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Flexible AC transmission system compensation on a utility transmission system

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FLEXIBLE AC TRANSMISSION SYSTEM COMPENSATION ON A UTILITY TRANSMISSION SYSTEM

by

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ABSTRACT

**Flexible AC Transmission System Compensation
On A Utility Transmission System**

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Power system security can be increased by the use of Flexible AC Transmission System devices, FACTS, in transmission systems experiencing high power flows. This thesis presents an analysis of one of these devices, namely, a Thyristor Controlled Series Compensator, TCSC, as applied to the Nevada Power Company 230kV southern transmission network. The methodology for choosing the appropriate location for the device and equations to accurately analyze the TCSC are developed. The analysis of the utility network is divided into three stages: 1) development of a benchmark, pre-TCSC case, establishing the real and reactive power transfer capabilities of the network, 2) identification of the critical contingencies at increased power transfers, and 3) evaluation of a TCSC device to mitigate the identified problem area. Results indicate that the application of a TCSC to the McCullough-Arden #2 230kV transmission line will

increase bulk power transfers into this area by 108 MW while mitigating a line outage and releasing increased power flows on a critically loaded line. This study also shows that the power system modeled will reach a steady-state condition within 18 cycles after the TCSC is inserted.

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I will never find enough ways to show you what your friendship has meant to me, I love you.

CHAPTER 1

INTRODUCTION

Utilities plan for the future by using calculated growth patterns and a complex analysis of the variables at work. During the 1974 energy crisis, the increase in fuel prices spurred a change in energy consumption rates. As a consequence, the predictable growth patterns of certain utility areas became less stable.

The impact of the 1970's created a permanent change in the power industry. In 1978 the Public Utility Regulatory Policies Act (PURPA) was passed. PURPA encouraged the construction of non-utility owned power generating facilities and required utilities to purchase power produced by qualified facilities (QFs) [1]. This act gave impetus to the idea of independent power producers (IPPs) who could sell their power to other utilities or customers, via a connecting utilities' transmission system. Cost differentials encouraged utilities to begin buying excess power at lower rates from neighboring utilities.

All of these elements helped to bring the climate of change that the entire power industry is experiencing today. EPAct, the 1992 Energy Policy Act, requires that utility companies provide *open access* to their transmission grids to allow for power transactions between sellers and buyers of power. As a consequence, consumers and suppliers of power may make direct sales transactions over transmission lines wholly owned by a third party. This is defined as Power Wheeling [2]. By wheeling power through their transmission systems, utility companies will take on the larger role of power carriers. The utility transmission systems are the primary focus for many new competitive pressures confronting a deregulated electric power industry.

A deregulated power market brings with it not only added competition, but also added physical strain in the form of bulk power transactions. For any bulk power system configuration to operate effectively, it must adhere to certain physical principals of electricity [1]: 1) electricity flows at the speed of light with essentially no storage of power in the system and 2) every flow of power from producer to consumer will follow the path of least resistance on a transmission network, not just the most direct or contractual path.

A problem with AC power delivery systems is a phenomenon called parallel path flow. When a utility sells power to another utility, both must be careful that no component of the entire network is overloaded. This is because lines which are not part of the direct power transfer path carry part of the load. This means the entire transmission carrying capacity of a network is only as great as its lowest limiting elements.

There are three types of constraints on any transmission system: thermal limits, voltage stability limits, and power stability limits. Transmission line thermal limits set the acceptable amount of load that a line can handle before it overheats and sags as a result of thermal expansion of the line. Voltage stability limits are linked with supplying sufficient reactive power. Reactive power does not lend itself to long distance transmission, therefore, intermediate support devices are needed for VAr compensation.

Should these devices fail due to a transient disturbance near a major load, the voltage can collapse and bring down the entire system. Power stability limits are placed on a system to help prevent loss of synchronism. Generators connected to the same power grid must remain synchronized. Transient faults on a transmission line can cause acceleration and deceleration of the generators attached to the system and possibly a split in power flow to the grid. Power loading limits are set to prevent this event [3].

An increase in bulk power transactions will test each of these limits. Utilities will need to build new transmission lines. The question becomes whether to build these new transmission lines in the immediate future or improve the carrying capacity of the lines already in existence. The capital expenditure involved with building new transmission line systems is substantial; more than $500,000 per mile [4]. It is also difficult to obtain the realty right-of-way contracts to allow construction. Improvements in load switching hardware would allow utilities to make the most of their lines and save approximately $6 billion in construction costs per 10% average capacity increase nationwide [4]. Expanding the carrying capacity of present transmission systems seems the most economical choice. To increase transmission traffic without pushing past the physical constraints of their power systems and still be cost competitive, utility companies need to consider new technological advances in transmission hardware [1].

Addressing the demand for power flow control, system stability and transmission capacity expansion, researchers are developing new solid-state controllers. These new devices will allow utilities to expand the use of their lines, pushing them to the edge of their physical limits. This could increase bulk power transfers by as much as 50% [3].

Large solid-state switching devices developed from thyristors comprise a new technology called Flexible AC Transmission Systems or FACTS.

Traditionally, mechanical switches have been used to allow utilities to shift loading conditions to compensate for AC power line limitations. These devices mainly include circuit breakers, tap changing transformers, and shunt capacitors. Thyristor based switches offer two significant advantages over their mechanical counter parts [5]: 1) faster switching speeds resulting in improved system stability over the entire grid, and 2) improved durability.

For example, a typical circuit breaker can take as long as 3 cycles to operate after receiving a signal to open, while thyristor switches can operate in approximately 1/32 of a cycle [5]. Mechanical switches are limited by the number of switching operations they can perform in a given time period. Furthermore, mechanical switches inherently wear out. Solid-state thyristor switching devices allow unlimited numbers of operations and have no mechanical parts which require replacement.

Thyristor controllers are not new. Static VAr compensators, SVCs, have been in use for approximately twenty years. Their purpose is to maintain voltage stability on heavily loaded lines. SVCs add shunt capacitance or inductance to the line to regulate the voltage. SVCs are the least effective when the voltage of a line falls too low due to heavy inductive load [6].

Narain G. Hingorani Sub-Synchronous Resonance damper, NGH-SSR damper, was invented to counteract subsynchronous resonance problems that develop when series compensation is added to cancel the line reactance. It was the precursor to the thryristor controlled series capacitor, TCSC. The TCSC offers the reduced line impedance of the traditional series compensated line but without the associated stability problems [7].

Static compensators or STATCOMs, are a significantly improved version of SVCs. STATCOMs are designed to add shunt compensation, but unlike SVCs, they do so at a faster rate while enhancing system stability. Static compensators use gate-turnoff-thyristors and a capacitor to exchange VArs between transmission line phases [8].

The thyristor controlled static phase regulator, TCPR, injects a variable series voltage on a transmission line. The magnitude of the voltage injected determines the amount of phase shift. This device can be used to solve loop flow problems, improve the transient stability and damp oscillations of a transmission system [9].

A Unified Power Flow Controller or UPFC can be considered the next generation in FACTS technology. This device combines the functionality of all the previously developed thyristor based controllers in one package. This technology synthesizes the wave forms of capacitors and reactors. It combines a shunt voltage control device with a series power flow controller. The device regulates voltage level as well as multidirectional real and reactive power flow [10].

Power systems of the future will become more complex to operate and less secure with large unscheduled power flows and high losses as large power transfers occur between independent power producers and the utilities they serve. System security can be increased by the use of Flexible AC Transmission System devices. In the chapters that follow, working models and the basic operation of some of these FACTS devices will be described. An analysis of a TCSC device as applied to the local 230kV utility network will be investigated.

Chapter 2 outlines the basic operating characteristics of several of the FACTS devices previously described at high voltage levels of 230kV and above. Due to the nonlinear nature of FACTS devices, Chapter 3 will describe the harmonic profile of the SVC, STATCON, TCSC, and UPFC. An overview of the reduced network model of the Nevada Power Company (NPC) transmission system used for this thesis and the software tools utilized for steady-state and transient analysis are summarized in Chapter 4. Summary reports of the NPC transfer capability are reviewed and contingency line outage reports are developed to identify a candidate transmission line for placement of a TCSC device in Chapter 4.

Results and conclusions from this study are summarized in Chapters 5 and 6. This study indicates that placement of a thyristor controlled series reactor on the NPC McCullough-Arden #2 230kV line will mitigate a contingency outage on the NPC Mead-Winterwood 230kV line. It does this by increasing power flows on the McCullough-Arden #2 230kV line by a little more than 300MW while reducing the current flows on a critically loaded line (Mead-Basic 230kV line). This entire redistributed power transfer to the McCullough-Arden #2 230kV line via the TCSC is complete within an 18 cycle damping time.

CHAPTER 2

FLEXIBLE AC TRANSMISSION SYSTEM DEVICES

Several factors have influenced new technological developments in the area of electric power transmission system compensation. The dependence of utility customers on reliable electrical supplies has become more critical. The western area power outage during the summer of 1996 is an example of the necessity for reliable power. Deregulation of the power industry has spurred further development in the area of power line compensation schemes. Acquiring rights-of-way to build new transmission circuits to handle the increase in bulk power transfers has become more difficult. The inability to acquire necessary rights-of-way in the U.S. and elsewhere is known as the corridor crisis. These reasons have given impetus to the flood of new transmission line compensation schemes being developed.

This chapter begins with an outline of basic compensation concepts. Next, various passive and active compensation circuits will be described showing how thyristor controlled transmission line compensation can increase system stability and raise safe power transfer margins.

2.1 Basic Mechanisms of Compensation

Power networks have two limiting constraints to bulk power transfers: 1) Stability - major synchronous machines must remain in stable synchronism, and 2) Correct voltage levels - bus and line voltages must be kept close to their acceptable or rated values. Stability in power systems can be defined as a power system's ability to recover from various temporary disturbances, such as, faults and switching operations. The limit of a power system to maintain synchronism as power transfers are gradually increased is the steady-state stability limit of the system. Dynamic stability can be defined as the rate of recovery that a power system takes following a minor disturbance. Transient stability is the ability of a system to recover from a major disturbance. A transient stability limit is defined as the maximum pre-disturbance power transfer that a network is capable of having prior to a major disturbance from which it can recover. Dynamic and transient stability limits are used in determining the operating safety margins of a power system.

Voltages must be kept in acceptable limits, usually ± 5%. Maintaining a nominal voltage value on a power system requires enough reactive power to sustain the magnetic fields necessary to transmit and use alternating current. Heavy loads can cause undervoltage conditions. A power system experiencing an undervoltage condition is approaching its steady-state stability limits. Conversely, light loads produce overvoltage conditions. A power system experiencing an overvoltage runs the risk of flashovers, insulation breakdown, possible generator heat damage or generator instability.

Power flow in an AC transmission line is governed by three parameters: line impedance, the magnitude of the receiving and sending-end voltages, and the respective voltage phase angles. Consider the uncompensated transmission line pictured in Figure 1. The fundamental equation describing real power flow in an electrically short, lossless AC transmission line is given by:

$$P = \frac{E_1 E_2}{X_l} \sin(\delta_{12}) \tag{1}$$

where P = Power (MW)

E_1 = Sending-end transmission line source voltage (kV),

E_2 = Receiving-end transmission line voltage (kV),

δ_{12}= Angular difference ,(δ_1-δ_2), of phasors E_1 & E_2,

X_l= Transmission line impedance (Ω).

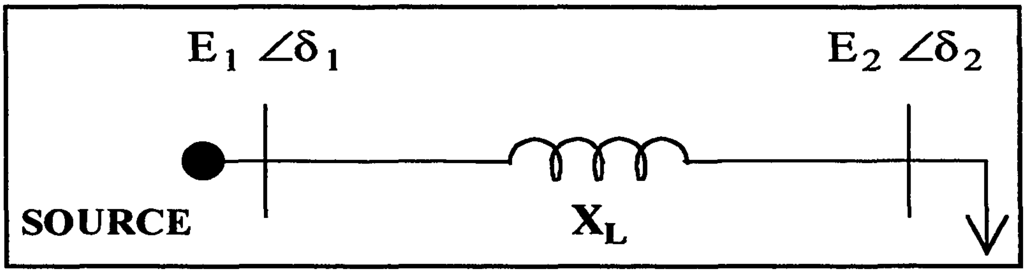

Figure 1: Uncompensated transmission line model.

Equation (1) is valid for both synchronous and nonsynchronous loads. The maximum real power transfer and the steady-state stability limit occur when δ_{12} is equal to 90° i.e.,

$$P_{max} = \frac{E_1 E_2}{X_l} \qquad (2)$$

Any angular difference between the sending and receiving-end voltages greater than 90° causes an out-of-step condition between the sending and the receiving generator shafts. A safe operating region for uncompensated transmission lines is generally at a voltage phase angle difference of less than 30°. The approximate reactive power entering each end of the line model in Figure 1 is [13]:

$$Q = \frac{E_1 E_2}{X_l}\left(1 - \cos(\delta_{12})\right) \qquad (3)$$

Consider the simplified model of a compensated transmission line in Figure 2. In this model, the impedance of the line has been divided in half and VAr support has been placed at the midpoint of the line. Shunt reactive compensation will increase the total real power flow on the line. The increase in real power is represented by:

$$P = 2\frac{E_1 E_2}{X_l}\left(\sin(\frac{\delta_{12}}{2})\right) \qquad (4)$$

Similarly, the reactive power provided by the compensator will be:

$$Q = 4\frac{E_1 E_2}{X_l}\left(1 - \cos\frac{\delta_{12}}{2}\right) \qquad (5)$$

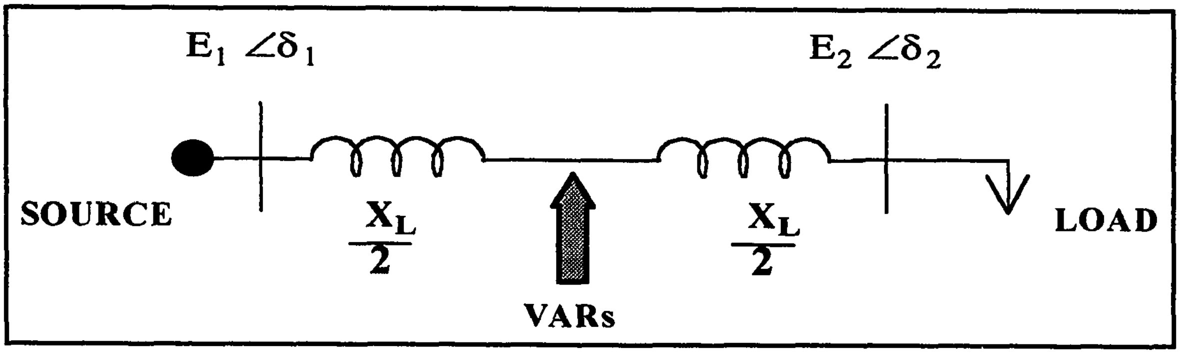

Figure 2: Compensated lossless transmission line model.

A change in the three power transmission parameters shown in the fundamental power equation (1) can increase or decrease the amount of real power transferred. It is this phenomenon that is explored and maximized in the emerging solid-state transmission compensation controllers. Generally, it is assumed that the receiving and sending-end voltage magnitudes will fluctuate only slightly about their nominal values.

2.2 FACTS Devices

The real power transfers can be altered by a change in the transmission voltage angle, by using a phase shifter, or a change in the transmission line impedance, by using the various compensation methods described in this chapter. In the sections that follow, a basic description of the operating characteristics of several FACTS devices will be given. The following table lists these compensators and their attributes.

Table 1: Flexible AC Transmission compensation devices and their attributes.

TYPE	ATTRIBUTES
Static VAr Compensator (SVC)	Voltage control, VAr compensation, damping of oscillations
Static compensator (STATCOM)	Voltage control, VAr compensation, damping of oscillations, transient stability
Thyristor-Controlled Series Capacitor (TCSC) or Advanced Series Compensator (ASC)	Power control, voltage control, series impedance control, damping of oscillations, transient stability
Unified Power Controller (UPFC)	Power control, voltage control VAr compensation damping of oscillations, transient stability
NGH-SSR damper , (NGH-SSR = Narain G. Hingorani sub-synchronous resonance)	Damping of oscillations, series impedance control, transient stability
Thyristor-Controlled Phase angle Regulator (TCPR)	Power control, phase angle control, damping of oscillations, transient stability
Thyristor-Controlled dynamic brake	Damping of oscillations, transient stability

2.2.1 Static VAr Compensators

Static VAr Compensators (SVCs) control specific elements of a power system by providing active shunt reactive compensation that either generates or absorbs reactive power. The term *static* refers to the fact that unlike synchronous compensators an SVC has no moving parts.

Since the late 1970's, SVCs have been increasingly utilized in transmission system compensation schemes. They can be used to enhance the following:

1) prevention of voltage collapse, 2) improve transient stability margins, 3) improve damping of system oscillations, and 4) mitigate power frequency overvoltages.

A Static VAr System (SVS) can consist of a combination of the following elements: Thyristor-Controlled Reactor (TCR); Thyristor-Switched Capacitor (TSC); Thyristor-Switched Reactor (TSR); Fixed Shunt Capacitor (F C); and Saturated Reactor (SR).

TCRs include a reactor in series with a bi-directional thyristor switch. Figure 3 shows a TCR in parallel with a fixed shunt capacitor. Generally, the SVS acts as a variable reactive load or adjustable susceptance which is continuously altered to keep the AC voltage nearly constant. It does this by controlling the reactive current drawn or supplied to the system. By adding fixed or switched capacitor banks to the bus where the basic TCR is attached, the dynamic range of the SVS can be extended.

Thyristors conduct on half cycles of the natural frequency of the power system. Their conduction depends on the thyristor firing angle α, which is measured from the zero crossing of the voltage. Full conduction is obtained at a firing angle of 90°. Partial conduction is achieved at firing angles between 90°and 180°. Angles of less than 90° produce asymmetrical currents with DC components.

The current waveform becomes less sinusoidal as the firing angle increases from 90° to 180°. Harmonic frequencies are generated by the thyristor switches of the SVC at firing angles between 90° and 180°. Chapter 3 will present a brief harmonic analysis of this device.

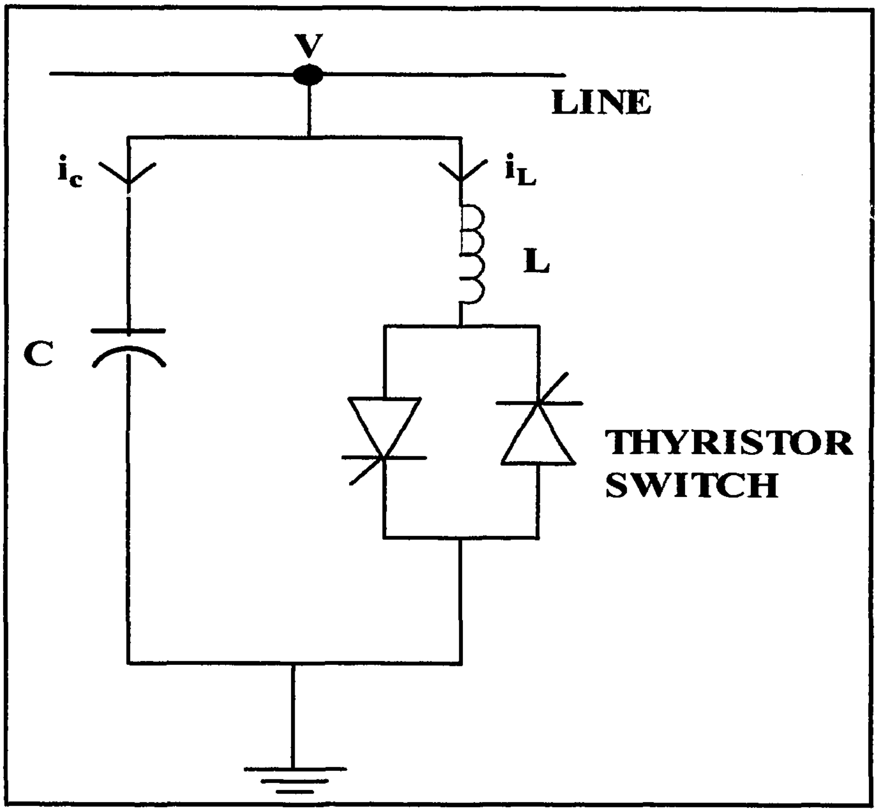

Figure 3: Ideal Static VAr Compensator.

2.2.2 Static Compensator

Static Compensators (STATCOMs) are used to provide a rapid controlled source of reactive power. STATCOMs are sometimes called advanced SVCs. They are a newer, improved version of the old rotating machine synchronous condenser and they are the first FACTS device to be designed with gate turnoff thyristors (GTOs). STATCOMs have a major advantage over SVCs in that they are more independent of voltage over a wider range. They also have a faster response time when compared to the SVC.

STATCOMs operate by absorbing energy during one part of the cycle and returning it during another part. Like their older mechanical counter part, the rotating synchronous condenser, the STATCOM is a capacitive compensator when the controlled voltage is in phase and higher than the line voltage, on the other hand, the STATCOM is an inductive compensator when the controlled voltage is lower than line voltage. The rotating synchronous condensers use the back emf of the machine to provide a controllable synchronous impedance in connection with the supported transmission line. STATCOMs provide an adjustable AC voltage source to the line via a solid-state DC-to-AC inverter. The DC terminal voltage is supported by a charged capacitor bank. Figure 4 shows a basic model for this compensator.

A practical application of this controller would be voltage regulation during a transmission network load schedule increase, thus allowing a reduction in the use of tap changes on transformer banks. In addition, the STATCOM can be designed for specific load compensation, as in the case of an arc furnace. Because the inverter can be designed with a higher bandwidth, the STATCOM can be made to compensate the non-sinusoidal unbalanced currents of an arc furnace [12].

The STATCOM has an additional advantage over the SVC in that it occupies less space, offers very little distortion over a wide voltage range and is cost competitive. The harmonic content for this device are discussed in the next chapter.

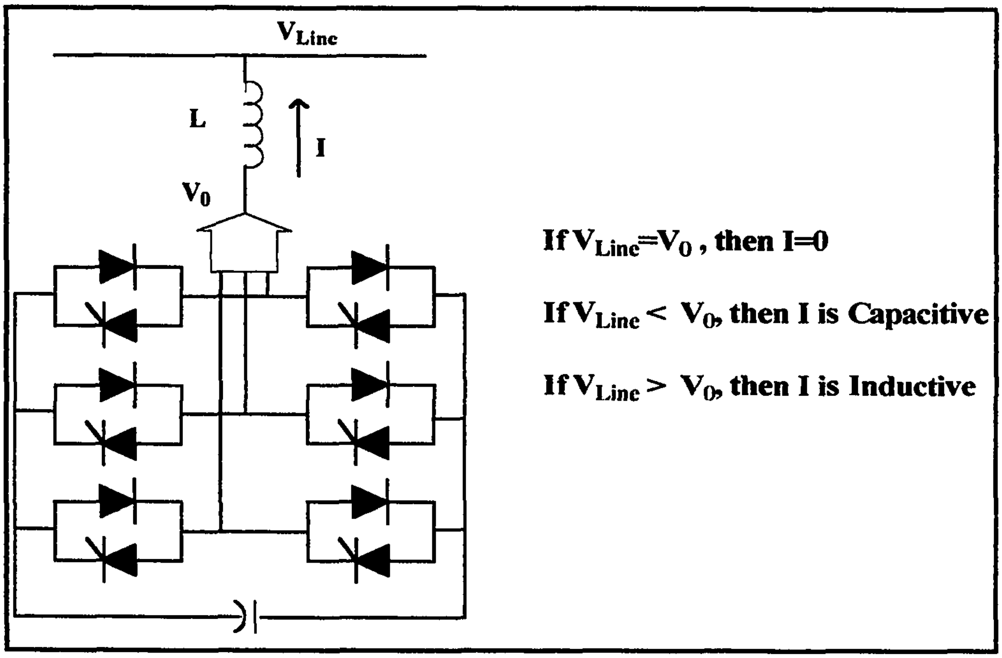

Figure 4: Simplified model of a STATCOM.

2.2.3 Thyristor Controlled Series Capacitors

Capacitors connected in series with an AC transmission line reduce the total line impedance and allow additional power to be scheduled and transferred across the line. They increase the effective natural load, the small-signal stability limit and improve voltage regulation. Unlike shunt capacitors, series capacitors reduce both the characteristic impedance and the electrical length of the line.

Thyristor controlled series compensation (TCSC) offers fast insertion and vernier control that rapidly changes the amount of effective capacitance in series with a transmission line. TCSC devices have the following advantages: 1) fast damping on heavily loaded lines, 2) reduced liability to create sub-synchronous resonance, 3) increased transient stability; and 4) power flow control. Figure 5 shows a simple model of a TCSC.

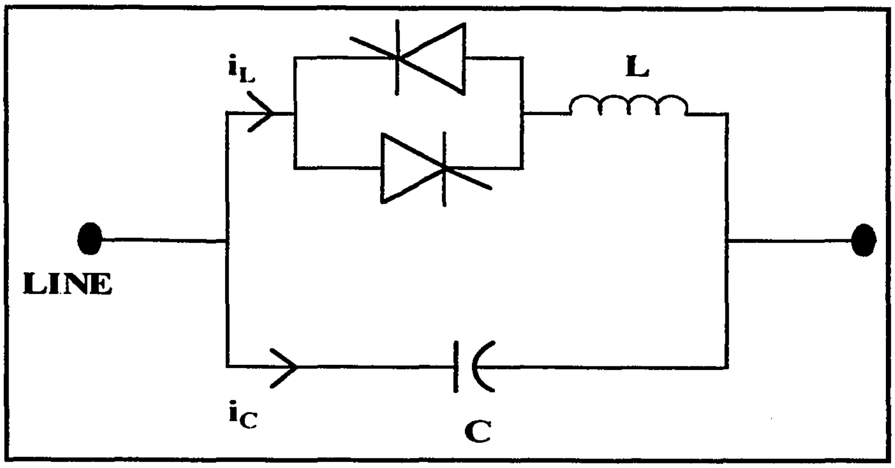

Figure 5: Simple model of a TCSC.

The TCSC devices have three modes of operation: 1) blocking - zero thyristor conduction, 2) bypass - full thyristor valve conduction, and 3) vernier - partial thyristor conduction. In blocking mode the device has the impedance of the series capacitor only. In bypass mode the impedance of the device is that of the small inductor and the series thyristor valves. In partial conduction mode the circuit's capacitive value is greater than that of the series capacitor alone. This value is determined by the duration of the current conducted through the thyristor valve. The thyristor firing angle determines the mode of operation and thus the total injected compensation impedance.

Like the other FACTS devices discussed so far, TCSCs also produce harmonics. Specifically, series compensated transmission lines are one of the primary causes of sub-synchronous resonance. An examination of the impedance equations, as well as, the harmonic currents and voltages associated with this controller will be addressed in the following chapter.

2.2.4 Unified Power Flow Controller

The Unified Power Flow Controller (UPFC) is a real-time thyristor based controller. Its purpose is to provide real time simultaneous control of all basic power system parameters. The function of the controller can be changed from that of a phase shifter to that of a series compensation device without additional equipment or regulation. The concept of the UPFC is to incorporate in one device all of the attributes of the other FACTS devices into one controller. The generalized UPFC is designed to accomplish the following objectives [10]: 1) terminal voltage regulation, 2) combined series line compensation and terminal voltage control, 3) phase angle regulation and terminal voltage control, and 4) any combination of items 1-3.

Figure 6 shows the basic components defining a UPFC. The DC-DC converter consists of two three-phase voltage source converters and a DC-link capacitor. Each converter has three sets of GTO valves and diode valves in anti-parallel directions to permit bi-directional current flow. Neglecting any losses, the UPFC, in the steady-state condition, will not absorb or inject real power in reference to the system. Therefore the voltage of the DC-link capacitor connecting the two inverters remains at a constant pre-determined value.

To achieve terminal voltage regulation the injected voltage V_i has an angle of zero and the magnitude is changed to reflect the desired output terminal voltage.

$$V_{o,new} = V_i + V_o \tag{6}$$

where V_i = Injected Terminal Voltage. (kV)

V_O = Output Terminal Voltage. (kV)

The injected voltage can be defined in this way:

$$V_i = \pm \Delta V_O \tag{7}$$

Adding or subtracting a voltage value to the line can be done by using series compensation. The UPFC injected voltages will equal the sum of the change in output voltage phasor, V_o, and the capacitive voltage phasor component, V_c. Depending on whether V_c lags or leads the input line current determines the positive or negative value of the capacitive voltage quantity.

$$V_i = V_c + \Delta V_o \tag{8}$$

where V_c = Capacitive voltage phasor component. (kV)

The combined phase shifting and voltage regulation function of the UPFC can be developed by changing the injected line voltage to reflect a terminal voltage adjustment, previously described and adding a phase shifting quantity [10]:

$$V_i = \left[2\, V_o \sin\left(\frac{\alpha}{2}\right) e^{\pm j \frac{\pi}{2}} \right] + \Delta V_o \tag{9}$$

Note that the resulting output voltage will have the same magnitude value as a simple voltage regulator and the phase of the output voltage will reflect the desired value. Adding each of these individual quantities together will result in a voltage controlled, series compensated and phase shifted value adjustment to the receiving end voltage of the transmission system.

Now, let the injected phase shifted voltage amount be represented by V_s. The resulting equation for the injected voltage will be:

$$V_i = V_c + V_s + \Delta V_o \tag{10}$$

Where V_s = Phase shifted voltage amount (kV).

Complex algorithms are used in the feedback and control systems of the UPFC to determine the injected voltage values and the resulting gating commands of the voltage control GTOs in the DC-DC converters. The unified power flow controller uses microprocessor based systems to make the necessary complex algorithmic decisions in sample times of less than 10 microseconds. The greatest advantage of this comprehensive and complicated controller design is an almost instantaneous response time to dynamic and transient power system oscillations.

The UPFC is not without a caveat, it injects harmonics into the transmission system. These multiples of the fundamental frequency must be identified and appropriate network filters applied. The UPFC has a similar characteristic harmonic fingerprint as that of the STATCOM. Subsequent discussions on this topic will clarify the problem and possible solutions.

