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Synchrophasors' Application in SVC for Industrial Networks

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DEDICATION

To my mother, whose instilment of the value of education, hard work, responsibility and dedication is the greatest gift any parent can give their children. To my entire family for their endless and continuous support in all my endeavors and to my wife whose support and patience was invaluable during my pursuit of higher education.

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SYNCHROPHASORS' APPLICATION IN SVC FOR INDUSTRIAL NETWORKS

KAREEM M. SUHWAIL

ABSTRACT

It is widely understood that as fuel and energy prices continue to increase, new and innovative ways of becoming more energy efficient will be required. This couldn't be more apparent than in industry, where every decision is constrained by economics. Power factor correction is a cost effective way for industry to have economically sound improvements with maximum efficiency benefits. It is proposed that in large industrial systems, where an SVC (Static Var Control) system could be used, synchrophasor measurements could also be used to control the SVC and provide enhanced historical analysis. Currently, many protective relays used in industry provided by SEL (Schweitzer Engineering Laboratories) already have this capability built-in. While synchrophasor measurement technology is still relatively unknown, they are a powerful tool that could greatly increase power system control, efficiency and historical data analysis.

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CHAPTER I

MOTIVATION FOR THESIS

1.1 DISTRIBUTION NETWORK ISSUES

There are many problems facing large industrial manufacturing facilities in today's business environment; not the least of which are energy costs due to consumption of electricity and power distribution reliability. Thousands of facilities across the nation from small electric utilities to chemical plants, steel mills and waste management facilities, attempt to generate power by reclaiming unused or wasted process energy to offset their electricity costs.

Many of these same facilities also have abnormally large inductive loads that cause poor power factors on both their distribution grids and the grid of the electric utility. This presents the engineering community with large opportunities for energy management improvements in these facilities.

The inspiration for my thesis comes from a steel mill where I had the pleasure to work. Like most steel mills in the United States, this steel mill is very old. Parts of the facility are over 100 years old, while much of the inter-mill power distribution system is 70+ years old. The mill has two power houses that perform different functions. One power house generates compressed air for use at a blast furnace and provides steam to the plant. While the other power house, originally built in 1917, generates power to sell back to the utility. This mill was heavily expanded under a government grant during World War II to increase steel production for the war effort. As a result, there is a mixture of technology from the 1940s through modern day.

This facility has a number of steam driven generating units, both 25Hz and 60Hz, which have a combined peak generating capacity of approximately 32MW. The boilers that produce the steam are multi-fuel units that can burn either natural gas or blast furnace gas.

Blast furnace gas is a byproduct of the iron reduction process and has a BTU value in the 80-100 range, while the BTU value of natural gas is approximately 1000 BTU/cubic ft. This variable BTU makes it much more difficult to control the boilers and power generation varies continually as a result.

The mill has a special contract that allows them to buy electricity from the electric utility at a lower cost than they can produce it for while burning natural gas. However, they can generate power from burning blast furnace gas at the lowest cost possible. While blast furnace gas can be seen as a free fuel and through its consumption help mitigate environmental constraints, it also poses a problem. Blast furnace gas has a variable BTU value and is available only when the blast furnaces are running. The amount of blast furnace gas produced is continuously variable. There are blast furnace gas swings every time a blast furnace stove is taken on or off gas and when the blast furnace operators adjust the amount of injectants (O_2, NG or fuel oil) used. This causes the amount of power being generated to continuously change.

Moreover, the infrastructure of the mill's power distribution system poses many additional challenges. For example, the mill has more than two dozen substations scattered throughout the facility with varying degrees of size and dependence. Much of the high voltage cabling is old and poorly maintained.

Some of the cabling runs underground and has been known to have grounding faults in the past. The substations have a mix of new and decaying equipment.

It is common to have voltage profile issues and periodically equipment will drop out as a result (4-5 times per year). It is also common to have power factors below 0.6. This poor voltage profile and power factor is the primary motivation for this thesis. A proposed method to help correct this problem will be explored throughout this thesis along with a power system simulation to validate findings.

1.2 SYNCHROPHASORS AND STATIC VAR CONTROL

Static VAR Control (SVC) is a popular component of today's Flexible AC Transmission Systems (FACTS). While they have been used extensively on the transmission side of the power grid, their implementation at the distribution or customer level is in its infancy.

The static var controller uses an algorithm and semiconductor components to control a bank of capacitors and/or inductors that can inject or absorb reactive power from the grid as needed. Currently, the feedback variables used to control the SVC are a mix of both calculated and estimated values. Bus voltages are easily measured, but until recently, phase angles had to be estimated by the use of state estimating software. This reliance on state estimated values provides an opportunity for improved control methods and technology.

The proposed measurement method explored throughout this thesis utilizes synchrophasor technology. Synchrophasors have the ability to provide phase angle measurements that are directly measured in excess of 30 times per second. [1] This gives the utility or generating industrial facility greater accuracy and speed in phase angle metering.

When synchrophasors are used as feedback for the static var controller, it provides an improved line voltage profile and power factor control. When large capacitor or inductor banks are switched on with mechanical circuit breakers, they introduce large transients into the network. The benefit of using synchrophasors with SVC may allow for not only more accurate control but less switching events. Over time, this can help improve the life span of network devices due to reduced transients.

1.3 Synchrophasors and Static Var Control as a Remedy

The primary problem plaguing the mill's power system is poor voltage profile and power factor. The implementation of an SVC and synchrophasor solution would be extremely beneficial in the short-term, while providing long term benefits ranging from increased power generation to reduced downtime. Additionally, the ability to monitor line phase angles when specific equipment is put on line or taken off line will allow the mill to understand the effect they are having on their power factor and voltage profile. Thus, the mill's operators will be able to make better decisions that will drive efficiency improvements.

Since, the mill has poor quality conductors connecting many of its buses, synchrophasor technology will aid in the real time calculations of line ratings. It is known that power lines have different characteristics in different weather conditions. It would be a beneficial to know when power lines are being overloaded or are in need of immediate maintenance.

In addition to the benefits of synchrophasor technology discussed throughout this thesis, a Phasor Monitoring Unit (PMU) also has the ability to measure line frequency. This is an added benefit since there have been numerous device failures because of faulty power supplies. The suspected problem has been dirty power with harmful harmonics that prematurely cause power supplies to fail. Monitoring line frequency will help identify when these issues are present.

Recently, there has been discussion of expanding the mill and adding an electric arc furnace. This would add a tremendous amount of stress on the mill's distribution network. The corrective benefits a synchrophasor based SVC system provides would alleviate that stress and keep the network as reliable and efficient as possible.

1.4 Economic considerations

While power factor fines are not the industry norm, their impact on industry is increasing. The cost of generating power is ever-increasing with the rising cost of fossil fuels and the environmental constraints placed upon them.

In addition to hard costs, such as fines or fuel, there are many soft costs that must be taken into account. The ability to better control power flow and voltage profile will benefit the life span and reliability of network devices, reduce maintenance and help alleviate down time.

1.5 Thesis Organization

This thesis is organized into six chapters. Chapter I describes the motivation for the development of this thesis. Chapter II holds a review on synchrophasor technology. What synchrophasor technology is, how it works and how it can be used. In Chapter III, different methods for power factor correction in industry are compared. They range from simple and cheap to complex and expensive. Chapter IV shows the simulation of an example industrial power system that has been developed in PSCAD. The results are then analyzed and a brief economic analysis is included. Chapter V discusses how SCADA systems typically used in industrial systems can be designed to interface with PMUs (Phasor Monitoring Units) and what PMU manufacturers could possibly do to increase technology adaptation. Finally, Chapter VI summarizes the conclusion of this thesis and provides some ideas for future research.

CHAPTER II

REVIEW OF SYNCHROPHASOR TECHNOLOGY

2.1 WHAT ARE PHASORS AND HOW ARE THEY CALCULATED

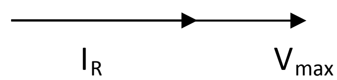
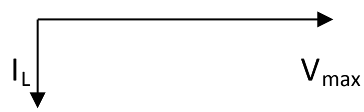
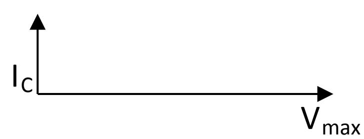
Phasors are a complex representation of the magnitude (V_{max} or I_{max}), angular frequency (ω) and phase angle (δ) of a sinusoidal voltage or current. As shown below, this sinusoidal voltage or current can be represented with reference to either the sine or cosine with the equation (2) being the most accepted form.

$$v(t) = V_{max}\sin(\omega t - \delta_v)\ , i(t) = I_{max}\sin(\omega t - \delta_v) \qquad (1)$$

$$v(t) = V_{max}\cos(\omega t + \delta_v)\ , i(t) = I_{max}\cos(\omega t + \delta_v) \qquad (2)$$

Typically, phasors are shown in polar ($V_{max}\angle\delta$) form. Table 1 shows the phasor diagrams of a pure resistive load, pure inductive load and pure capacitive load. It is demonstrated that the phase angle difference between the voltage and current are zero for a pure resistive load, 90^{o} lagging (-90^{o}) for the inductive load and 90^{o} leading ($+90^{o}$) for the capacitive load.

TABLE 1 Typical phasor diagrams

Pure Resistive Load	
Pure Inductive Load	
Pure Capacitive Load	

As stated previously, phasors are a complex representation of the magnitude (V_{max} or I_{max}) and phase angle (δ) of a sinusoidal voltage or current. This is illustrated graphically in Figure 2.1 below. An additional consideration to note is that while a sinusoidal waveform moves across the time axes and performs its cycles according to its angular frequency (ω), the phasor representation cannot do the same. Phasors will rotate around the origin at its angular frequency (ω) in the counter clockwise direction.

