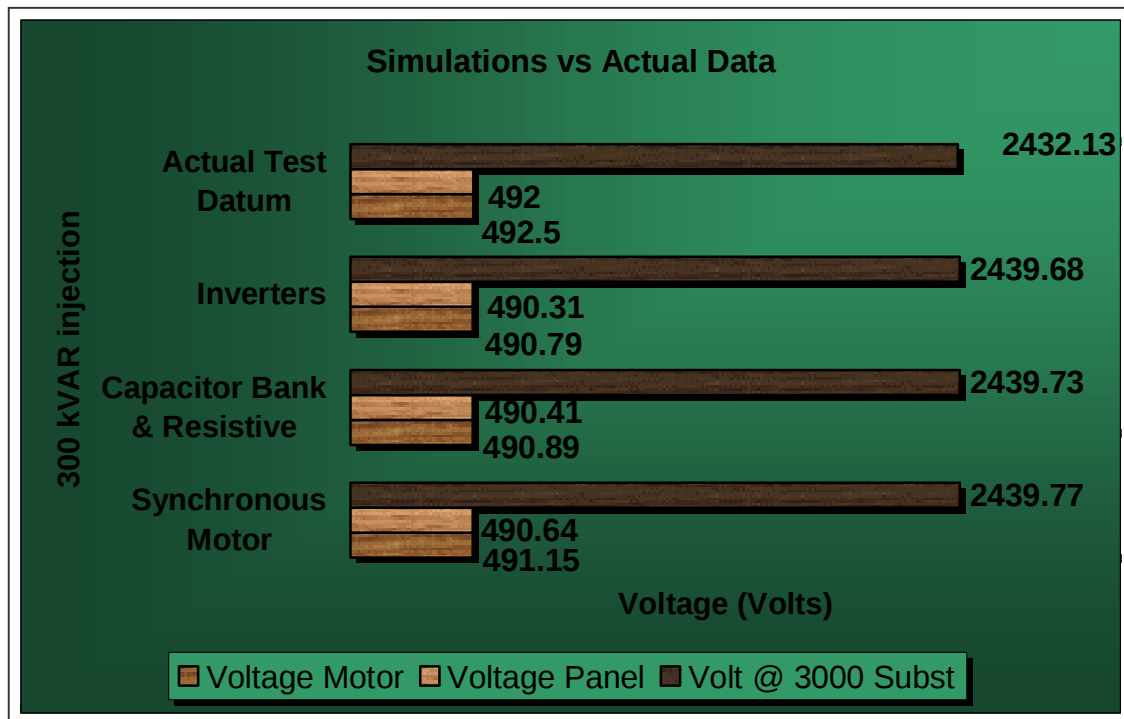


Figure 5.16 Comparison of Different Reactive Power Compensation Devices

5.5 Summary

Chapter 5 illustrated the results of the simulations. The comparison between real-time data and the simulated data was done for two cases while predictions were made for how the power system might respond to the compensation of loads. The simulation model results are close to the real values on a local basis. However, the system fails to track the changes on a global system, and is therefore unable to accurately track or predict the overall system behavior.

Chapter 6

CONCLUSIONS AND FUTURE WORK

6.1 Overview

In this chapter, conclusions will be made based on the results obtained in Chapter 5. A synopsis of the research will be provided followed by key features. Next, a discussion of the solution methods will be made. Finally, suggestions will be provided for future work.

6.2 Conclusions

The purpose of this thesis was to simulate power system response to reactive power compensation. Since the electrical power system is dynamic in nature, and because of the complexity of the non-linear loads, different methods of instantaneous quantities need to be studied to predict discrepancies between the simulation and the actual data.

The U.S. Power Grid is constantly increasing in size because of demand requirements. The lack of investment in infrastructure has diminished the systems' capabilities of expansion. Moreover, the new market structure calls for fast response and interaction between generating companies and utilities. This, in turn with unpredictable consumer demand, a vertical system organization, and economic limitations complicates the task of designing a reliable, rigid electrical power system.

System modeling and simulation can help reduce the level of complexity by testing the grid's condition while maintaining an economical feasible solution. These

programs however need to incorporate dynamic events and allocate resources in a reasonable amount of time. There are many changes that need to be implemented in order to have a reliable system. Since DER is already available and in addition to being close to the loads, a practical alternative is to use them for reactive power compensation.