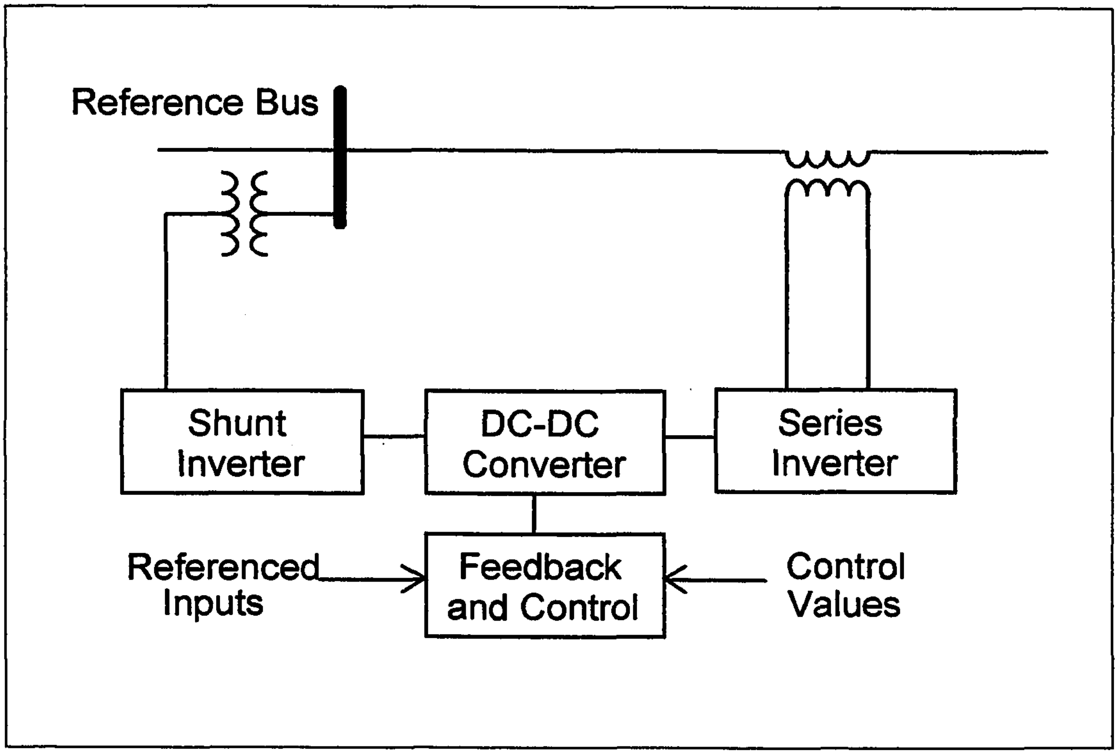

Figure 6: Basic model of a Universal Power Flow Controller

2.2.5 Other Types of Thyristor-Based Controllers

2.2.5.a NGH-SSR Damper

This device is used for dynamic balancing of transmission lines with series compensation. Series compensated transmission lines are the primary cause of sub-synchronous resonance (SSR). The name of this controller indicates that it is used in sub-synchronous resonance mitigation schemes. The phenomenon of SSR problems can cause motor shaft oscillation. This is a serious problem and requires fast, dynamic responsive protection equipment. The NGH-SSR can quickly address this problem by inserting a variable amount of impedance to a target transmission line thus quickly matching the frequency perturbation. The device consists of a resistor in series with bi-directional thyristor switches connected in parallel with a series capacitor [7].

2.2.5.b Thyristor Controlled Phase Angle Regulator

High-speed, high voltage phase shifting is important when compensating for parallel power flows. In the shadow of advancing large bulk power transactions, the phenomenon of parallel power flows will be a reality that today's utilities must face. Thyristor controlled phase angle regulators (TCPR) provide utility dispatchers the ability to regulate the transmission voltage angle to maintain balanced power flows in more than one transmission line. TCPRs offer control of the transmission angle making it possible to increase the transient and dynamic stability limits of the system.

Thyristor controlled phase angle regulators (TCPRs), like the conventional phase-shifters with mechanical tap-changers, operate by providing quadrature voltage injection to the transmission line's line to neutral terminal voltage [13]. The power flow controller of the TCPR requires power or angle measurements. These measurements in combination with a series insertion transformer with three different excitation windings can produce a more than 20 step variation in injected line voltage. This can be done using less than 12 thyristor switches per phase. The switches are arranged such that any winding can be bypassed or its polarity reversed. Because TCPRs do not produce real or reactive power they exchange any powers supplied or absorbed with the network to which is connected. This can mean a large voltage drop when this type of tap-changing transformer phase shifter injects voltage through a line. To counter this problem TCPRs should be placed near a generating source or designed with a controllable reactive shunt compensator [13].

2.2.5.c Thyristor-Controlled Dynamic Brake

This controller introduces a typically large value resistance to compensate for load loss and the resulting generator transient response. This keeps the generator in synchronism with the network when a large load is lost. The energy dissipated by the dynamic brake is proportional to the generator current, unlike other dynamic brakes that employ the use of shunt resistors and therefore are proportional to the source voltage. The primary use for this device is to control dynamic transmission system balance [4].

CHAPTER 3

HARMONIC PROFILE OF FACTS DEVICES

It is the inherent nature of thyristor controllers to cause harmonics. Waveform distortions are caused by the switching action of thyristors. This chapter will mathematically outline the characteristic equations for four of the FACTS devices discussed in the previous chapter and develop a harmonic profile for each. The FACTS devices examined in this chapter include: Static VAr Compensator, Thyristor Controlled Series Compensator, Static Compensator, and the Unified Power Flow Controller.

3.1 Static VAr Compensators

Figure 3 in Chapter 2 is an example of an SVC device. It shows a fixed capacitor in parallel with a thyristor controlled reactor (TCR). An SVC operates in three conduction modes: partial, full and no conduction. Each of these modes is controlled by the firing angle, α, applied to the thyristor valves. The firing angle is measured from the zero crossing of the system supply voltage. The conduction angle, γ, is measured from the peak system supply voltage. At full conduction, the firing angle, α, is equal to 90° and the TCR behaves as if its thyristors were short circuited. Figure 7 shows the voltage and current waveforms of an SVC at full conduction.

Partial conduction occurs at firing angles between 90° and 180°. Figure 8 shows the current wave form at a conduction angle, γ, of 10°, and therefore a firing angle, α, of 100°.

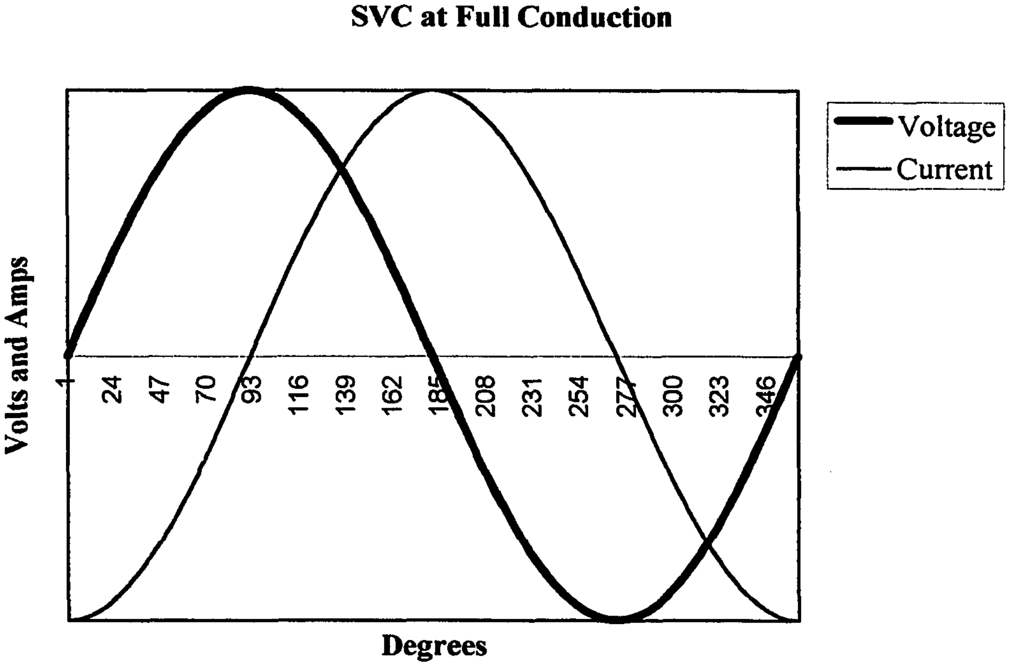

Figure 7: SVC at full conduction, γ=0°, α=90°.

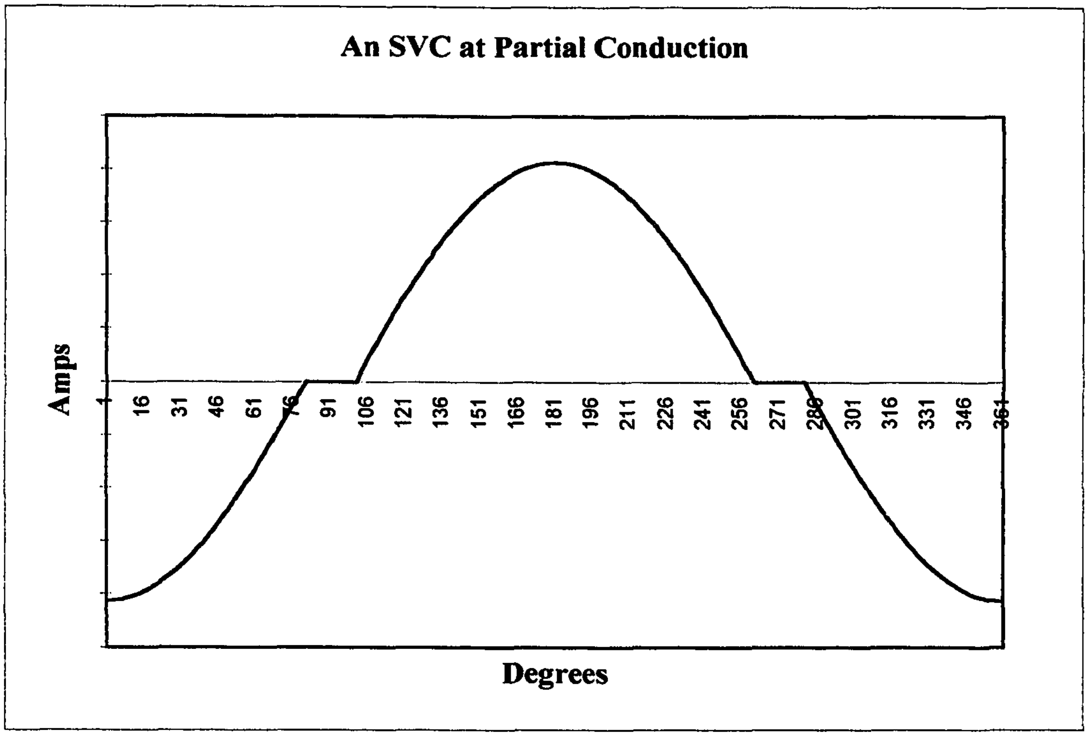

Figure 8: SVC at partial conduction, γ=10° and α=100°

The conduction angle, γ, for the SVC circuit is described by the following relationship:

$$\alpha = \frac{\pi}{2} + \gamma \tag{11}$$

Let the magnitude for the current and the impedance at full conduction for the SVC be defined as:

$$I_{L0} = \frac{V}{\omega L}, \text{ when } \alpha = 90^\circ \text{ and } Z_{L0} = \omega L \tag{12}$$

The instantaneous voltage value will be:

$$v = \sqrt{2}\, V \cos(\omega\, t) \tag{13}$$

Solving for the instantaneous current:

$$v = L\frac{di}{dt} \tag{14}$$

$$\Rightarrow\ i = \sqrt{2} I_{L0} \int_{\gamma}^{\omega t} \cos(\varphi)\, d\varphi = \sqrt{2} I_{L0}\big(\sin(\omega t) - \sin(\gamma)\big) \tag{15}$$

during conduction: $\omega\, t = \gamma \ \rightarrow\ \omega\, t = \pi - \gamma$

where: $i = 0 \ \text{ for } \ 0 < \omega t < \gamma$

The fundamental component of the current waveform is:

$$I_1 = \frac{1}{\sqrt{2}}\frac{4}{\pi}\int_{\gamma}^{\frac{\pi}{2}} i(t)\sin(\omega t)\, dt \ \Rightarrow\ I_{L0}\left(\frac{\pi - 2\gamma - \sin(2\gamma)}{\pi}\right) \tag{16}$$

where: $$\frac{I_1}{I_{L0}} = \frac{1}{\pi}\big(\pi - 2\gamma - \sin(2\gamma)\big) = \frac{1}{\pi}\big(2\pi - 2\alpha + \sin(2\alpha)\big) \tag{17}$$

By increasing the firing angle, the conduction time of the inductor is decreased thus reducing the fundamental current, I_1. Therefore the value of the impedance is a function of the firing angle, α. Full conduction and maximum impedance in the inductive leg of the SVC is achieved at a firing angle of 90°. A minimum impedance value is achieved at a firing angle of 180°.

$$Z_{L(\alpha)} = \frac{\pi Z_{L0}}{2\pi - 2\alpha + \sin(2\alpha)} \tag{18}$$

The harmonics generated by SVC devices increase as the firing angle, α, increases. The increase in the firing angle reduces the conduction angle and causes a less sinusoidal current wave form, as seen in Figure 8. Equation 19 reveals the Fourier analysis rms value of the nth harmonic current component in a TCR, where n= 3, 5, 7,... and γ is the conduction angle of the thyristor switches. Recall that $\gamma = \alpha - 90°$.

$$\frac{I_n}{I_{L0}} = \frac{2}{\pi}\left[\frac{\sin(n-1)\gamma}{n(n-1)} + \frac{\sin(n+1)\gamma}{n(n+1)}\right] \tag{19}$$

A plot of the harmonic content of the current is shown in Figure 9.

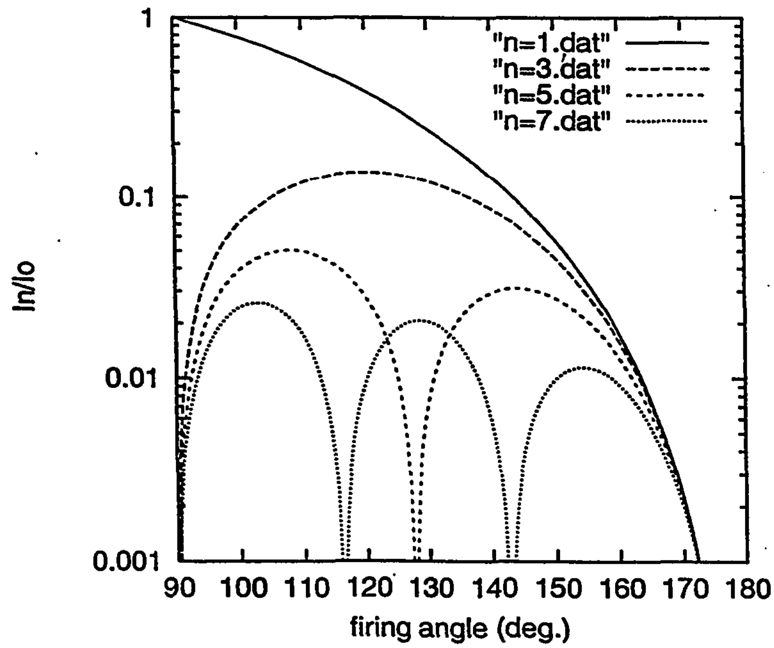

Figure 9: Harmonic content of SVC current.

The impedance of the SVC is the parallel combination of the capacitor and TCR impedance.

$$Z_{SVC} = -j\frac{X_{L1}X_C}{X_{L1}-X_C} \tag{20}$$

If $X_C < X_{L0}$ then the impedance of the SVC is capacitive value for all firing angles. If $X_C > X_{L0}$ then the impedance of the SVC is inductive for firing angles below a resonant angle, $\alpha < \alpha^*$, and is capacitive for firing angles above a resonant angle, $\alpha > \alpha^*$. At the resonant firing angle, α^*, the impedance of the TCR branch of the SVC equals that of the capacitive branch:

$$Z_L(\alpha^*) = X_C \Rightarrow \frac{\pi X_{L0}}{2\pi - 2\alpha^* + \sin(2\alpha^*)} = X_C \tag{21}$$

Figure 10 shows the impedance of the SVC when $X_C > X_{L0}$.

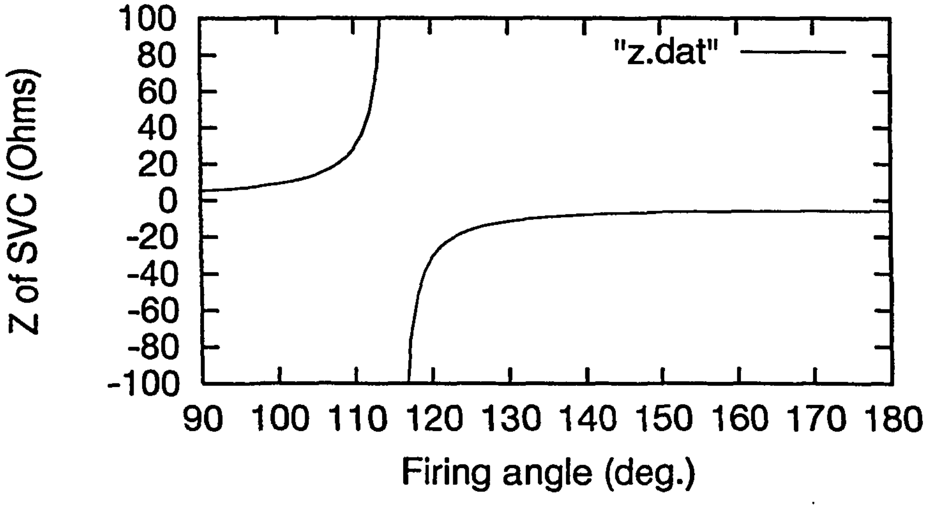

Figure 10: Impedance of SVC when $X_C > X_{L0}$.

3.2 Harmonics generated by STATCOMs

The output power wave of the STATCOM has a pulsed-step shape. The total number of GTO valves used in the design of the inverter determines the pulse number of the STATCOM. The higher the pulse number, the closer the injected voltage reflects a sinusoidal shape. The pulsed nature of this circuit is due to the arrangement of the switching circuits, diodes and thyristors, as shown in Figure 4 of Chapter 2.

The injected voltage produced by a STATCOM can be described by the following:

$$V_n = \frac{V_1}{n} \tag{22}$$

where $n = ik \pm 1$

and $k =$ The pulse number.

$i =$ Integer value.

For example, if $k = 6$, a six pulses per cycle, then

$$V_5 = \frac{V_1}{5},\ V_7 = \frac{V_1}{7},\ V_{11} = \frac{V_1}{11},\ V_{13} = \frac{V_1}{13},\ldots \tag{23}$$

If $k = 24$ then

$$V_{23} = \frac{V_1}{23},\ V_{25} = \frac{V_1}{25},\ V_{47} = \frac{V_1}{47},\ V_{49} = \frac{V_1}{49},\ldots \tag{24}$$

Figures 11, 12, and 13 show voltage wave forms for a 6-pulse, 12-pulse, and 24-pulse STATCOM. As can be seen from the plots, the higher the k number or pulse number the more closely the wave shape reflects the desired sinusoidal form. Lower order harmonics are eliminated from being injected to the system the higher the pulse number.

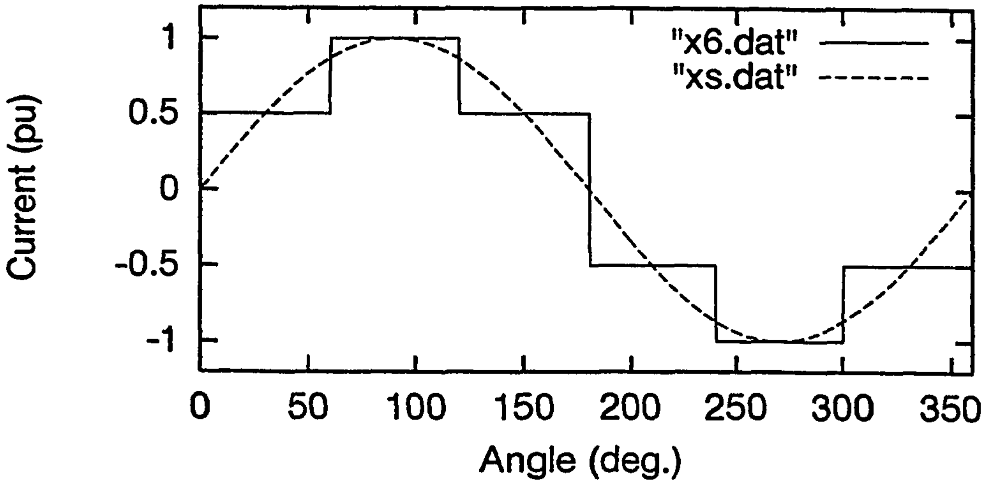

Figure 11: Six pulse voltage waveform, where x6.dat is the pulsed output and xs.dat is the desired sinusoidal output.

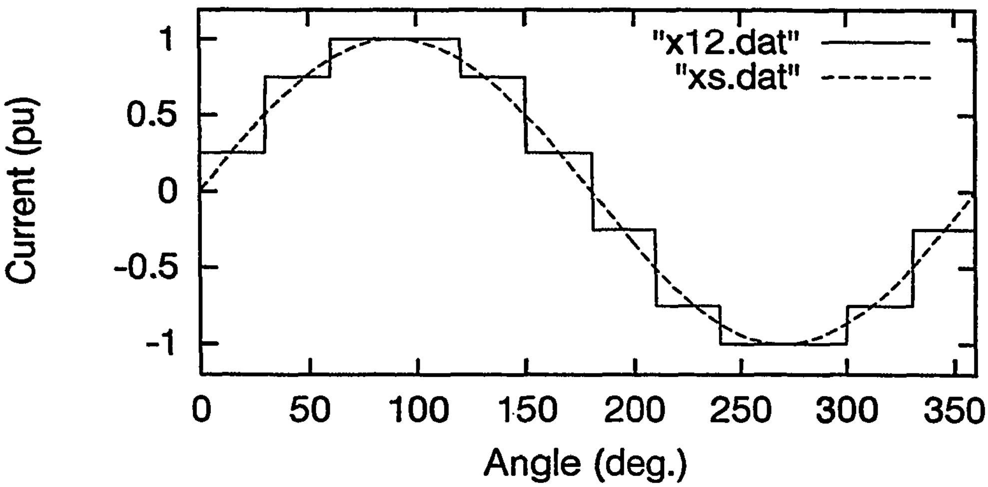

Figure 12: Twelve pulse voltage waveform, where x12.dat is the pulsed output and xs.dat is the desired sinusoidal output.

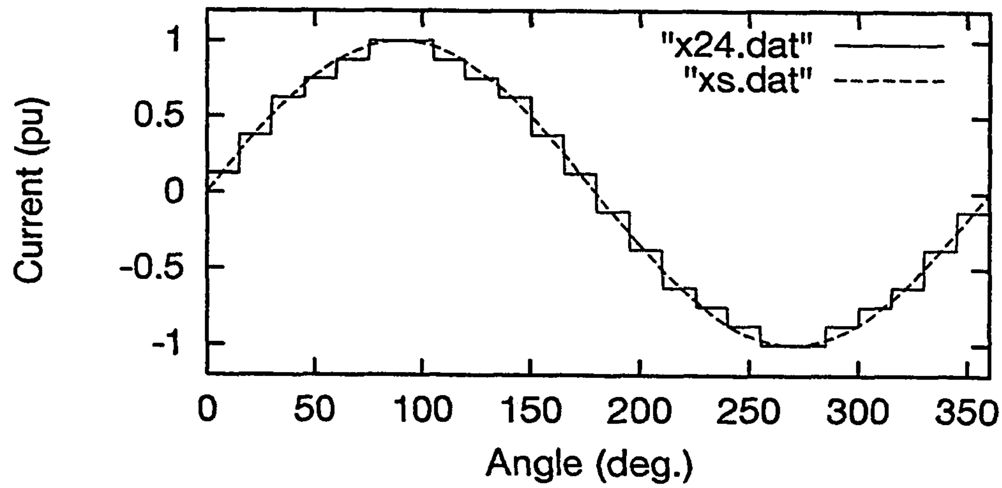

Figure 13: Twenty-four pulse voltage waveform, where x24.dat is the pulsed output and xs.dat is the desired sinusoidal output.

3.3 Thyristor Controlled Series Compensators

Chapter 2 introduced the TCSC where the typical model for this device shown in Figure 5 of Chapter 2 includes a capacitor in parallel with a TCR. The idea behind the thyristor control series compensator is that by adjusting the firing angle of the thyristor valves it is possible to increase the fundamental frequency voltage in the series compensation circuit. The increased voltage capability results in an increased compensation level with a total impedance $X(\alpha)$ of the circuit [20]. The following relationship between the line loading and capacitive voltage exists [21]:

$$X(\alpha) = X_C \frac{U_C(\alpha)}{I_{line}} \tag{25}$$

where X_C = The nominal reactance of the TCSC capacitor.

$U_C(\alpha)$ = The capacitor voltage in p.u. of nominal voltage.

I_{line} = The line current in p.u. of the nominal current.

The firing angle range for bi-directional thyristor valve controllers is between 90° and 180°. The Fourier analysis of this circuit shows the gives the following equation used in calculating the harm … e[20]:

$$V_n(\alpha) = \frac{2\omega}{\pi}\int_0^{\alpha} V_c(t,\alpha)\cos(n\omega t)\; d(\omega t)$$

$$V_n(\alpha) = \frac{2\omega}{\pi}\int_0 V_c(t,\alpha)\cos(n\omega t)\; d(\omega t) \tag{26}$$

Helbing and Karaday in reference [20] found that the 3rd harmonic in the TCSC design is dominant given typical values for the capacitor and inductor components. As the firing angle, α, decreases, the 3rd harmonic increases.

Helbing and Karady make a vital assumption when performing their analysis of the TCSC, that is that the current is sinusoidal when the bus voltage is assumed infinite. The sinusoidal current concept doesn't apply in cases where the bus voltage is infinite. Consider the following:

Let the voltage potential across the infinite bus be the following:

$$v_s = \sqrt{2}V\cos(\omega t) \tag{27}$$

Let L, L_L, and C represent the transmission line inductance, compensator inductance and capacitance. The corresponding reactances at the power frequency are X, X_L, and X_C.

In the OFF state the thyristor switches do not conduct and the TCSC device can be viewed as consisting of the capacitor only. The current of the TCSC device during the OFF state can be described as:

$$i^{off} = a_0 \sin(\omega t) + x_0 \sin(\omega_0 t) + y_0 \cos(\omega_0 t), \tag{28}$$

Where the coefficients a_0 and ω_0 are respectively given by,

$$a_0 = \frac{\sqrt{2}V}{X_c - X} = \frac{\sqrt{2}V\omega}{L(\omega^2 - \omega_0^2)}, \tag{29}$$

$$\omega_0 = \frac{1}{\sqrt{LC}}. \tag{30}$$

The constants x_0, y_0, representing the natural response, will be depend on the initial state of the TCSC device. In the OFF state the thyristor the line voltage is related to the current:

$$v^{off} = L\frac{d}{dt}i^{off} \tag{31}$$

Where the compensator voltage would be:

$$v_c^{off} = v_s - v^{off} = v_s - L\frac{d}{dt}i^{off} \tag{32}$$

During the ON state the TCSC thyristors are conducting. The current in the ON state can be described:

$$i^{on} = a_1 \sin(\omega t) + x_1 \sin(\omega_1 t) + y_1 \cos(\omega_1 t) \tag{33}$$

where the a_1, of the forced response, and ω_1, of the natural response, are respectively given by:

$$a_1 = \frac{\sqrt{2}V(X_l - X_c)}{X_l X_c - X(X_l - X_c)} = \frac{\sqrt{2}V(1-\omega^2 X_l C)}{\omega\left[\omega^2 L L_l C - (L + L_l)\right]} \tag{34}$$

$$\omega_1 = \sqrt{\frac{L + L_l}{L L_l C}} \tag{35}$$

The voltage across the line and the voltage across the compensator in the ON state are related to the current by the following expressions:

$$i_l^{on} = i^{on} - C\frac{d}{dt}v_c^{on} = CL\frac{d^2}{dt^2}i^{on} + i^{on} - C\frac{d}{dt}v_s \tag{36}$$

Four equations are needed to solve for the variables x_0, y_0 in equation (28) and x_1, y_1 in equation (33). Solution to the values of these variables will produce the steady state current and voltage waveforms. Three of the four necessary equations can be determined from the instantaneous current values in the compensator inductor, the line inductor and also the voltage across in the capacitor. For a selected firing angle, α, measured from the zero crossing of the compensator voltage:

$$i^{off}(\alpha^-) = i^{on}(\alpha^+) \tag{37}$$

$$i_l^{on}(\alpha) = 0 \tag{38}$$

$$v_c^{off}(\alpha) = v_c^{on}(\alpha) \tag{39}$$

The last relationship derived from the steady-state condition where wave symmetry is required, i.e. the capacitor voltage and inductor voltages are both zero at

$\omega t = \pi$. This means that both the line and inductor currents reach their maximum value:

$$\frac{d}{dt} i_{on}(\pi) = 0 \qquad (40)$$

Equations (29)-(33) depend only on x_1 and y_1 and are solved in terms of circuit parameters. These results are inserted in (27) and (33) to solve for x_0 and y_0. Exact analytical expressions of line current can be used to determine the harmonic components injected into the infinite buses at different levels of compensation.

3.4 Universal Power Flow Controllers

The universal power flow controller attempts to control both the voltage stability level, as well as, the real and reactive power flow on a transmission system. It does this by using two voltage source inverters and a DC to DC converter; see Chapter 2, Figure 6. Because of the arrangement of the GTO valves in the converter circuit of the device, the wave shape produced by the UPFC is similar in nature to the pulsed wave shape describe for the STATCOM. Most of these harmonics can be reduced using a harmonic neutralizing structure.

Various methods of connecting FACTS devices to a three phase system eliminate most harmonics. If the firing angles are symmetrical for both thyristors then only odd harmonics are generated. The triplen harmonics can be eliminated in a balanced system by connecting the device in a delta configuration to the three phase system. Pulsing two sets of TCRs, thyristor controlled reactors, can also eliminated the 5^{th} and 7^{th} harmonics.

Capacitive filters can eliminate the remainder. Even harmonics are produced only if the conduction angles of the two oppositely poled thyristor switches are unequal [23].

The next chapters will describe a simple power system application of a FACTS device and the results.

CHAPTER 4

TRANSMISSION SYSTEM MODEL AND ANALYSIS TOOLS

In deciding to study the application of FACTS devices on Nevada Power Company's (NPC) power transmission system network, it was necessary to identify three critical elements: 1) What power flow limitations exist in the NPC system? 2) Which FACTS device would be a reasonable solution to relieving the limitations identified in part one? 3) Where is a possible location for placement of the chosen FACTS device? The methodology developed for this task involved the following iterative four step process:

1) Define the NPC power system under study.
2) Review benchmark reports establishing the real and reactive power transfer capabilities of the high-voltage transmission line network in the southern Nevada area.
3) Review critical transmission line contingency outage reports; identifying possible candidate transmission lines for the placement of compensation at increased levels of power transfer.
4) Classification of a FACTS device to address the identified problem area.

The following sections address the steps in this process and also describes the research tools used.

