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A Power Systems Transients Controller Using Transient Analysis Of Control Systems (Tacs) Modules.

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A POWER SYSTEMS TRANSIENTS CONTROLLER USING TRANSIENT ANALYSIS OF CONTROL SYSTEMS (TACS) MODULES

by

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DEDICATION

"With all wisdom and understanding, He made known to us the mystery of his will according to his good pleasure, which he purposed in Christ, to be put into effect when the times reach their fulfillment—to bring unity to all things in heaven and on earth under Christ." (Ephesians 2:9-10)

This thesis is dedicated to my mother, Pamela P. Smith, my sisters, Sherelle C. Minnis, Yvette L. Ferguson, Tamita L. Munroe and Lakeisha J. Munroe, Kiersten Gray my brother, Patrick O. Ferguson, my god-parents, Darnell and Jichelle Gray, my nieces and my nephews, for their love and support that served as a source of strength and encouragement.

BIOGRAPHICAL SKETCH

Shonique L. Miller was born on July 25, 1984, in Nassau, Bahamas, to Pamela Minnis and Albert Miller. She is the younger sister of Sherelle Minnis, Yvette Ferguson, Tamita Munroe and Lakeisha Munroe. In 2008 she received the Bachelor of Science degree in Electrical Engineering from North Carolina Agricultural and Technical State University in Greensboro, North Carolina. In 2009, Shonique passed the Fundamentals of Engineering examination for the state of North Carolina. In 2010, her paper, Improving the Performance of the Truncated Fourier Series Least Squares (TFSLS) Power System Load Model Using an Artificial Neural Network Paradigm was accepted and published by the Intelligent Data Engineering and Automated Learning Conference (IDEAL). She is a summa cum laude candidate for the Master of Science degree in Electrical Engineering.

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Furthermore, I offer words of thanks and gratitude to all of my colleagues in the Machine Intelligence and Power Associated Research (*MIPAR*) Laboratory, Joseph Tabron, Kenneth Jones, Wen Fang, and Charles Winley for their friendship, support, and assistance throughout my matriculation in the electrical engineering master's program.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

TABLES **PAGE**

LIST OF ABBREVIATIONS

DC	Direct Current
AC	Alternating Current
RBFGRNN	Radial Basis Function Generalized Regression Neural Network
ERCOT	Electric Reliability Council of Texas
ANN	Artificial Neural Network
TFSLS	Truncated Fourier Series Least Squares
ATP	Alternative Transient Program
EMTP	Electromagnetic Alternative Transient Program
TACS	Transient Analysis of Control Systems
PSTC	Power System Transient Controller
pu	Per unit
kHz	Kilo Hertz
VSD	Variable Speed Drives
kV	Kilo Volt
BPA	Bonneville Power Administration
RAM	Random Access Memory
RLC	Resistance-Inductance-Capacitance Parameter
RL	Resistance-Inductance Parameter
kVA	Kilo Volt-Amperes
MVA	Mega Volt-Amperes

Vm	Amplitude of sinusoidal voltage signal
θ	Phase of sinusoidal voltage signal
T	Period of sinusoidal voltage signal
f	Frequency of sinusoidal voltage signal
Φ	Phase shift between Signal 1 and Signal 2
C	Capacitance
i	Current
Q	Charge
V	Voltage
p	Instantaneous power
W	Energy
n	Number of cycles of sinusoidal voltage
Δt	Delay between Signal 1 and Signal 2
SW_C_1	Control switch 1
SW_C_2	Control switch 2

ABSTRACT

Miller, Shonique L. A POWER SYSTEMS TRANSIENTS CONTROLLER USING TRANSIENT ANALYSIS OF CONTROL SYSTEMS (TACS) MODULES. **(Advisor: Dr. Gary L. Lebby),** North Carolina Agricultural and Technical State University.

In the electrical power industry one of the most challenging tasks is to produce and provide electrical energy in a safe, reliable, efficient and economically sound manner under stressed conditions such as: (i) harmonic variation, (ii) frequency variation, (iii) voltage magnitude variation, (iv) transient overvoltages and inrush currents after a disturbance to the power system occurs. There are many disturbances that occur that provoke transients in power systems including: (i) lightning, (ii) capacitor switching events, (iii) faults, (iv) startup of motors and generators. Although they last for very short periods of time, the appearance of these transient overvolatges and inrush currents can be lethal to sensitive equipment within the power system.

The objectives of this research are to: (a) develop and present a power system controller to protect power systems from electrical transients after system disturbances; (b) enhance system operation. A Power System Transient Control System (*PSTC*) has been designed and it is capable of preventing overvoltage signals from being distributed in the power system assuring acceptable system operation. This study emphasizes capacitor switching and fault analysis for three phase power systems.

The *PSTC* is an electronic device that is connected to the power system whose principle operation is based on a minimum/maximum tracking method. It performs

switching operations at the optimum switching point on the signal where there is minimum switching stress and is responsible for selecting the optimum switching point automatically.

The Alternative Transients Program (*ATP-EMTP*), software used for the digital simulation of transient phenomena, is used to simulate the controlled switching needed for regulating the transient disturbances observed in this research. The control switching in *ATP-EMTP* is done via Transient Analysis Control System (*TACS*) modules.

CHAPTER 1

INTRODUCTION

1.1 The Electric Power System

In September 1882 the first complete electric power system built by Thomas Edison and consisting of a generator, cables, fuses, meters and loads began operation in New York City [1]. This direct current (DC) system supplied power to 59 customers in a 1.5km radius. The development of motors by Frank Sprague and the addition of motor loads added to such systems sparked the growth of one of the world's largest industries [1]. DC systems were superseded by alternating current (AC) systems and the introduction of the transformer and three phase networks laid the foundation of the vast interconnected electrical grid of North America today [1]. Today, North America has three major grids:

- The Western Interconnection
- The Eastern Interconnection
- Electric Reliability Council of Texas (or ERCOT)

Although they can vary in size and structural components, all electric power systems have the same basic characteristics and can be modeled as a set of generators and a set of loads interconnected by a transmission network. Figure 1.1 illustrates the model of a modern power system. Power is generated and fed into the transmission network and distributed to the loads. This interconnected system is non-linear and dynamic in nature [1].

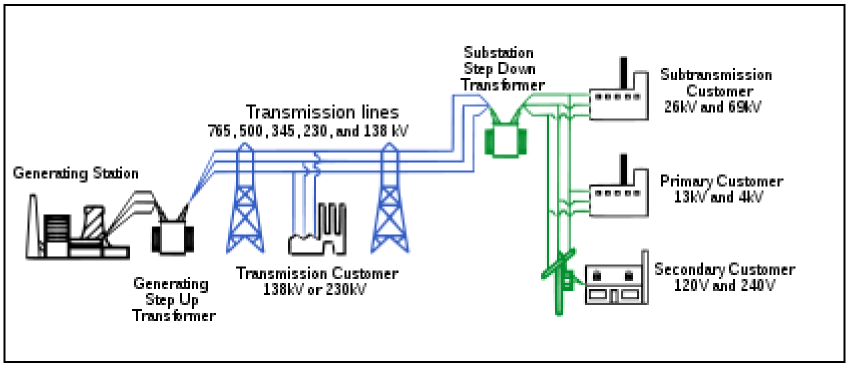


Figure 1.1. Model of a Modern Power System

1.2 Load Planning and Forecasting

Public electric utilities must always be prepared to serve the peak demand load reliably and must remain knowledgeable of the minimum demand load so as to coordinate maintenance or energy storage procedures. This important feature of any public electric utility is a major reason as to why power system planning, modeling and forecasting is a critical step in strategic planning for the utility. The objective of most companies would be to ensure it has the ability to continually provide its services to its customers. Strategic planning must be done to ensure that the power industry maintains its ability to provide secure and reliable services. Consequently, study of the growth and behavior of the load becomes imperative and this study must be accurate and concise [2].

Artificial Neural Networks have been instrumental in modeling power system loads [2, 3, and 4]. Despite their ability and robustness, there are several issues that have not been addressed routinely in the literature including: (i) modeling load deviations caused by effects of weather and other occurrences, (ii) prediction of special days such as Mondays, Fridays and holidays, (iii) incorporation of operator knowledge in the forecasting model, (iv) failure to capture all information during training [2].