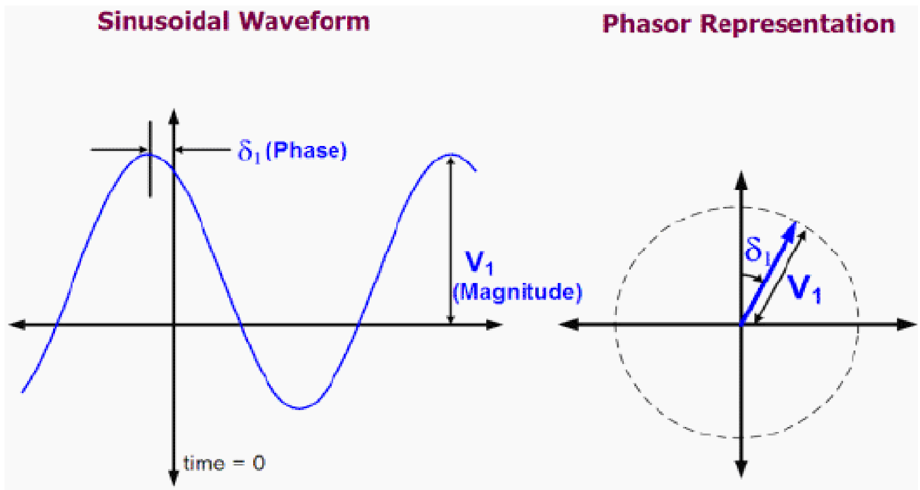


Figure 2.1 – Cosine Representation of Sinusoidal Waveform and Phasor Representation [1]

According to the mathematical description shown above, phasor representation is only possible for pure sinusoids. Since real world power signals consist of numerous signals of different frequencies it is necessary for us to extract the signal components that comprise the principal frequency we are interested in.

This signal extraction can be done through the use of Fourier transforms. A common method of calculating Fourier transforms in digital system processing is through the use of discrete-time Fourier transforms (DTFT). This is accomplished by taking periodic samples of a continuous function.

An important concern to note is that our phasor calculation is a highly dynamic value. It is necessary to parse this continuous signal into smaller incremental periods ($k\Delta t$, $k=0, \pm1, \pm2 \ldots$) where the phasor can be assumed to be static. [11] This incremental period is referred to as the “data window”. In a synchrophasor network, it is critical that the “data windows” among all phasor monitoring units (PMU) are properly synchronized. This synchronization will ensure all data are being parsed from the same moment in time.

In today’s grid applications, phasors are typically calculated by PMUs. The data produced by numerous PMUs installed throughout a network are collected by PDCs (Phasor Data Collector). PMUs used to calculate voltage phasors are placed at buses while current phasors are calculated at branches.

Synchrophasors are essentially an extension of this phasor technology. What makes synchrophasors special is a time stamp, determined by a GPS unit, which is attached to each phasor measurement. This time stamp gives engineers the ability to view data across the power network and capture a complete understanding of what state the network is in at a given moment.

This time synchronization is extremely helpful in diagnosing and troubleshooting problems, whether they are in the past or currently occurring. While the field of diagnostics through synchrophasors is still growing and shows great promise, synchrophasors have other special features that will lend them to greater uses.

Current technology only allows for direct measurement of the voltage or current magnitude, but not the phase angle. Phase angles are calculated by a computer running state estimation software. These calculated angles are not always the most accurate because of computer processing time delays, errors or incompleteness of the state estimator's algorithm. Synchrophasors can be used to alleviate these constraints by providing data to improve the state estimation algorithm to more accurately represent current grid conditions and measure phase angles directly.

Another benefit is that phasors are calculated quickly. Most PMUs can calculate up to 30 times per second with some new models calculating in excess of 60+ times per second. [1] Additionally, the GPS timestamp is provided by satellite GPS hardware that is accurate to the millisecond or better. In contrast, most SCADA systems scan in the 2 to 4 second range. [1] This sub-SCADA data collection shows dynamics that would otherwise have never been seen.

There were only 250 PMUs installed across North America in 2010. [1] While that number is expected to increase exponentially, there is great opportunity for the improved metrology that synchrophasors provide.

It will be demonstrated throughout this thesis that the ability to accurately measure voltage and current magnitudes as well as phase angles, attach them to an extremely precise time stamp, and continue to do so in excess of 30 times per second makes synchrophasor technology an ideal candidate for both monitoring functions and control.

2.2 Current Implementations of Synchrophasor Technology

Currently synchrophasor technology has primarily been used as a tool to improve grid reliability and help diagnose emerging system problems. This type of real time, high speed and time synchronized data allows operators to get a broad, yet detailed understanding of the current state of the network.

Utilities have numerous systems that attempt to look at transmission and distribution networks from a broad perspective. These types of systems are called WAMs (Wide Area Monitoring Systems). Figure 2.2 shows a generic WAM system where three protective relays with advanced PMU capabilities are measuring pertinent data from various grid locations. These data are then collected by an SVP (Synchrophasor Vector Processor), which acts as a PDC (Phasor Data Collector), across a WAN (Wide Area Network). Additionally, a satellite GPS clock would be installed but is assumed necessary and isn't shown in the figure.

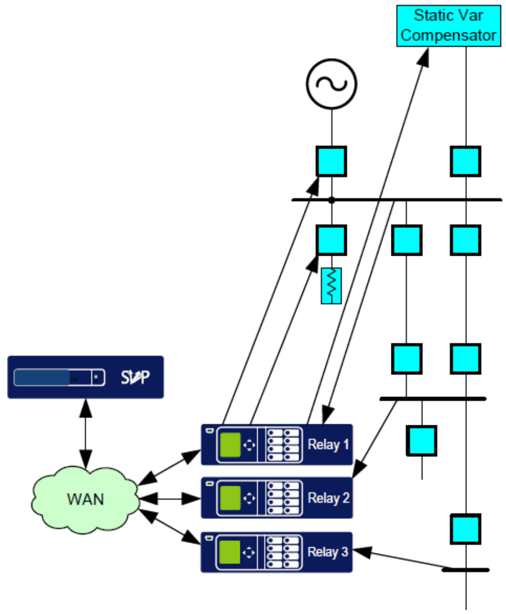


Figure 2.2 –Common WAMS with Synchrophasor Vector Processing and SVC [4]

Synchrophasors are becoming an integral component of WAMS and are providing critical new data that allow operators to better perform their jobs. A good example of the increasingly important role synchrophasors are playing is demonstrated in Figure 2.3.

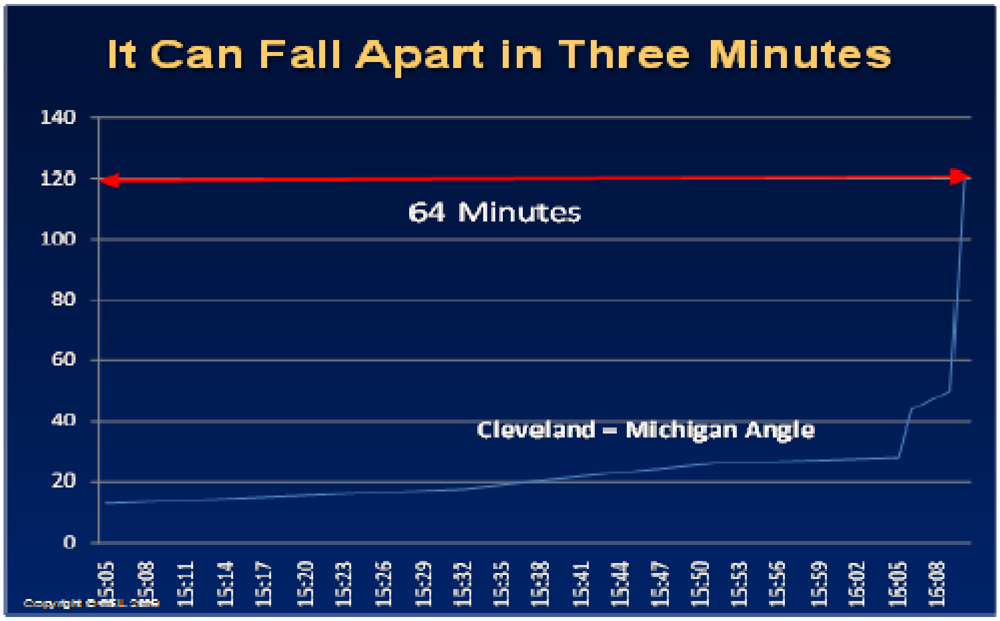


Figure 2.3 – Ohio-Michigan Phase and Diverging on Aug. 14, 2003 [1]

In Figure 2.3, provided by Schweitzer Engineering Laboratories, the phase angle between Cleveland and Michigan on August 14, 2003 is shown to slowly diverge over the course of approximately one hour. In the final 3 minutes, the divergence became extreme and caused the giant blackout that affected the entire northeastern United States. In 2003, PMUs were not installed at this interconnection. Had they been installed, Cleveland operators would have been able to identify that there was a potential problem and understand its severity much sooner.

An obstacle that is slowly being overcome with synchrophasors is base lining. In Figure 2.3, the phase angle between Cleveland and Michigan was shown to be approximately 15^{o} but slowly grew to approximately 30^{o} before the system broke down. If PMU data were being collected over a period of time, an understood *normal* or base line could have been identified so proper alarm limits would have been understood. If it was determined that 15^{o} was normal for that time of day and weather conditions, operators could have had in excess of 30 minutes to divert disaster through islanding and other preventative measures.