4.1 Nevada Power Company's Transmission System

Nevada Power Company's (NPC) service territory is a 4,500 square mile area encompassing the Las Vegas valley and delivering power to approximately 500,000 customers representing roughly 1.2 million residents. The company has been listed in recent years as one of the fastest growing utilities in the U.S. . Nevada Power Company faces a wide range of power delivery challenges due to the continual influx of new residents to the southern Nevada area. Presently, NPC provides a peak summer load of approximately 3,400 MW and 1,450 MVArs (uncompensated). Real power to meet this demand is generated locally and imported via high-voltage transmission tie lines. A list of the wholly or partially owned NPC power generation plants is given in Table 2.

Table 2: NPC Generation facilities and their real power output [18].

Name of Generation Plant	Real Power Output
Reid Gardner #1, #2, #3, #4	605 MW
Harry Allen	72 MW
Mohave	196 MW
Navajo	255 MW
Clark	687 MW
Sunrise	149 MW
Qualified Facilities	300 MW
TOTAL	**2,264 MW**

At a growth rate of more than 6%, NPC does not generate enough local power to meet this load. Power imports equaling approximately 46% of the total power demand are purchased via bulk power contracts from outside power producers [18]. The power bought from outside the company is brought into the Las Vegas valley through high voltage transmission tie lines. Transmission levels at NPC are defined as those levels transferring power at or above 69kV. Distribution levels at NPC are defined as those levels transferring power below 69kV. This thesis is only concerned with transmission levels. NPC has transmission levels 69kV, 138kV, 230kV and 345kV. Table 3 shows a list of transmission system tie lines.

Table 3: NPC northern and southern system tie lines [16].

Northern or Southern Area Tie Line	From:	To:
Northern 345kV	Redbutte	Harry Allen
Southern 230kV	McCullough	Tolson
Southern 230kV	McCullough	Arden #2
Southern 230kV	McCullough	Faulkner
Southern 69kV	Mead	Winterwood
Southern 69kV	Mead	Clark East
Southern 69kV	Mead	AWT
Southern 230kV	Mead	Decatur
Southern 230kV	Mead	Winterwood
Southern 230kV	Basic	Clark East
Southern 230kV	Basic	Clark West

Figure 14 shows a generalized view of NPC tie lines, while Figure 15 shows a line diagram of the 69kV with 138kV transmission system (see in pocket). Figure 16 shows the 230kV and higher transmission system.

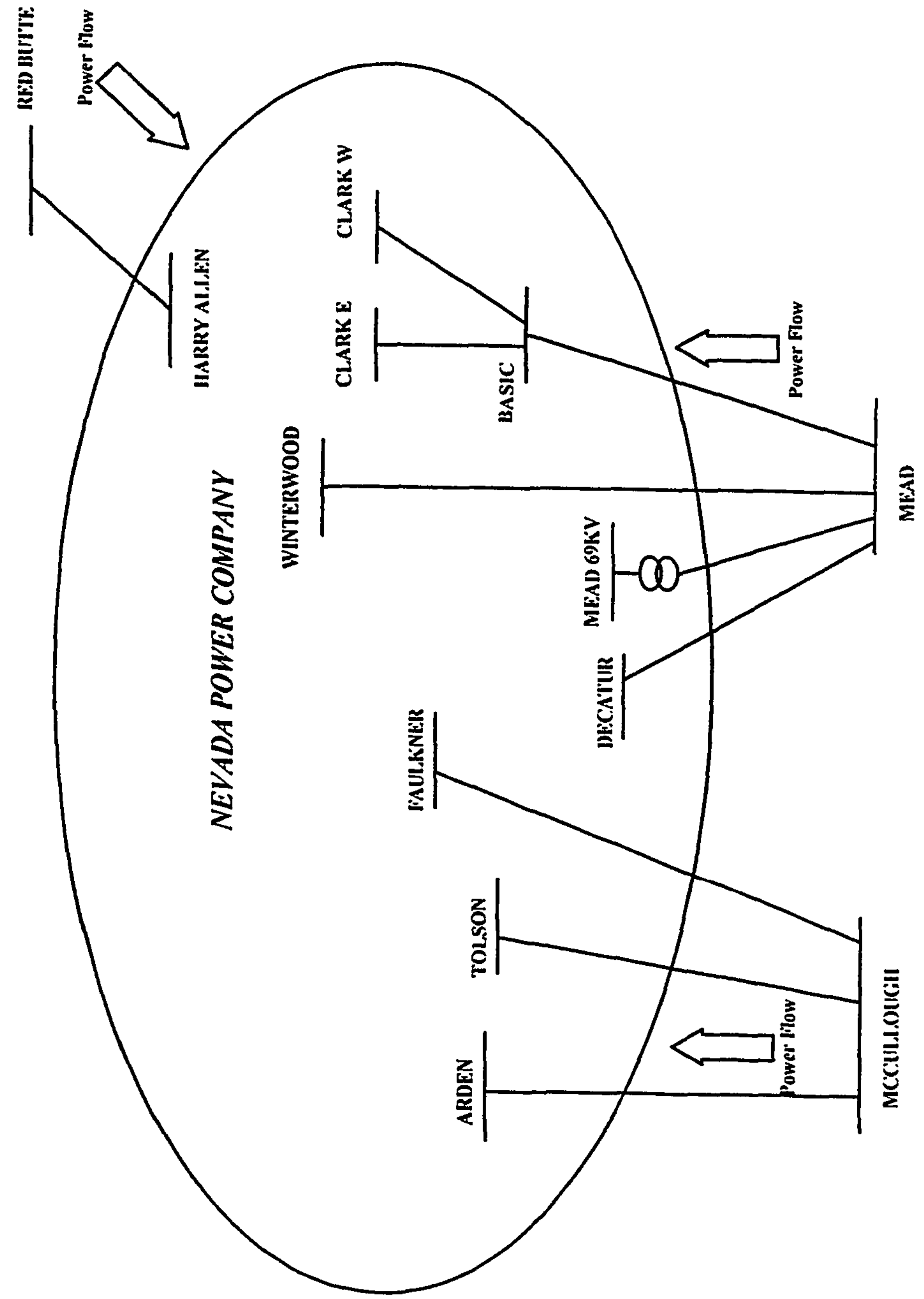

Figure 14: NPC's transmission system tie lines.

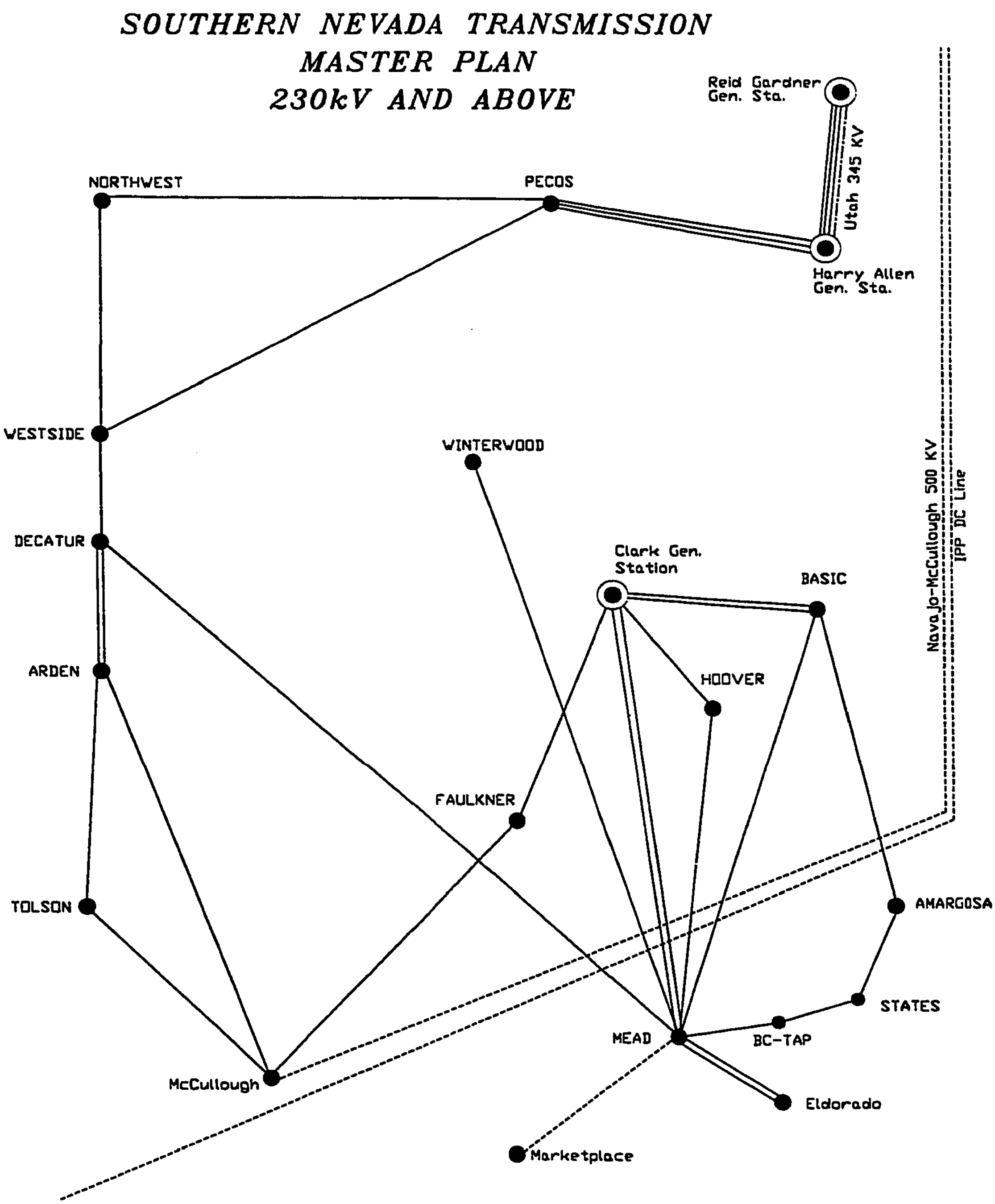

Figure 16: NPC 230kV and higher transmission system.

In addition to the large real power load, NPC must also supply a reactive power load. Reactive power demands increase during the summer when Las Vegas Valley air conditioning motors represent a large inductive load. Currently, NPC addresses this aspect of their total power load via transmission and distribution reactive power supplies in the form of capacitor banks, as well as generating up to 750 MVArs internally. Also, NPC, imports some of the reactive power it needs across tie lines. Importing reactive power is not an acceptable practice and NPC is currently increasing the number of VAr support units on its system [16].

This brief review of NPC's power flow profile reveals a dependence on large real power imports. This dependence stresses the importance of a strong, reliable and flexible transmission system grid to maintain dependable power delivery to their customers. NPC is engaged in a balancing act to keep up with an incredible growing power demand. To continue to increase real power imports to match the load, NPC must do two things: First, the company must build new high voltage transmission lines. Second, NPC must install reactive power support equipment. As previously discussed, the rights-of-way needed to construct new transmission lines are difficult to obtain and the process of obtaining these rights-of-way is time consuming. Building new transmission lines or reconstructing old lines is expensive and in some instances can't be achieved if the tie line used for imports is not wholly owned by NPC. It seems that another method of increasing real power imports is needed. This thesis suggests a possible solution to this problem.

A recommendation cited in an NPC planning department study of system transmission transfer limits suggests that in order to import bulk power purchases of the future, "The viability of adding series compensation to the existing 230 kV tie lines should be investigated... [16]." The addition of a series capacitor compensation scheme to existing tie lines would enable increased real power imports during the heavy summer season. A FACTS device used for series compensation, a TCSC, would have added benefits that classical series compensation alone would not have. A thyristor controlled device would operate faster and require less maintenance than a mechanically controlled device. A TCSC would allow an increased measure of operator control over the power flows in the future after new lines are built. The next step becomes finding a probable location for placement of a series compensator. NPC benchmark reports establishing real power transfers and NPC internal transmission system reports are discussed in the next section.

4.2 Finding a Possible Location for Series Compensation

NPC bases power import limits on studies of transmission system stability and line thermal limits under conditions of credible single contingency outages. These studies establish which transmission lines, transformers and other power equipment load to their emergency ratings during increased imports and simulated fault conditions. In these studies power planning engineers locate the weakest links in NPC's power grid. NPC performs these studies for a certain year by modeling the entire NPC power system for that year including parts of the transmission grid covering the western half of the U.S., and then systematically increasing the power imports while reducing the internal generation until either a line or a transformer is loaded to its emergency rating upon the loss of one of the tie lines, or the voltage at a transmission bus decreases below 90%.

Table 4 shows a summary of the projected NPC power transfer capability and the elements that limit further imports. The data obtained for the first 3 years of this table comes from the NPC 1994 Resource Plan. The last entry for the year 1999 is derived from an updated system base case to be discussed in a subsequent section.

Table 4: NPC total internal system transfer capability and limiting elements.

Year	Transfer Capability	Limiting Element	Owner of Limiting Element
1996	1835 MW	Mead-Basic 230 kV Line	WAPA
1997	1909 MW	Arden-Decatur 230 kV Line	NPC
1998	2016 MW	Mead-Basic 230 kV Line	WAPA
1999	2875.5 MW	Mead-Basic 230 kV Line	WAPA

It can be observed in Table 4, that the limiting elements are the Mead-Basic 230kV line and the Arden-Decatur 230kV line. The defining difference between these two lines is that of ownership. The Mead-Basic 230kV line is owned by the Western Area Power Association, WAPA. The conditions causing the Mead-Basic overload are desirable for study due to the fact that, since NPC doesn't own this line, it doesn't have direct control of the power flow on it.

In 1996, at a transfer level of 1835 MW, 300 MW imported from the Harry Allen-Red Butte 345kV tie line and the remainder on the southern area ties, an outage of the Mead-Winterwood 230kV tie line produces an overload condition on the Mead-Basic 230kV line. The emergency rating for the Mead-Basic line is 924 Amps. Under the conditions listed, the Mead-Basic line operates at 923.9 Amps [16].

In 1998, at a transfer level of 2016 MW, 300 MW imported from the Harry Allen-Red Butte tie line and the remainder on the southern area ties, an outage of the Mead-

Decatur 230kV line causes the Mead-Basic line to operate at 100% of its emergency rating [16].

In 1999, at a transfer level of 2875.5 MW, 300 MW imported from the Red Butte-Harry Allen tie line and the remainder on the southern area ties, an outage of the Mead-Winterwood 230kV line causes the Mead-Basic line to operate at 100% of its emergency rating. A complete listing of the emergency ratings for all of the tie lines can be found in Appendix I.

Due to the fact that NPC does not own the Mead-Basic 230kV line and therefore cannot easily address its conductor limitations by direct means, it appears that redirecting power flow off this line would be a desirable outcome. Series compensation placed on an appropriate tie line could redirect some of the current off the Mead-Basic line and will allow a more attractive power routing schedule given a single contingency outage. Candidate tie lines for investigation of series compensation placement had to have additional current carrying capacity during Mead-Basic overload conditions, i.e. the Mead-Winterwood and Mead-Decatur line outages.

Research of the tie lines listed in Table 3 narrowed the search down to one candidate line. The McCullough-Arden #2 230kV line is a bundled conductor of type 954 ACSR. Appendix I lists the current carrying capacity of a bundled conductor 954 ACSR line at 95°C emergency rating as 1.963 kA. A benchmark study indicated that at the contingency outage of the Mead-Winterwood 230kV line, approximately only 44% of the McCullough-Arden #2 230kV current carrying capacity of the line was being utilized. A similar report developed for the contingency outage of the Mead-Decatur 230kV line indicated that only 54% of the McCullough-Arden #2 230kV current carrying capacity of the line was being utilized. The carrying current of the candidate tie line can be calculated using the following equation:

$$I_{carry} = \frac{\sqrt{(P)^2 + (Q)^2}}{\left(\sqrt{3}V_{sending}\right)} \quad (41)$$

Where $V_{sending}$ = Line-to-Line voltage at the McCullough 230kV bus,

P = The real power flowing on the McCullough-Arden #2 230kV line,

Q = The reactive power flowing on the McCullough-Arden#2 230kV line.

The benchmark power flow reports developed for this analysis are listed in Appendix II. These reports were developed using a steady-state power flow analysis software tool discussed in the next section of this chapter.

The subsequent steps in the research process required defining the conditions under which to study the system imports and the research tools to use for steady-state and transient conditions. The following analysis criteria was used:

- Power flows used were for an updated 1999 heavy summer base case, *1999 HS5*, as named by NPC. This base case for the network includes additional transmission network construction that the base system case used for the 1994 NPC Resource plan does not include. Transfer capabilities for the 1999 base case used for this thesis are listed in Table 4.
- Steady-state analysis benchmark power flow values to be established using NPC system simulation computer programs and then duplicated using computer simulation resources at UNLV.

- Transient analysis to be performed using computer system simulation resources at UNLV.

The following sections briefly describe the tools and data used to meet the above conditions.

4.3 Research Tools-WSCC Power Flow Program and PSCAD/EMDTC Electromagnetic Transients Program

One of the tools that the NPC transmission planning department uses to define real power transfer limits is the Western System Coordinating Council's (WSCC) Interactive Power Flow System (IPS) computer simulation program and power system case database. The WSCC is an affiliation of interconnected utilities in the western half of the U.S. including parts of Canada and Mexico. The WSCC establishes planning and operating guidelines, as well as system analysis tools, to an alliance of utilities in an effort to maintain area wide power delivery and reliability [17]. The WSCC provides not only power flow analysis programs to its utility members, but also a comprehensive up-to-date, accurate database model of the entire interconnected western area power system. All steady-state analysis benchmarks for this thesis were performed using the WSCC's IPS program. Benchmark steady-state values produced by the IPS program are used throughout this thesis as a target to verify those data values produced by the author using another software program described in the following paragraph. *1999 HS5* is the name given by NPC for the 1999 heavy summer power transmission system used to model the steady-state studies in this thesis and derived from the necessary WSCC data.

PSCAD/EMTDC, a UNIX-based electromagnetic transient software program, was purchased by the University of Nevada, Las Vegas engineering department, specifically to perform the transient analysis of the FACTS enhanced NPC system. PSCAD/EMTDC is an electromagnetic transients software program similar to Electric Power Research Institute's (EPRI) well known EMTP program. PSCAD/EMTDC was developed at the Manitoba HVDC Research Center. This software package was chosen because of its ability to model FACTS devices and a variety of complex power utility circuits in an X-Windows environment. In this program, a comprehensive palette of components is available, including gate-turnoff-thyristors (GTOs). The process of circuit construction is similar to that of drawing a schematic diagram of the power circuit under study. After the circuit is constructed, it is run using a separate module. In this module it is possible to select the graphs and observe them in a way similar to watching an oscilloscope trace. The model developed in the PSCAD/EMTDC software was verified for accuracy against the benchmark steady-state values established by NPC.

4.4 Developing a Reduced Model of the Nevada Power Transmission System

The NPC system contains over 200 buses, 1,599 miles of transmission line and 11,200 miles of distribution line[18]. The enormity of this system prevented the author from modeling the entire NPC system in the PSCAD/EMTDC software. A reduced model including the southern NPC transmission system and tie lines was developed from the 1999 WSCC heavy summer load base case for use in the transient studies. Figure 17 shows a generalized view of the reduced transmission system created using the PSCAD/EMTDC software.

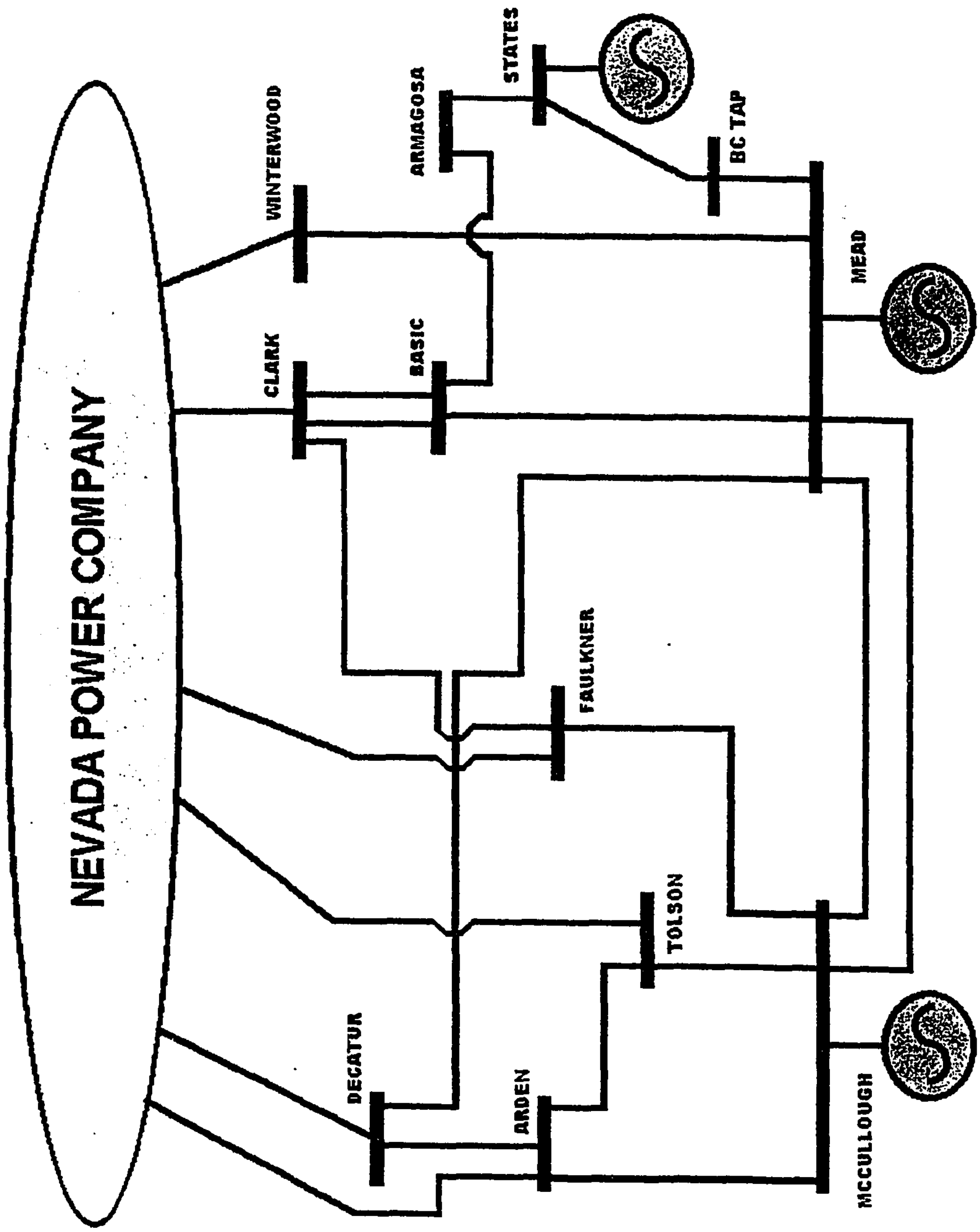

Figure 17: The reduced NPC transmission system model.

The following system modeling criteria was used:

- Only the southern area tie lines and 230kV system will be modeled.
- Power flows from the southern area of the NPC system to the load center in the north. Power will be injected at the McCullough 230kV, Mead 230kV and States 230kV buses in the south using ideal voltage sources.
- All sections of the system below 230kV will be modeled as an impedance load at the appropriate bus using the steady-state power flow results from the WSCC's IPS program. The following load model (Figure 18) and equations are used.

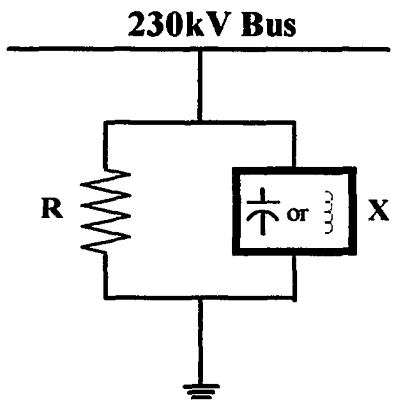

Figure 18: Basic load model.

For resistance:

$$R = \frac{V^2}{P} \tag{42}$$

For reactance:

$$X = \frac{V^2}{Q} \tag{43}$$

Where V is the line to ground voltage at the bus.

P is the real power flowing into the bus,

Q is the reactive power flowing into or out of the bus.

- Because all of the tie lines used in this study are below 150 miles in length they will be constructed using pi-models as depicted in Figure 19.

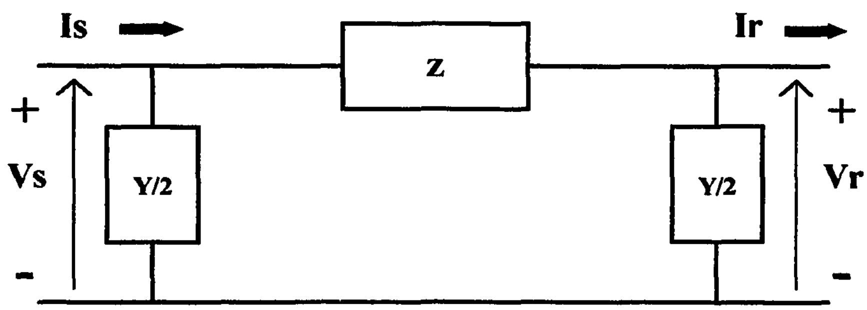

Figure 19: Pi circuit model used for transmission lines [19].

In Figure 19: V_s is the sending voltage,

V_r is the receiving voltage,

I_s is the sending current,

I_r is the receiving current,

Z is the series impedance,

$Y/2$ is the shunt admittance.

Values for the impedances and admittances of the lines used in this model are provided by NPC.

- The TCSC will be modeled using a circuit and controller developed by the manufacturers of the PSCAD/EMTDC program. Reference [22] outlines the basic current control system duplicated by the Manitoba HVDC Research Center and used in this thesis. The values developed for the capacitor, inductor and firing angle of the TCSC circuit are discussed in Chapter 5.

The reduced NPC PSCAD/EMTDC model was tested for accuracy against the IPS program for steady-state power flows and bus voltage benchmark values for an error rating of between +/-10%. Due to the complexity of the modeling involved only the single contingency of the Mead-Winterwood 230kV line outage was considered. Chapter 5 discusses the steady-state and transient results of placing a TCSC on the McCullough-Arden #2 230kV transmission line.

CHAPTER 5

STEADY STATE AND TRANSIENT RESULTS

Chapter 4 reviewed the NPC transmission power transfer capability reports and defined a clear problem. A critical failure of the Mead-Winterwood 230kV line causes the Mead-Basic 230kV line to operate at its emergency conductor rating of 924 Amps. The Mead-Basic 230kV line is a bottleneck in the NPC southern transmission power transfer corridor. An outage on the Mead-Winterwood 230kV line prevents NPC from importing any more real power. The McCullough-Arden #2 230kV line was identified in Chapter 4 as a candidate line for placement of a series compensation device. The goal in reducing the McCullough-Arden #2 230kV line impedance by using a TCSC is to determine that if by doing so, the current flow is reduced on the Mead-Basic 230kV line. If the FACTS device reduces the current flow on the Mead-Basic 230kV line, the next goal would be to determine how much increased real power could be imported on the series capacitor compensated system. It is also important to identify the transient behavior of the FACTS device immediately after switching. This chapter discusses the results of pursuing these goals.

The following outline defines the steps taken to identify the steady-state and transient results of placing a FACTS device on the McCullough-Arden #2 line:

1) Apply a series capacitor to the McCullough-Arden #2 230kV line in the WSCC 1999 heavy summer case with the Mead-Winterwood 230kV line taken out of service. Use the WSCC IPS power flow program to obtain the results.
2) If the results from step 1 show that current flows on the Mead-Basic 230kV line are reduced, then using the WSCC IPS program, find out the amount of increased real power transfers that series compensation on the McCullough-Arden #2 230kV line allows.
3) If the results from steps 1 and 2 show that current flows on the Mead-Basic 230kV line are reduced and that power transfers are increased into the NPC system, then develop benchmark reports using the WSCC IPS program. The values obtained will be used for modeling loads of the reduced NPC system in the PSCAD/EMTDC software.
4) Verify bus voltages and power flows in the reduced NPC system model. Use the benchmark IPS program results obtained from step 3 and compare them with the results obtained using the PSCAD/EMTDC software.
5) Develop transient and steady-state results using a TCSC circuit model in the verified and tested PSCAD/EMTDC reduced NPC system from step 4 .

5.1 Steady-State Results Using the WSCC's IPS System Program

It is assumed that at steady-state the TCSC behaves similar to a standard series capacitor and can therefore be modeled as such. The next question to address is where on the McCullough-Arden #2 230kV line to place the series capacitor. A series capacitor bank, in theory, can be placed at any location along a line. Factors influencing the choice of location include: cost, fault level, and the efficacy of improving transmission line transfer capability and voltage profile. The factor that is of concern to this study is that of improving transmission line transfer capability. The following locations are typically considered: midpoint, line terminations, and 1/3 or 1/4 of the total line distance. One disadvantage of locating the series compensation device at a transmission line's midpoint is the accessibility of the unit for maintenance. For the purposes of experimentation, the standardized size restrictions of utility grade capacitor banks or that of available real estate to house the TCSC device were not considered in finding the optimum compensation level or final installation location. The McCullough bus is owned by the Los Angeles Department of Water and Power (LADWP) and not by NPC. Placement of a TCSC at the McCullough bus would involve extensive discussion, agreements, contracts and reviews between NPC and LADWP. The Arden 230kV bus, which is owned by NPC, was decided to be the best location for placement of the TCSC.

A series capacitor whose value equaled varying percentages of the total McCullough-Arden #2 230kV line impedance up to a maximum of 70% of the total line impedance was placed at the Arden bus with the Mead-Winterwood 230kV line outaged. Table 5 shows the numerical result which are depicted graphically in Figure 20.

Table 5 and the graph indicate that at a 70% compensation level of the total impedance of the McCullough-Arden #2 230kV line, the current flows on the Mead-Basic 230kV line decrease from 924 Amps to 871.3 Amps during a Mead-Winterwood 230kV line outage. This is a positive indication that the McCullough-Arden #2 230kV

Table 5: Series Compensation on the McCullough-Arden #2 230kV line with Mead Winterwood 230kV line outaged.