Lebby, Stevenson and Shi developed a power system load model using the Radial Basis Function Generalized Regression Neural Network (RBFGRNN). The load model used the truncated Fourier series representation to describe the observed winter heat and cooling peaks of the power system load data. Figures 1.2 and 1.3 illustrate the performance of the RBFGRNN results as compared to the original load data. It is observed that in both illustrations, the ANN failed to capture all of the pertinent peak and valley load information. From observing the trace alone, it can be deduced that the statistical measure of accuracy for the modeled load is not at its best value [3].

In her dissertation, Williams integrated predictive neural autoregressive load modeling with economic dispatch to address both planning and forecasting analysis and operational cost reduction. Her research presents a forecasting mechanism that possess the versatility to address temporal variations, general enough to be transferred easily from one set of data to another and accurate enough for economic dispatch decisions [4]. When observing the forecasted results that were developed using the Group Method for Data Handling (GMDH), it is seen that again the ANN paradigm failed to capture all of the pertinent load information.

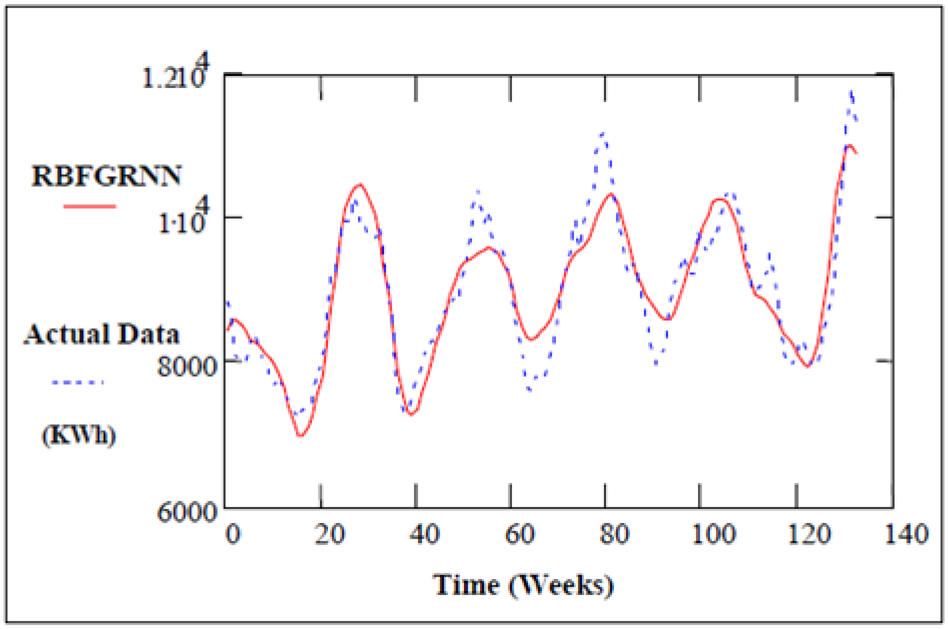


Figure 1.2. Actual Data –vs. - RBFGRNN Training Results

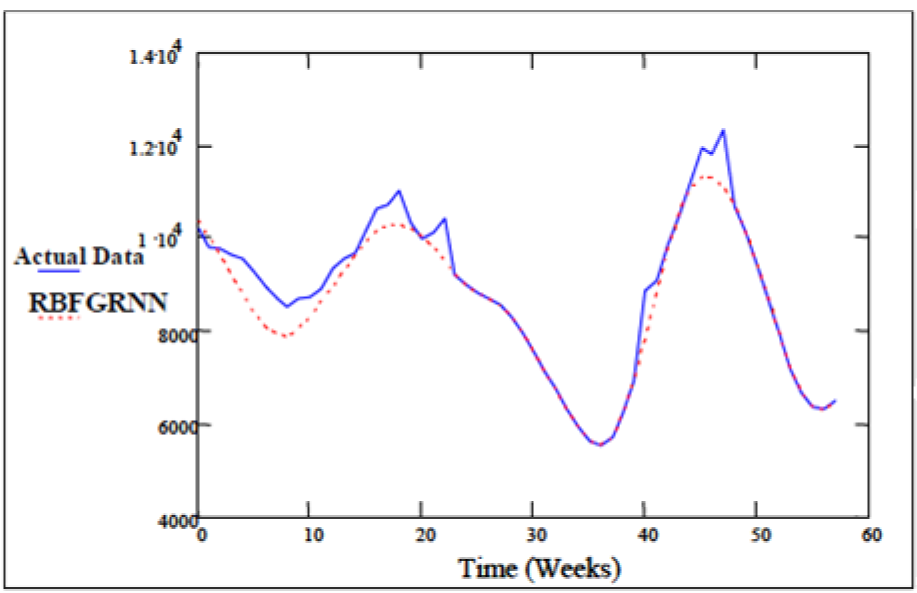


Figure 1.3. Actual Data –vs. - RBFGRNN Forecast Results

Miller, Lebby and Osareh discussed how to improve load modeling by improving the robustness of the Artificial Neural Network used to model and predict the load [2]. The issue addressed in the document was the ANN's failure to capture all information during training. It was suggested that if the peak and valley load data were extracted and modeled and this modeled inserted into the modeled data, the predicted load curve would improve in performance. Figure 1.4 shows the original load curve and Figure 1.5 shows the improved load curve. Statistically, the error measurements, goodness of fit, the Durbin-Watson and the test for homoscedasticity, all improved with the additional modeling technique.

Even though the publication presented an approach to improving the performance of the ANN, further improvement in load modeling can be achieved if the pattern and behavior of the load itself resembled more closely a sinusoidal pattern. This would make more accurate the attempt to model the load behavior as a sinusoidal Fourier series, and the residuals of the model would reflect more of the non-seasonal temperature effects upon the load.

Implementing a controlled switching technique to eliminate many of the non periodic load behaviors that occur as a result of transients would bring additional improvement to the shaping of the load, enhance load modeling and forecasting analysis and planning as residuals can be modeled more accurately based on the non-seasonal temperature affects of the region.

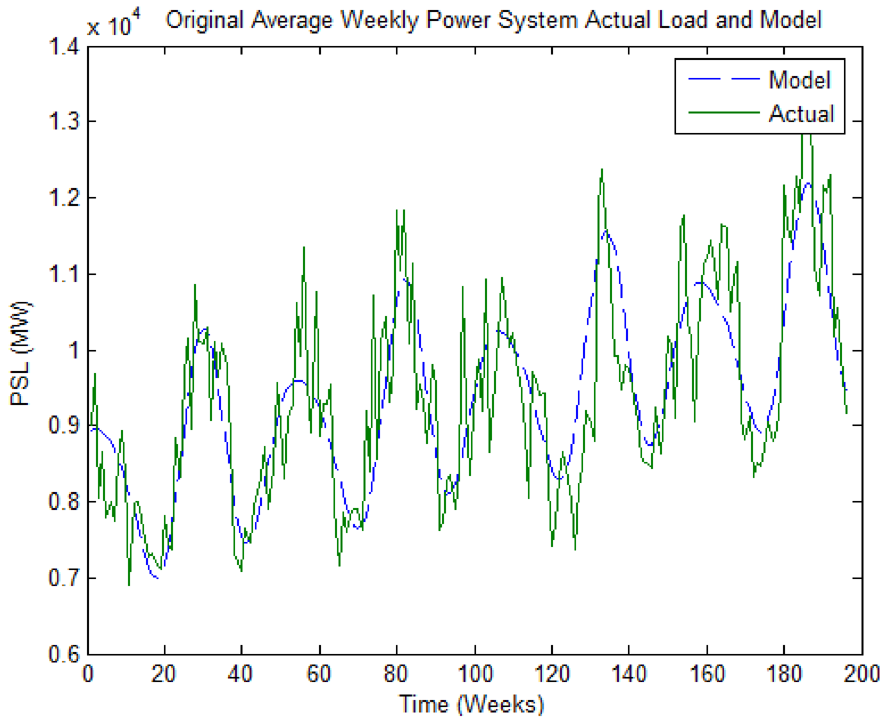


Figure 1.4. Original Average Weekly Power System Actual Load and Model

1.3 The Stability Problem

The electric power grid is highly non-linear and dynamic in nature. These characteristics are the result of the types of equipments and loads being used, the frequency of the addition and reduction in load size and the many different interconnections that exists between generation, transmission and distribution areas. The nature of the system, points to the somewhat fragile stability of the system and causes the system to be susceptible to certain occurrences that would cause there to be an imbalance in the systems operation. Any sudden change in circuit parameters can affect the system negatively because these changes will behave non-linearly as well. Utilities are ultimately responsible for ensuring that electrical energy is provided in a safe, reliable, economically and environmentally sound manner hence, the operating conditions of the power system are of major concern to power system engineers.