If other PMUs were installed at other locations across the region it would have been possible to see the effect this diverging angle was having on the regional network in other locations. This technology could be incredibly important across intra-utility tie lines. If a particular utility saw that there were issues across the tie line with a neighboring utility, the line could be disconnected to prevent a cascading event. This is one example of the many potential uses of synchrophasor technology.

Shown below in Figure 2.4 is an illustrative example of the impact synchrophasors can have on operations, planning and reliability considerations. The future research portion of Figure 2.4 will be discussed in the next section.

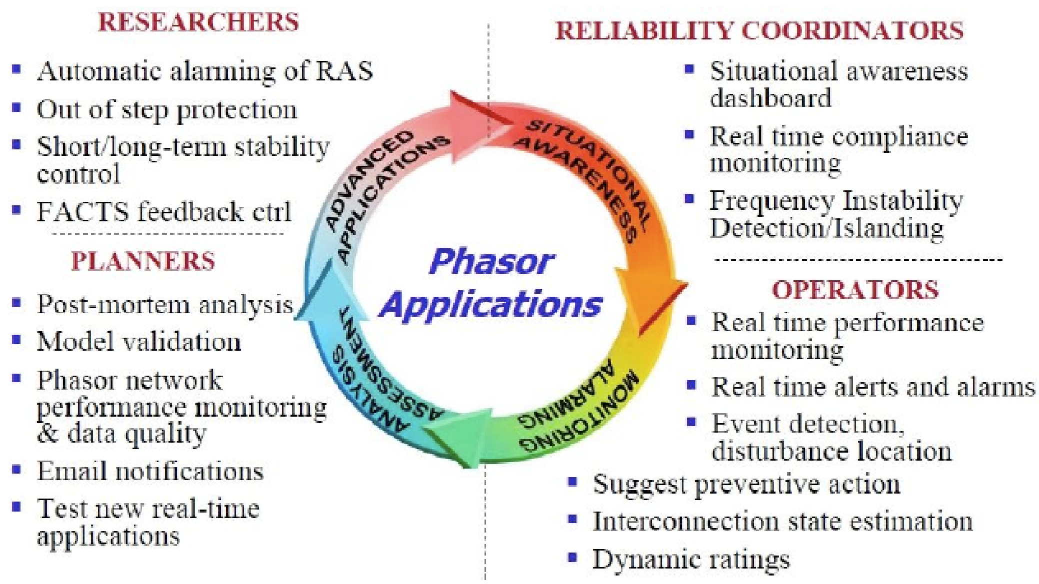


Figure 2.4 – Various Applications of Phasor Data [1]

2.3 Future Implementations of Synchrophasor Technology

While the technological implementation of synchrophasors thus far has produced great results, those results have been largely reactionary. Further research and implementation of synchrophasors will focus on proactive uses. This proactive approach will put synchrophasors at the forefront of power system automation and control. To just name a few applications, synchrophasor data can be used as feedback control for FACTS (Flexible AC Transmission System) devices, CUPS (Custom Power Systems) devices, islanding control and for safety alarming.

2.4 Future Implementations of Synchrophasor Technology in SVC

While synchrophasors have many promising uses, the focus of this thesis is its implementation in conjunction with SVC (Static Var Control). SVC on a power network is extremely important. The feedback control signals that are fed into the SVC's controller are typically estimated, thus being less accurate than ideal. Since synchrophasors can calculate phase angles directly, accurately and quickly they appear to be a natural fit for SVC.

When capacitor banks are switched on or off through the use of mechanical circuit breakers, significant transients are created. Additionally, the VAR compensation they provide is extremely coarse since the capacitors used are added in large increments. Using synchrophasor technology for SVC control will help to eliminate unnecessary switching and the resulting transients. In turn, this will help reduce grid stress and increase the life of protective relays and other equipment, including the capacitor bank itself.

CHAPTER III

INDUSTRIAL POWER FACTOR CORRECTION TECHNIQUES

3.1 FIXED CAPACITOR VAR COMPENSATION

The utilization of a shunt connected fixed capacitor for power factor correction has been around for decades. This capacitor provides a fixed amount of reactive power for a constant voltage. This fixed capacitor does not always provide the optimal amount of reactive power and doesn't have the greatest voltage regulation characteristics.

From a theoretical perspective, the reactance of a capacitor is shown below.

$$X_C = -\frac{1}{\omega C} \qquad where\ \omega = 2\pi f \quad (3)$$

The reactance provided by the fixed capacitor system is also a function of the voltage and current.

In the example below, voltage and current values were arbitrarily chosen and the reactance provided by a capacitor was determined to be 20 vars. The phase angle of -90^{o} shows that the vars are being injected by the capacitor into the system. It is shown that since the reactance provided varies by the magnitude and phase angles of the voltage and current, the fixed capacitor system will have poor voltage regulation and a variable reactance.

$$Since\ X = \frac{V}{I} \qquad \mathrm{X} = \frac{100\mathrm{V}\angle 0^{o}}{5\mathrm{A}\angle 90^{o}}$$

$$X = 20\angle \text{-}90^{o}\ var$$

However, the fixed capacitor is an extremely straightforward solution to install and maintain. This simplicity drives the installation cost of the fixed capacitor system down. Approximate cost per kvar is shown below in Table 2. With the cost of a simple fixed capacitor system less than one quarter that of SVC and with the cost disparity when compared to STATCOM even greater, it will be difficult for industrial facilities to overlook the economics.

TABLE 2 Cost Comparisons of Shunt Controllers [2]

Shunt Controller	Cost
Shunt Capacitor	\$8/kvar
SVC	\$40/kvar
STATCOM	\$50/kvar

While the costs are compelling, there are numerous drawbacks of this system. As mentioned previously, since it is not controllable, the fixed capacitor will not always provide the system with the properly desired amount of reactive power.

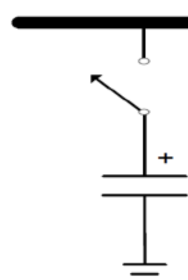


Figure 3.1 – Fixed Capacitor Topology

There are times when this topology will either provide too much or too little reactive power. Depending on the system, this could quite easily cause major problems. In addition, there are large transients introduced when the capacitors are mechanically switched on or off. This switching, which can occur multiple times a day, causes damage to protective relays, breakers and other power equipment. This design is quite popular today by not only large industrial facilities, but also with electrical utilities.

3.2 SVC (Static VAR Compensation)

Static var compensation (SVC) is an extension of the fixed capacitor topology. SVC is essentially made up of capacitor and inductor banks and a sophisticated control algorithm that controls power electronic semiconductor devices that are used to vary the effect of the capacitors/inductors. This topology is used by utilities and gives them a much closer to optimal solution to power factor correction.

Figure 3.2 shows a common SVC topology. This particular topology is called a fixed capacitor thyristor controlled reactor (FC-TSR) since the capacitors are fixed, but the current through the inductor is a function of the firing angles of the thyristors. This allows for coarse voltage control to be done by the capacitors and fine adjustment to be done through modulating the thyristor firing angles. The benefit of this topology is that the amount of reactive power injected or absorbed can be accurately controlled.

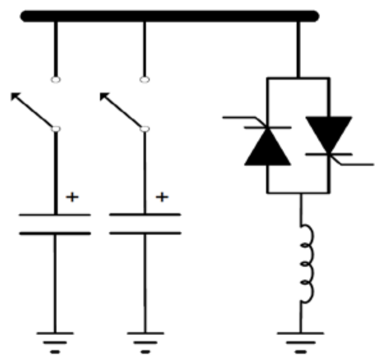


Figure 3.2 – SVC By Way of FC-TCR Topology

As discussed previously, the magnitude of the reactance provided by the fixed capacitor is shown below.

$$X_C = -\frac{1}{\omega C} \qquad where\ \omega = 2\pi f \quad (3)$$

However, we now have the thyristor controlled reactor (TCR) connected in parallel. The reactance provided by the TCR is derived with the assumption that higher order harmonics are negligible [5].

It is assumed that the voltage across the TCR is

$$v(t) = \hat{V}\cos\omega t \qquad (4)$$

The two thyristors are turned on alternately every half cycle with a delay angle α. Only one thyristor will be conducting when $\omega t \geq \alpha$ and no thyristors will conduct when $\omega t = \alpha$. Ohm's law states that the voltage across an inductor is L$\frac{di(t)}{dt}$ and since no current will flow when $\omega t = \alpha$ the current can be solved as

$$\frac{1}{\omega}\int_{\alpha}^{\omega t}\hat{V}\cos\omega t(d\omega t) = L\int_{0}^{I(t)}\frac{di(t)}{dt}$$

Upon integration the current is determined to be

$$i(t) = \frac{\hat{V}}{\omega L}[\sin\omega t - \sin\alpha] \quad \text{where: } \alpha \le \omega t \le \pi - \alpha \qquad (5)$$

Since the other thyristor will conduct during the second half cycle it can be determined that the current through it would be

$$i(t) = \frac{\hat{V}}{\omega L}[\sin\omega t + \sin\alpha] \quad \text{where: } \pi + \alpha \le \omega t \le 2\pi - \alpha \qquad (6)$$

Through analysis not covered in this thesis, it can be determined that the current has odd and quarter-wave symmetry. As a result, i(t) will only contain odd-numbered harmonics. Additionally, since this is a three phase system, all the triple-N harmonics (3^{rd}, 6^{th}, 9^{th}) are naturally canceled out. For these reasons, only the fundamental component of i(t) will be considered.