Percentage of Compensation %	Mead-Basic Line Amps	McCullough-Arden Line Amps	McCullough-Arden Line MW	McCullough-Arden Line MVAr
0	924.0	889.3	365.7	68.0
5	922.0	918.9	378.3	68.0
10	919.7	950.6	391.7	68.4
20	914.8	1021.7	422.0	68.7
30	908.8	1104.1	457.0	68.1
40	901.8	1200.0	498.0	66.0
50	893.6	1314.5	547.0	62.2
60	883.2	1453.1	606.2	56.6
70	871.3	1624.6	679.5	44.4

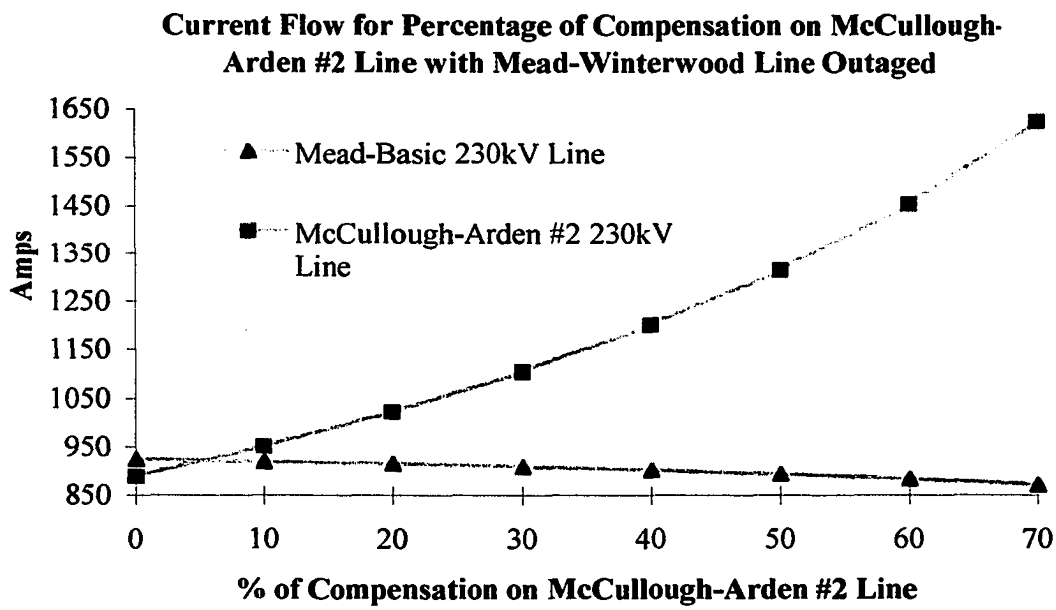

Figure 20: Graphical display of current flow on the lines indicated.

line is a viable location for placing a series capacitor and achieving the goal of current reduction on the Mead-Basic 230kV line.

Table 6 shows a comparison between the total real power transfer capability of the NPC system before and after the addition of series compensation. As previously described, the method for finding the new power transfer levels involves increasing system imports while simultaneously reducing the internal generation until transmission equipment operates at emergency levels during a contingency line outage. The limiting element remains the Mead-Basic 230kV line, but in this case with the line outage of McCullough-Arden #2 230kV line.

Table 6 : Comparison showing the increase in real power transfer after adding series compensation to the NPC system.

Year	Limiting Element	230kV Line Outage	Transfer Capability
1999	Mead-Basic 230kV line	Mead-Winterwood	2875.5 MW
1999	Mead-Basic 230kV line	McCullough-Arden #2	2984.3 MW
INCREASE in Real Power Transferred to the NPC System			**108.8 MW**

The steady-state results shown in Table 6, produced by the IPS power flow program indicate that placing a 70% compensation series capacitor on the McCullough-Arden #2 230kV line would allow an increase the area's real power transfers into the NPC system by a 108 MW margin. Appendix III lists a power flow report showing the increase in real power flows, see Section 3.

Another method for evaluating the affect of adding series compensation to the system is to examine the redistribution of power flows without increasing power imports. The change in real and reactive power flows before and after the addition of series compensation on the McCullough-Arden #2 230kV line with the outage of the Mead-Winterwood line are summarized in Table 7. The power flow changes on the other ties given the same conditions as in Table 7 showed an overall decrease in the amount of reactive power imported by approximately half.

Table 7: Real and reactive power flow changes on the McCullough-Arden #2 230kV Line without pushing up imports.

McCullough-Arden #2 230Kv Line	**Real Power in MW**	**Reactive Power in MVAr**
Before the addition of 70% series compensation	365.7	68.0
After the addition of 70% series compensation	679.5	44.4

The following steady-state reports were produced by the IPS power flow program to obtain the data necessary to model the reduced NPC system described in the next section: 1) Benchmark, WSCC, 1999 HS5, heavy summer NPC transmission system power flows without compensation and without line outages. 2) Benchmark, 1999 HS5, WSCC power flows with the Mead-Winterwood 230kV line outage and a 70% compensation series capacitor added to the McCullough-Arden #2 230kV line at the Arden 230kV bus. A listing of these reports can be found in Appendix III under sections 4 and 5.

5.2 Verifying the PSCAD/EMTDC NPC Power System Model

The desired output of a good model are accurate results. In order to determine if the reduced NPC system model described in Chapter 4 would produce an accurate picture of the NPC transmission system without an added FACTS device, it was necessary to verify the steady-state results obtained using the PSCAD/EMTDC program against those obtained with the IPS program. The next two subsections describe the results obtained from this verification process. First the NPC base case will be examined. The NPC base case will be defined as the benchmark, WSCC, 1999 HS5, heavy summer NPC transmission system power flows without compensation and without line outages (see Appendix III, Section 4). Second, the NPC system with the Mead-Winterwood 230kV line outaged and 70% series compensation without thyristor control on the McCullough-Arden #2 230kV line will be evaluated (see Appendix III, Section 5).

5.2.1 PSCAD/EMTDC Steady-State Results of the Base Case

Table 8 shows the voltage magnitude levels at the busses modeled in the PSCAD/EMTDC program as compared with the voltage magnitude figures obtained from the IPS program.

PSCAD/EMTDC results for the base case real and reactive power flows for both the lines and the bus loads are shown in Appendix IV. The percentage errors for all results in the base case PSCAD/EMTDC model were within the +/- 10% error tolerance as compared with the IPS program results.

Table 8: Base case voltage magnitude values comparison of the PSCAD/EMTDC reduced system model against the IPS program.

230kV Bus	Voltage in kV PSCAD/EMTDC	Voltage in kV IPS	Percent Error %
Arden	236.7	236.3	0.17
Armagosa	240.1	239.7	0.17
Basic	240.1	239.8	0.13
Clark 6	241.3	240.9	0.17
Clark East	241.0	240.7	0.12
Clark West	240.0	239.7	0.13
Decatur	234.0	233.7	0.13
Eastside	240.2	239.8	0.17
Faulkner	241.4	240.9	0.21
McCullough	242.5	242.1	0.17
Mead	240.6	240.2	0.17
Newport	240.2	239.7	0.21
States	240.5	240.1	0.17
Tolson	237.5	237.1	0.17
Winterwood	235.5	235.2	0.13

5.2.2 PSCAD/EMTDC Steady-State Results of the Uncontrolled Series Compensation Case

The insertion of series compensation for this PSCAD/EMTDC model was not controlled in any way, therefore, no thyristor switches were used in this model. The only purpose of this model was to verify the correct loading for each of the busses in the base case given the outage of the Mead-Winterwood 230kV line and the subsequent insertion of the 70% series capacitor. Appendix IV lists the steady-state power flow and magnitude voltage results for a 70% series compensated McCullough-Arden #2 230kV line with the Mead-Winterwood 230kV line taken out of service.

The figures obtained from this model indicated that the loading on each of the busses was within a +/-10% error tolerance as compared to the power flows produced using the IPS program. The steady-state results discussed thus far prepared the way for developing the model needed to study the transient effects of adding a TCSC to the McCullough-Arden #2 230kV line. The next section will outline the details of this study.

5.3 Transient and Steady-State Results Using the PSCAD/EMTDC to Model a FACTS Device

The previous sections showed how the reduced NPC PSCAD/EMTDC transmission system model had been verified to give acceptable results, the next step was to design and add a TCSC circuit to the model. Finally, the last step in this application would be to test the system for transient and continuous results. The next three subsections describe the outcome of this process.

5.3.1 Modeling the TCSC in the Reduced NPC PSCAD/EMTDC Model

Figure 5 in Chapter 2 shows a basic model of a TCSC circuit. In Chapter 3, mathematical representations of thyristor controlled devices were developed to show how the total impedance of a FACTS device can be varied by a change in the firing angle of the thyristor switches, (see Figure 10). By utilizing a current control scheme provided by the manufacturer of the PSCAD/EMTDC program to send firing pulses to the TCSC circuit, the remaining TCSC design parameters in this application included: 1) Resonant firing angle, α. 2) The value of the series capacitor and 3) lastly, the value of the inductor. The impedance of the series capacitor branch was fixed at 35% compensation of the McCullough-Arden #2 230kV line. The chosen resonant firing angle, α, was set at 115°. From the discussions in Chapter 3, the following relationship was solved to find the impedance of the inductor branch needed for a resonant firing angle of α = 115°:

$$X_{Leff} = X_C = \frac{\pi X_L}{2\pi - 2\alpha + \sin(2\alpha)} \quad (45)$$

Where X_{Leff} is the effective impedance of the inductor at the firing angle, α,

X_C is the impedance of the chosen series capacitor, and

X_L is the actual impedance of the inductor.

Once the inductor value was found, a list of effective TCSC compensation impedance values were determined based on the firing angle, α. Table 9 shows a list of firing angles and the percentage of series compensation produced at each. Figure 21 is the graphical representation of the effective TCSC impedance at various firing angles. A closer examination of Table 9 shows that the greatest variation in percentages of capacitive compensation is achieved between the angles of 120° and 140°. On Figure 20, this region is located on the knee of the capacitive portion of the graph. For a 70% compensation level a firing angle of 129° was used initially and later adjusted to 131° to achieve the desired results.

Table 9: Percentage of compensation at various firing angles for the McCullough-Arden #2 230kV line.

Firing angle, α	Percentage of Series Compensation (+) = inductive (-) = capacitive
90°	+31%
100°	+60%
115°	Infinite +/-
120°	-195%
130°	-71%
140°	-48%
150°	-40%
160°	-36%
170°	-35.2%
180°	-35%

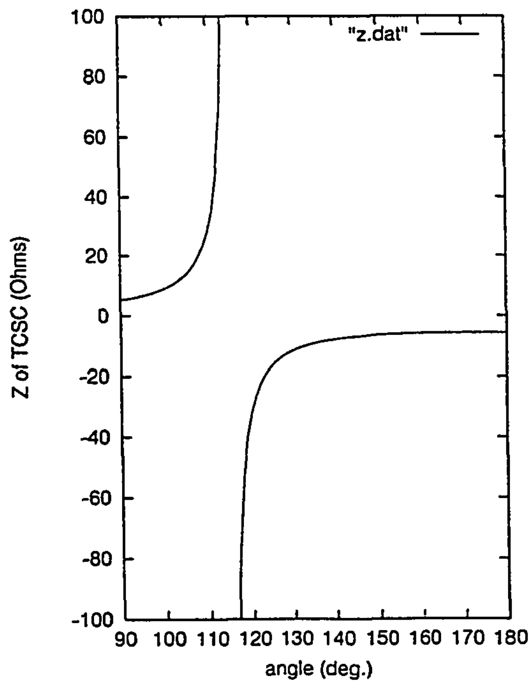

Figure 21: Effective TCSC impedance at various firing angles.

5.3.2 Transient Results and Harmonic Analysis

An experiment was designed to capture a transient picture of the TCSC in action during the first few cycles after the Mead-Winterwood 230kV line outage. A series of timed events were developed to produce dynamic system changes. First, the base case model of the reduced NPC system was allowed to settle to a steady-state condition. Next the Mead-Winterwood 230kV line was simultaneously switched-out while the TCSC circuit at the 230kV Arden bus was switched into the system. At the same time all of the loads modeled at the buses were adjusted to account for the system changes. A time outline of the experiment is shown in Table 10.

Table 10: Timed event outline of the TCSC insertion and data capture.

Time in Seconds	Action
0.0	Start the base case simulation
0.5	Switch-out the Mead-Winterwood 230kV line
0.5	Switch-out the base case bus loads.
0.5	Switch-in redistributed loads from the line outaged, compensated IPS program benchmark case.
0.5	Switch-in the TCSC circuit at the Arden bus.
1.0	Stop the simulation.

The next few figures show the measured currents and voltages of the McCullough-Arden #2 230kV line and the TCSC circuit. The damping time of the TCSC circuit can be seen in Section 1 of Appendix IV. This figure shows the current and voltage of the device. From this graph one can see that the circuit settles in approximately 0.3 seconds or 18 cycles after it has been inserted into the system.

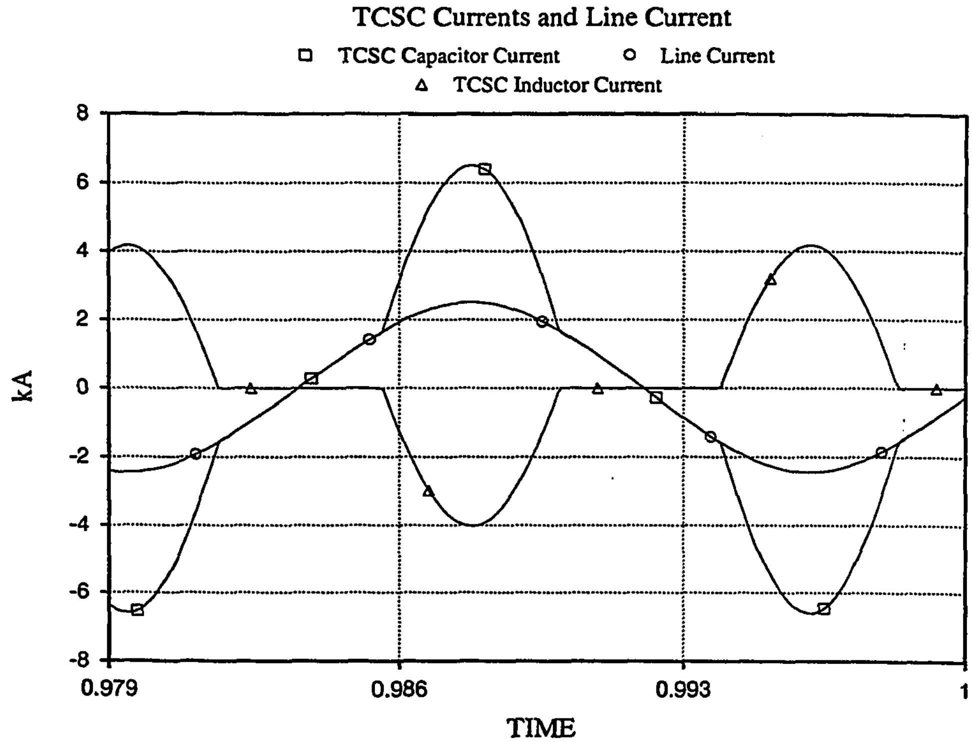

Figure 22: TCSC Currents and line current.

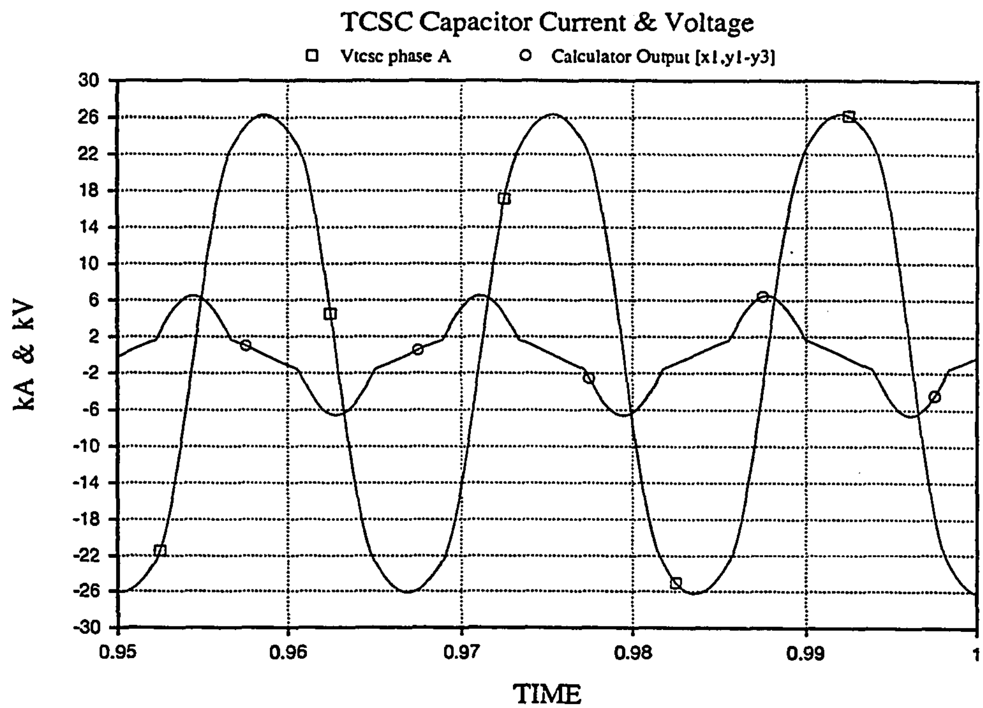

Figure 23: TCSC capacitor current and voltage.

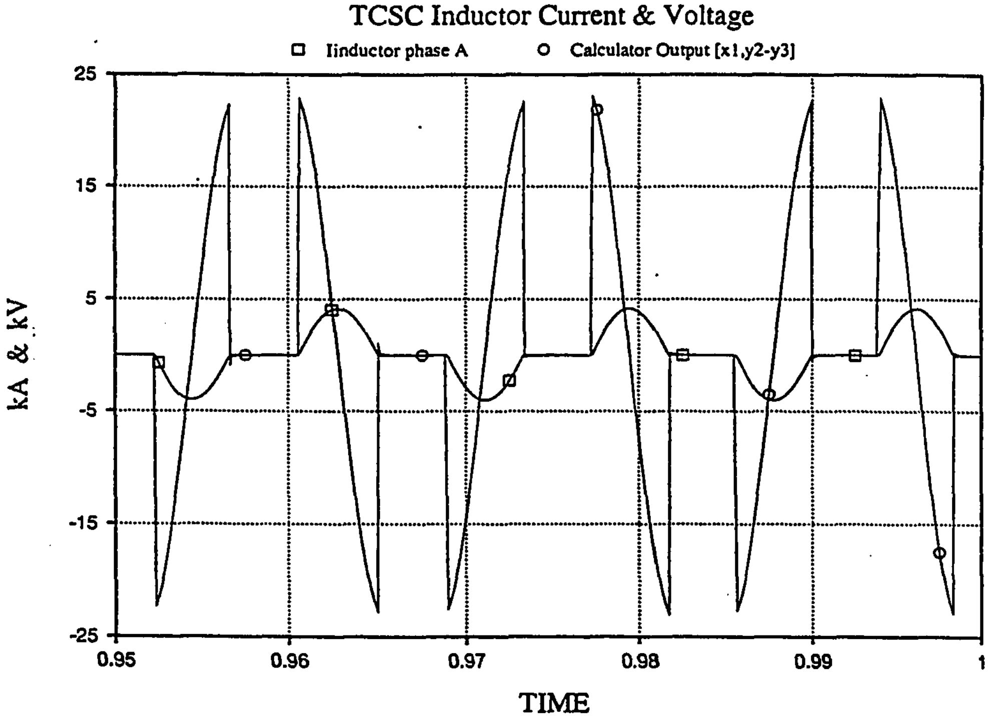

Figure 24: TCSC inductor current and voltage.

Harmonic analysis of the voltage across the TCSC circuit revealed a 10.2 % total harmonic distortion. This is a rather low figure considering that the voltage measured across the device at steady-state is only 26kV, representing 10.7% of the line-to-line voltage. The total harmonic distortion of the McCullough-Arden #2 230kV line current was calculated to be only 3.1%. The next two graphs show the magnitude content of the Fourier analysis for both line current and the voltage across the TCSC. The dominant harmonic in both is shown to be the third.

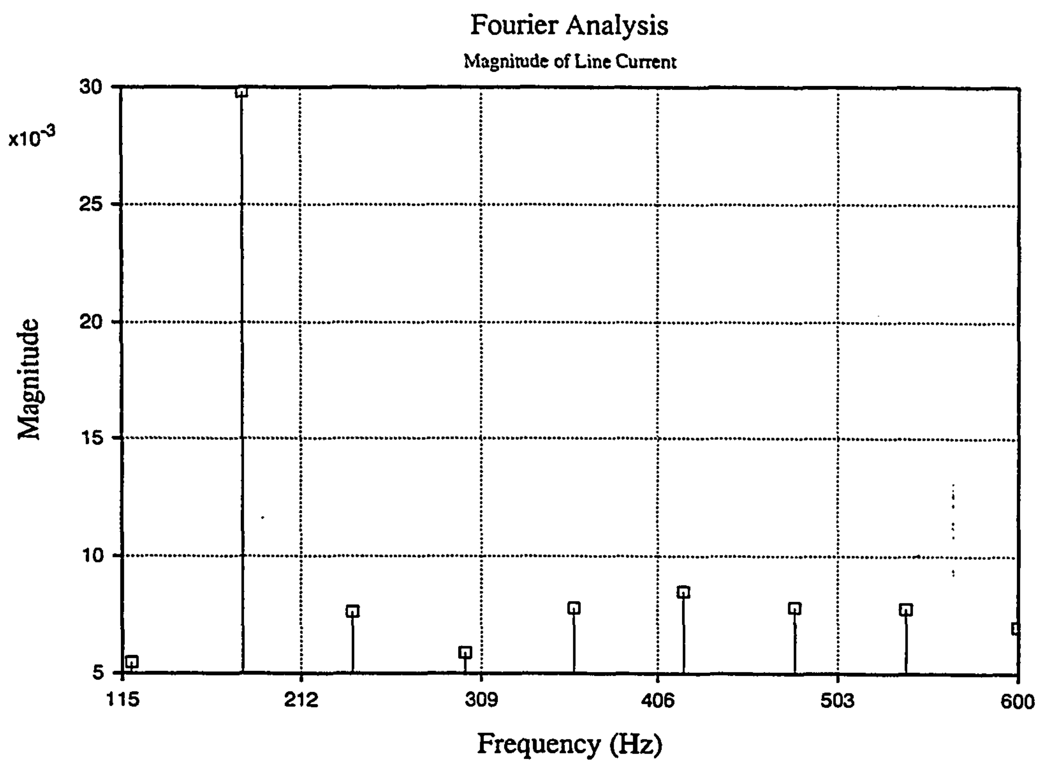

Figure 25: Magnitude measurements of the Fourier analysis of the McCullough-Arden #2 line current.

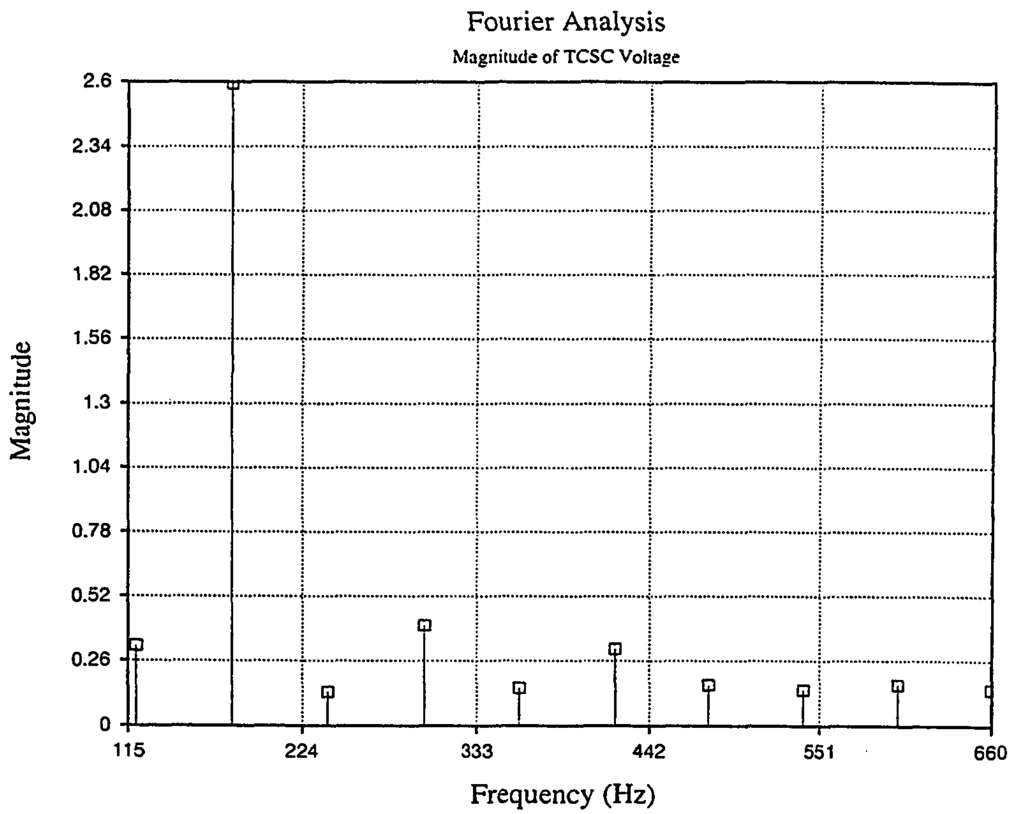

Figure 26: Magnitude of the Fourier analysis of the voltage across the TCSC.

5.3.3 Steady-State Results

The steady-state results obtained from the reduced NPC transmission system model in the PSCAD/EMTDC software closely matched those achieved with the IPS program. Table 11 is a comparison of the steady state power flow results from the reduced NPC model in the PSCAD/EMTDC program and those of the WSCC's IPS program for a series compensated McCullough-Arden #2 230kV line.

Table 11: Real and reactive power flow comparison for the compensated McCullough-Arden #2 230kV line.

Program Used	Real Power (MW)	Reactive Power (MVAr)
PSCAD/EMTDC	723	42.3
IPS	679.5	44.4

The percentage difference between the two sets of values shown in Table 11 is less than 10%. The reduced current on the Mead-Basic line measured in the PSCAD/EMTDC program varies from the final steady-state result of the IPS program by only 1.1%. Appendix III contains a complete listing of power flows, voltages and bus load measurements for this experiment.

CHAPTER 6

CONCLUSIONS

FACTS devices, unlike mechanically switched compensation devices, offer the benefits of increased switching speeds, reduced maintenance and extended number of allowed switching operations. Thyristor controlled series compensation devices quickly damp out transients and offer greater power flow control. These benefits elevate the stability of the system and raise the level of power grid security.

The analysis of the NPC utility network revealed that a study of series compensation applied to the 230kV southern area transmission tie lines could allow for increased real power transfers. Further investigation showed that the Mead-Basic 230kV line represents a limiting element given a contingency outage of the Mead-Winterwood 230kV line. Evaluation of a TCSC device, indicated that the application of the device to the McCullough-Arden #2 230kV transmission line will increase bulk power transfers into southern Nevada by 108 MW while mitigating the Mead-Winterwood line outage. The total harmonic distortion that the TCSC creates in the NPC system modeled is minimal. Furthermore, system reached a steady-state condition within 18 cycles after the TCSC was inserted.

It would be advisable for NPC to continue an investigation of series compensation using FACTS devices, possibly a study of a UPFC's. A cost versus benefits analysis was not the focus of this thesis, however, such a study needs to be performed by NPC to identify the feasibility of using this advanced technology. Also, it should be noted that one of the significant differences between the WSCC's IPS results and the results obtained for the reduced system model for the PSCAD/EMTDC software is the fact that the entire NPC system, and surrounding important power grids, are modeled in the WSCC's 1999 HS5 system case and not in the latter. The ability to focus on dynamic system load redistribution was not possible with the limited model that was created for study in this thesis using the PSCAD/EMTDC software. Further studies should include the complete NPC network.

APPENDIX I

CONDUCTOR NORMAL/EMERGENCY RATING CHART FOR NPC

TABLE 12: Conductor ratings in amperes [15].

TYPE	NORMAL 75°C	EMERGENCY 95°C
954 ACSR	855	1052
954 ACSR (bundled)	1600	1963
1272 AA	1002	1236
1272 AA (bundled)	1875	2313

TABLE 13: System tie line conductor normal and emergency ratings in amperes.

NAME (OWNER)	NORMAL 75°C	EMERGENCY 95°C
Basic-Mead 230kV (WAPA)	840	------
Basic-Armagosa 230kV (WAPA)	840	------
Armagosa-Hoover 230kV (WAPA)	840	------
Basic-Clark East 230kV (NPC)	764	939
Basic-Clark West 230kV (NPC)	764	939
Mead-Decatur 230kV (NPC)	855	1052
Mead-Winterwood 230kV (NPC)	837	1029
McCullough-Faulkner 230kV (NPC)	855	1052
McCullough-Arden #2 230kV (NPC)	1600	1963
Red Butte-Harry Allen 345kV	1948	2399

APPENDIX II

STEADY-STATE RESULTS USING WSCC'S IPS POWER FLOW PROGRAM

The following five sections list various reports produced from the WSCC's IPS program using the *1999 HS5* base case. This base case is the 1999 heavy summer case provided by the WSCC and augmented by Nevada Power to include the most up-to-date construction and data at the time this thesis was started.

Section 1: Power Flows for a Mead-Winterwood 230kV Line Outage, NPC System without Compensation.