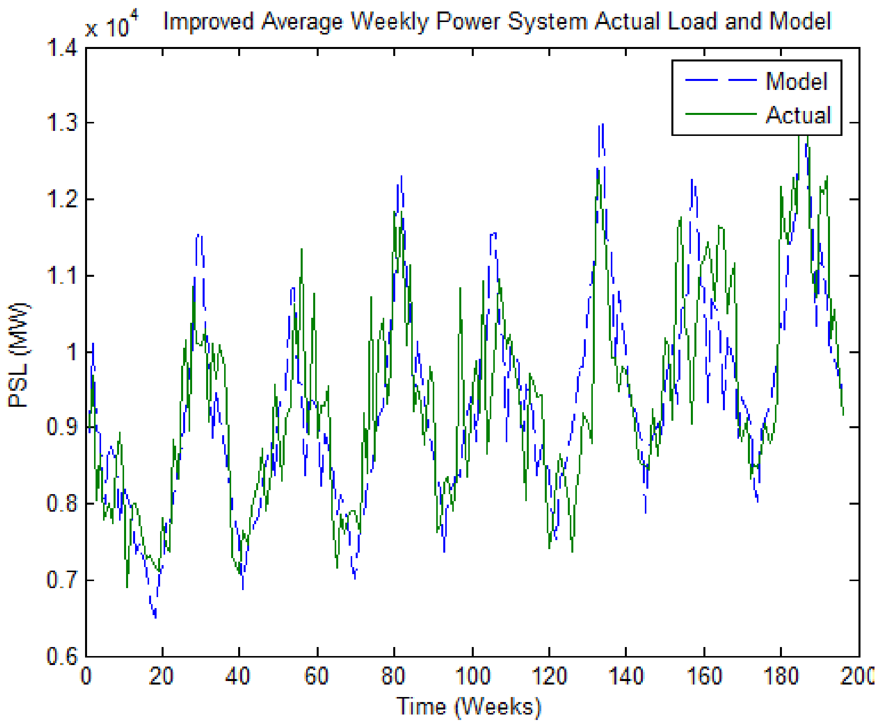


Figure 1.5. Improved Average Weekly Power System Actual Load and Model

One of the major problems experienced initially in power system engineering are the sustained oscillations in speed or hunting due to periodic variations in the torque applied to ac generators driven by reciprocating steam engines. Although the use of turbines have helped reduced this significant problem, maintaining synchronism between various parts of any power system becomes increasingly difficult as the system expands [5]. End use equipments are affected most by instability within the power system. They tend to be more sensitive to disturbances that may arise either from the power supplier or customer facilities which then brings the quality of the electrical energy provided into question. Power quality variations that can cause problems with sensitive loads and equipment can be caused either by disturbances or steady state variations [5]. This study will focus solely on disturbances that affect power quality.

If all the measured physical quantities that describe the operating condition of the power system can be considered constant, the system is said to be in steady state operation. A disturbance is any occurrence that induces a sudden change or sequence of changes in one or more of the system parameters or operating quantities. Transmission system faults, loss of generating units, line switching, load switching and capacitor switching are some examples of large disturbances that occur frequently in any power system [5]. The electrical transients that can result when these disturbances occur can be dangerous to sensitive equipment and loads.

1.4 The Proposed Solution

Although power is the rate of delivery of energy and is proportional to the product of the voltage and current, it is difficult to define or control this quantity in a meaningful manner. The power supply system can only control the quality of the voltage and has no control over the currents drawn due to the dynamic nature of the loads [6].

The proposed controller (Figure 1.6) will block any surge or transient voltage signals before it reaches the power system loads and equipment. This controller is connected to the power system and is used to perform switching operations at the optimum point on the receiving signal where there is minimum switching stress. The main operating principle of the controller is based on the minimum/maximum tracking method of the signals.

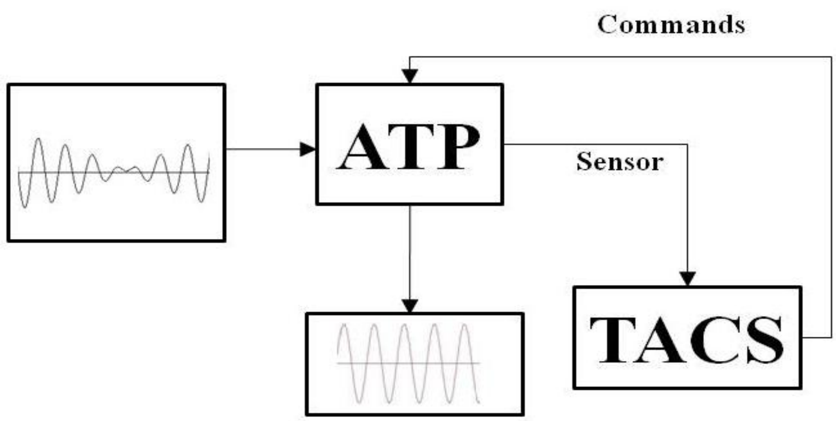


Figure 1.6. Power System Transients Controller (*PSTC*)

CHAPTER 2

ELECTRICAL TRANSIENTS

2.1 Definition

An electrical transient is defined as the outward manifestation of a sudden change in circuit conditions, as when a switch opens or closes or a fault occurs on a system [7]. Although the transient period is particularly short (lasting from a few nanoseconds to milliseconds), and this amount of time is seemingly significant when compared with the time spent in the steady state operating conditions, these transient periods are of significant importance.

During transient periods, circuit components are subjected to the greatest stresses from excessive currents and voltages. At the load end of the system, sensitive electronics that experience transient surges can exceed its designed breakdown voltage causing equipment damage and ultimately failure. Transient voltage surges comprise the most severe and immediate danger to sensitive electrical and electronic equipment. The result is an estimated $26 billion-per-year cost to U.S. companies in lost time, equipment repair, and equipment replacement [6]. Addressing these issues are pertinent to the reliability and efficiency of the system. The first key activity involved in addressing transients is recognition; understanding that transient overvoltages can produce equipment responses different than what is anticipated and expected. In this regard it is important to know that transients can be classified as either impulsive or oscillatory, which reflect the wave-shape of a current or voltage transient [6].

2.2 Impulsive Transients

An impulsive transient is a sudden, non-power frequency change in the steady state condition of voltage, current or both that is unidirectional in polarity and is either primarily either negative or positive. Impulsive transients are normally characterized by their rise and decay times and the most common cause of impulsive transients is lightning. Figure 2.1 illustrates a current impulsive transient caused by lightning.

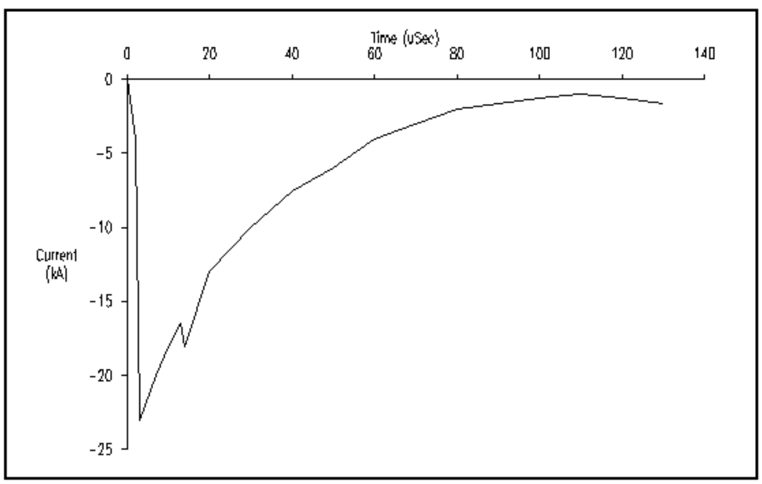


Figure 2.1. Lightning Stroke Current Impulsive Transient

Impulsive transients are usually not conducted far from the point of entry into power system. The high frequencies involved in impulsive transients can be changed quickly by circuit components and can display extremely different characteristics when viewed from different instances on the power system. Impulsive transients can produce oscillatory transients because they can excite the natural frequency of power system circuits [6].