By performing a Fourier series analysis of the fundamental component of i(t) where k=1 the current can be determined.

$$i_1(t) = \hat{I}_1\cos(\omega t + \theta_1) \text{ where: } \hat{I}_1 = \sqrt{a_1^2 + b_1^2} \text{ and } \theta_1 = \arctan\frac{-b_1}{a_1}$$

However, due to symmetry considerations $a_1 = 0$. Thus $\theta_1 = -\frac{\pi}{2}$ and the current is determined to be

$$i_1(t) = b_1 \cos(\omega t - \frac{\pi}{2}) = b_1 \sin \omega t$$

Since $b_1 = \frac{2}{\pi}\int_{\alpha}^{\pi-\alpha} i(t)\sin \omega t d\omega t$ and through substituting for i(t)

$$b_1 = \frac{2\hat{V}}{\pi\omega L}\int_{\alpha}^{\pi-\varepsilon}[\sin \omega t - \sin \alpha]\sin \omega t d\omega t$$ then upon integrating

$$b_1 = \frac{2\hat{V}}{\pi\omega L}\{\frac{\pi - 2\alpha}{2} - \frac{1}{2}[\cos(2\pi - 2\alpha) - \cos 2\alpha] - \sin\alpha(-\cos(\pi - \alpha) + \cos\alpha)\}$$

However, through simplification and the use of trigonometric identities b_1 can be shown as such

$$b_1 = \frac{\hat{V}}{\omega L}[1 - \frac{2\alpha}{\pi} - \frac{1}{\pi}\sin 2\alpha]$$

As a result, the current at the fundamental frequency is shown as

$$i_1(\alpha, t) = \frac{\hat{V}}{\omega L}[1 - \frac{2\alpha}{\pi} - \frac{1}{\pi}\sin 2\alpha]\sin \omega t \qquad (7)$$

This can be further simplified if it’s assumed that $\alpha \neq 0$. If that assumption is made, the current is shown as

$$\hat{I}_1(\alpha) = \frac{\hat{V}}{\omega L}[1 - \frac{2\alpha}{\pi} - \frac{1}{\pi}\sin 2\alpha] \qquad (8)$$

With the current known, the impedance of the TCR can be determined.

Voltage Provided by Fixed Capacitor: $V = \frac{\hat{V}}{\sqrt{2}}\angle 90^0$

Current though the TCR: $I_1(\alpha) = \frac{\hat{I}(\alpha)}{\sqrt{2}}\angle 0^0$

Where $\hat{I}_1(\alpha) = \frac{\hat{V}}{\omega L}[1 - \frac{2\alpha}{\pi} - \frac{1}{\pi}\sin 2\alpha]$

$$Z_{TCR}(\alpha) = \frac{V}{I_1(\alpha)} = \frac{\frac{\hat{V}}{\sqrt{2}}\angle 90^0}{\frac{\hat{I}(\alpha)}{\sqrt{2}}\angle 0^0} = \frac{j\hat{V}}{\frac{\hat{V}}{\omega L}[1 - \frac{2\alpha}{\pi} - \frac{1}{\pi}\sin 2\alpha]} = \frac{j\omega L}{[1 - \frac{2\alpha}{\pi} - \frac{1}{\pi}\sin 2\alpha]} \qquad (9)$$

As a result, the inductive reactance of the TCR at any frequency is

$$X_{TCR}(\alpha) = \frac{X_L}{1 - \frac{2\alpha}{\pi} - \frac{1}{\pi}\sin 2\alpha}, where\ \alpha = thyristor\ firing\ angle \qquad (10)$$

Thus, by combining the fixed capacitor and the TCR in parallel, the complete reactance provided by the FC-TSR would be.

$$X_{TCR}(\alpha) = \frac{\omega L\left(-\frac{1}{\omega C}\right)}{1 - \frac{2\alpha}{\pi} - \frac{1}{\pi}\sin 2\alpha - \frac{1}{\omega C}}, where\ \alpha = thyristor\ firing\ angle \qquad (11)$$

Taking the TCR topology one step further, it is also possible to add thyristor switched capacitors (TSC). Figure 3.3 shows a topology which incorporates both TCR and TSC. This gives extremely accurate, flexible control and minimized transients on the network.

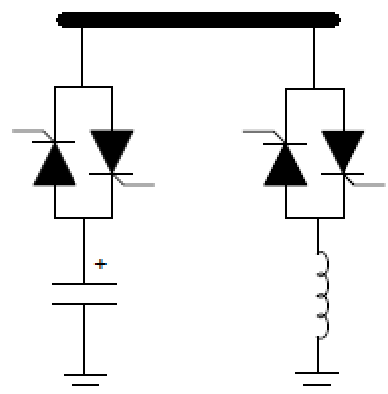


Figure 3.3 – SVC By Way of TSC & TCR Topologies

However, the drawbacks of the TSC-TCR topology are seen as added complexity, cost and an increase in losses due to the semiconductor components.

3.3 DSTATCOM (Distribution Static Compensator)

A new topology that is currently more expensive, but is growing in popularity is DSTATCOM. STATCOM (Static Compensator) and DSTATCOM (Distribution Static Compensator) are essentially the same topology. However, they differ in their size and application. STATCOM is primarily used for transmission and DSTATCOM is primarily used for distribution. Additionally, DSTATCOM is sometimes used for voltage flicker protection at large industrial facilities such as electric arc furnaces.

DSTATCOM takes a constant DC voltage source and inverts it to the proper signal required for compensation through the use of fully controllable semiconductor devices.

While DSTATCOM is slightly more expensive than SVC due to the expense to manufacture semiconductor components, their ability to provide more optimal VAR control, voltage regulation and flicker suppression has led to their market adoption. In addition, DSTATCOM generates harmonics with lower amplitudes and at higher frequencies than those of a conventional SVC. [3] This allows for easier harmonic filtering.

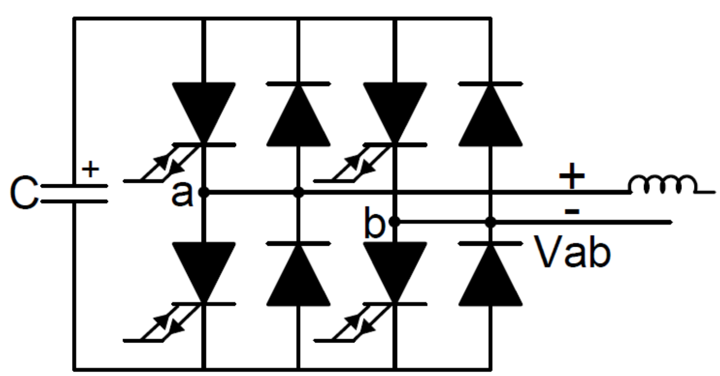


Figure 3.4 – Single Phase STATCOM Topology

Going forward, DSTATCOM faces obstacles surrounding cost, complexity and losses due to additional semiconductor components. Unlike SVC, DSTATCOM requires the use of fully controllable switching elements. This requires the use of gate turn off thyristors (GTO) as shown in Figure 3.4, insulated gate bi-polar transistors (IGBT), integrated gate commutated thyristors (IGCT) or any other similar devices. Such devices are quite expensive to produce at the rating levels required and are a major contributing factor to the increased cost of the topology. Additionally, DSTATCOM has increased complexity by the use of the H bridge inverter design. Neither the fixed capacitor nor the SVC topologies have this issue due to no inverter being required.

The economic case could be made that while the losses for the DSTATCOM are slightly higher, they can also save money by better voltage regulation. However, a more accurate economic analysis would need to be completed on a case by case basis.

3.4 Additional considerations of power factor correction

All of the discussed techniques for power factor correction are typically accompanied by a number of other devices and considerations. Since the cost of the required semiconductor devices are a function of their ratings, it's quite common to use step down transformers to bring the required semiconductor ratings to a reasonable cost level.

As a result of the capacitor/inductor switching required in these topologies, transients at the switching event are introduced. Additionally, harmonics are introduced and engineers routinely design tuned trap filters to remove or minimize specific harmonics. It is also understood that there are particular safety devices used to protect the semiconductor components, but since their implementation is beyond the scope of this paper, they will not be discussed here.

CHAPTER IV

SIMULATION OF CURRENT MILL POWER SYSTEM

4.1 SIMULATION OF THE MILL'S POWER DISTRIBUTION NETWORK

To protect the privacy of the steel mill in question, a simplified generic circuit was used for simulation. While a more accurate simulation would have expanded the scope of the simulation, including increased licensing costs, without increasing the significance of the simulation.

The test circuit was simulated in PSCAD (Power Systems Computer Aided Design). This time domain based software has become the industry standard to analyze electromagnetic power system transients. It is incredibly powerful, relatively easy to use and allows for not only the design of power systems, but also for the detailed design of control schemes. Shown below, in

Figure 4.1, is the sample circuit used for the simulation. This is the circuit implemented in PSCAD software. As it can be seen, there are two buses, a number of loads, a power source and an SVC. The power source is intended to simulate the electric utility. Considering the small amount of power the mill generates for itself in relation to the power it draws from the utility, it was assumed to be negligible for this simulation. The loads given are highly inductive and are intended to provide an accurate representation of the highly inductive motor loads the mill uses every day.

The SVC is rated at 600MVA, 500MVA of which is provided by 4 switched capacitor banks. The SVC is placed at the load side in order to put it as close to the loads as possible. The SVC block displayed in Figure 4.1 only pertains to the power electronic side of the SVC. The brains behind the SVC are in the control circuit, as it tells the SVC block whether to switch capacitors on or off, or to switch in additional inductance when necessary. The control shown in the circuit in Figure 4.2 circuit makes these decisions in real time depending on feedback it receives from meters placed in the power system circuit.