AREA TOTALS	MW	MVAR
LOAD	4420.2	135.0
LOSSES	95.4	1284.9
GENERATION	1632.3	574.7
SCHEDULED EXPORT	-2875.5	
ACTUAL EXPORT	-2883.2	
SPINNING RESERVE	127.7	

LOAD + LOSSES	MW	MVAR
AREA	4515.5	1419.9

	AREA IMPORT		SYSTEM IMPORT	
TIE LINE	MW	MVAR	MW	MVAR
REDBUTTE 345 - HA PS 345 KV	309.7	-23.7	309.7	-23.7
MCCULLOUGH - FRIAS 230 KV	362.4	47.9	362.4	47.9
MCCULLOUGH 230 - ARDEN #2 230 KV	365.5	67.8	365.5	67.8
MCCULLOUGH 230 - GIBSON 230 KV	407.7	-11.4	407.7	-11.4
MOHAVE 500 - LAUGHLIN 69 KV	95.0	16.2	95.0	16.2
STATES 230 - EAS TAPE 230 KV	280.8	-17.4		
MEAD 230 - BASIC 230 KV	384.2	-12.0		
BC TAP 230 - BC TAPNV 230 KV	16.1	6.6		
MEAD 230 - DECATUR 230 KV	374.7	43.6	374.7	43.6
MEAD A 69 - MEAD NPC 69 KV	107.1	10.8		
MEAD B 69 - MEAD NPC 69 KV	107.1	10.8		
BASIC 230 - CLARK E 230 KV			228.2	-88.0
BASIC 230 - CLARK W 230 KV			238.7	-27.5
MEAD NPC - WINTERWOOD (BB TAP 1) 69 KV			75.6	4.0
MEAD NPC - CLARK E (BB TAP2) 69 KV			58.9	1.5
MEAD NPC - LV WASH (BB TAP 3) 69 KV			39.8	-5.0
MEAD 230 - PAHRUMP 230 KV	72.8	-24.5		
JACKASSF 138 - LTHRPWLS 138 KV			8.0	-8.9
TORTISE - REID GARDNER 230 KV			-74.5	-17.9
MEAD NPC - SEARCHLIGHT 69 KV			2.7	4.7
TOTALS	2883.1	114.7	2492.4	3.3

	SYSTEM GENERATION		
UNIT	MW	PMAX	MVAR
RG 1	110.0	115.0	22.3
RG 2	110.0	115.0	22.1
RG 3	110.0	115.0	22.8
RG 4	245.0	275.0	84.0
CLARK 1	-----	42.0	-----
CLARK 2	-----	66.0	-----
CLARK 3	-----	67.0	-----
CLARK 4	49.0	50.0	27.5
CLARK 5	73.0	73.0	30.0
CLARK 6	73.0	73.0	30.0
CLARK 7	73.0	73.0	30.0
CLARK 8	73.0	73.0	30.0
CLARK 9	39.3	85.0	39.4
CLARK 10	85.0	85.0	42.3
SUNRISE 1	80.0	80.0	20.4
SUNRISE 2	69.0	69.0	17.7
SUNRISE 3	70.0	70.0	30.0
SUNRISE 4	-----	70.0	-----
SUNRISE 5	-----	70.0	-----
HA CT1	70.0	72.0	22.4
NCA1 CT113.8	22.0	23.0	8.5
NCA1 CT213.8	22.0	23.0	8.5
NCA1 CT313.8	22.0	23.0	8.4
NCA1 ST 13.8	19.0	20.5	8.4
NCA2 CT113.8	22.0	23.0	3.6
NCA2 CT213.8	22.0	23.0	3.6
NCA2 CT313.8	22.0	23.0	3.5
NCA2 ST 13.8	19.0	20.5	3.5
SAGUAR 113.8	30.0	36.0	11.6
SAGUAR 213.8	30.0	36.0	11.6
SAGUAR 313.8	30.0	36.0	11.6
LVCOGEN 13.8	43.0	50.0	21.0

END OF REPORT !!!

Section 2: Power Flows for a Mead-Decatur 230kV Line Outage, NPC System without Compensation.

AREA TOTALS	MW	MVAR
LOAD	4420.2	135.0
LOSSES	96.5	1297.7
GENERATION	1632.3	582.0
SCHEDULED EXPORT	-2875.5	
ACTUAL EXPORT	-2884.4	
SPINNING RESERVE	127.7	

LOAD + LOSSES	MW	MVAR
AREA	4516.7	1432.7

TIE LINE	AREA IMPORT MW	AREA IMPORT MVAR	SYSTEM IMPORT MW	SYSTEM IMPORT MVAR
REDBUTTE 345 - HA PS 345 KV	316.6	-20.7	316.6	-20.7
MCCULLOUGH - FRIAS 230 KV	403.2	53.1	403.2	53.1
MCCULLOUGH 230 - ARDEN #2 230 KV	416.8	76.1	416.8	76.1
MCCULLOUGH 230 - GIBSON 230 KV	377.6	-12.6	377.6	-12.6
MOHAVE 500 - LAUGHLIN 69 KV	94.9	16.3	94.9	16.3
STATES 230 - EAS TAPE 230 KV	277.8	-17.4		
MEAD 230 - BASIC 230 KV	·378.3	-12.5		
BC TAP 230 - BC TAPNV 230 KV	16.1	6.6		
MEAD A 69 - MEAD NPC 69 KV	103.4	10.7		
MEAD B 69 - MEAD NPC 69 KV	103.4	10.7		
MEAD 230 - WINTERWOOD 230 KV	322.7	38.2	322.7	38.2
BASIC 230 - CLARK E 230 KV			216.4	-89.2
BASIC 230 - CLARK W 230 KV			240.9	-25.3
MEAD NPC - WINTERWOOD (BB TAP 1) 69 KV			72.0	3.7
MEAD NPC - CLARK E (BB TAP2) 69 KV			57.7	1.5
MEAD NPC - LV WASH (BB TAP 3) 69 KV			36.9	-4.9
MEAD 230 - PAHRUMP 230 KV	73.6	-24.1		
JACKASSF 138 - LTHRPWLS 138 KV			9.5	-9.3
TORTISE - REID GARDNER 230 KV			-74.5	-17.9
MEAD NPC - SEARCHLIGHT 69 KV			2.8	4.5
TOTALS	2884.4	124.4	2493.5	13.5

UNIT	SYSTEM GENERATION MW	PMAX	MVAR
RG 1	110.0	115.0	22.7
RG 2	110.0	115.0	22.5
RG 3	110.0	115.0	23.2
RG 4	245.0	275.0	85.7
CLARK 1	-----	42.0	-----
CLARK 2	-----	66.0	-----
CLARK 3	-----	67.0	-----
CLARK 4	49.0	50.0	28.1
CLARK 5	73.0	73.0	30.0
CLARK 6	73.0	73.0	30.0
CLARK 7	73.0	73.0	30.0
CLARK 8	73.0	73.0	30.0
CLARK 9	39.3	85.0	40.0
CLARK 10	85.0	85.0	43.0
SUNRISE 1	80.0	80.0	19.3
SUNRISE 2	69.0	69.0	16.8
SUNRISE 3	70.0	70.0	30.0
SUNRISE 4	-----	70.0	-----
SUNRISE 5	-----	70.0	-----
HA CT1	70.0	72.0	23.1
NCA1 CT113.8	22.0	23.0	8.7
NCA1 CT213.8	22.0	23.0	8.7
NCA1 CT313.8	22.0	23.0	8.6
NCA1 ST 13.8	19.0	20.5	8.6
NCA2 CT113.8	22.0	23.0	3.6
NCA2 CT213.8	22.0	23.0	3.6
NCA2 CT313.8	22.0	23.0	3.4
NCA2 ST 13.8	19.0	20.5	3.4
SAGUAR 113.8	30.0	36.0	12.2
SAGUAR 213.8	30.0	36.0	12.2
SAGUAR 313.8	30.0	36.0	12.2
LVCOGEN 13.8	43.0	50.0	22.4

END OF REPORT !!!

Section 3: New Import Levels for 70% Compensation on the McCullough-Arden #2 230kV Line and Line Outage.

AREA TOTALS	MW	MVAR
LOAD	4420.2	135.0
LOSSES	103.4	1351.9
GENERATION	1539.3	590.1
SCHEDULED EXPORT	-2972.7	
ACTUAL EXPORT	-2984.3	
SPINNING RESERVE	140.7	

LOAD + LOSSES	MW	MVAR
AREA	4523.5	1486.9

TIE LINE	AREA IMPORT MW	AREA IMPORT MVAR	SYSTEM IMPORT MW	SYSTEM IMPORT MVAR
REDBUTTE 345 - HA PS 345 KV	318.5	-18.7	318.5	-18.7
MCCULLOUGH - FRIAS 230 KV	477.1	82.0	477.1	82.0
MCCULLOUGH 230 - GIBSON 230 KV	410.6	-1.9	410.6	-1.9
MOHAVE 500 - LAUGHLIN 69 KV	95.4	16.0	95.4	16.0
STATES 230 - EAS TAPE 230 KV	280.5	-14.9		
MEAD 230 - BASIC 230 KV	383.5	-9.5		
BC TAP 230 - BC TAPNV 230 KV	16.1	6.6		
MEAD 230 - DECATUR 230 KV	398.5	56.8	398.5	56.8
MEAD A 69 - MEAD NPC 69 KV	105.7	11.4		
MEAD B 69 - MEAD NPC 69 KV	105.7	11.4		
MEAD 230 - WINTERWOOD 230 KV	319.0	58.8	319.0	58.8
BASIC 230 - CLARK E 230 KV			223.1	-85.8
BASIC 230 - CLARK W 230 KV			242.2	-25.2
MEAD NPC - WINTERWOOD (BB TAP 1) 69 KV			74.4	4.3
MEAD NPC - CLARK E (BB TAP2) 69 KV			58.5	1.6
MEAD NPC - LV WASH (BB TAP 3) 69 KV			38.9	-4.7
MEAD 230 - PAHRUMP 230 KV	73.7	-23.3		
JACKASSF 138 - LTHRPWLS 138 KV			9.3	-8.5
TORTISE - REID GARDNER 230 KV			-74.5	-17.9
MEAD NPC - SEARCHLIGHT 69 KV			2.3	4.9
TOTALS	2984.3	174.7	2593.3	61.7

UNIT	SYSTEM GENERATION MW	PMAX	MVAR
RG 1	110.0	115.0	23.6
RG 2	110.0	115.0	23.3
RG 3	110.0	115.0	24.1
RG 4	245.0	275.0	89.3
CLARK 1	-----	42.0	-----
CLARK 2	-----	66.0	-----
CLARK 3	-----	67.0	-----
CLARK 4	30.0	50.0	29.7
CLARK 5	73.0	73.0	30.0
CLARK 6	73.0	73.0	30.0
CLARK 7	73.0	73.0	30.0
CLARK 8	73.0	73.0	30.0
CLARK 9	45.3	85.0	42.8
CLARK 10	85.0	85.0	45.5
SUNRISE 1	-----	80.0	-----
SUNRISE 2	69.0	69.0	19.3
SUNRISE 3	70.0	70.0	30.0
SUNRISE 4	-----	70.0	-----
SUNRISE 5	-----	70.0	-----
HA CT1	70.0	72.0	24.5
NCA1 CT113.8	22.0	23.0	9.2
NCA1 CT213.8	22.0	23.0	9.2
NCA1 CT313.8	22.0	23.0	9.0
NCA1 ST 13.8	19.0	20.5	9.0
NCA2 CT113.8	22.0	23.0	3.8
NCA2 CT213.8	22.0	23.0	3.8
NCA2 CT313.8	22.0	23.0	3.7
NCA2 ST 13.8	19.0	20.5	3.7
SAGUAR 113.8	30.0	36.0	14.1
SAGUAR 213.8	30.0	36.0	14.1
SAGUAR 313.8	30.0	36.0	14.1
LVCOGEN 13.8	43.0	50.0	24.2

END OF REPORT !!!

Section 4: Base Case Power Flows, NPC System without Compensation, No Line Outages.

BUS NAME ACTUAL KV	VOLTS-PU ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
MCCULLGH230.	1.0524	0.0	0.0	0.0	0.0	0.0	0.0							
242.1 KV	7.5							2	ARDEN 230	328.6	58.8	3.2	18.1	49.8
								1	DAVIS 230.	-7.1	16.1	0.1	-18.8	3.6
								1	FRIAS 230	325.5	41.2	4.2	20.9	91.5
									GIBSON 230	330.9	-18.4	3.9	20.4	92.4
								1	MCCULLGH500.	-195.0	-66.7	0.1	12.1	
								2	MCCULLGH500.	-195.0	-66.7	0.1	12.1	
								3	MCCULLGH500.	-225.6	-75.1	0.2	13.9	
								1	MEAD 230.	-181.2	55.4	0.4	1.8	53.0
								2	MEAD 230.	-181.2	55.4	0.4	1.8	53.0

BUS NAME ACTUAL KV	VOLTS-PU ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
ARDEN 230	1.0275	0.0	0.0	0.0	0.0	0.0	0.0							
236.3 KV	2.3			TCUL TAP 233.67/138.00					ARDEN 138	131.2	-12.5	0.0	4.6	43.9
									DECATUR 230	210.7	82.3	0.9	2.7	64.6
									FRIAS 230	-138.4	-21.9	0.2	-0.2	40.0
								2	MCCULLGH230.	-325.4	-40.7	3.2	18.1	50.1
									RILEY 230	121.9	-7.2	0.1	-2.4	18.6

BUS NAME ACTUAL KV	VOLTS-PU ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
~~FRIAS~~ TOLSON 230	1.0309	0.0	0.0	0.0	0.0	0.0	0.0							
237.1 KV	2.9								ARDEN 230	138.7	21.7	0.2	-0.2	40.0
				TCUL TAP 233.98/138.00					FRIAS 138	182.6	-1.4	0.0	6.3	60.9
								1	MCCULLGH230.	-321.3	-20.3	4.2	20.9	91.7

BUS NAME ACTUAL KV	VOLTS-PU ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
~~GIBSON~~ FAULKNER 230	1.0474	0.0	0.0	0.0	0.0	0.0	0.0							
240.9 KV	3.0								CLARK 6 230	160.6	-22.0	0.2	0.0	45.4
				TCUL TAP 238.43/138.00					GIBSON 138	166.4	-16.7	0.0	5.3	55.7
									MCCULLGH230.	-327.0	38.8	3.9	20.4	92.3

BUS NAME ACTUAL KV	VOLTS-PU ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
CLARK 6 230	1.0473	0.0	0.0	0.0	0.0	0.0	0.0							
240.9 KV	2.5			TCUL TAP 238.60/138.00					CLARK 138	160.4	-22.1	0.1	6.7	54.7
									GIBSON 230	-160.4	22.1	0.2	0.0	45.4

BUS NAME ACTUAL KV	VOLTS-PU ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
MEAD 230.	1.0445	0.0	0.0	0.0	0.0	0.0	0.0							
240.2 KV	9.4							1	BASIC 230	344.9	-22.7	3.4	23.6	98.9
								1	BC TAP 230.	39.6	2.6	0.0	-1.2	9.9
									E CAMINO 230.	103.9	-11.0	1.7	-11.4	27.9

BUS NAME / ACTUAL KV	VOLTS-PU / ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	TAP	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
									[illegible]	[illegible]	[illegible]				
										DECATUR 230	327.3	32.5	7.0	37.1	92.5
									1	ELDORADO230.	-45.3	28.7	0.0	-5.7	5.6
									2	ELDORADO230.	-44.6	28.0	0.0	-5.8	5.5
									1	HOVRA1A216.5	-237.6	35.7	2.4	38.8	
									1	HOVRA5A6230.	-237.6	37.0	2.4	8.5	70.5
									1	HOVRA7-9230.	-237.6	37.0	2.4	8.5	70.5
									1	HOVRN1N216.5	-237.6	35.7	2.4	38.8	
									1	HOVRN3N416.5	-237.6	35.7	2.4	38.8	
									1	HOVRN5N616.5	-239.0	29.3	1.0	32.3	
									1	HOVRN7N816.5	-239.0	29.3	1.0	32.3	
									1	MCCULLGH230.	181.6	-53.7	0.4	1.8	53.4
									2	MCCULLGH230.	181.6	-53.7	0.4	1.8	53.4
								TAP 230.00/287.00	1	MEAD 287.	72.0	-52.1	0.0	1.5	21.3
									1	MEAD 345.	69.4	-91.3	0.0	1.7	19.1
									1	MEAD 500.	-311.1	-26.3	0.0	10.2	25.3
								TAP 230.00/ 69.00	1	MEAD 69.0	0.0	0.0	0.0	0.0	
								TCUL TAP 230.86/ 69.00		MEAD A 69.	97.5	17.9	0.1	7.8	79.3
								TCUL TAP 230.86/ 69.00		MEAD B 69.	97.5	17.9	0.1	7.8	79.3
										PAHRUMP 230	69.0	-25.4	0.9	-21.0	24.8
								TAP 230.00/287.00	1	VICTORVL287.	72.0	-52.1	1.2	-77.5	21.3
										WINTERWD 230	278.0	28.7	4.0	18.0	80.2

BUS NAME / ACTUAL KV	VOLTS-PU / ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	TAP	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
DECATUR 230	1.0159	0.0	0.0	0.0	0.0	0.0	0.0								
233.7 KV	1.2									ARDEN 230	-209.8	-79.5	0.9	2.7	64.8
								TCUL TAP 230.65/138.00		DECATUR 138	200.9	-2.9	0.0	7.6	67.0
								TCUL TAP 223.74/ 69.00		DECATURE 69	184.5	38.5	0.3	15.5	77.9
								TCUL TAP 229.36/ 69.00		DECATURW 69	176.2	-22.1	0.3	14.7	69.6
										MEAD 230.	-320.3	4.6	7.0	37.1	92.6
										WESTSIDE 230	-31.5	61.4	0.0	-2.5	10.7

BUS NAME / ACTUAL KV	VOLTS-PU / ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	TAP	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
WINTERWD 230	1.0224	0.0	0.0	0.0	0.0	0.0	0.0								
235.2 KV	3.8									MEAD 230.	-274.0	-10.7	4.0	18.0	80.4
								TCUL TAP 231.52/138.00		WINTERWD 138	274.0	10.7	0.2	13.4	91.4

BUS NAME / ACTUAL KV	VOLTS-PU / ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	TAP	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
BC TAP 230.	1.0440	0.0	0.0	0.0	0.0	0.0	0.0								
240.1 KV	9.2								1	BC TAPNV 230	16.1	6.6	0.0	0.0	
									1	MEAD 230.	-39.6	-3.7	0.0	-1.2	9.6
									1	STATES 230.	23.5	-2.9	0.0	-1.2	6.3

BUS NAME / ACTUAL KV	VOLTS-PU / ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	TAP	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
STATES 230.	1.0439	0.0	0.0	0.0	0.0	0.0	0.0								
240.1 KV	9.2								1	BC TAP 230.	-23.5	1.7	0.0	-1.2	6.3
										EAS TAPE230.	260.3	-22.9	0.6	2.9	74.8
									1	HOOVERA316.5	-116.8	10.4	0.0	13.1	86.9
									1	HOOVERA416.5	-120.0	10.8	0.0	13.8	89.2

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EAS TAPE230.  1.0429    0.0     0.0     0.0     0.0     0.0     0.0 -------------------------------------------------------
   239.9 KV      8.2                                                   EASTSIDE230.  259.7   -25.8     0.4     1.9  62.7
                                                                       STATES  230. -259.7    25.8     0.6     2.9  74.8

  BUS NAME  VOLTS-PU  ...GENERATION.. ......LOAD..... .....SHUNT..... ID                LINE FLOWS      LINE LOSSES   PCT
ACTUAL KV    ANGLE       MW     MVAR     MW    MVAR     MW     MVAR      BUS NAME     MW     MVAR      MW    MVAR  LOAD

EASTSIDE230.  1.0427    0.0     0.0     0.0     0.0     0.0     0.0 -------------------------------------------------------
   239.8 KV      7.5                                                   EAS TAPE230. -259.3    27.7     0.4     1.9  62.7
                                                                       EAS TAPW230.  233.3   -27.9     0.3     1.2  56.5
                                            TAP 230.00/ 69.00  1 EASTSIDE69.0   13.0     0.1     0.0     0.1   5.2
                                            TAP 230.00/ 69.00  2 EASTSIDE69.0   13.0     0.1     0.0     0.1   5.2.

  BUS NAME  VOLTS-PU  ...GENERATION.. ......LOAD..... .....SHUNT..... ID                LINE FLOWS      LINE LOSSES   PCT
ACTUAL KV    ANGLE       MW     MVAR     MW    MVAR     MW     MVAR      BUS NAME     MW     MVAR      MW    MVAR  LOAD

EAS TAPW230.  1.0428    0.0     0.0     0.0     0.0     0.0     0.0 -------------------------------------------------------
   239.9 KV      6.8                                                   EASTSIDE230. -233.0    29.2     0.3     1.2  56.4
                                                                       NEWPORT 230.  233.0   -29.2     0.7     3.0  67.3

  BUS NAME  VOLTS-PU  ...GENERATION.. ......LOAD..... .....SHUNT..... ID                LINE FLOWS      LINE LOSSES   PCT
ACTUAL KV    ANGLE       MW     MVAR     MW    MVAR     MW     MVAR      BUS NAME     MW     MVAR      MW    MVAR  LOAD

NEWPORT 230.  1.0424    0.0     0.0     0.0     0.0     0.0     0.0 -------------------------------------------------------
   239.7 KV      5.6                                                   AMARGOSA 230  208.2   -32.3     0.3     0.9  60.4
                                                                       EAS TAPW230. -232.2    32.1     0.7     3.0  67.2
                                            TAP 230.00/ 69.00  1 NEWPORT 69.0   12.0     0.1     0.0     0.1   6.0
                                            TAP 230.00/ 69.00  2 NEWPORT 69.0   12.0     0.1     0.0     0.1   6.0

  BUS NAME  VOLTS-PU  ...GENERATION.. ......LOAD..... .....SHUNT..... ID                LINE FLOWS      LINE LOSSES   PCT
ACTUAL KV    ANGLE       MW     MVAR     MW    MVAR     MW     MVAR      BUS NAME     MW     MVAR      MW    MVAR  LOAD

AMARGOSA 230  1.0424    0.0     0.0     0.0     0.0     0.0     0.0 -------------------------------------------------------
   239.7 KV      5.2                        TCUL TAP 229.26/138.00     AMARGOSA 138   19.4     1.1     0.0     0.3  32.4
                                                                       BASIC    230  188.6   -34.3     0.2     0.5  54.9
                                                                       NEWPORT 230. -208.0    33.2     0.3     0.9  60.4

  BUS NAME  VOLTS-PU  ...GENERATION.. ......LOAD..... .....SHUNT..... ID                LINE FLOWS      LINE LOSSES   PCT
ACTUAL KV    ANGLE       MW     MVAR     MW    MVAR     MW     MVAR      BUS NAME     MW     MVAR      MW    MVAR  LOAD

BASIC    230  1.0426    0.0     0.0     0.0     0.0     0.0     0.0 -------------------------------------------------------
   239.8 KV      4.8                                                   AMARGOSA 230 -188.4    34.8     0.2     0.5  54.9
                                            TAP 224.25/ 13.80          BA 1A   13.8    8.2     2.3     0.0     0.2  22.6
                                            TAP 224.25/ 13.80          BA 1B   13.8   36.7    14.5     0.0     4.0 105.2*
                                            TAP 224.25/ 13.80          BA 2A   13.8   37.5     7.5     0.0     3.7 101.9*
                                            TAP 224.25/ 13.80          BA 2B   13.8    9.1     2.7     0.0     0.2  25.2
                                            TAP 224.25/ 13.80          BA 3A   13.8   15.7     8.3     0.0     0.8  47.4
                                            TAP 224.25/ 13.80          BA 3B   13.8   14.9     5.5     0.0     0.6  42.3
                                                                       CLARK E  230  199.1   -92.5     0.6     1.6  69.3
                                                                       CLARK W  230  208.9   -29.3     0.6     2.1  66.6
                                                                     1 MEAD    230. -341.5    46.3     3.4    23.6  98.8
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BUS NAME ACTUAL KV	VOLTS-PU ANGLE	...GENERATION.. MW	MVAR	......LOAD..... MW	MVAR	.....SHUNT..... MW	MVAR	ID	BUS NAME		LINE FLOWS MW	MVAR	LINE LOSSES MW	MVAR	PCT LOAD
CLARK W 230	1.0423	0.0	0.0	0.0	0.0	0.0	0.0								
239.7 KV	3.8								BASIC	230	-208.3	31.4	0.6	2.1	66.5
					TCUL TAP	234.59/	69.00		CL 6911	69	82.9	-12.7	0.1	4.6	44.2
					TCUL TAP	234.58/	69.00		CL 6912	69	125.3	-18.7	0.2	7.0	53.0

Section 5: Power Flows, NPC System with 70% Compensation on the McCullough-Arden #2 230kV Line and a Mead-Winterwood Line Outage.

BUS NAME / ACTUAL KV	VOLTS-PU / ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
MCCULLGH230.	1.0522	0.0	0.0	0.0	0.0	0.0	0.0							
242.0 KV	6.8							2	ARDEN 230	680.4	48.9	13.5	25.8	101.7
								1	DAVIS 230.	-16.6	16.9	0.1	-18.6	4.8
								1	FRIAS 230	225.8	41.7	2.0	7.1	64.1
									GIBSON 230	340.9	-21.9	4.1	22.0	95.3
								1	MCCULLGH500.	-224.1	-65.5	0.1	15.5	
								2	MCCULLGH500.	-224.1	-65.5	0.1	15.5	
								3	MCCULLGH500.	-259.2	-73.4	0.3	17.9	
								1	MEAD 230.	-261.5	59.3	0.8	8.0	75.1
								2	MEAD 230.	-261.5	59.3	0.8	8.0	75.1

BUS NAME / ACTUAL KV	VOLTS-PU / ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
ARDEN 230	1.0297	0.0	0.0	0.0	0.0	0.0	0.0							
236.8 KV	3.6			TCUL TAP 234.98/138.00					ARDEN 138	177.3	-13.9	0.1	8.3	59.3
									DECATUR 230	345.8	83.9	2.1	9.9	101.5
									FRIAS 230	-14.8	-39.3	0.0	-1.6	12.0
								2	MCCULLGH230.	-666.9	-23.0	13.5	25.8	
									RILEY 230	158.6	-7.7	0.2	-1.5	24.2

BUS NAME / ACTUAL KV	VOLTS-PU / ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
FRIAS 230	1.0328	0.0	0.0	0.0	0.0	0.0	0.0							
237.6 KV	3.6								ARDEN 230	14.9	37.7	0.0	-1.6	11.5
				TCUL TAP 235.18/138.00					FRIAS 138	208.9	-3.1	0.0	8.3	69.6
								1	MCCULLGH230.	-223.7	-34.6	2.0	7.1	64.3

BUS NAME / ACTUAL KV	VOLTS-PU / ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
GIBSON 230	1.0479	0.0	0.0	0.0	0.0	0.0	0.0							
241.0 KV	2.1								CLARK 6 230	178.3	-29.0	0.2	0.4	50.6
				TCUL TAP 239.15/138.00					GIBSON 138	158.5	-14.9	0.0	4.8	53.1
									MCCULLGH230.	-336.8	43.9	4.1	22.0	95.2

BUS NAME / ACTUAL KV	VOLTS-PU / ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
CLARK 6 230	1.0481	0.0	0.0	0.0	0.0	0.0	0.0							
241.1 KV	1.6			TCUL TAP 239.99/138.00					CLARK 138	178.0	-29.4	0.2	8.1	61.0
									GIBSON 230	-178.0	29.4	0.2	0.4	50.5

BUS NAME / ACTUAL KV	VOLTS-PU / ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
MEAD 230.	1.0452	0.0	0.0	0.0	0.0	0.0	0.0							
240.4 KV	9.5							1	BASIC 230	362.6	-17.9	3.7	26.4	103.8

	1	BC TAP 230.	48.7	5.0	0.0	-1.1	11.8
	E	CAMINO 230.	105.9	-10.6	1.8	-11.0	28.4
	W	CAMINO 230.	105.9	-10.6	1.8	-11.0	28.4
	1	DAVIS 230.	35.3	3.0	0.2	-16.7	
		DECATUR 230	309.3	34.0	6.3	32.2	87.4
	1	ELDORADO230.	-29.0	29.4	0.0	-5.9	4.3
	2	ELDORADO230.	-28.5	28.7	0.0	-6.0	4.2
	1	HOVRA1A216.5	-237.6	36.5	2.4	38.8	
	1	HOVRA5A6230.	-237.6	37.8	2.4	8.5	70.5
	1	HOVRA7-9230.	-237.6	37.8	2.4	8.5	70.5
	1	HOVRN1N216.5	-237.6	36.5	2.4	38.8	
	1	HOVRN3N416.5	-237.6	36.5	2.4	38.8	
	1	HOVRN5N616.5	-239.0	30.3	1.0	32.3	
	1	HOVRN7N816.5	-239.0	30.3	1.0	32.3	
	1	MCCULLGH230.	262.3	-51.3	0.8	8.0	75.3
	2	MCCULLGH230.	262.3	-51.3	0.8	8.0	75.3
TAP 230.00/287.00	1	MEAD 287.	74.5	-51.8	0.0	1.6	21.7
	1	MEAD 345.	74.1	-91.0	0.0	1.8	19.6
	1	MEAD 500.	-268.1	-23.8	0.0	7.6	21.8
TAP 230.00/ 69.00	1	MEAD 69.0	0.0	0.0	0.0	0.0	
TCUL TAP 231.11/ 69.00		MEAD A 69.	103.2	19.4	0.1	8.6	84.0
TCUL TAP 231.11/ 69.00		MEAD B 69.	103.2	19.4	0.1	8.6	84.0
		PAHRUMP 230	69.4	-24.6	0.9	-20.9	24.8
TAP 230.00/287.00	1	VICTORVL287.	74.5	-51.8	1.3	-76.9	21.7

BUS NAME ACTUAL KV	VOLTS-PU ANGLE	...GENERATION.. MW	MVAR	......LOAD..... MW	MVAR	.....SHUNT..... MW	MVAR		ID	BUS NAME	LINE FLOWS MW	MVAR	LINE LOSSES MW	MVAR	PCT LOAD
DECATUR 230	1.0159	0.0	0.0	0.0	0.0	0.0	0.0								
233.7 KV	1.8									ARDEN 230	-343.7	-73.9	2.1	9.9	101.6
								TCUL TAP 231.47/138.00		DECATUR 138	254.2	-3.8	0.0	12.3	84.8
								TCUL TAP 224.67/ 69.00		DECATURE 69	205.1	38.6	0.4	18.8	86.2
								TCUL TAP 230.32/ 69.00		DECATURW 69	196.0	-21.5	0.4	18.0	77.3
										MEAD 230.	-303.0	-1.9	6.3	32.2	87.6
										WESTSIDE 230	-8.6	62.5	0.0	-2.6	9.7

BUS NAME ACTUAL KV	VOLTS-PU ANGLE	...GENERATION.. MW	MVAR	......LOAD..... MW	MVAR	.....SHUNT..... MW	MVAR	ID	BUS NAME	LINE FLOWS MW	MVAR	LINE LOSSES MW	MVAR	PCT LOAD
BC TAP 230.	1.0443	0.0	0.0	0.0	0.0	0.0	0.0							
240.2 KV	9.3							1	BC TAPNV 230	16.1	6.6	0.0	0.0	
								1	MEAD 230.	-48.7	-6.1	0.0	-1.1	11.8
								1	STATES 230.	32.7	-0.5	0.0	-1.2	8.7

BUS NAME ACTUAL KV	VOLTS-PU ANGLE	...GENERATION.. MW	MVAR	......LOAD..... MW	MVAR	.....SHUNT..... MW	MVAR	ID	BUS NAME	LINE FLOWS MW	MVAR	LINE LOSSES MW	MVAR	PCT LOAD
STATES 230.	1.0440	0.0	0.0	0.0	0.0	0.0	0.0							
240.1 KV	9.2							1	BC TAP 230.	-32.6	-0.7	0.0	-1.2	8.7
									EAS TAPE230.	269.5	-20.9	0.7	3.2	77.4
								1	HOOVERA316.5	-116.8	10.6	0.0	13.1	86.9
								1	HOOVERA416.5	-120.0	10.9	0.0	13.8	89.3