2.3 Oscillatory Transients

An oscillatory transient is a sudden, non-power frequency change in the steady state condition of voltage, current, or both, that includes both positive and negative polarity values. An oscillatory transient consists of a voltage or current whose instantaneous value changes polarity rapidly. Oscillatory transients are described by their predominant frequency, duration and magnitude. They can be classified as being high frequency, medium frequency or low frequency oscillatory transients [6].

High frequency oscillatory transients are oscillatory transients that have a primary frequency component greater than 500 kHz with a typical duration measured in microseconds, and are often the result of a local system response to an impulsive transient [6].

A transient with a primary frequency between 5 and 500 kHz with a measured duration in the tens of microseconds is termed a medium frequency oscillatory transient. Figure 2.2 shows a medium frequency oscillatory transient caused by back to back capacitor energization. Cable switching can also induce medium frequency oscillatory transients as well as system response to an impulsive transient [6].

A transient with a primary frequency component less than 5 kHz and a duration from 0.3 to 50ms is a low frequency oscillatory transient. These transients are typically encountered on utility sub-transmission and distribution systems. Many events can cause these transients to occur, the most frequent being capacitor bank energization.

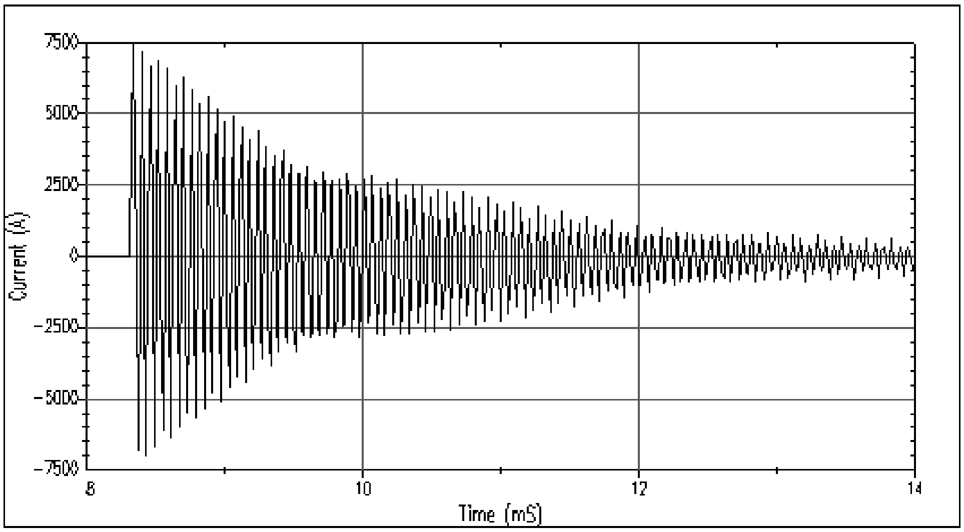


Figure 2.2. Medium Frequency Oscillatory Transient Caused by Back-to-back Capacitor Switching

Oscillatory transients with predominant frequencies less than 300 Hz can also be found on distribution systems and are generally associated with transformer energization and ferro-resonance [6].

There are many different causes of transient phenomena. This research and investigation will describe only two different types of these cases: capacitor switching and single phase fault.

2.4. Capacitor Switching

One of the most common switching events on utility systems is capacitor switching. Predominately, loads on the electric utility are inductive in nature and the systems themselves have to supply the reactive power consumed. One of the most practical ways for the utility to provide this reactive power is through capacitor banks [8]. In addition, capacitor banks are also used to correct a lagging power factor or provide system voltage support. The use of such banks in distribution systems can be fixed or switchable [8].

Rotating machines, electronic VAR compensators and other alternatives are much more costly, many of which have high maintenance costs, and thus capacitor banks are more common on power systems [6]. Capacitor switching, although inexpensive, provoke transient over-voltages on the power system. These voltages, if large enough, can damage sensitive equipment.

Owing to the frequent nature of capacitor switching incidents, coupled with the high switching over-voltages involved, capacitor switching transients are of special concern. High-frequency and magnitude transients produced, introduce excessive electrical and mechanical stresses [9]. Moreover, there is always a voltage transient induced when capacitor banks are switched in. Transient over-voltages due to utility capacitor switching typically reaching 1.8 pu, might be magnified at the customer load bus to magnitudes of up to 2.6 pu Voltage magnification due to capacitor switching, occurs when the transient oscillating frequency is close to the natural frequency of the inductor–capacitor circuit at the load bus formed by the system impedance and the power factor correction capacitors. Short-duration over-voltages that do not damage equipment may still cause sensitive loads such as variable speed drives (VSDs) to unexpectedly disrupt a critical load from the system. Resizing the customer power factor correction capacitors or step-down transformer are not practical solutions and thus, controlling the transients that occur must be done at the utility capacitor [6]. To date, various methods of controlling capacitor energization transients at the utility capacitor have been implemented by the industry [9]. These methods include the use of pre-insertion resistors and inductors and synchronous closing; each with their unique advantages and disadvantages in terms of cost, reliability and effectiveness.

Figure 2.3 shows the circuit used to study capacitor switching. The switching will occur at capacitor bank one. When the capacitor voltage is switched in, transient voltages will be created across the capacitor bank loads and other equipment as shown in Figure 2.4.

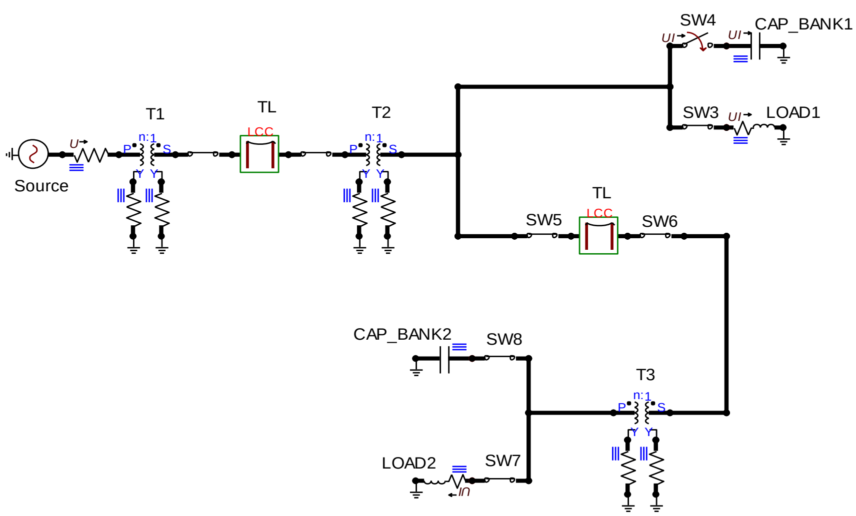


Figure 2.3. One-line Diagram for 3Φ Capacitor Switching Analysis

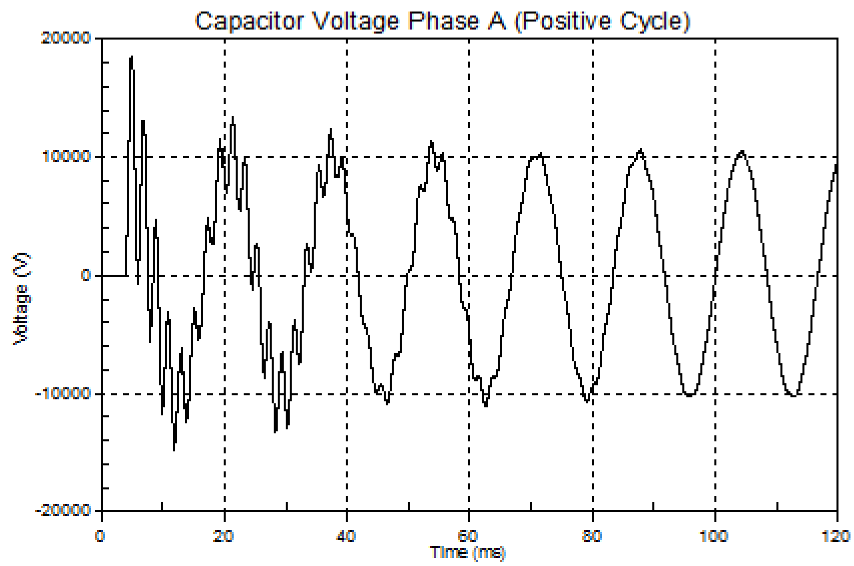


Figure 2.4. Capacitor Voltage Phase A (Positive Cycle)