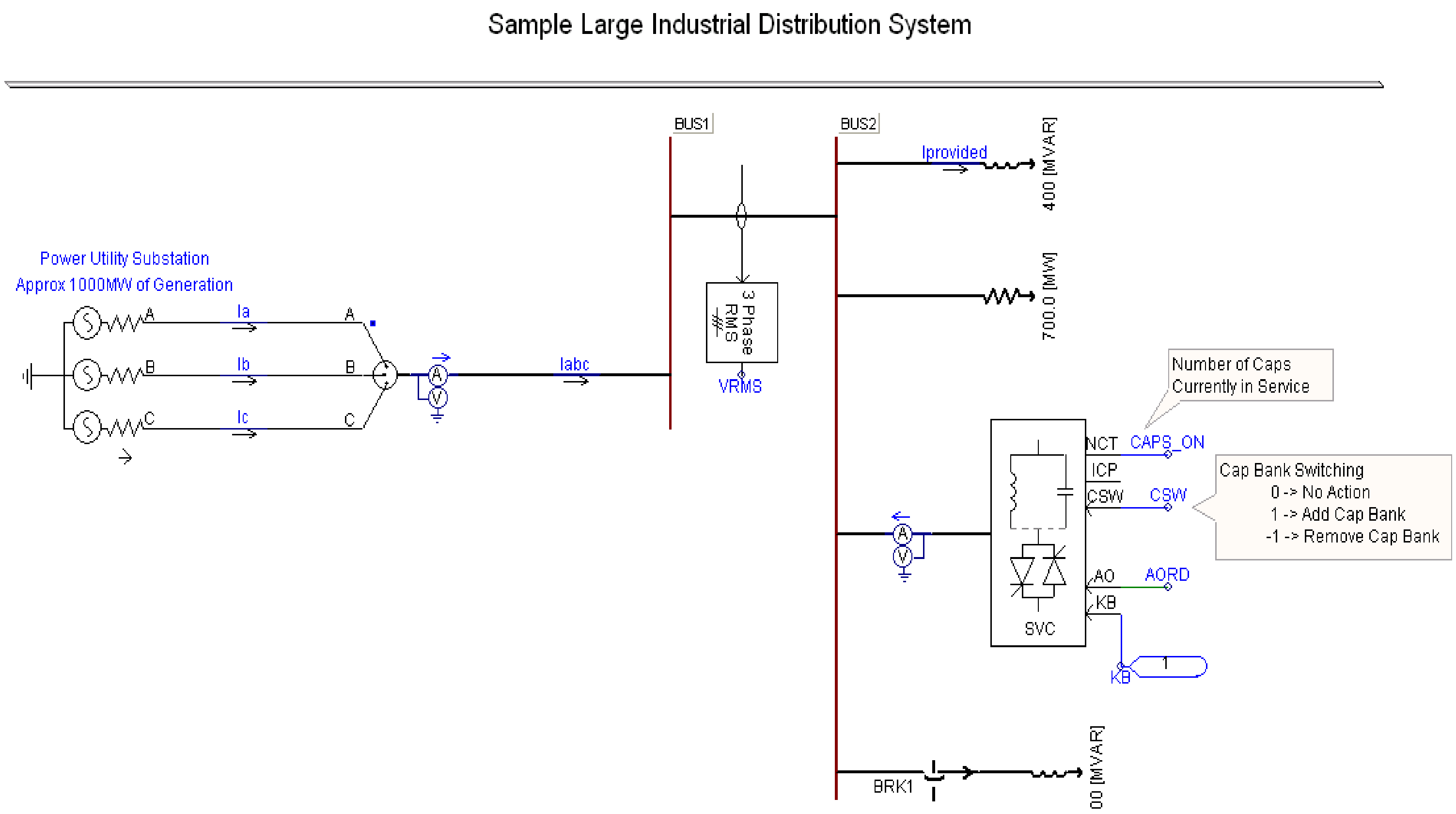


Figure 4.1 – Sample Large Industrial Test Circuit

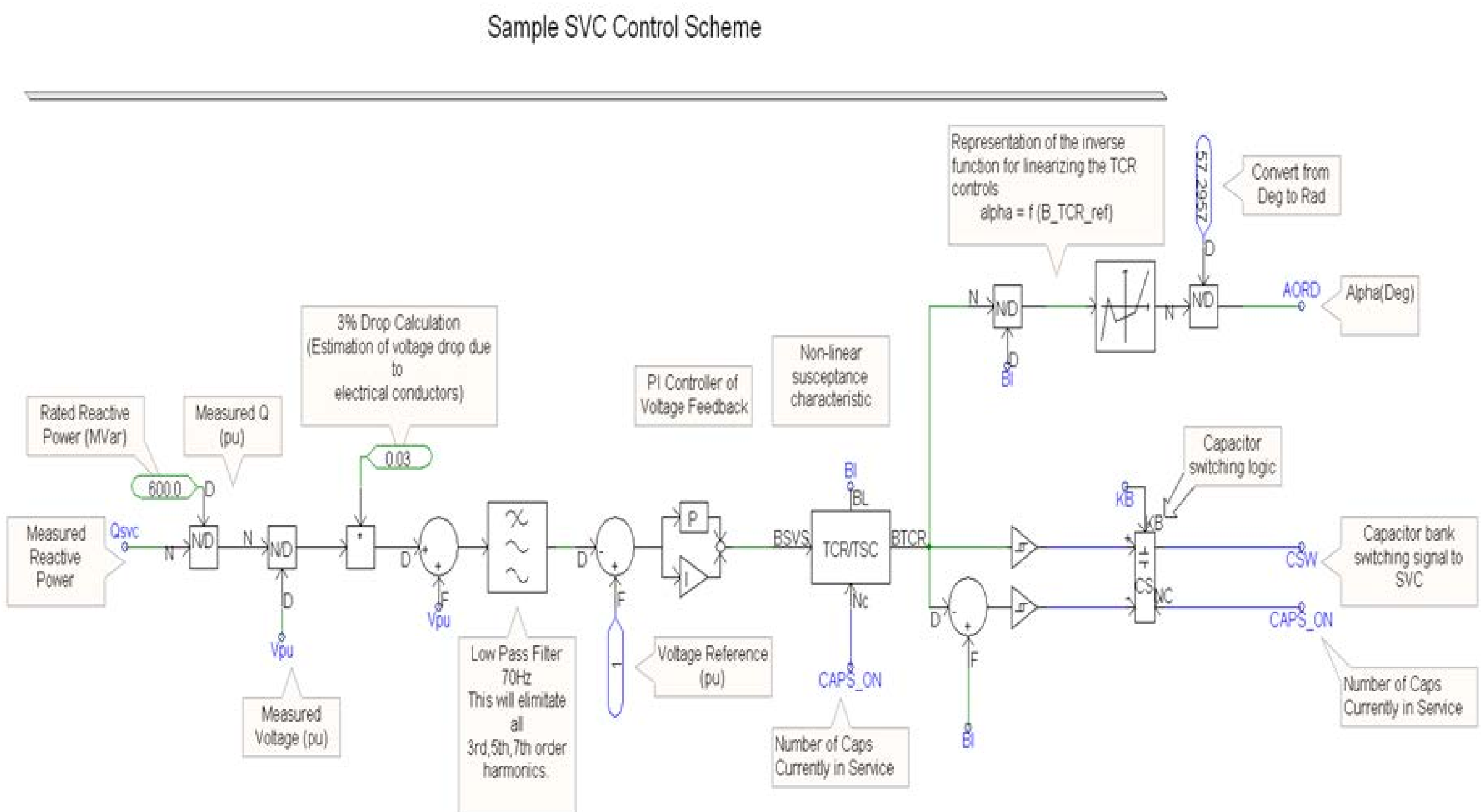


Figure 4.2 – Control Circuit for Sample Large Industrial Test Circuit

This control circuit takes the reactive power measured in per-unit terms that the SVC outputs and works to drive that to the minimum necessary to achieve a per-unit voltage of 1. The error signal of the per-unit voltage is fed to a PI controller that ramps the TCR/TSC control block to request additional capacitors or switch capacitors off. A low pass filter designed at 70Hz is also added to filter out any higher order harmonics and provide for a cleaner control signal.

With the SVC turned off, the circuit is left to operate in its normal but poor condition. Figure 4.3 displays that the circuit is pulling approximately 700MW of power from the electric utility and Figure 4.4 shows approximately 356 VAR is also being pulled. The current drawn is approximately 62A peak and is represented by Figure 4.5.