BUS NAME ACTUAL KV	VOLTS-PU ANGLE	...GENERATION.. MW	MVAR	......LOAD..... MW	MVAR	.....SHUNT..... MW	MVAR	ID	BUS NAME	LINE FLOWS MW	MVAR	LINE LOSSES MW	MVAR	PCT LOAD
EAS TAPE230.	1.0428	0.0	0.0	0.0	0.0	0.0	0.0							
239.8 KV	8.2								EASTSIDE230.	268.8	-24.1	0.4	2.1	64.8
									STATES 230.	-268.8	24.1	0.7	3.2	77.3

BUS NAME ACTUAL KV	VOLTS-PU ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
EASTSIDE230.	1.0425	0.0	0.0	0.0	0.0	0.0	0.0							
239.8 KV	7.4								EAS TAPE230.	-268.4	26.2	0.4	2.1	64.8
									EAS TAPW230.	242.4	-26.4	0.3	1.5	58.6
						TAP 230.00/	69.00	1	EASTSIDE69.0	13.0	0.1	0.0	0.1	5.2
						TAP 230.00/	69.00	2	EASTSIDE69.0	13.0	0.1	0.0	0.1	5.2

BUS NAME ACTUAL KV	VOLTS-PU ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
EAS TAPW230.	1.0425	0.0	0.0	0.0	0.0	0.0	0.0							
239.8 KV	6.7								EASTSIDE230.	-242.0	27.9	0.3	1.5	58.5
									NEWPORT 230.	242.0	-27.9	0.8	3.3	69.8

BUS NAME ACTUAL KV	VOLTS-PU ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
NEWPORT 230.	1.0418	0.0	0.0	0.0	0.0	0.0	0.0							
239.6 KV	5.5								AMARGOSA 230	217.2	-31.4	0.3	1.0	63.0
									EAS TAPW230.	-241.2	31.2	0.8	3.3	69.8
						TAP 230.00/	69.00	1	NEWPORT 69.0	12.0	0.1	0.0	0.1	6.0
						TAP 230.00/	69.00	2	NEWPORT 69.0	12.0	0.1	0.0	0.1	6.0

BUS NAME ACTUAL KV	VOLTS-PU ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
AMARGOSA 230	1.0417	0.0	0.0	0.0	0.0	0.0	0.0							
239.6 KV	5.0				TCUL TAP	229.88/	138.00		AMARGOSA 138	18.4	0.8	0.0	0.3	30.7
									BASIC 230	198.5	-33.3	0.2	0.6	57.7
									NEWPORT 230.	-216.9	32.5	0.3	1.0	62.9

BUS NAME ACTUAL KV	VOLTS-PU ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
BASIC 230	1.0419	0.0	0.0	0.0	0.0	0.0	0.0							
239.6 KV	4.7								AMARGOSA 230	-198.3	33.9	0.2	0.6	57.7
						TAP 224.25/	13.80		BA 1A 13.8	8.2	2.3	0.0	0.2	22.6
						TAP 224.25/	13.80		BA 1B 13.8	36.7	14.5	0.0	4.0	105.2
						TAP 224.25/	13.80		BA 2A 13.8	37.5	7.5	0.0	3.8	101.9
						TAP 224.25/	13.80		BA 2B 13.8	9.1	2.7	0.0	0.2	25.2
						TAP 224.25/	13.80		BA 3A 13.8	15.7	8.3	0.0	0.8	47.4
						TAP 224.25/	13.80		BA 3B 13.8	14.9	5.5	0.0	0.6	42.3
									CLARK E 230	216.4	-88.9	0.6	2.0	73.9
									CLARK W 230	218.8	-30.1	0.7	2.5	69.7
								1	MEAD 230.	-358.9	44.2	3.7	26.4	103.7

BUS NAME ACTUAL KV	VOLTS-PU ANGLE	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	SHUNT MW	SHUNT MVAR	ID	BUS NAME	LINE FLOWS MW	LINE FLOWS MVAR	LINE LOSSES MW	LINE LOSSES MVAR	PCT LOAD
CLARK E 230	1.0452	0.0	0.0	0.0	0.0	0.0	0.0							
240.4 KV	3.8								BASIC 230	-215.8	90.9	0.6	2.0	73.7
					TCUL TAP	244.55/	69.00		CL 6904 69	65.0	-27.9	0.2	7.7	69.3
					TCUL TAP	244.47/	69.00		CL 6907 69	150.8	-62.9	0.4	19.0	80.5

ACTUAL KV	ANGLE	MW	MVAR	MW	MVAR	MW	MVAR		BUS NAME		MW	MVAR	MW	MVAR	LOAD
CLARK W 230	1.0415	0.0	0.0	0.0	0.0	0.0	0.0								
239.5 KV	3.6								BASIC	230	-218.2	32.6	0.7	2.5	69.7
								TCUL TAP 235.29/ 69.00	CL 6911	69	86.9	-13.2	0.1	5.1	46.2
								TCUL TAP 235.28/ 69.00	CL 6912	69	131.3	-19.4	0.2	7.7	55.5

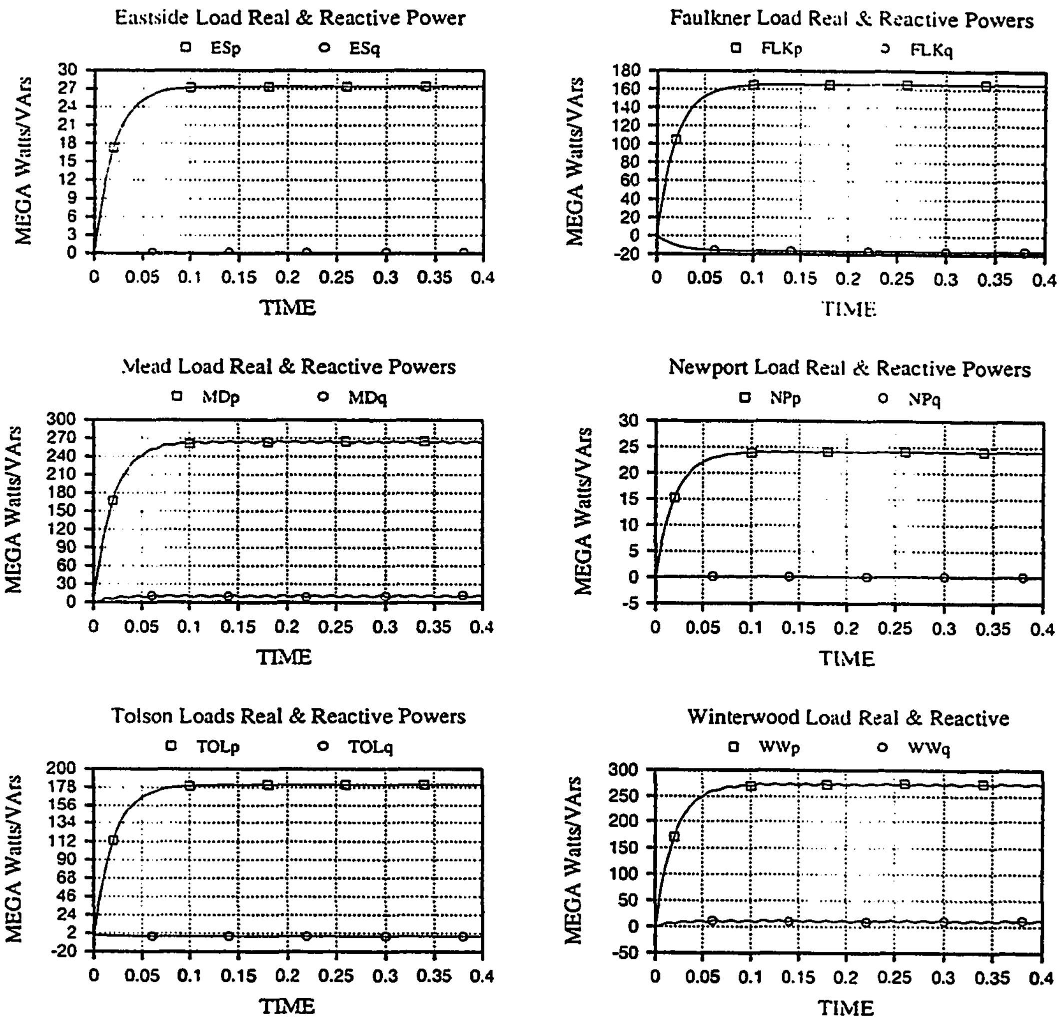
APPENDIX III

STEADY-STATE RESULTS USING PSCAD/EMTDC PROGRAM

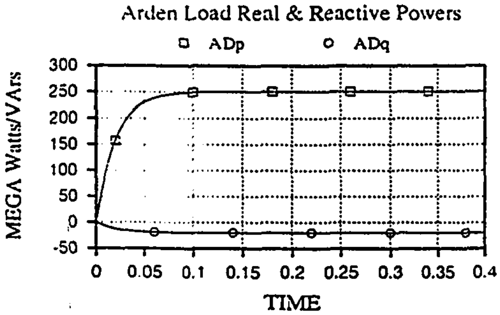
The following five sections list various reports produced from the PSCAD/EMTDC program using the reduced NPC system model. Values developed for use in this model were based on the 1999 heavy summer case provided by the WSCC and augmented by Nevada Power to include up-to-date construction and data as it pertains to this thesis.

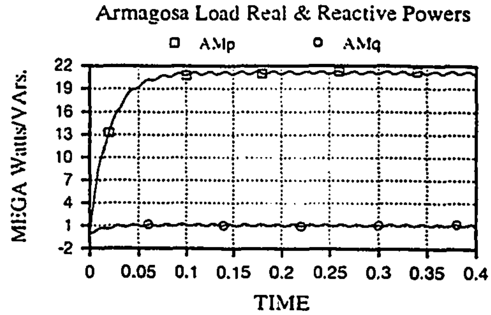
Section 1: Base Case, all lines in service.

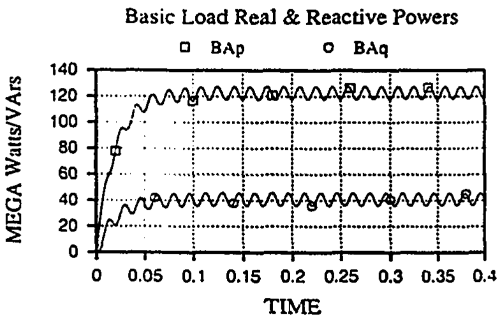
BASE CASE LOAD POWERS

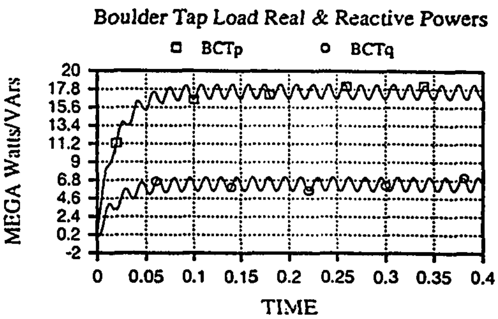


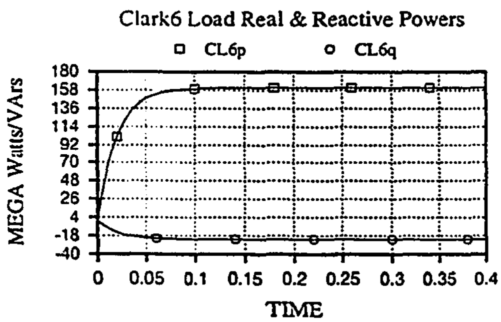
BASE CASE LOAD POWERS

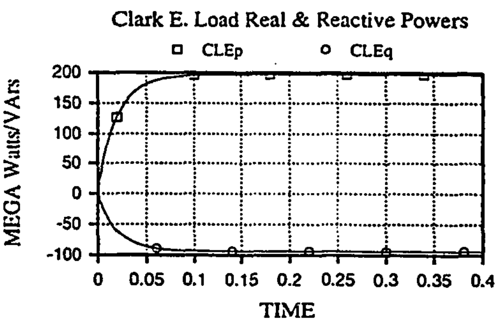


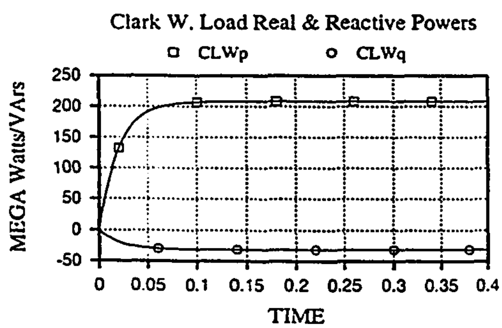


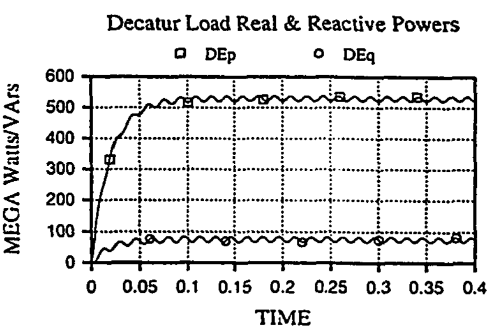






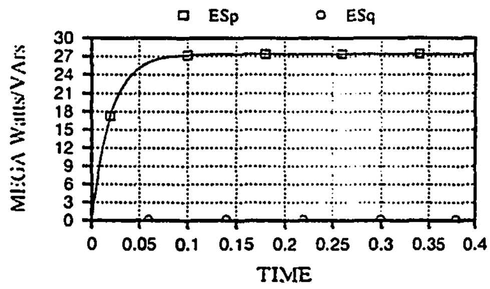




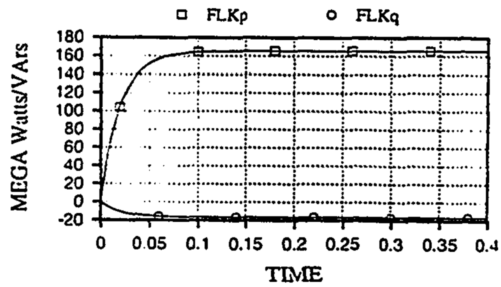


BASE CASE LOAD POWERS

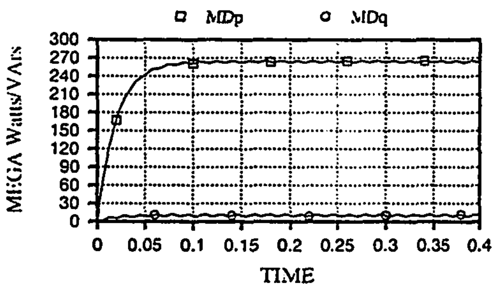
Eastside Load Real & Reactive Power



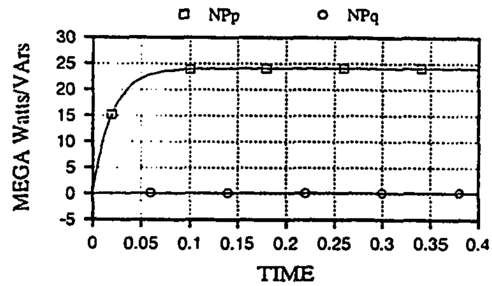
Faulkner Load Real & Reactive Powers



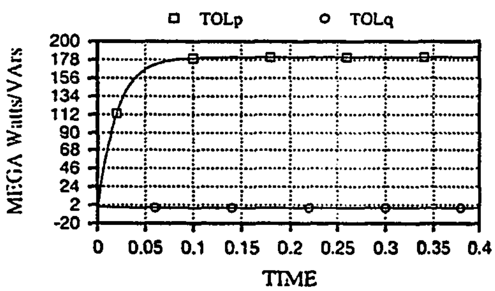
Mead Load Real & Reactive Powers



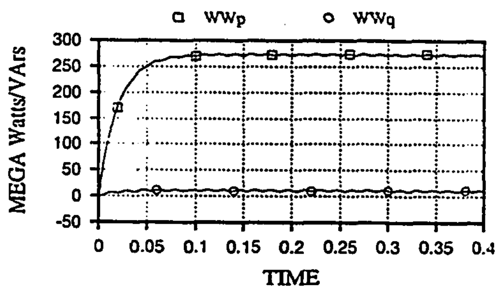
Newport Load Real & Reactive Powers



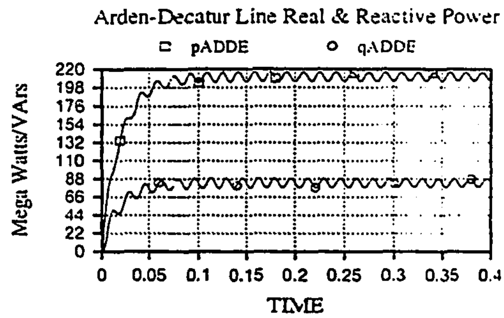
Tolson Loads Real & Reactive Powers

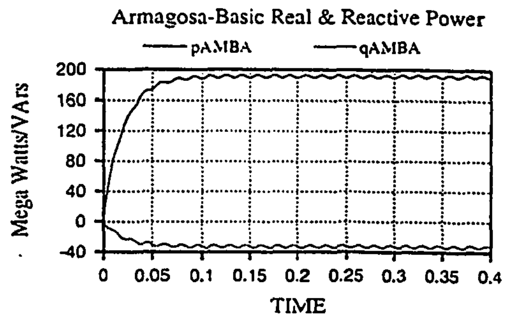


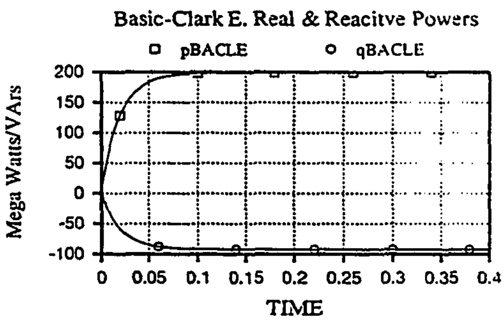
Winterwood Load Real & Reactive

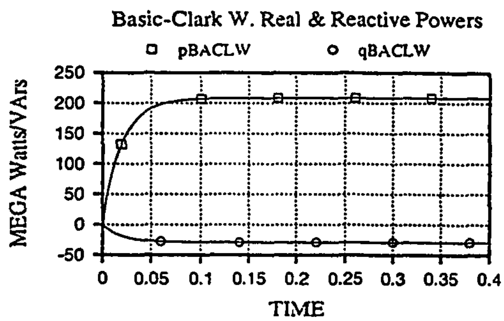


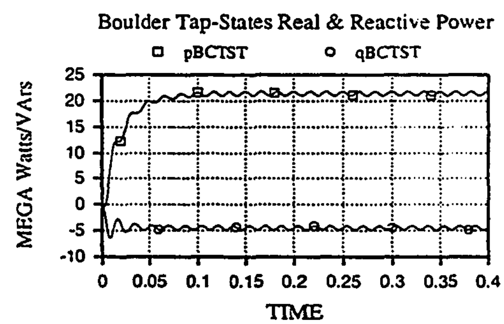
BASE CASE LINE POWER FLOWS

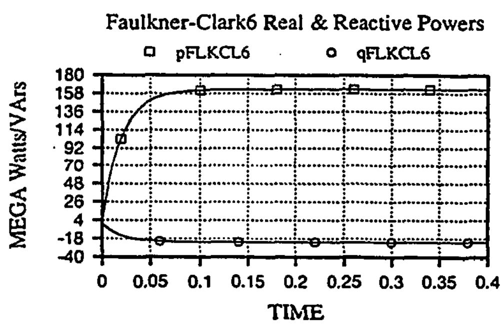


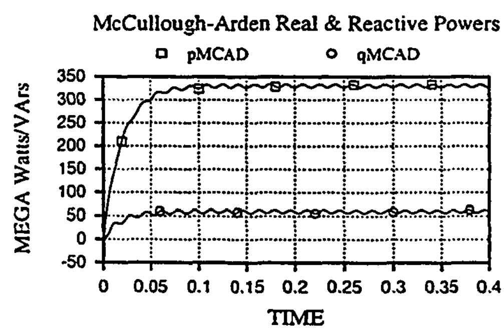


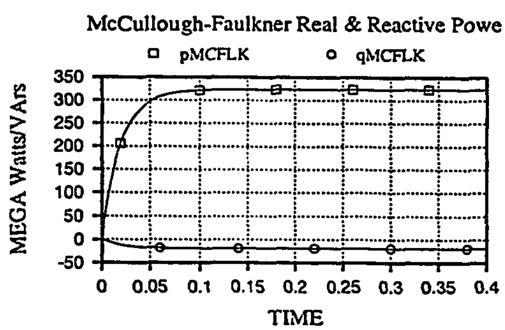






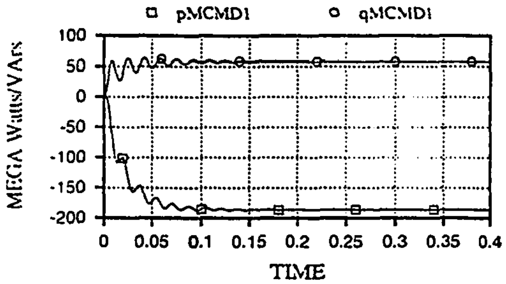




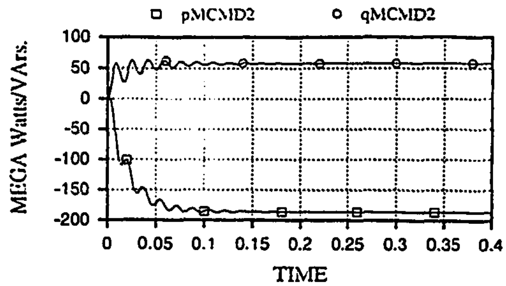


BASE CASE LINE POWER FLOWS

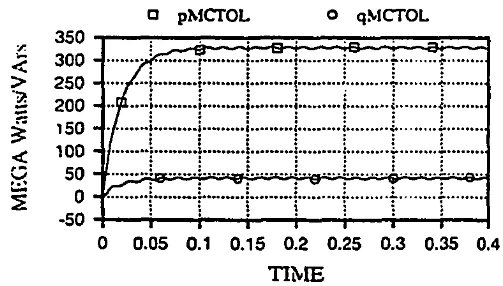
McCullough-Mead 1 Real & Reactive Powers



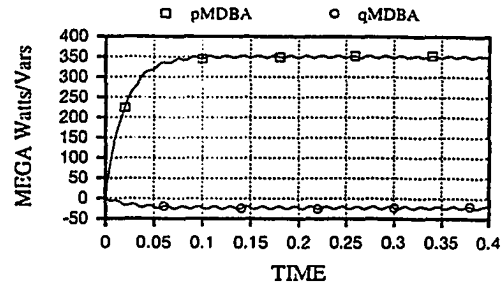
McCullough-Mead 2 Real & Reactive Powers



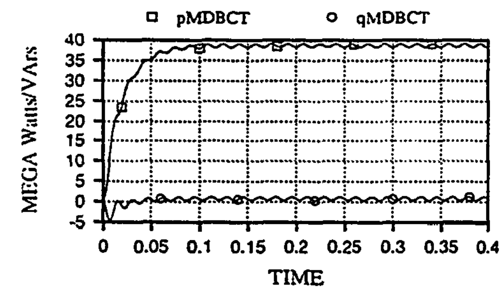
McCullough-Tolson Real & Reactive Powers



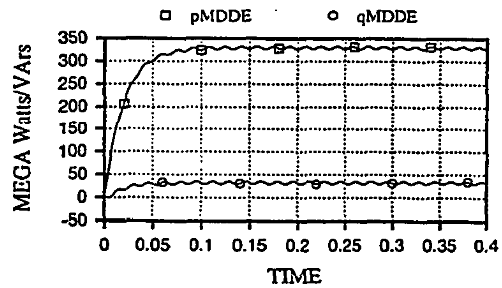
Mead-Basic Real & Reactive Powers



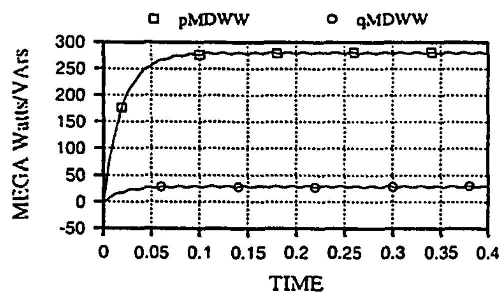
Mead-Boulder Tap Real & Reactive Powers



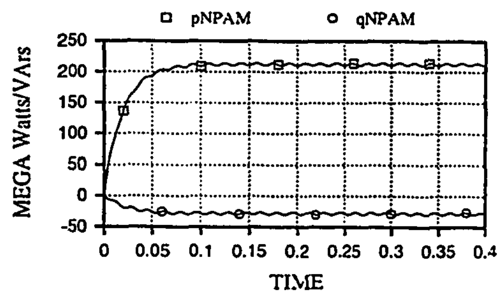
Mead-Decatur Real & Reactive Powers



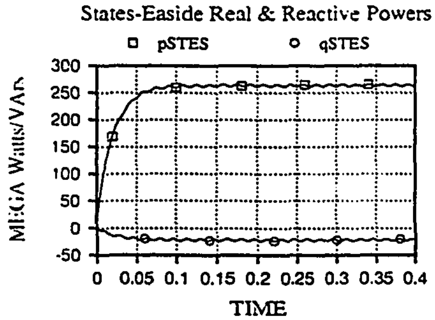
Mead-Winerwood Real & Reactive Powers

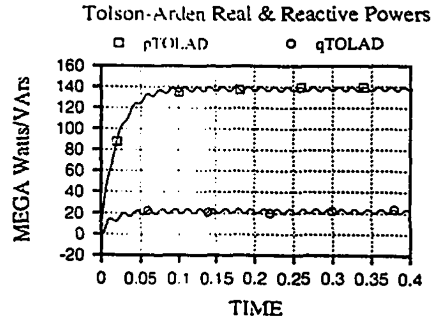


Newport-Armagosa Real & Reactive Powers



BASE CASE LINE POWER FLOWS

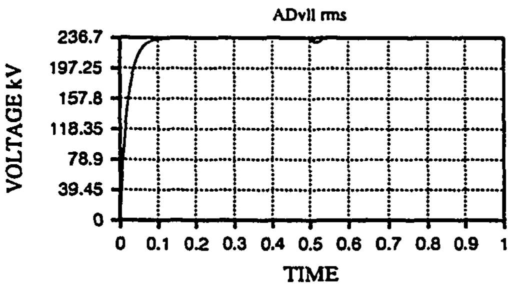




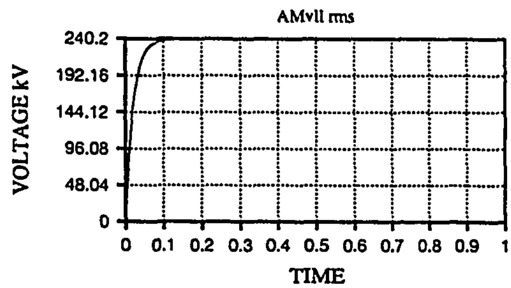
Section 2: Uncontrolled 70% Compensation on the McCullough-Arden #2 230kV Line.