2.5 Single Phase-to-Ground Fault

A fault is any occurrence that causes interference with the normal flow of current in the power system [10]. While most faults on transmission lines of 115 kV and higher are caused by lightning (induced voltage or direct strikes) [6], loss of power, voltage dips, and overvoltages will also occur, as consequences of other natural events, physical accidents, equipment failure, or disoperation owing to human error. Other natural events that can cause faults are wind, ice, earthquake, fire, explosions, falling trees, flying objects, physical contact by animals, and contamination. Accidents include faults resulting from vehicles hitting poles or contacting live equipment, unfortunate people contacting live equipment, digging into underground cables, human errors, and so on

[11]. These occurrences cause insulation at the point of fault to be momentarily subjected to voltage stress in excess of its dielectric strength [12].

In poly-phase systems, a fault may affect each phase equally and is called a symmetrical fault. Most faults that occur, however on poly-phase systems, do not affect each phase equally and these are called asymmetrical faults.

Asymmetrical faults include the following, with very approximate percentages of occurrence [12]:

- Phase-to-phase: 8%-10%
- Phase-to-phase-to ground: 10%–17%
- Single phase-to-ground: 70%–80%

Phase-to-phase asymmetrical faults not involving ground occurs when there is a short circuit between lines, caused by ionization of air, or when lines come into physical contact, for example due to a broken insulator. Phase-phase-to ground faults occur when two lines come into contact with the ground (and each other), and are commonly due to storm damage. If the fault is temporary, opening circuit breakers to isolate the faulted portion of the line and then reclosing after a few cycles to allow deionization at high speeds are usually successful after most faults. Permanent faults are those faults in which reclosing would not be possible regardless of the interval between opening and closing. Permanent faults are caused by lines being on the ground, by insulator strings breaking because of ice loads, by permanent damage to towers and by surge arrester failures.

Single-phase- to ground faults are among the most frequent faults seen on the electric power system [7] and will be the focus of this study. These faults are often permanent and cannot be addressed by reclosing. Figure 2.5 shows the one-line diagram of a 3 phase system with a single phase to ground fault on phase ‘c’ of the system. The ground switch in the Figure, closes at *t=4 ms*, creating a short circuit fault. Figure 2.6 shows the voltage across load 1 on phase ‘c’ after the fault has occurred. It is observed that the voltage approaches zero after about one cycle.

Figure 2.7 shows the load 1 voltages on phases ‘a’ and ‘b’. It is seen that not only does the line-to-ground fault cause the voltage on the ‘c’ phase to oscillate about zero; it produces surges on different phases as well.

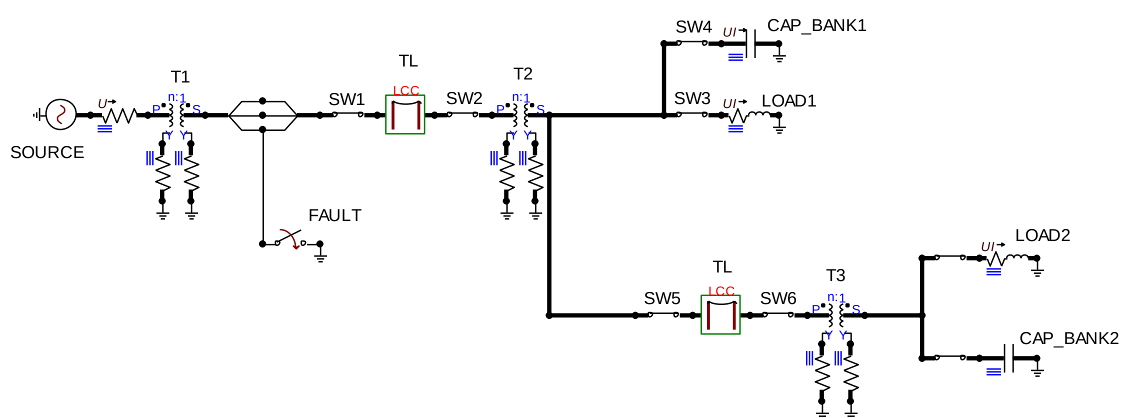


Figure 2.5. One-line diagram for 3Φ Single Phase-to-Ground Fault

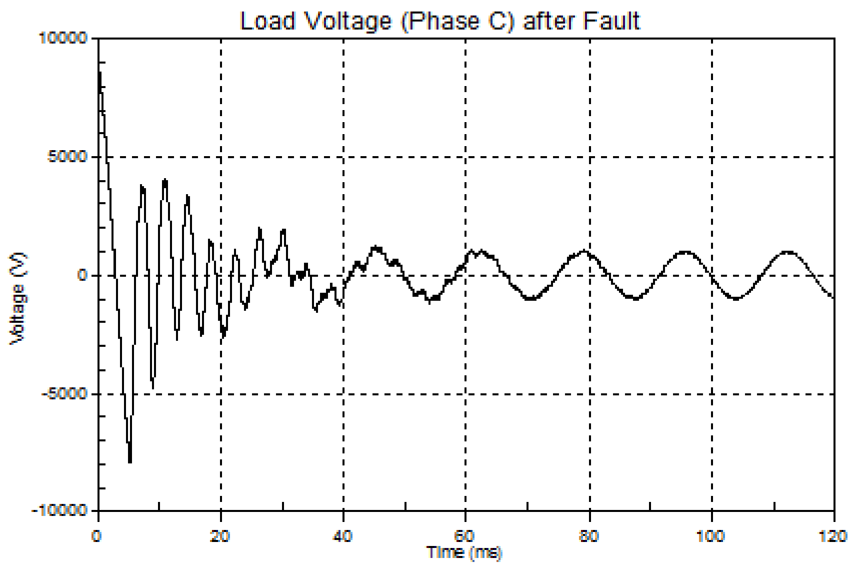


Figure 2.6. Load Voltage (Phase C) after Fault

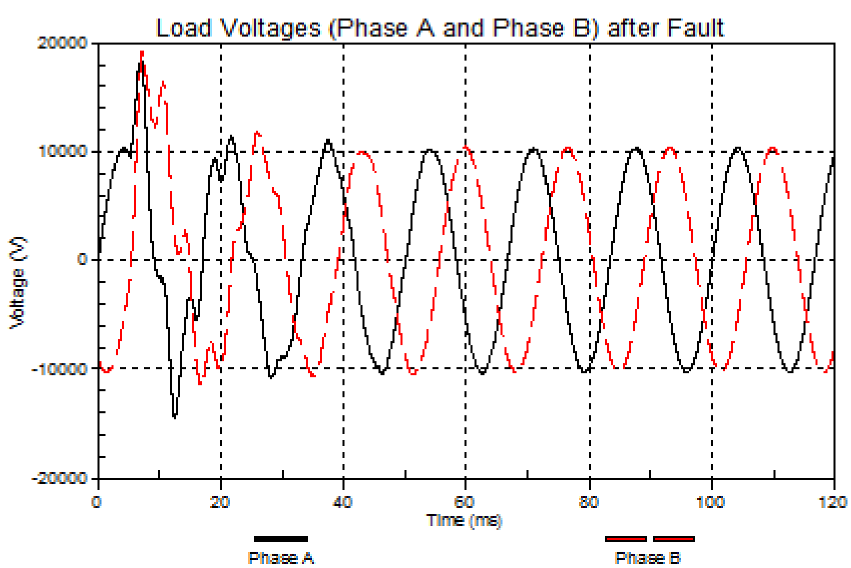


Figure 2.7 Load Voltages (Phase A and Phase B) after Fault

CHAPTER 3

ALTERNATIVE TRANSIENTS PROGRAM (*ATP-EMTP*)

3.1 Introduction

To ensure the reliable operation of an electric power system and expansion planning, power engineers must perform a variety of network studies such as fault analysis, load flow analysis, stability analysis and the analysis of electromagnetic transients. Of these, the analysis of electromagnetic transients is of extreme difficulty and complexity. *EMTP* is one of the most widely used software for digital simulation of both electromechanical and electromagnetic transient phenomena [13]. The *EMTP* has been specifically developed for power system problems and can solve any network which consists of interconnections of resistances, inductances, capacitances, single and multiphase π-circuits and distributed parameter lines. The Transient Analysis of Control Systems (*TACS*) allow for the analysis of control systems in *EMTP*.