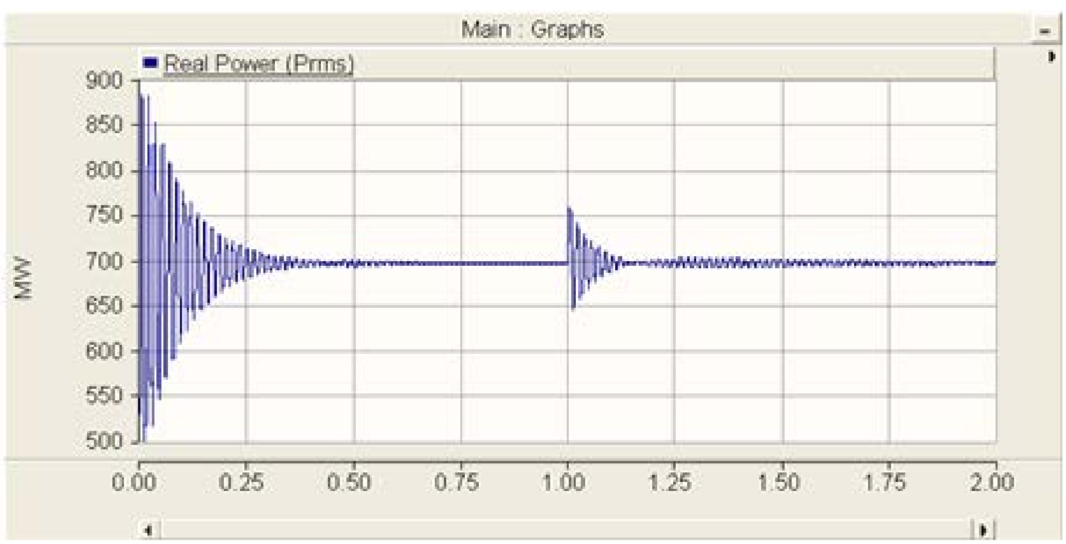


Figure 4.3 – Real Power Flowing from Utility

As it can be seen, at approximately 1 second, a circuit breaker is scheduled to close and introduce an additional load of approximately 100MVAR. This is intended to simulate a large motor being turned on. The effect of this load is demonstrated in Figures 4.4 and 4.5. At the 1 second mark in Figure 4.3, the reactive power flow increased by 100MVAR. Furthermore, there is an additional bump in the current being drawn from the power utility as displayed in Figure 4.4.

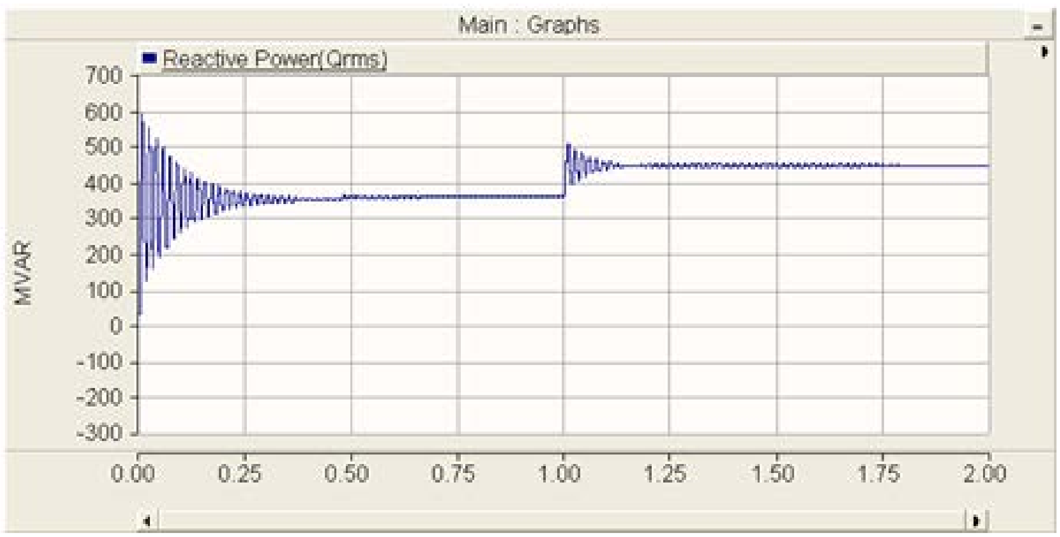


Figure 4.4 – Reactive Power Flowing from Utility

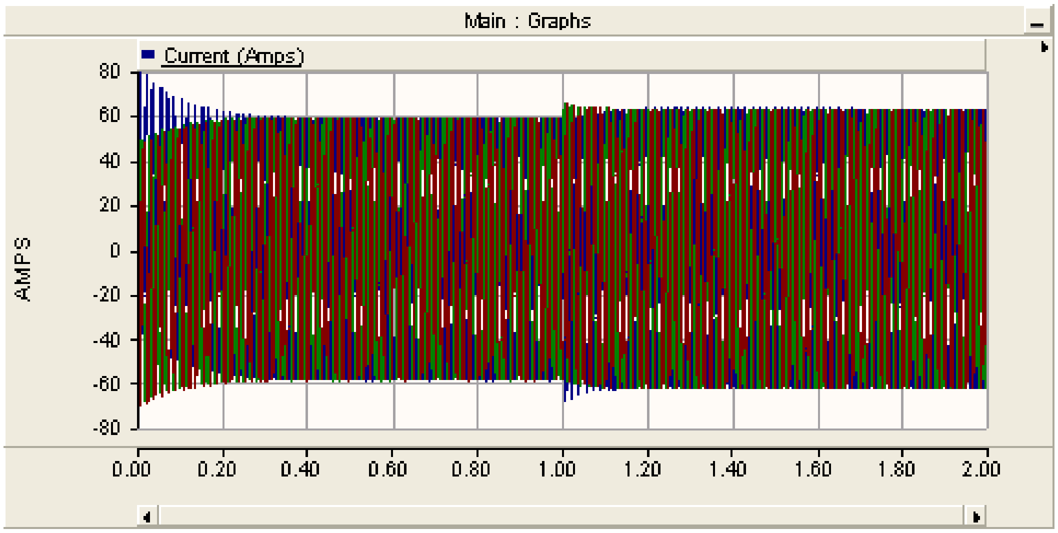


Figure 4.5 – Current Flowing from Utility

In order to calculate the power factor the fundamentals of the power triangle are used and are shown in Figure 4.6.

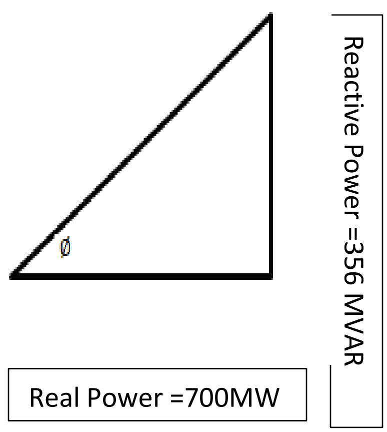


Figure 4.6 – Power Triangle Representation before SVC

$$\emptyset = \tan^{-1}\frac{356}{700} = 26.95°$$

$$pf = \cos 26.95° = .89$$

While the power factor of .89 is not terrible and not quite indicative of the poor nature of the real life power system we are emulating, it is hardly ideal and still has a great deal of room for improvement.

4.2 The Corrective Results of SVC

After enabling the SVC there were dramatic reductions in the reactive power provided from the electric utility and thus a reduction in the current being drawn. Figure 4.7 displays the reactive output from the SVC. After approximately .5 seconds, the SVC comes to a steady state of 458 VAR.

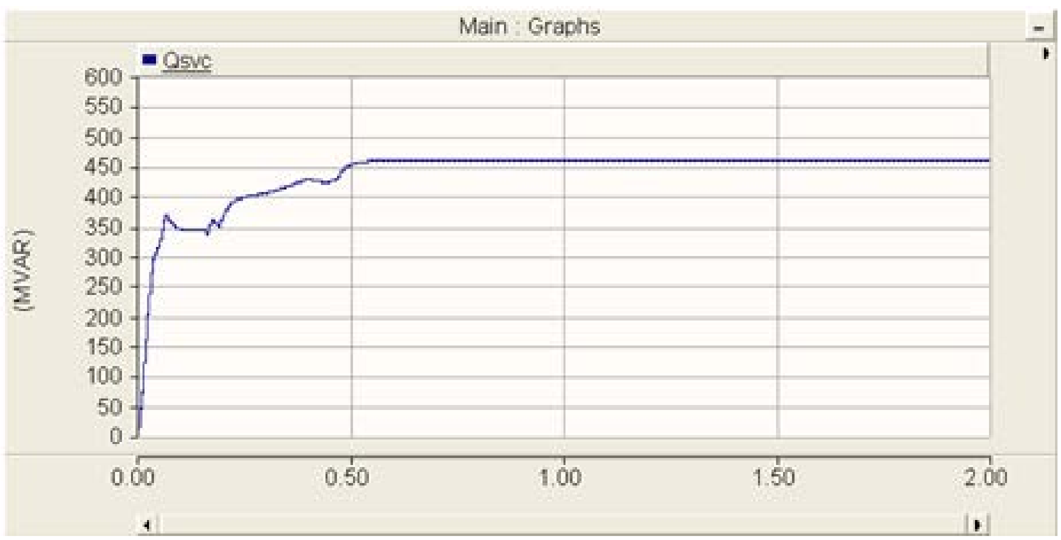


Figure 4.7 – Reactive Power Produced by the SVC

During the first second of the simulation the SVC is actually over producing reactive power and is emitting approximately 97 VAR back onto the electric utilities distribution network, as displayed in Figure 4.8. After the breaker is closed at the 1 second mark, the amount of reactive power being provided to the electric utility is nearly zero.