UNCONTROLLED COMPENSATION CASE VOLTAGES

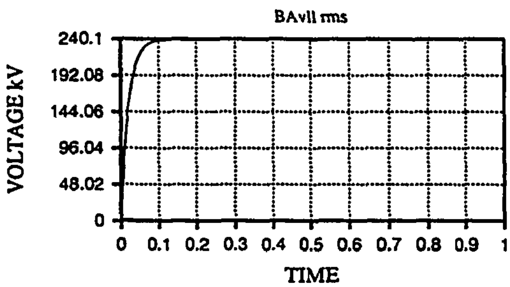
Arden rms Bus Voltage



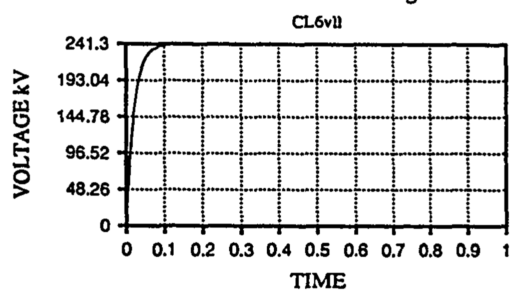
Armagosa rms Bus Voltage



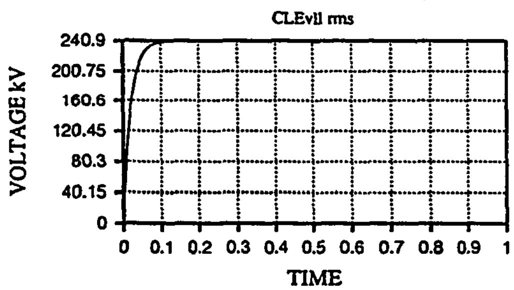
Basic rms Bus Voltage



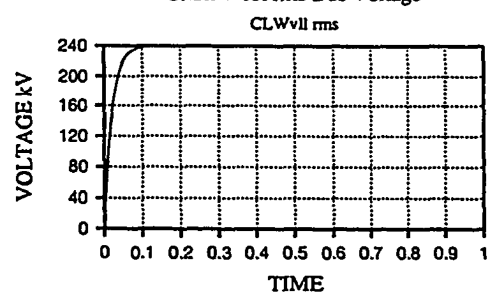
Clark 6 rms Bus Voltage



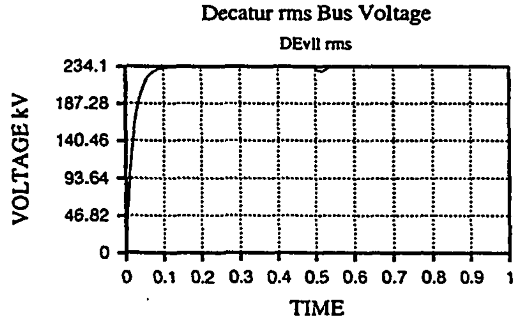
Clark East rms Bus Voltage



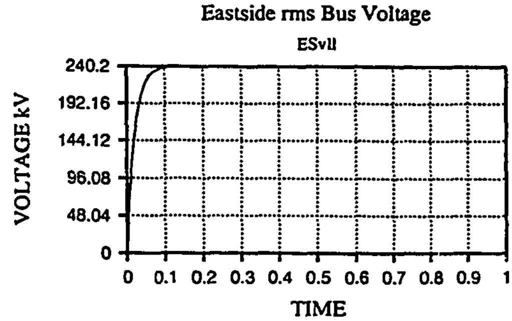
Clark West rms Bus Voltage



Decatur rms Bus Voltage

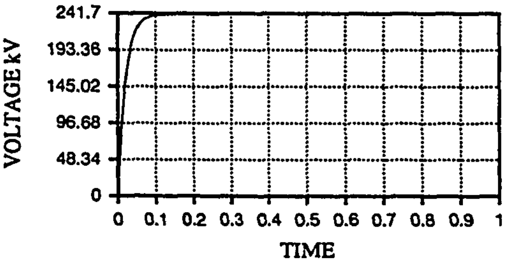


Eastside rms Bus Voltage

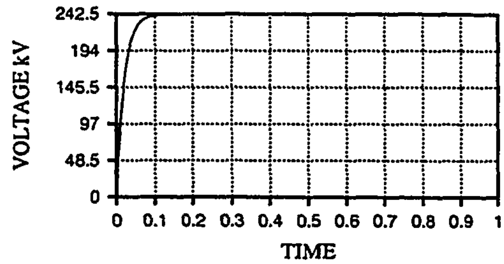


UNCONTROLLED COMPENSATION CASE VOLTAGES

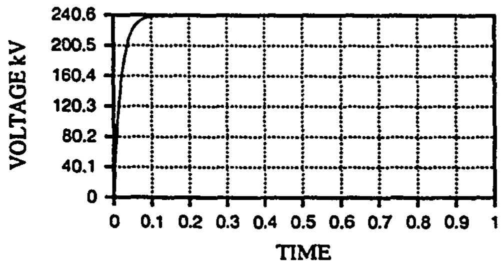
Faulkner rms Bus Voltage



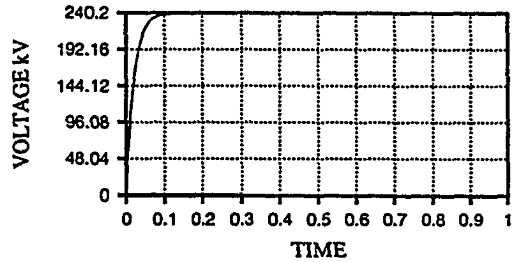
McCullough rms Bus Voltage



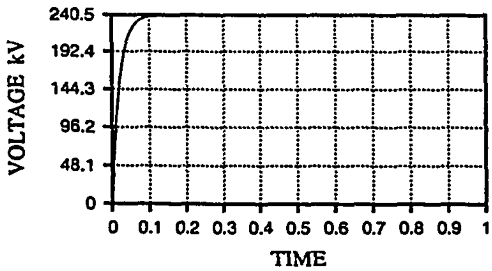
Mead rms Bus Voltage



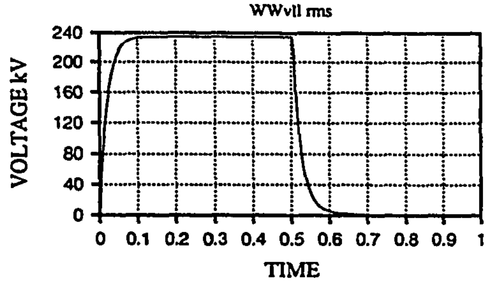
Newport rms Bus Voltage



State rms Bus Voltage

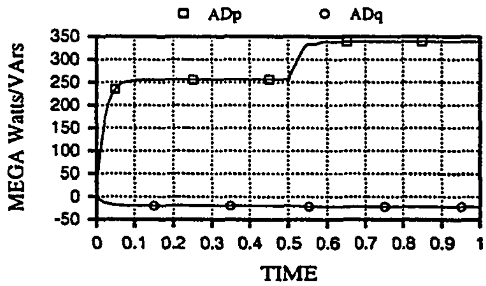


Winterwood rms Bus Voltage

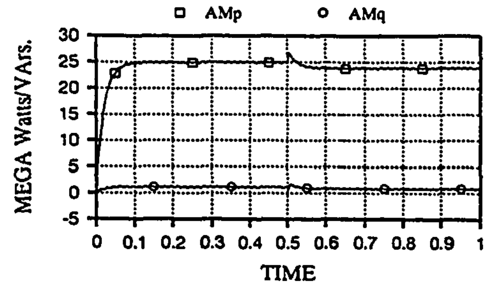


UNCONTROLLED COMPENSATION CASE LOAD POWERS

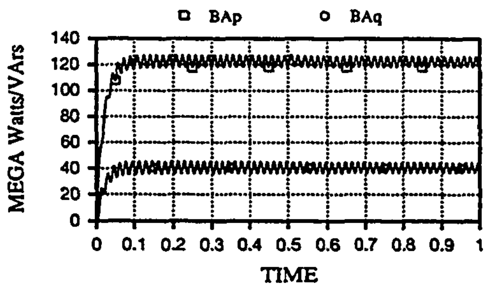
Arden Load Real & Reactive Powers



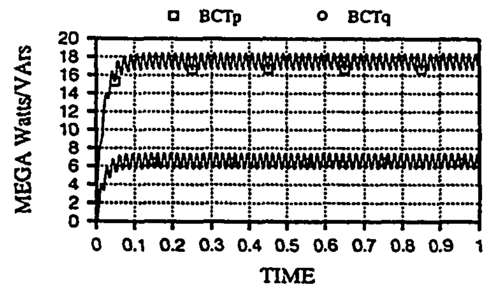
Armagosa Load Real & Reactive Powers



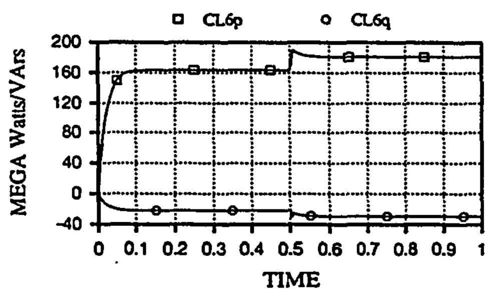
Basic Load Real & Reactive Powers



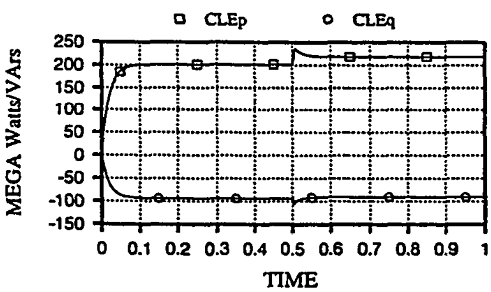
Boulder Tap Load Real & Reactive Powers



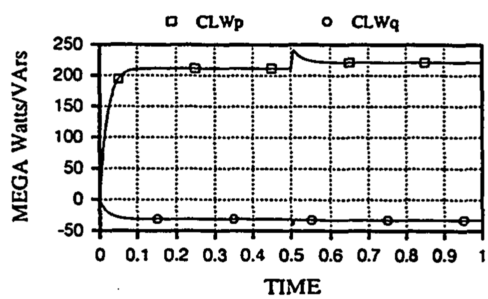
Clark6 Load Real & Reactive Powers



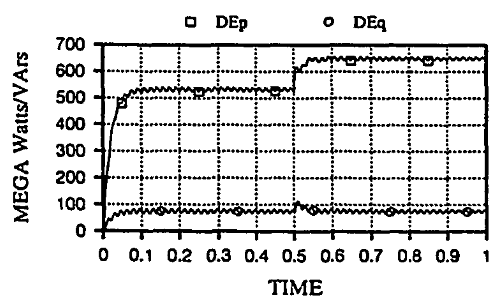
Clark E. Load Real & Reactive Powers



Clark W. Load Real & Reactive Powers

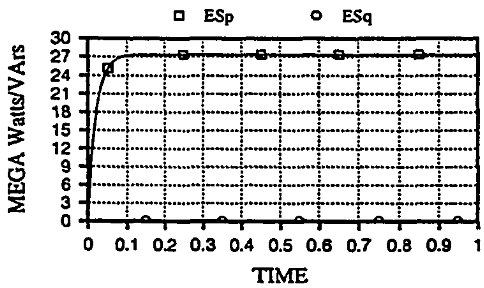


Decatur Load Real & Reactive Powers

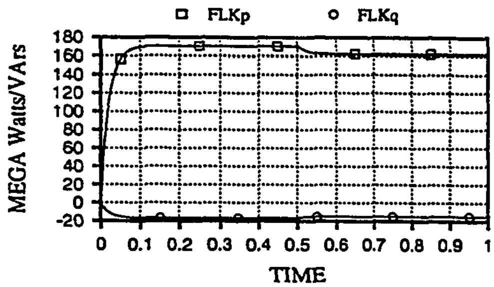


UNCONTROLLED COMPENSATION LOAD POWERS

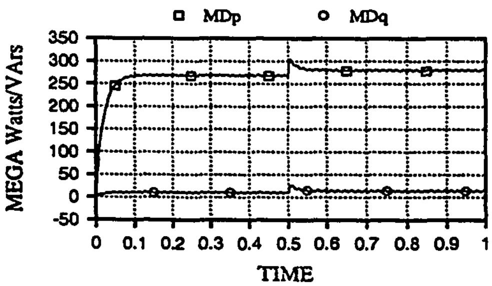
Eastside Load Real & Reactive Power



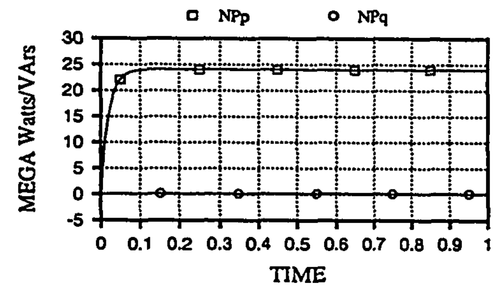
Faulkner Load Real & Reactive Powers



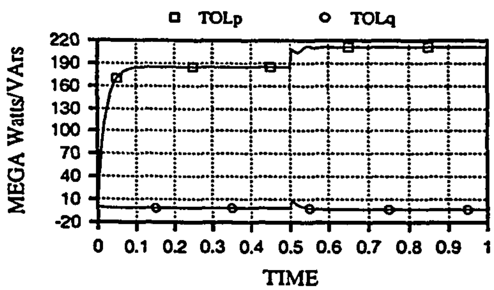
Mead Load Real & Reactive Powers



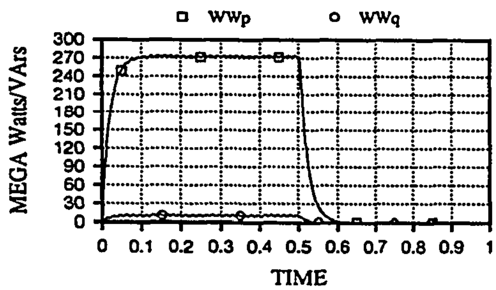
Newport Load Real & Reactive Powers



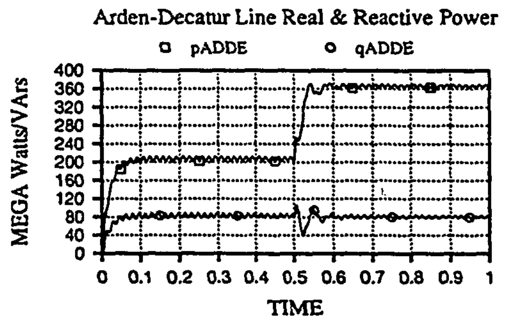
Tolson Loads Real & Reactive Powers

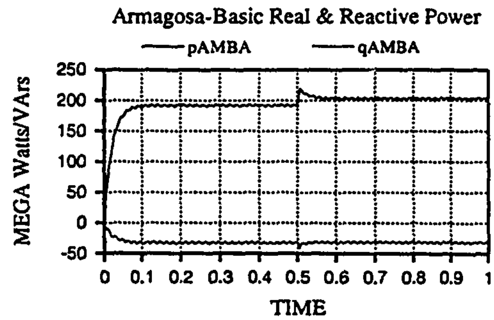


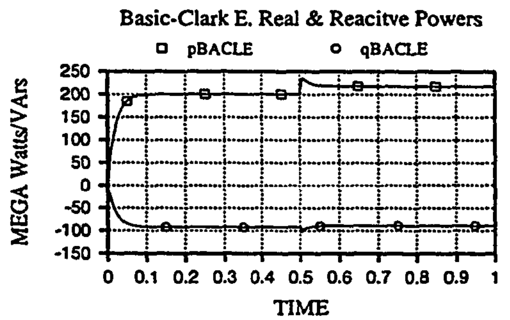
Winterwood Load Real & Reactive

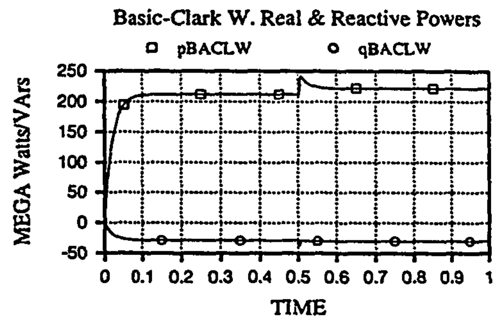


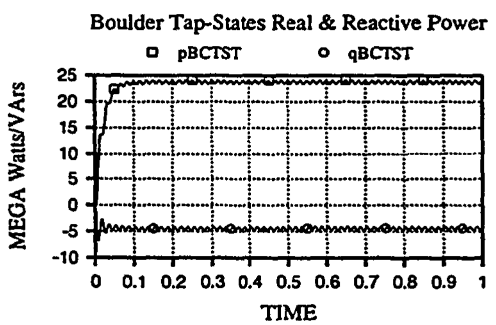
UNCONTROLLED COMPENSATION CASE LINE POWER FLOWS

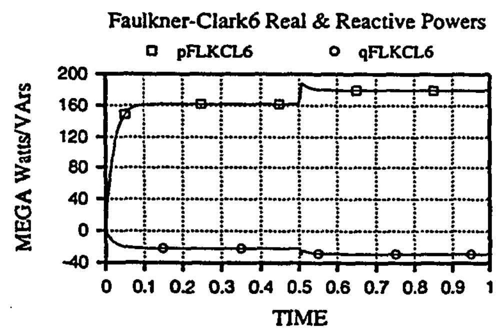


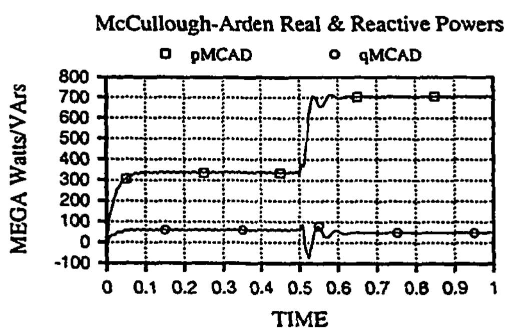


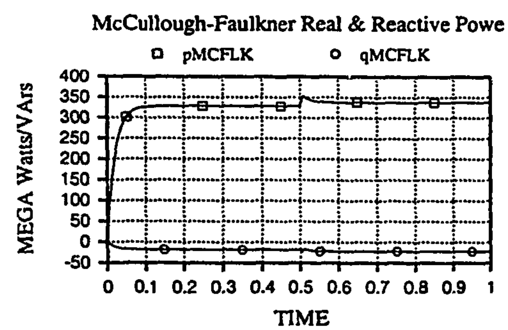




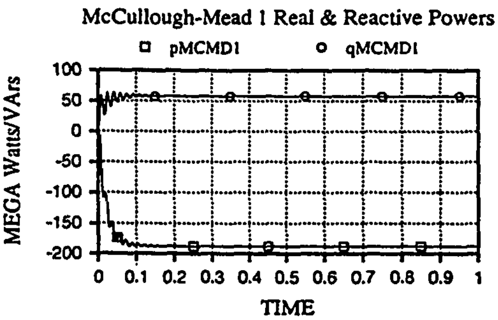


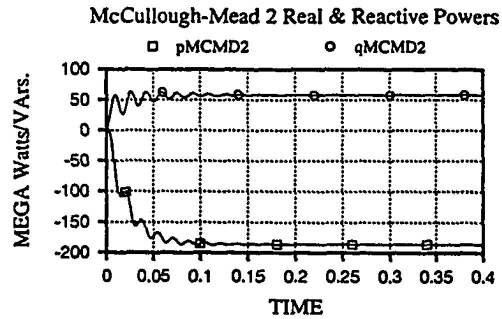


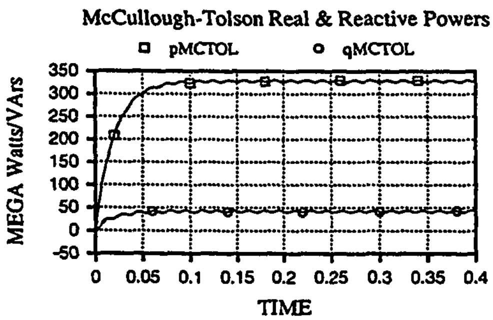


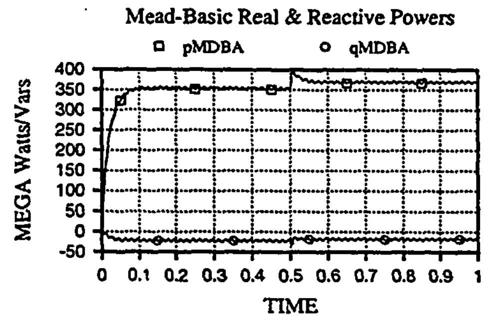


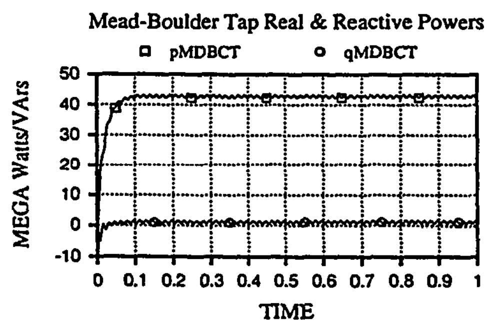
UNCONTROLLED COMPENSATION CASE LINE POWER FLOWS

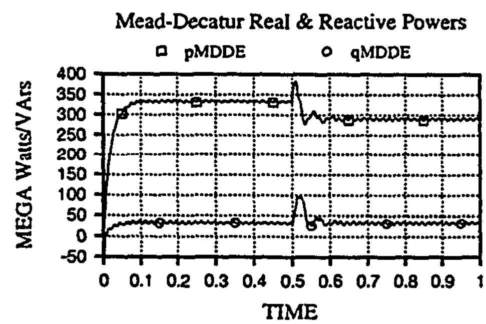


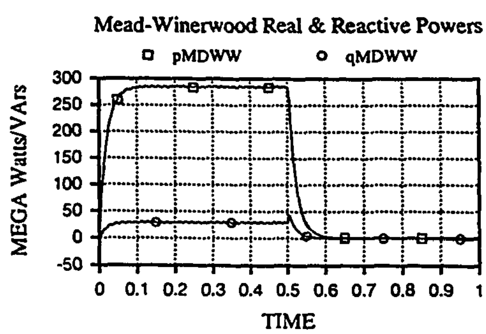


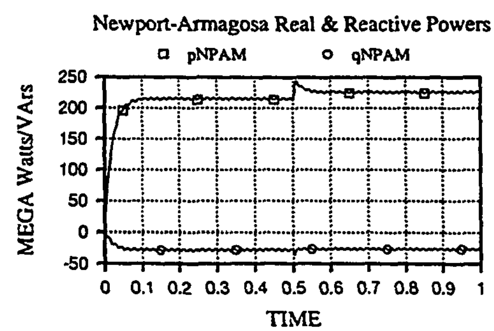




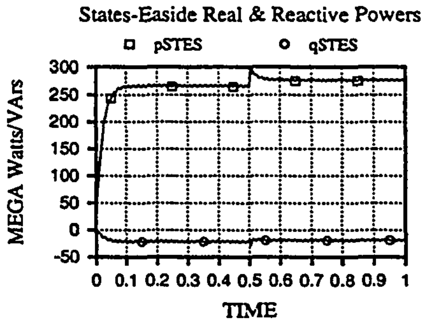


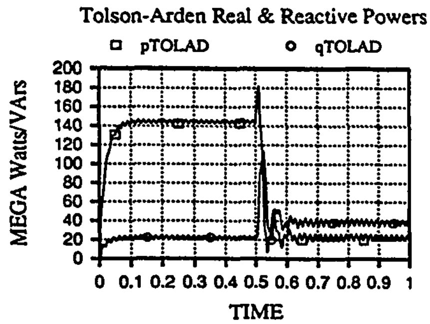






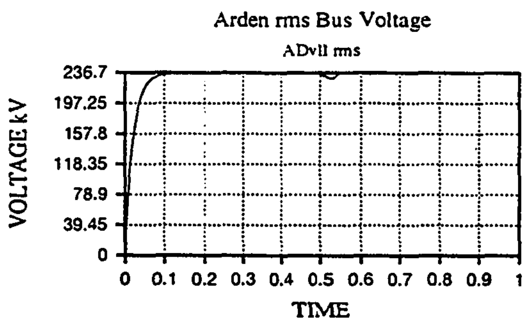
UNCONTROLLED COMPENSATION CASE LINE POWER FLOWS

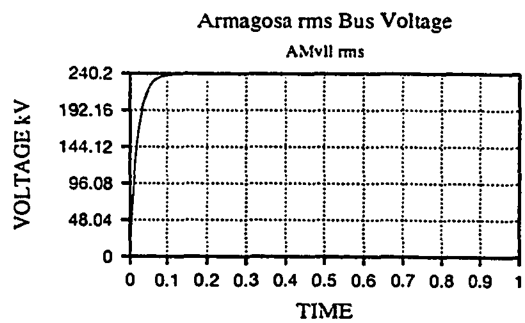


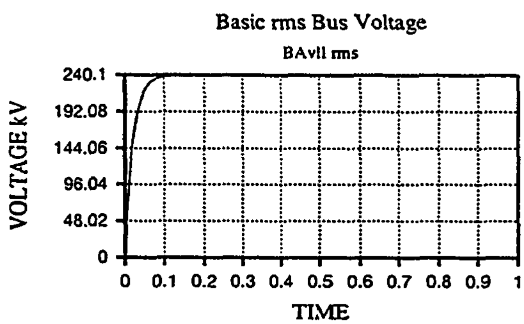


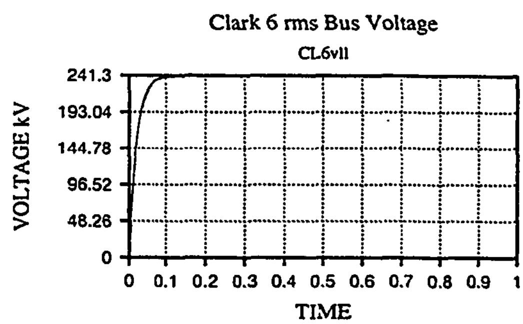
Section 3: TCSC inserted into the Modeled NPC System.