The Alternative Transients Program (*ATP-EMTP*) is a universal program system for digital simulation of transient phenomena of electromagnetic as well as electromechanical nature. With this digital program, complex networks and control systems of arbitrary structure can be simulated. *ATP-EMTP* has extensive modeling capabilities and additional important features besides the computation of transients [13]. The *ATP-EMTP* dates back to early in 1984, when Drs. Meyer and Liu did not approve of proposed commercialization of *BPA's EMTP*. Dr. Liu and Dr. Meyer started a new program from a copy of BPA's public-domain *EMTP* [13].

3.2 Program Capabilities

ATP-EMTP Tables are dimensioned dynamically at the start of execution to satisfy the needs of users and their hardware (e.g., *RAM*). No absolute limits have ever been observed, and the standard version has limits that average more than 20 times default Table sizes. Table 3.1 shows maximum limits for standard program distribution [13].

Table 3.1. Maximum Capability in *ATP-EMTP*

Power System Elements	Maximum Capability
Buses	6000
Branches	10000
Switches	1200
Sources	900
Nonlinear Elements	2250
Synchronous Machines	90

3.3 Operating Principles

- Solve the algebraic, ordinary and partial differential equations that are associated with the interconnection of lumped parameters.
- Trapezoidal rule of integration is used to solve differential equations of system components in time domain.
- Program output consists of component variables as functions of time for those variables requested by the user. Both printed and plotted output is possible.

- Initial conditions can be determined automatically by a steady state, phasor solution or they can be entered by the user for simpler components.
- Modeling of control systems and components with non-linear characteristics such as arcs and coronas enabled through the interfacing capability of the *EMTP* to *TACS* and *MODELS* simulation programs.
- Symmetric and unsymmetrical disturbances such as faults, lightning surges, and any kind of switching operations can be simulated.
- *FREQUENCYSCAN* allows the calculation of frequency response of phasor networks.
- *TACS* and *MODELS* can be used to simulate dynamic systems [13].

3.4 ***MODELS***

MODELS in *ATP-EMTP* is a description language supported by an extensive set of simulation tools for the representation and study of time-variant systems [13]. The description of each model is enabled using free-format; keyword-driven syntax of local context and that is largely self-documenting. *MODELS* allow the description of arbitrary user-defined control and circuit components, providing a simple interface for connecting other programs/models to *ATP-EMTP*. As a general-purpose programmable tool, *MODELS* can be used for processing simulation results either in the frequency domain or in the time domain.

3.5 *ATPDRAW*

ATPDRAW is a graphical, mouse driven preprocessor for *ATP-EMTP* on the *MS-DOS* platform. Using *ATPDRAW*, one builds a graphical picture of an electric circuit by picking objects from menus, connecting and editing objects, and keying data interactively. *ATPDRAW* then creates the corresponding *ATP-EMTP* input data file, it supports 65 standard components. The Data Base Module feature of *ATP-EMTP* can be used to create user-specified objects [14].

3.6 Components in *ATPDRAW*

There are two different classifications of components in *ATPDRAW*, standard components and *TACS* [14]. The standard components include Linear Branches, Line models, Switches, Sources, Machines Transformers. The *TACS* components include Transfer functions (with or without limits), Sources (*DC*, *AC*, PULSE, RAMP, *EMTP* node voltage), *FORTRAN* Statements (1-phase, Single line statement), Devices, type 50-54 and 58-66 and Initial condition devices.

3.7 Transient Analysis of Control Systems (*TACS*)

TACS can simulate mechanical and electromechanical systems, non-linear response, create models for devices or behavior not represented by built in *ATP-EMTP* models and multi-frequency or variable frequency sources. It offers a dynamic, interactive module between the power system (*ATP-EMTP*) and control system (Figure 3.1). It and can read parameters such as node voltages, branch currents, switch status, and machine angle from power system or electrical network.

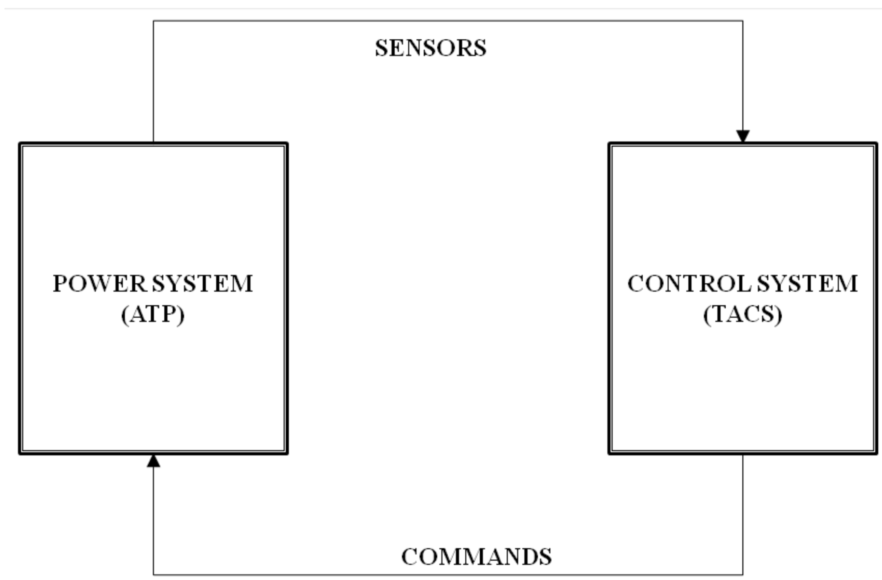


Figure 3.1. Interaction between Power System (*ATP*) and Control System (*TACS*)

After analyzing and calculating based on the received parameters, it sends as commands, the information regarding voltage source, current source and switch control [13]. This feature of *TACS* is what is desirable during controlled switching analysis for power systems engineers.

3.8 Line/Cable Constants

The program called *ATP_LCC* supports the modeling of line constants and cables in *ATP-EMTP*. In this program, the user specifies the cross section and material data for an overhead line or cable system in input windows. Based on the user-specified data, a corresponding *ATP-EMTP* file will be generated to be processed by *ATP-EMTP* for creation of a punch file or a matrix output file. The program consists of two parts; one for Line Constants support and one for Cable constants. These two parts are handled independently in the program with separate input windows [13].

3.9 The Output Processor (*TOP*)

The Output Processor (*TOP*) is capable of reading measurement data from a variety of measurement instruments and simulation programs, including *ATP-EMTP. TOP* uses a system called the stack to simplify handling data from various sources. *TOP* is a Windows compatible software that can view data files generated from a variety of simulation programs such as, ASCII Text, PQDIF (IEEE-P1159-3), PSCAD®, and EPRI/DCG *EMTP* for Windows, ATP (Alternate Transients Program), Cooper Power Systems V-HarmTM, and EPRI Power Quality Diagnostic System.

Graphs generated in *TOP* can be exported to a variety of file formats such as IEEE PQDIF, IEEE COMTRADE (.CFG), Windows Metafile (.WMF), PorTable Network Graphic (.PNG), Comma Separated Variable (.CSV), and ASCII Tabbed Text just to name a few. The software also provides a variety of ways to visualize the data.