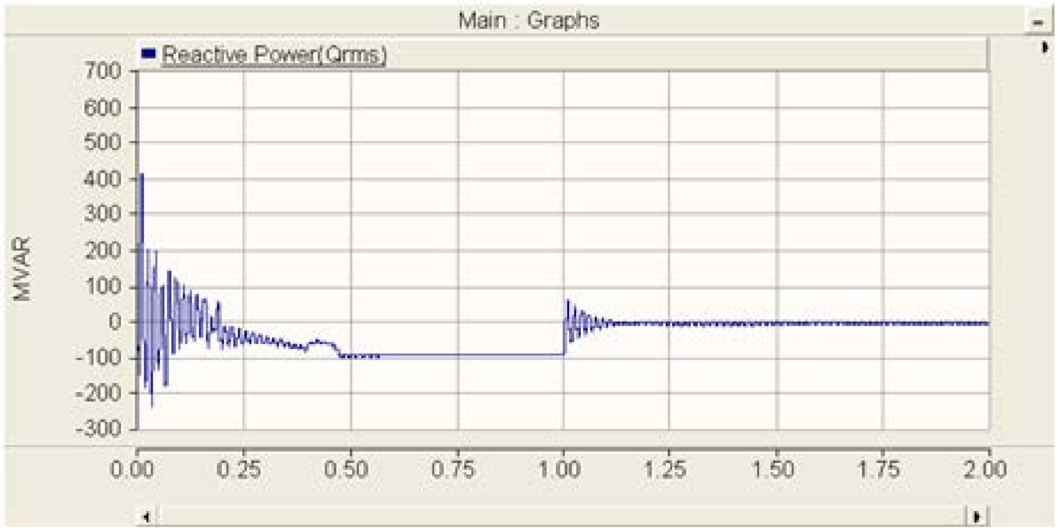


Figure 4.8 – Reactive Power Provided to the Electric Utility

Shown in Figure 4.9 and the following calculations is the improvement in the power factor to near unity. Please note that these calculations are done before the additional load of 100MVAR was switched on by the breaker. During the time after the circuit breaker is closed, the original system had a worse power factor and the electric utility was forced to generate more reactive power. While the SVC was active, the SVC was able to improve the power factor even closer to unity.

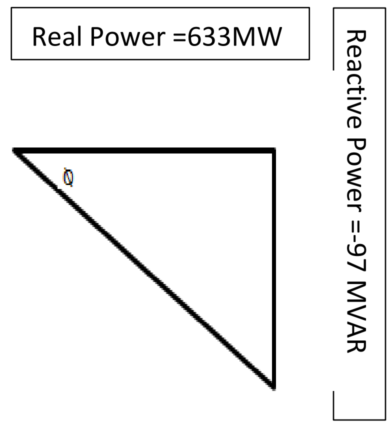


Figure 4.9 – Power Triangle Representation after SVC

$$\emptyset = \tan^{-1}\frac{97}{700} = 15.32°$$

$$pf = \cos 15.32° = .988$$

While the improvement in the power factor can reduce the amount of real power being drawn by improving the efficiency of the network, it will also prevent future fines from the utility and help improve power quality on the local industrial power distribution network.

4.3 Synchrophasors Take SVC to the Next Level

Now that the benefits of the SVC are evident, there is one other factor that may enhance SVC even further. The part of the PSCAD simulation that hardly gets recognition is the metering. While not commonly discussed, metering happens to be an important part of designing an excellent engineering solution.

Currently, there is no good way to meter the changes in reactive power fast enough for a SCADA system to react. Systems that are used by the electric power utility usually contain state estimation software that use complex electrical models to determine the pertinent phase angles for the SVC to properly operate. These systems are expensive and are out of reach of industrial customers.

The use of synchrophasor measurements as the feedback necessary for control is an emerging technology. As discussed previously, synchrophasors can calculate the necessary phase angles in real time, thus providing the optimal feedback signal for the control circuit of the SVC.

Further economic benefits are seen in the increasing use of Schweitzer engineering laboratories (SEL) protective relays in industry and their built in capability to act as a phasor monitoring units (PMU). While this is not enough hardware to completely set up a synchrophasor system, it is a great stepping stone and will make the economic case easier to make.

4.4 DEMONSTRATION OF EFFICIENCY IMPROVEMENTS PROVIDED BY SVC

SVC does not only provide benefits in power factor correction, but they also help ensure all electric machines are operating at their peak performance. To help demonstrate this, Figure 4.10 shows a sample circuit with inductive and resistive loads in parallel. Since the amount of power required to operate an induction machine is $P = \omega\tau$ and $\tau \propto |V|^2$, it would be ideal to provide the induction machine with its rated voltage.

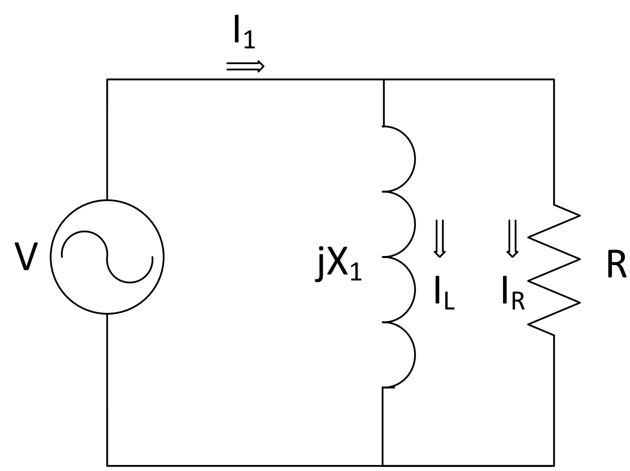


Figure 4.10 – Sample Circuit with Inductive and Resistive Loads in Parallel

In Figure 4.10, it is assumed that $V = |V|\angle 0$ and that $|V|$ is a constant voltage. To calculate the amount of real power supplied by the power source, current I_1 must be solved for. In order to solve for I_1, the equivalent impedance seen by the source must be determined.

$$Z_P = \frac{jX_1R}{R + jX_1} \bullet \frac{R - jX_1}{R - jX_1} = \frac{X_1^2 R + jR^2 X_1}{R^2 + X_1^2} \qquad (12)$$

For simplicity reasons, it is assumed that X_1=R and as a result Z_p can be simplified.

$$Z_P = \frac{(1+j)R^3}{2R^2} = \frac{(1+j)R}{2} \qquad (13)$$

The magnitude of Z_P as well as the phase angle of the impedance, Θ_1 can now be calculated.

$$|Z_P| = \sqrt{\frac{1}{4}R^2 + \frac{1}{4}R^2} = \frac{R}{\sqrt{2}} \qquad \text{and} \qquad \tan\theta_1 = \frac{\frac{1}{2}R}{\frac{1}{2}R} = 1\ ,\ \theta_1 = 45^o$$

$$\therefore Z_P = \frac{R}{\sqrt{2}}\angle 45^o$$

The current I_1 can be calculated to be

$$I_1 = \frac{V}{Z_P} = \frac{|V|\angle 0^o}{R\angle\theta_1} \bullet \sqrt{2} = \sqrt{2}\frac{|V|}{R}\angle -\theta_1 \qquad (14)$$

Since the current I_1 has been determined, we can calculate the real power provided by the power source.

$$P_1 = |V||I_1|\cos\theta_1 \qquad (15)$$

By substituting for I_1,

$$P_1 = |V|\sqrt{2}\frac{|V|}{R}\cos(45^o) = \frac{|V|^2}{R}\sqrt{2} \bullet \frac{\sqrt{2}}{2} = \frac{|V|^2}{R} \qquad (16)$$

In order to demonstrate how the SVC can raise a dropping voltage, consider a reactive inductance connected in series with Z_P.

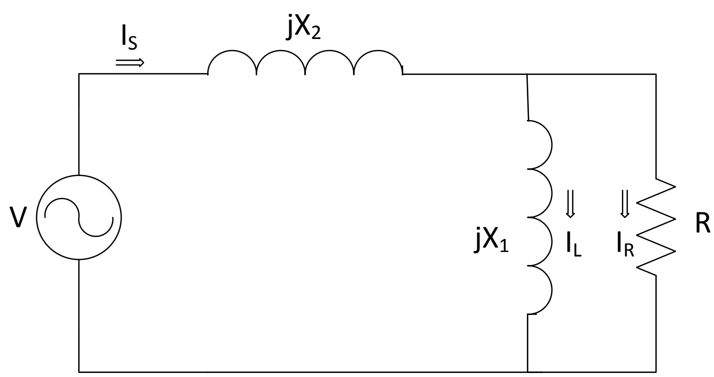


Figure 4.11 – Sample Circuit with a Series Inductive Reactance

Again, the total impedance for the circuit is calculated and then simplified by assuming X_2=X_1=R.

$$Z_{Tot} = Z_P + jX_2 = \frac{R}{2} + j\frac{R}{2} + jX_2 \qquad (17)$$

$$Z_{Tot} = \frac{R}{2} + j\frac{3R}{2}$$

$$\left|Z_{Tot}\right| = \sqrt{\frac{R^2}{4} + \frac{9R^2}{4}} = R\sqrt{\frac{10}{4}} = R\sqrt{\frac{5}{2}} \qquad (18)$$

and

$$\tan\theta_2 = \frac{\frac{3}{2}R}{\frac{R}{2}} = 3 \qquad \theta_2 = 71.5^o$$

$$\therefore \left|Z_{Tot}\right| > \left|Z_P\right| \text{ and } \theta_2 > \theta_1$$

Since the equivalent impedance is now known, we can determine the amount of real power provided by the source. In order to calculate the real power provided we must first determine the voltage across the resister.

It is determined that by

KVL: $V = jX_2 I_S + V_P$ and KCL: $I_S = I_L + I_R$

It is also proven by Ohm's Law that $I_L = \frac{V_P}{jX_1}$ and $I_R = \frac{V_P}{R}$

$$\therefore V = jX_2\left[\frac{V_P}{jX_1} + \frac{V_P}{R}\right] + V_P = \left[\frac{X_2}{X_1} + j\frac{X_2}{R} + 1\right]V_P \qquad (19)$$

Since it is assumed that X_2=X_1=R, V can be simplified.

$$V = [2 + j]V_P$$

$$V_P = \frac{|V|}{|2 + j|} = \frac{|V|\angle 0}{\sqrt{4+1}} \angle\left(\arctan\frac{1}{2}\right) \qquad (20)$$

It was proven in the first example that real power provided to the load can be determined as such.

$$P_2 = \frac{|V_P|^2}{R} = \frac{|V|^2}{5R} \text{ and that } P_2 < P_1 \qquad (21)$$

Through determining the real power provided to the load it is shown that once the series inductive reactance is added, the voltage across the load has drops and therefore the real power drops substantially.