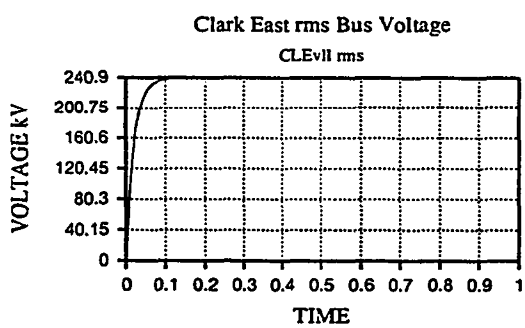
TCSC CASE BUS VOLTAGES

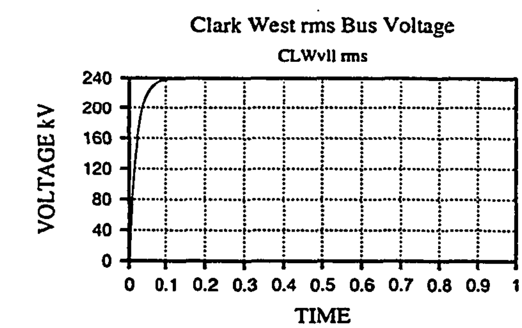


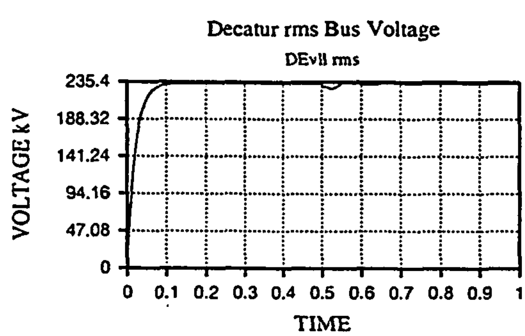


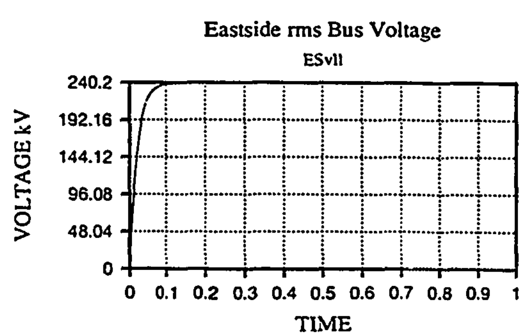




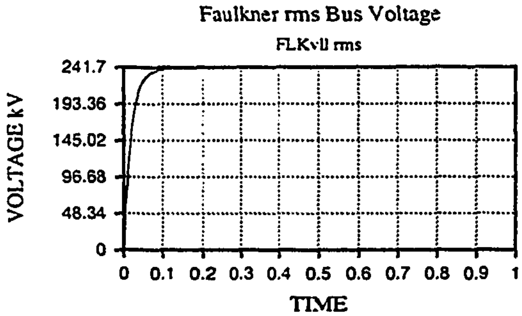


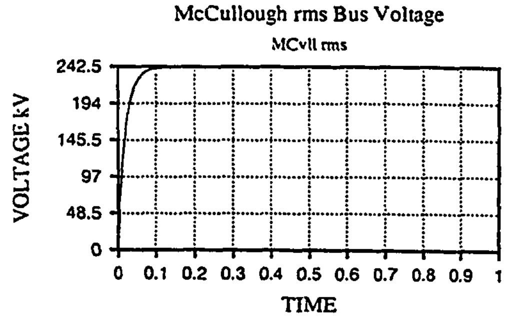


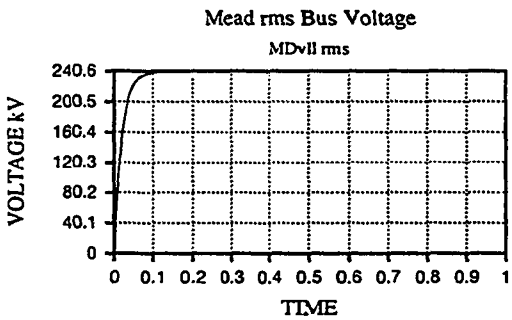


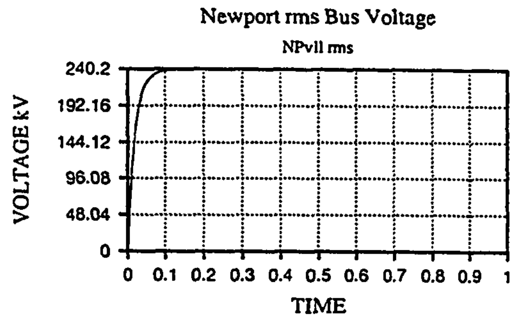


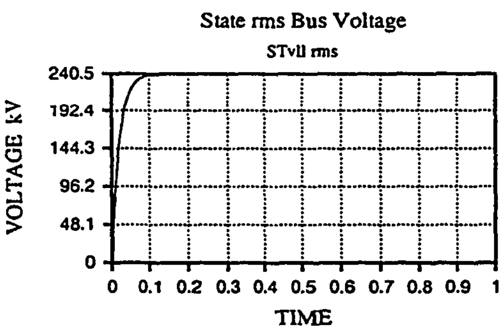
TCSC CASE BUS VOLTAGES

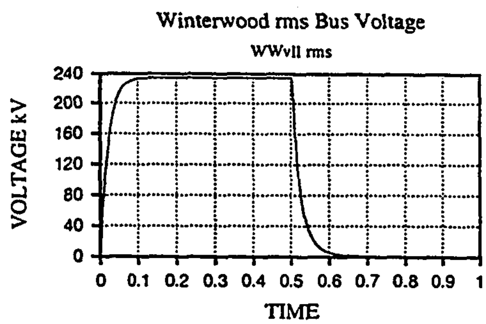


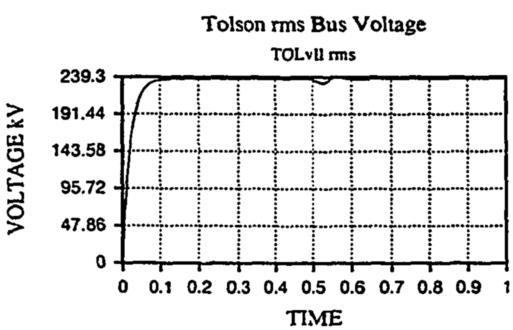




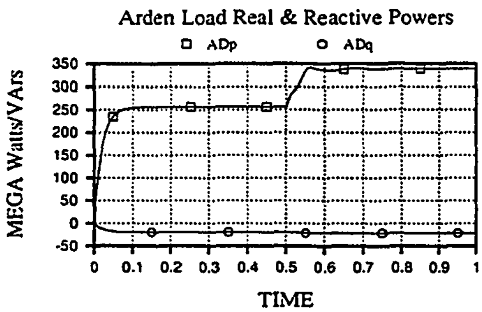


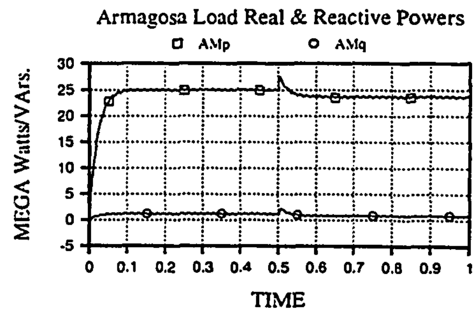


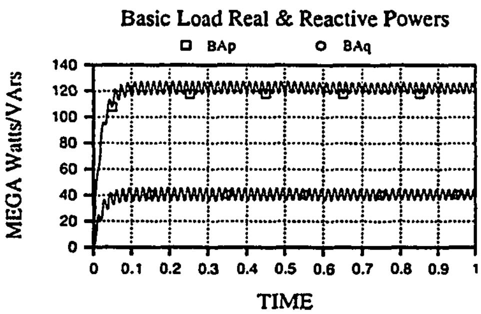


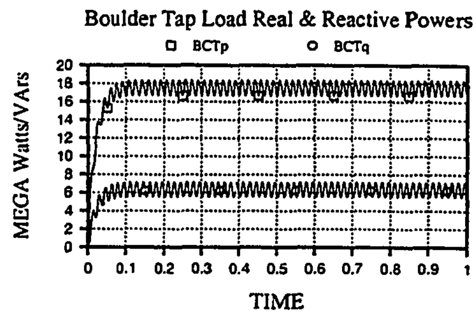


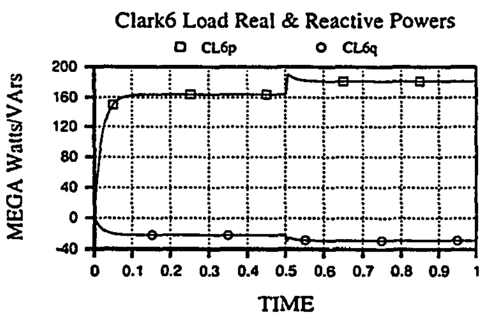
TCSC CASE LOAD POWERS

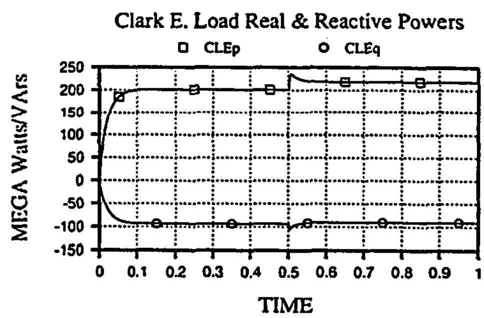


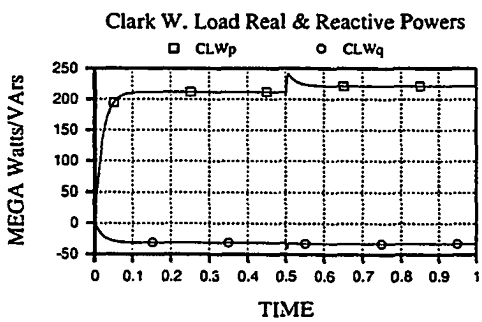


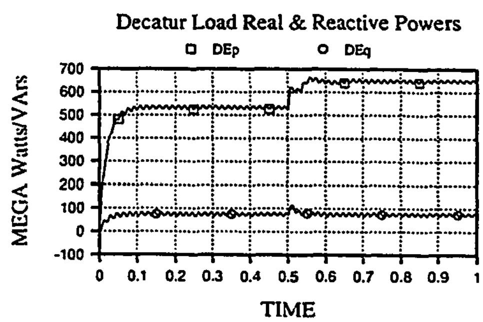






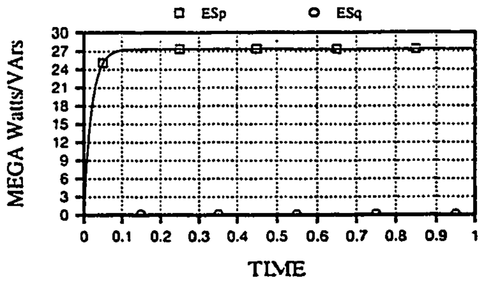




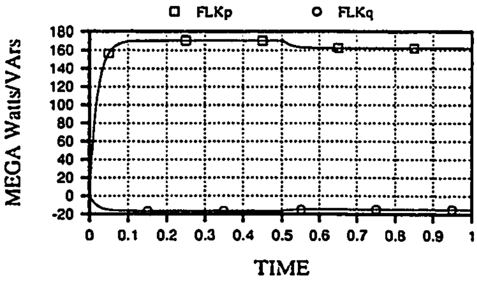


TCSC CASE POWER FLOWS

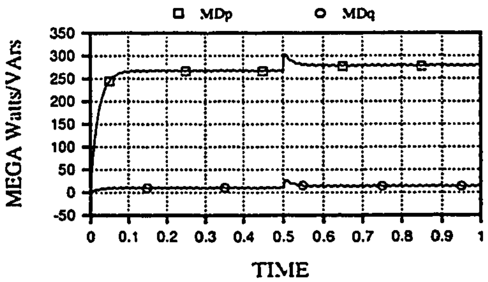
Eastside Load Real & Reactive Power



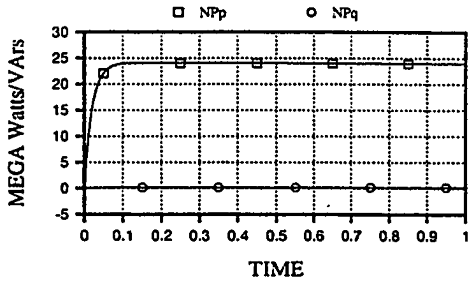
Faulkner Load Real & Reactive Powers



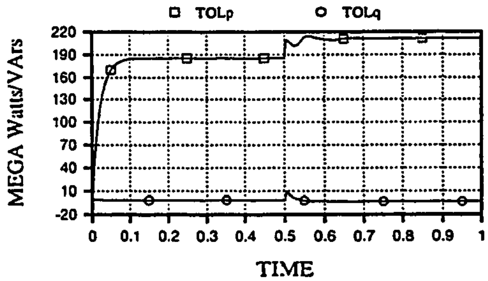
Mead Load Real & Reactive Powers



Newport Load Real & Reactive Powers



Tolson Loads Real & Reactive Powers



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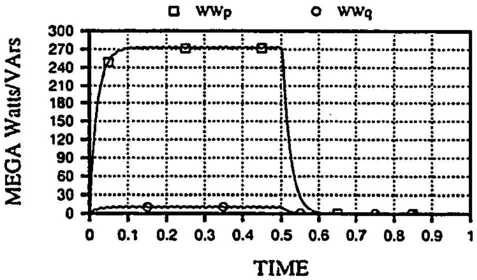
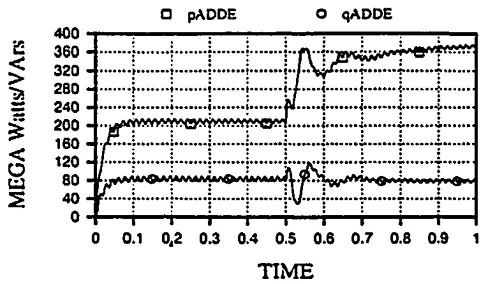
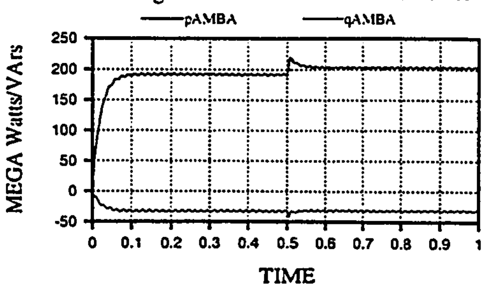


TCSC CASE LINE POWER FLOWS

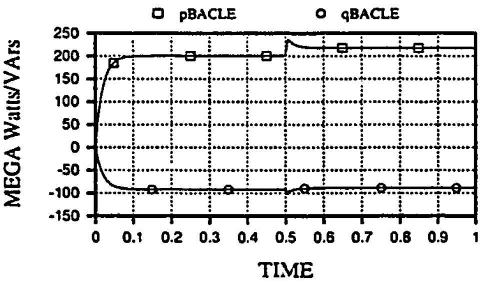
Arden-Decatur Line Real & Reactive Power



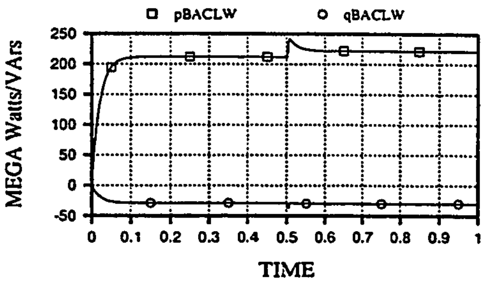
Armagosa-Basic Real & Reactive Power



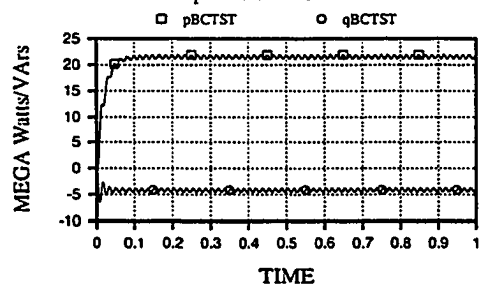
Basic-Clark E. Real & Reacitve Powers



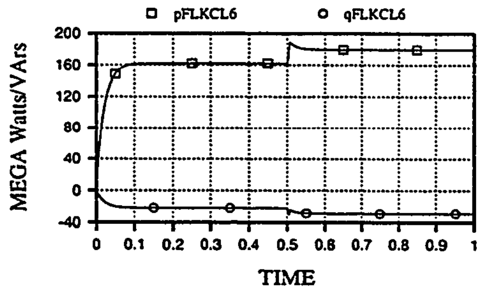
Basic-Clark W. Real & Reactive Powers



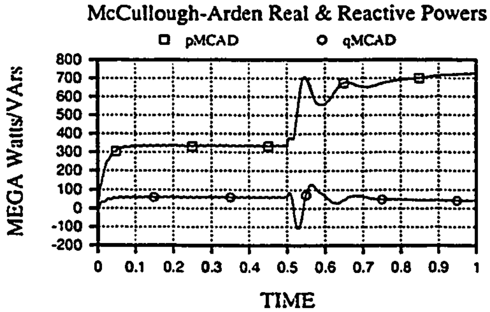
Boulder Tap-States Real & Reactive Power



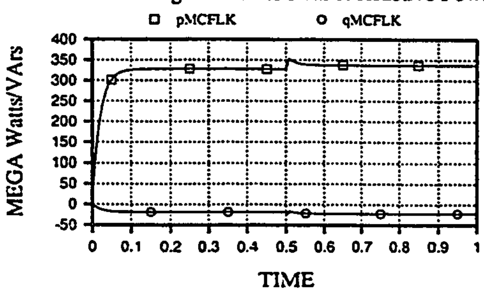
Faulkner-Clark6 Real & Reactive Powers



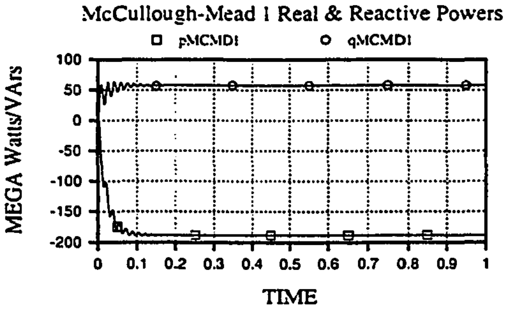
McCullough-Arden Real & Reactive Powers

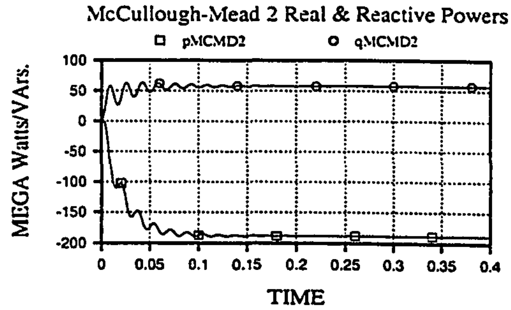


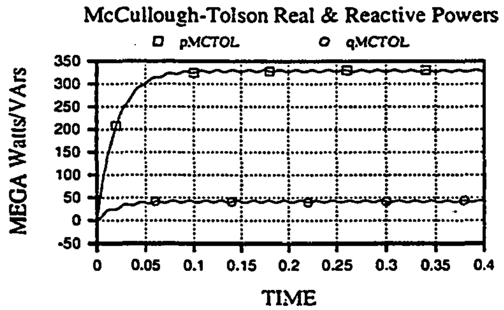
McCullough-Faulkner Real & Reactive Powe

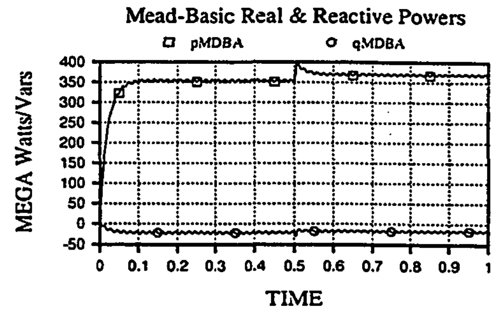


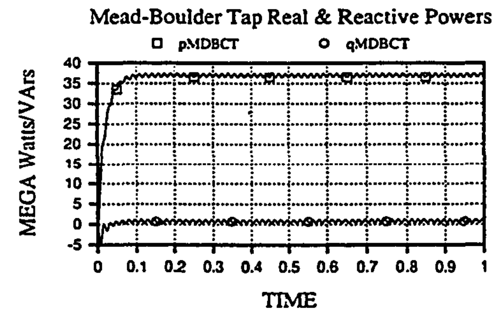
TCSC CASE LINE POWER FLOWS

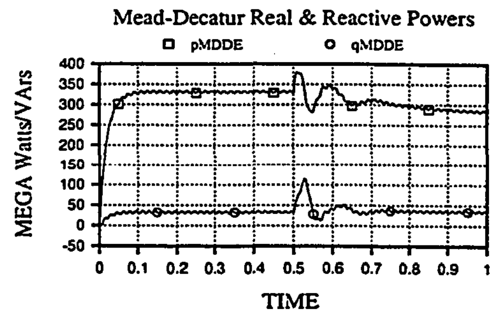


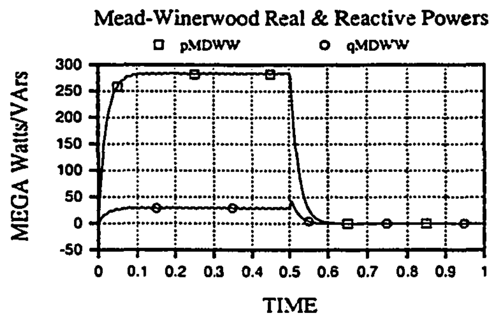


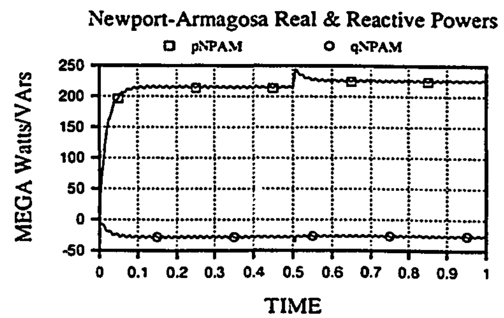




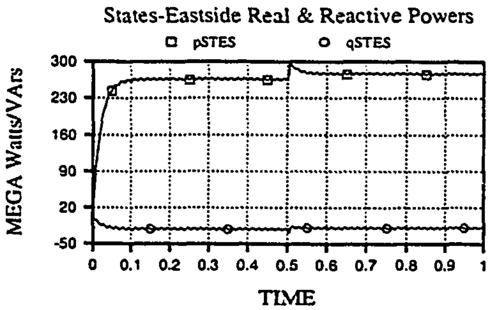


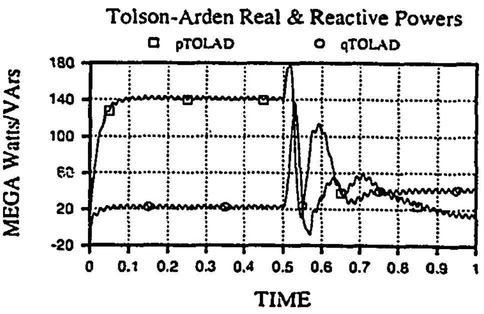






TCSC CASE LINE POWER FLOWS



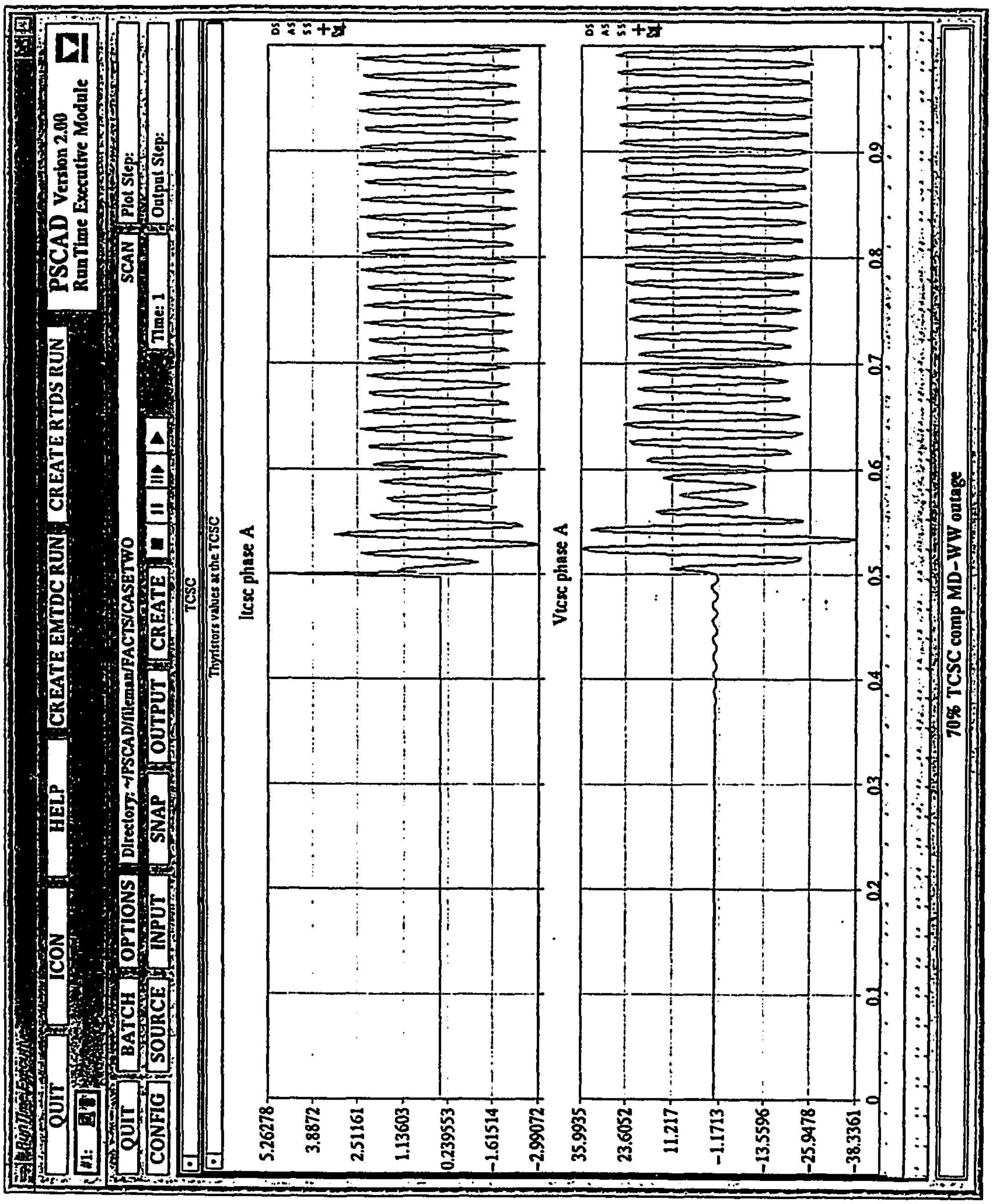


APPENDIX IV

PSCAD/EMTDC RUNTIME REPORT

The following section shows a runtime computer screen shot of the TCSC voltage and current.

Section 1: Runtime computer screen shot of the TCSC voltage and current.



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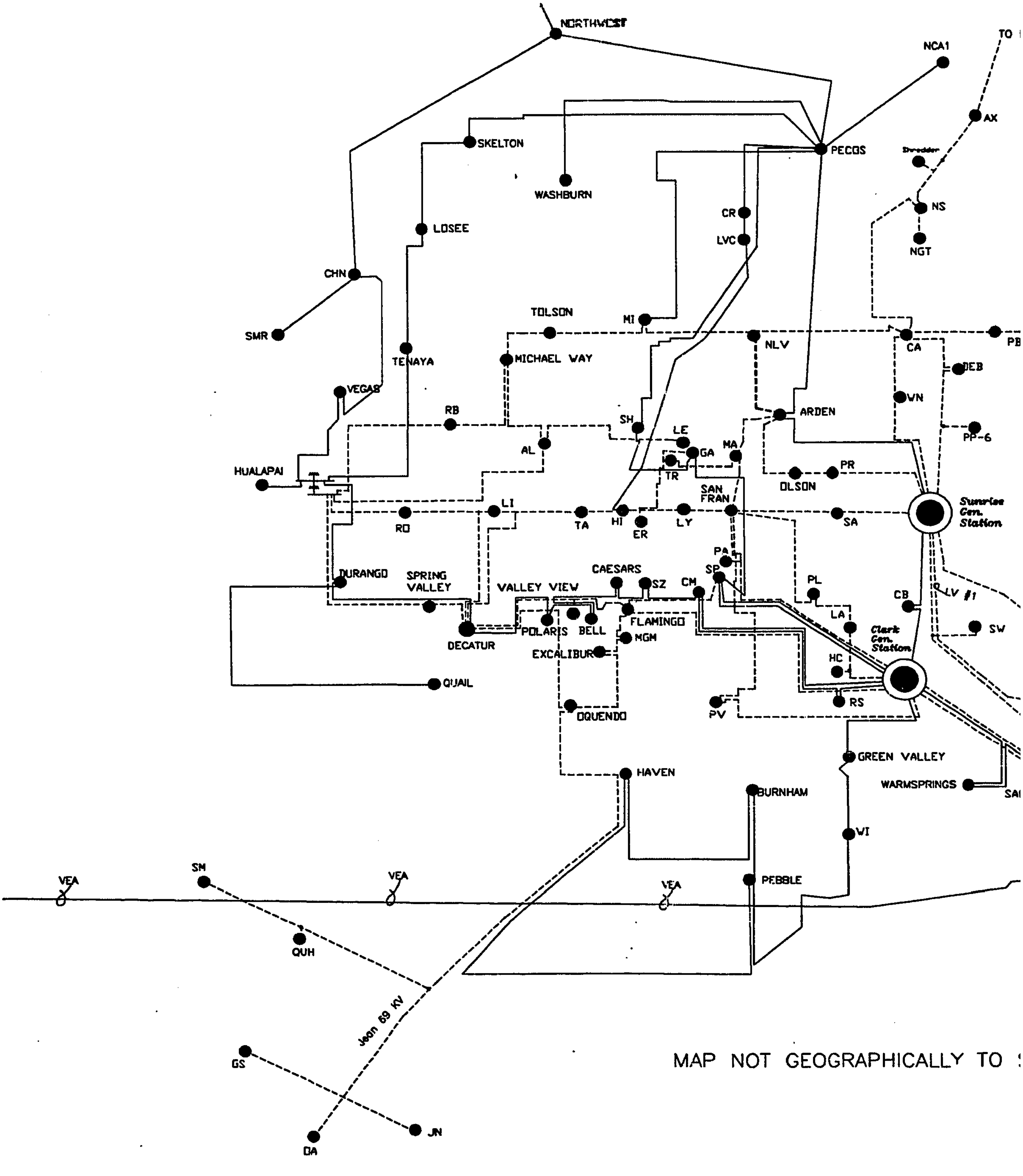
Committee Member, Dr. William L. Brogan, Ph. D.
Committee Member, Dr. Shahram Latifi, Ph. D.
Graduate Faculty Representative, Dr. Penny Amy, Ph. D.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HAVEN
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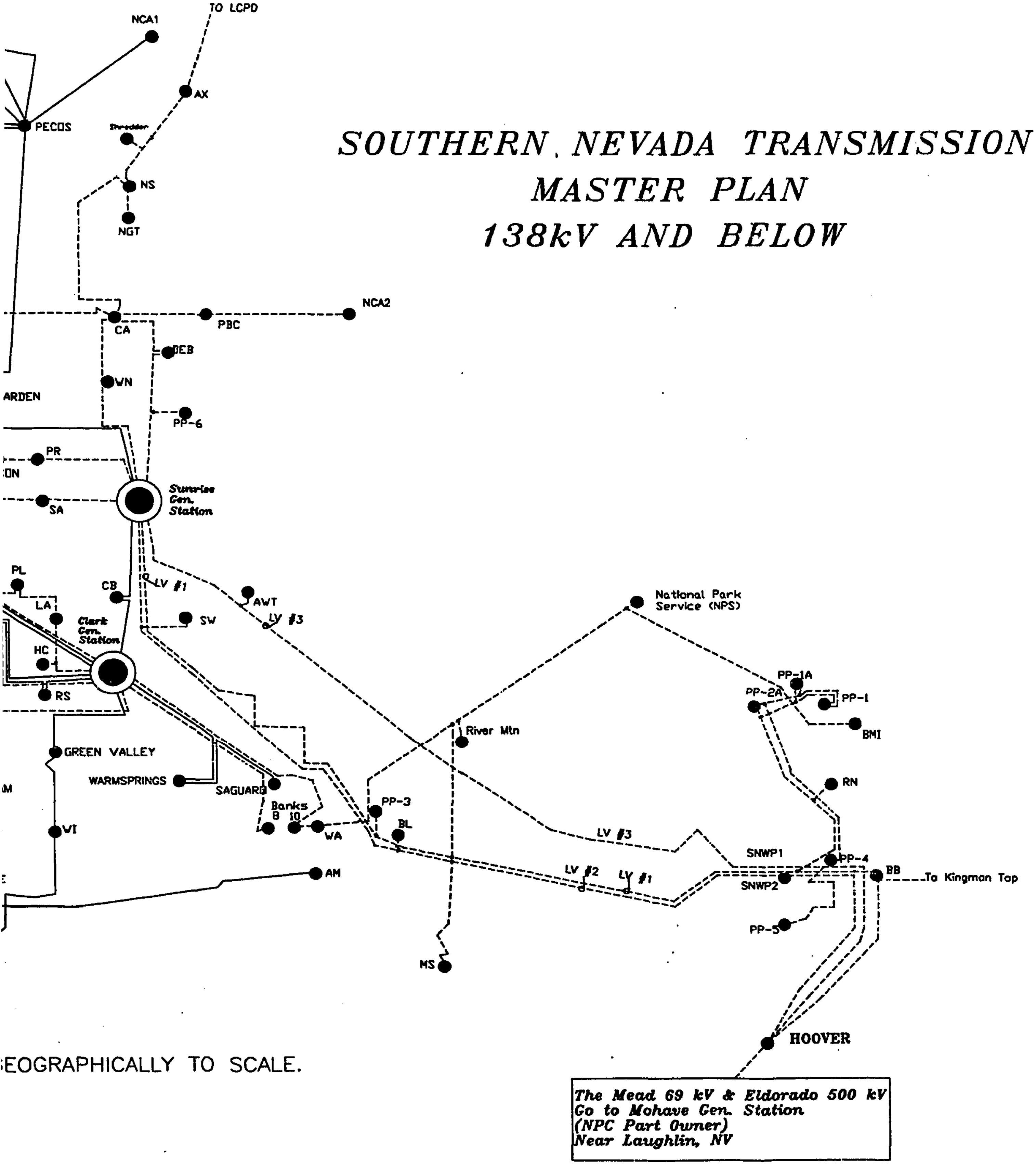
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MASTER PLAN
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TO LCPD
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PECOS
NS
NGT
NCA2
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PBC
DEB
WN
ARDEN
PP-6
PR
SA
Sunrise Gen. Station
PL
CB
LV #1
AWT
LV #3
SW
LA
Clark Gen. Station
HC
RS
National Park Service (NPS)
PP-1A
PP-2A
PP-1
BMI
River Mtn
GREEN VALLEY
WARMSPRINGS
SAGUARO
Banks
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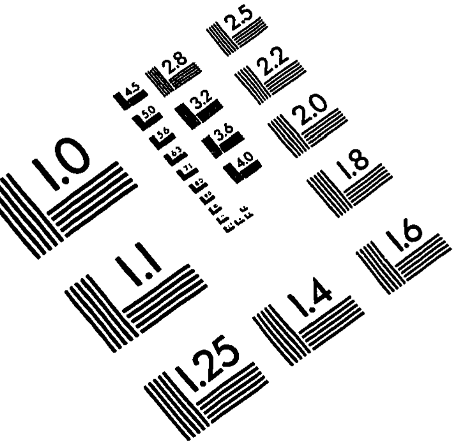
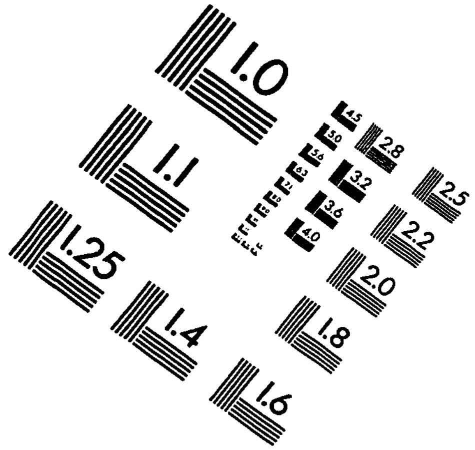
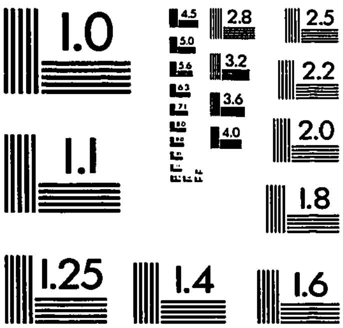
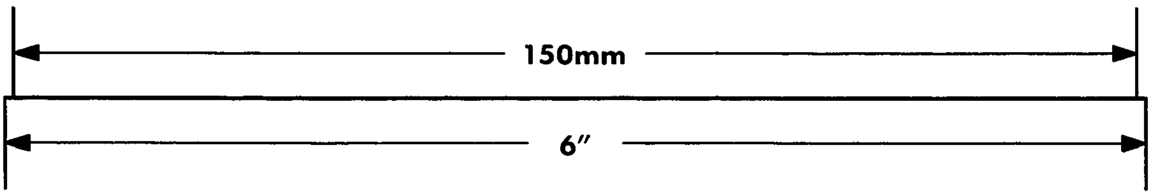
10
WA
PP-3
BL
RN
LV #3
SNWP1
PP-4
LV #2
LV #1
BB
To Kingman Tap
SNWP2
PP-5
VI
AM
MS
HOOVER
EOGRAPHICALLY TO SCALE.
The Mead 69 kV & Eldorado 500 kV Go to Mohave Gen. Station (NPC Part Owner) Near Laughlin, NV

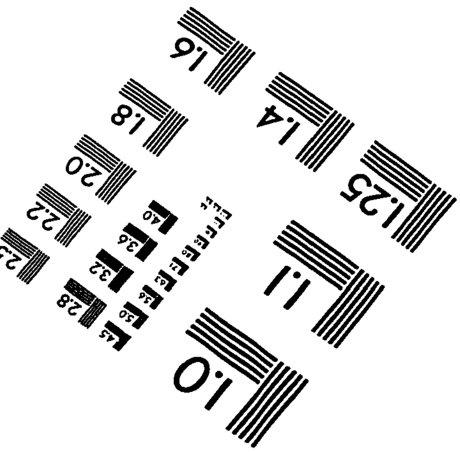
IMAGE EVALUATION TEST TARGET (QA-3)

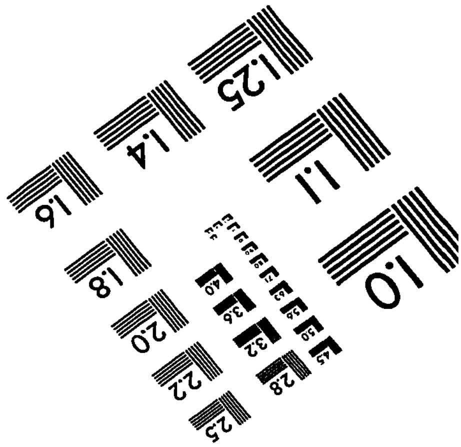












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