Data can be seen as waveform and spectrum plots, frequency response plots, summary Tables, summary bar/volume charts, cumulative probability charts, probability density charts, 3-D magnitude duration histograms.

CHAPTER 4

MINIMUM/MAXIMUM TRACKING METHOD

4.1 Reducing Energy Losses

The retail sale of electrical energy involves the flow of electricity from some point of generation through a power delivery system to the final consumer. The delivery system consists of thousands of transmission and distribution lines, substations, transformers and other equipment scattered over a very broad geographical areda (Figure 4.1) [15].

Delivering reliable electricity efficiently is of paramount importance to electric utilities. Of equal importance to these utilities is the generation of power in the most economical way possible [16].

Electrical losses vary according to load conditions. Although, these losses may seem small when compared to the amount if energy generated, these losses represent real cost at the expense if the utility. Ultimately, the operating and maintenance costs of the power utility will be incurred by the customers. Minimizing the total costs of operation is one way of minimizing consumer costs. This minimization of operating costs includes minimizing losses in the system [13].

In areas where an increase in peak demand load is forecasted, it may be possible to satisfy this new demand from existing installations by using the kVA capacity released by shunt capacitors instead of investing in new generation. Power factor is the ratio of the effective power to the total power on the line. The severity of losses that can be sustained due to reactance on the line can be significant, for example, with an 80% power factor; a distribution feeder with a maximum capacity of 6MVA can only deliver 4.8 MVA [15]. It can be deduced that poor power factor can create considerable cost and consequences on a power system. One way to improve the power factor is by implementing shunt capacitors [15].

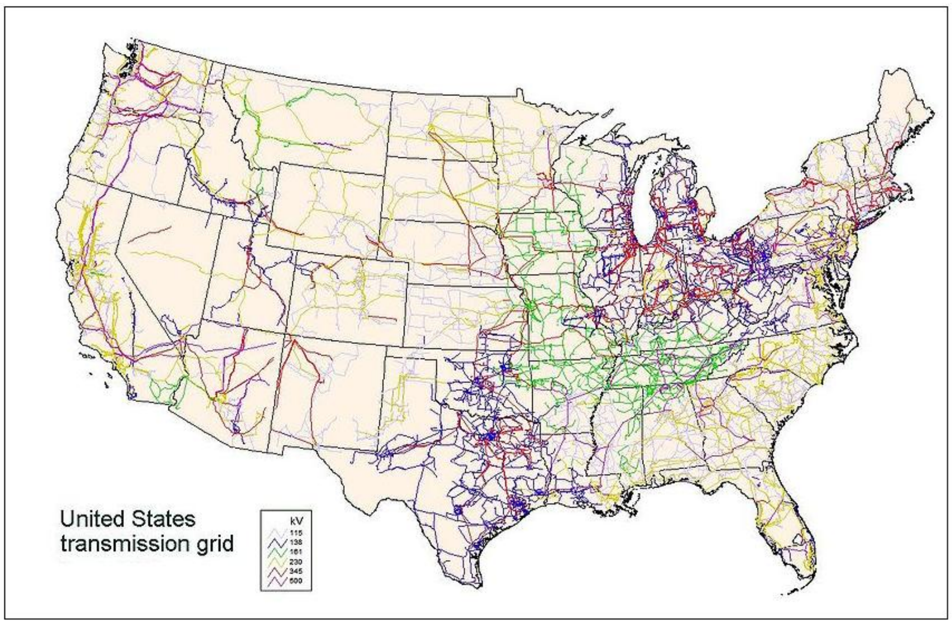


Figure 4.1. North American Electric Grid (Complex View)

In areas where an increase in peak demand load is forecasted, it may be possible to satisfy this new demand from existing installations by using the kVA capacity released by shunt capacitors instead of investing in new generation.

Power factor is the ratio of the effective power to the total power on the line. The severity of losses that can be sustained due to reactance on the line can be significant, for example, with an 80% power factor; a distribution feeder with a maximum capacity of 6MVA can only deliver 4.8 MVA [15]. It can be deduced that poor power factor can create considerable cost and consequences on a power system. One way to improve the power factor is by implementing shunt capacitors [15].

Reactive impedance in addition to reactive loads can result in significant drops in voltage on the distribution system. Reactive power support from automatic shunt compensators help maintain the voltage at high levels and increases the system voltage profile capabilities and prevent the risk of voltage collapse [16].

4.2 Capacitors

As discussed previously, capacitors are an essential element of the power system and are used to improve power factor, increase system efficiency, improve voltage profile, and supply of magnetizing current from inductive loads [17].

The operation and character of a capacitor can best be described by referring to Figure 4.2, which illustrates two parallel metal plates with area *A* and an attached conducting wire, that are separated a distance d by a dielectric (insulator). If a constant current is flowing through the top plate is established, a steady flow of positive charges is directed at the top of the plate. The dielectric does not allow the charges to pass, so they accumulate at the top of the plate. The continuous nature of current through an electric component means that a similar condition must exist at the bottom plate, i.e. positive charges must leave the bottom plate to establish proper exiting current; leaving behind a net negative charge in the lower plate. A voltage between the plates is produced due to the charge unbalance between the two plates.

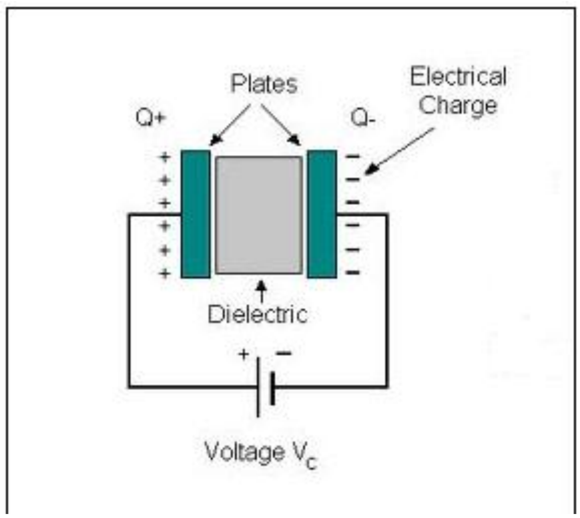


Figure 4.2. Parallel Plates Forming a Capacitor

This voltage is directly proportional to the charge of the plates [17]. The mathematical representation of this is shown in equation 4.1.

$$i = \frac{dQ}{dt} = \frac{dv(t)}{dt} \tag{4.1}$$

The capacitance can be written in terms of the voltage and charge as:

$$C = \frac{Q}{v} \tag{4.2}$$

Where

i -current in amperes,

Q- charge in Coulombs,

v- voltage across capacitor in volts,

t- time in seconds.

By writing the dependence of *i* and *v* on time and integrating, we obtain equation 4.3.

$$v(t) = \frac{1}{C}\int_{-\infty}^{t} i(\tau)d\tau \tag{4.3}$$

The instantaneous power flowing to the capacitor is:

$$p(t) = v(t)i(t) = Cv(t)\frac{dv(t)}{dt} \tag{4.4}$$

Integrating the instantaneous power over all past time to the present time gives the energy stored in the capacitor as:

$$w(t) = \frac{1}{2} C v^2(t) \qquad (4.5)$$

Figure 4.3 shows the graphical representation for the voltage, current, instantaneous power and energy for the capacitor. From equation 4.4, it is seen that at points where V is zero, P is also zero and the energy curve also has its minimum at the same point. This characteristic can also be seen on the graphical representation of these parameters for the capacitor.

The voltage across the capacitor cannot change instantaneously. As a result, oscillatory transients are created across its plate as it tries reaches to its steady state condition. It is proposed that if the capacitor is energized at voltage point zero, where, power and energy are minimum, the amount of disturbances will be minimized.

Since the power system can be represented as an electrical circuit made up of combinations of resistances, inductances, and capacitances. The circuit is normally energized and carrying load until disturbances occur. These disturbances can be modeled and corresponded to the closing or opening of switches. The closing or opening of any such switches will cause a redistribution of circuit parameters that are generally accompanied by transient periods with momentarily but relatively high resultant currents and voltages. If the switching operation can be done when elements such as capacitors and loads are at minimum energy levels, transients created during this transition are minimum [18].