If this was an induction motor, it would be operating below its rated voltage. This leaves room for efficiency improvements that could be achieved by adding an SVC.

The SVC shown in Figure 4.12 is simulated by a capacitor in parallel with the load. The purpose of this capacitor is to bring the magnitude of V_P back to V and thus bringing P_2 back to P_1. The question is how large of a capacitor will be able to do this? If the capacitor is too small, it will be insufficient and if it is too large, it will over compensate.

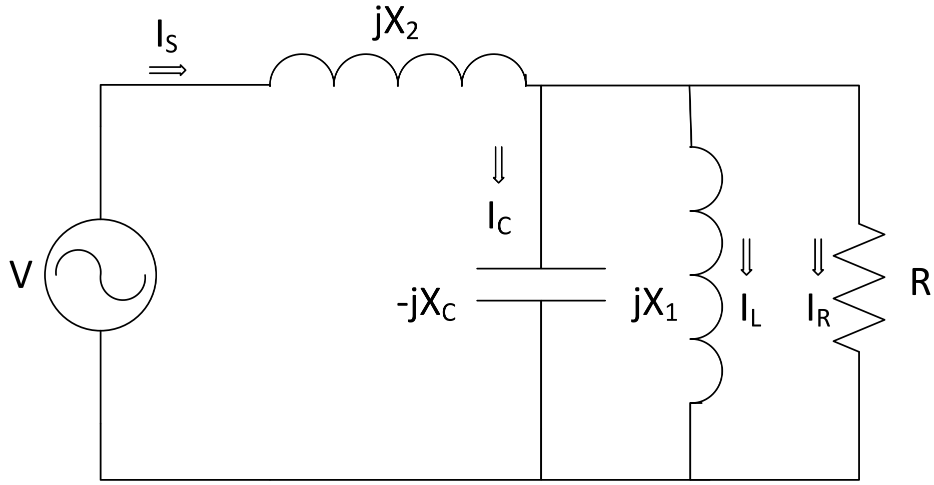


Figure 4.12 – Sample Circuit with a Series Inductive Reactance and an SVC

It is determined that by

KVL: $V = jX_2 I_S + V_P$ and KCL: $I_S = I_C + I_L + I_R$

It is also proven by Ohm's Law that

$$I_S = \frac{V_P}{-jX_C} + \frac{V_P}{jX_1} + \frac{V_P}{R} \text{ and } I_S = \frac{V - V_P}{jX_2}$$

$$\therefore \frac{V - V_P}{jX_2} = \frac{V_P}{-jX_C} + \frac{V_P}{jX_1} + \frac{V_P}{R} \qquad (22)$$

Solving for V_P it is determined that

$$V_P = \frac{V}{\left[\frac{1}{jX_2} - \frac{1}{jX_C} + \frac{1}{jX_1} + \frac{1}{R}\right]} \qquad (23)$$

In order for $|V_P| = |V|$, magnitude of the denominator must be equal to 1.

$$\sqrt{\frac{1}{R^2} + \left(\frac{1}{X_2} - \frac{1}{X_C} + \frac{1}{X_1}\right)^2} = 1$$

Through further simplification and the assumption that X_1=X_2=R it is determined that

$$\sqrt{\frac{1}{R^2} + \left(\frac{X_1 X_C - X_1 X_2 + X_2 X_C}{X_1 X_2 X_C}\right)^2} = 1$$

$$\sqrt{\frac{1}{R^2} + \left(\frac{R X_C - R^2 + R X_C}{R^2 X_C}\right)^2} = 1$$

$$\sqrt{\frac{1}{R^2} + \frac{4R^2 X_C - 4R^3 X_C + R^4}{R^4 X_C^2}} = 1$$

$$1 + \frac{4R^2 X_C^2 - 4R^3 X_C + R^4}{R^2 X_C^2} = R^2$$

$$X_C^2 + 4X_c^2 - 4RX_C + R^2 = R^2$$

$$5X_C^2 = 4RX_C$$

$$X_C = \frac{4}{5}R \qquad (24)$$

Now that it is known that the real power provided to the load has reduced to $\frac{1}{5}$ the original value, and that the sizing of the SVC should be $\frac{4}{5}$ the size of the resistive load, an economic analysis can be done.

If it is assumed that the original amount of real power required to drive the load was 500MW and after the addition of the series reactance only 100MW was being delivered to the load, it is obvious that 400MW of power was lost due to inefficiencies. If this load was left to run in this manner for 24hrs a day and 365 days a year, at a cost of $50 per MWhr, it would cause losses of $175 Million per year. In accordance with Table 2, a cost of $40 per kVAR is assumed for the SVC and at the required size of 400MVAR; it would cost approximately $16 Million to install the appropriate SVC.

While this is an extreme case that is used for demonstration purposes, the SVC can provide real savings by boosting the efficiency across the whole distribution network. Considering the steel mill in question throughout this thesis has in excess of 200,000 HP in loads, there could be a substantial monetary savings achieved by boosting efficiency.

CHAPTER V

SCADA INTEGRATION OF SYNCHROPHASOR DATA

5.1 SCADA INTEGRATION OF SYNCHROPHASOR DATA

A current weakness that is hindering the adaptation of synchrophasors beyond the electric utility surrounds the integration of synchrophasor data into current SCADA (Supervisory Control and Data Acquisition) systems. SCADA systems are the architecture of choice in industrial automation. SCADA systems include PLCs (Programmable Logic Controllers), HMIs (Human Machine Interfaces) and historians. The PLC is where all control logic and the interface to process instrumentation is housed. The HMI is a graphical interface that is designed to help the operator interface more efficiently with the process that the PLCs are controlling. The historian is a data collection tool that typically includes a database of historical process data and can include charting software to enable trending and historical process analysis.

PLCs typically use proprietary operating systems that are designed to be robust, reliable, and feature-rich. However, HMIs and historians and typically windows-based server class machines that are constrained by the windows environment. While PLCs, when operated at their limits, have the ability to adjust their scan time down to 5-10ms, HMIs and historians typically scan for updated data every 5-10 seconds. It is possible to improve this 5-10 second scan time, but this may put added stress on the computer hardware, software and networking systems involved. Since most synchrophasor data are collected at intervals of 100ms or less, this speed can be met by today's PLCs, but windows based systems cannot keep up.

As such, this is a major growth area for synchrophasor technology and an area for further innovation. Currently, proprietary hardware and software are needed to interface PMUs (Phasor Monitoring Units) with the PLCs in a SCADA system. Since the process automation field is quickly moving to Ethernet based control systems, it may help in aiding the adaptation for synchrophasor technology into the industrial world provided that PMU manufacturers would integrate Ethernet communications and required drivers to interface with their products. Furthermore, there are a number of other communication protocols that are highly deterministic that could be implemented. Controlnet, devicenet, Mudbus Plus and industrial Ethernet are just a few other examples. Giving engineers the ability to interface with PMUs will make them much less of a “Black Box” that people don’t understand and will lead to greater adaptation.

If one were able to interface the PMU and configure a PLC to interface with it, HMIs and historians (being windows based) would still leave a technological hurdle to overcome. A possible compensation to this dilemma would entail designing a small historian that is integrated into the PMU. This small historian would log the last 60-120 seconds of data, thus allowing the historian to poll the PMUs small historian data table and populate its own database. This would give the historian the ability to log data at a faster rate than it could otherwise do. Additionally, the HMI could be configured to update in the 1-2 second range if the supporting systems were properly engineered. While the PMU is recording data much faster than every 1-2 seconds, human reaction time is easily limited to this slower range. An HMI updating faster than 1-2 seconds would add tremendous engineering complexity with little benefit. As long as the PLC is able to scan at similar speeds to the PMU, it will be able to control as necessary. Since the Historian would now log data at the time resolution required to analyze synchrophasor data, synchrophasors may be successfully integrated into SCADA systems.

CHAPTER VI

CONCLUSION

6.1 CONCLUSION

With increasingly volatile energy and commodity prices becoming a reality, it has become more apparent that industrial facilities need to reduce energy consumption and drive efficiency. A major source for improved efficiency is in power factor correction. A number of correction methods have been explored and while synchrophasors and static var control were the primary focus of this thesis, it is not always the most economically sound or optimal decision. Hopefully, awareness of power factor correction as a method to improve power system efficiency, stability and longevity will continue to be examined as industry strives to improve the bottom line.

One can only hope that manufacturers will begin to develop PMUs and synchrophasor devices that are directed towards industry. As long as PMUs remain the “Black Box” they currently are, it will be more challenging for engineers to take the risk to invest in a widely unknown technology.

6.2 Recommendations for Future Work

Synchrophasor technology is still in its infancy. There is a great deal of future work needed to reduce costs and increase adaptation. As the “smart grid” continues to grow and FACTS become more common place, there is a greater need for improved monitoring and control. While using synchrophasor technology for monitoring is generally known and documented, there is great deal of research to be done in feedback control applications for FACTS systems.

The methods used for feedback control in today’s automation fields have highly standardized processes and protocols that must be followed. These standards need to be redeveloped to encompass synchrophasor technology. Setting standardized communication protocols and methods of control would greatly impact the cost and adaptation rate of synchrophasor technology for feedback control systems.

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