In conclusion, reactive power compensation is one of the many controllable variables that can aid in predicting system behavior and assisting in system contingencies. Oak Ridge National Laboratory is working together with private industry to alleviate the financial burden on developing new technologies. Program simulators can reduce this cost by integrating systems and testing equipment before implementing it. The greatest advantage is in their availability to predict the system's response to a predetermined state.

The first tests conducted in the Reactive Power Laboratory were for characterization of equipment and subsequent power system response to their contribution of non-active power. On both the synchronous condenser and inverter, the local response (panels) was simulated and the results were comparable to the real data. On a global response, the simulation is inconclusive and erroneous since each load is held constant when in reality they vary dynamically.

Overall, SKM by itself cannot simulate dynamic events. The software program needs real time inputs from SCADA type control systems and state estimation techniques to simulate the dynamic power system response. Even though tests can be conducted and compared to the simulations, discrepancies from the software as well as system unpredictability make SKM a useful but not indicative tool.

6.3 Future Work

Power generating companies, utilities and private industry are working together to find possible solutions to the system's saturation. Further development in this area is not only a possibility, but also a necessity. The RPL has ample cases and equipment for test scenarios and topologies. The next milestone will be to test the synchronous condenser and the inverters simultaneously to compensate for a load. This test can give an insight into the location and size of compensation equipment. Next, the equipment will be tested in parallel to determine the possibility of a centralized control system. From this test, other tests can be made to determine which device should be a base, and which should be the immediate response unit. Lastly, integration with other equipment such as micro turbines, fuel cells or wind power should be considered.

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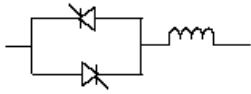
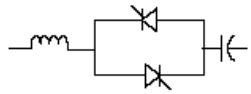
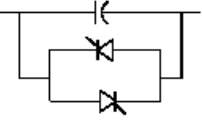
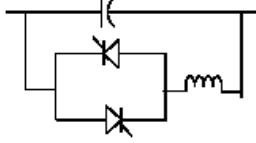
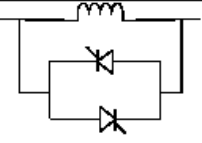
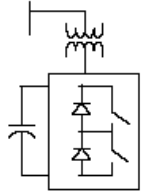
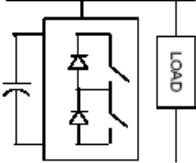
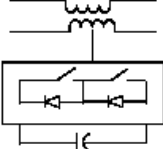
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APPENDICES

A summary of FACTS controllers' configurations

Controller	Circuit configuration	System functions	Control principle
TCR/TSC - Thyristor Controlled or Switched Reactor		- Regulate voltage - Improve stability	VAR control by varying L in the shunt connection
TCC/TSC – Thyristor Controlled or Switched Capacitor		- Regulate voltage & compensate VAR - Improve stability	VAR control by varying C in the shunt connection
TSSC – Thyristor Switched Series Capacitor		- Control power flow - Improve stability	Power and VAR control through varying C .
TCSR – Thyristor Controlled Series Capacitor		- Control power flow - Improve stability - Limit fault current	Power and VAR control through varying C & L in shunt connection
TCSR – Thyristor Controlled Series Reactor		Limit fault current	Current control by inserting L in series.
STATCOM Static Synchronous Compensator		- Regulate voltage & compensate VAR - Improve stability	VAR control through current control in shunt connection
Active Filter (Shunt Connected)		Harmonic current filtering	Inject canceling harmonic current into the source
SSSC – Static Series Synchronous Compensator		- Control power flow - Improve stability	VAR control through series voltage control.

[18]

Vita

Pierre Alexandre Bohême was born in San Jose, Costa Rica in 1976. He received his Bachelors of Science from the University of Memphis in December 2002.

After that Pierre went on to pursue his Masters of Science in Electrical Engineering, specializing in Power Electronics and Power System Analysis at the University of Tennessee at Knoxville. Pierre received his Masters of Science in August 2006. During his graduate studies he worked as part of the Reactive Power Compensation, and Facilities Development Division group at Oak Ridge National Laboratory performing power system analysis. His area of interest is Power Electronics and Power System Distribution.