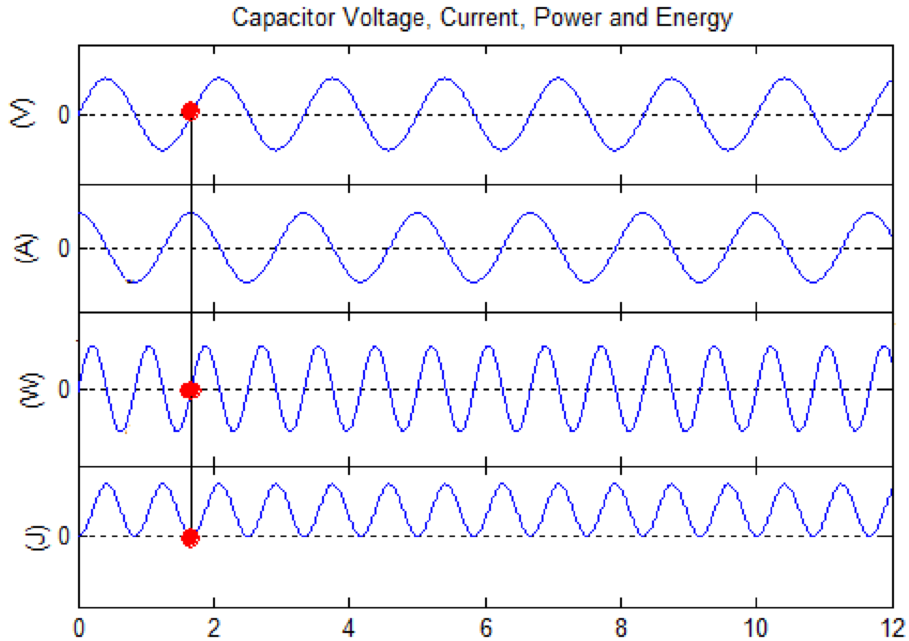


Figure 4.3. Voltage, Current, Power and Energy Curves for the Capacitor

4.3 Minimum/Maximum Tracking Method

To find the minimum value on a signal, the signal parameters and expressions must be understood.

4.3.1 The Sinusoidal Signal. A sinusoidal voltage source produces a sinusoidal voltage that varies with time that can be expressed as a sine or cosine function [17]. It is defined by equation 4.6 and Figure 4.4 shows the voltage versus time plot of a sinusoidal voltage. It is important to note that sinusoidal waveform is repetitive in nature and is called a periodic waveform. The time

for the sinusoid to pass through one cycle is called its period and denoted by *T*.

$$v(t) = V_m \sin(\omega t + \theta) \tag{4.6}$$

The reciprocal of the period (equation 4.7) is the frequency of the waveform, which gives the number of cycles per second.

$$f = \frac{1}{T} \tag{4.7}$$

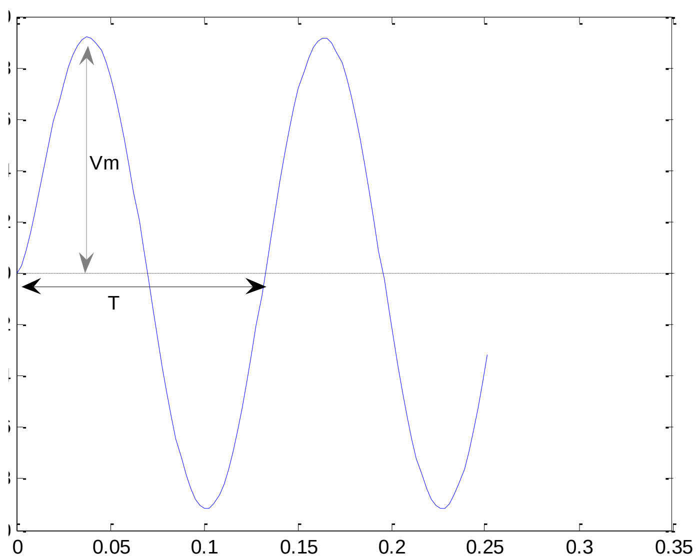


Figure 4.4. Sinusoidal Voltage Signal

The coefficient of t in equation 4.6 contains the numerical value of T or f. Omega (ω rad/s) represents the angular frequency of the sinusoidal function, or

$$\omega = 2\pi f = \frac{2\pi}{T} \tag{4.8}$$

The angle θ in eq. 4.6 is the phase angle of sinusoidal voltage. Note that if θ is positive, the waveform shifts to the left, whereas if θ is negative, the function shifts to the right.

4.3.2 Switching Scenarios. In each full cycle of a sinusoidal waveform, there occurs a positive half cycle (first half of the signal) and a negative half cycle (second half of the signal). Switch closing can be done during either of these cycles. Figure 4.5 marks the two half cycles and gives examples of the times chosen to close a switch in each half cycle. The time interval for the first (t_1) and second (t_2) events, respectively, can fall in the range of:

$$t_1 = (2n-1) \ \ half\ cycle \tag{4.8}$$

$$t_2 = 2n \ \ half\ cycle \tag{4.9}$$

Where

n= *1, 2, 3… n,*

t_1= represent the switching in the positive half cycle, and

t_2= represent the switching in the negative cycle.

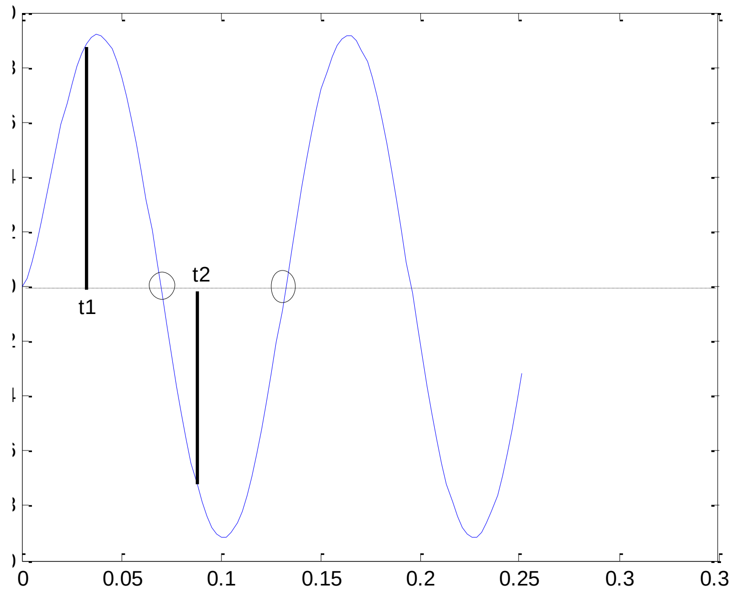


Figure 4.5. Two Different Possible Switching Scenarios

If switches are closed at t_1 then the minimum magnitude of the signal must be obtained and if the switches are closed at t_2 the maximum magnitude of the signal must be obtained. These minimum and maximum points are also zero crossing points in the corresponding regions [18].

4.3.3 Minimum Tracking for Positive Half Cycle. Zero crossing within the positive cycle of a signal, t_1, is the point in which the sine function has the minimum value. In the positive cycle, two points satisfy this criterion. The first minimum point or zero crossing occurs prior to the switching event and the second point is the point at which the signal is changing polarity. The first point is not to be considered as the occurrence is prior to the switching event and no longer has an effect on system minimization [18].

To find the minimum point in the positive half cycle, two signals with the same frequency of the original sinusoid will follow each other with a small delay of Δt seconds. Since Δt, is a small value, it would appear as if the signals are on top of each other. $Signal_2$ will lag $Signal_1$ by:

$$\Phi = \frac{\Delta t}{T} * 360 \tag{4.10}$$

Where

Φ - phase angle in degree with respect to signal1

T – period of signal1 in seconds and,

Δt – the time delay between the two signals in seconds.

The signs of the two signals change at $Point_1$ as depicted in Figure 4.6. The time t, when the value of the voltage signal is zero can be calculated by equation 4.11.

$$t = \left(\frac{1}{2}T\right) - t_1 \tag{4.11}$$

.

At this time t, the sign of $Signal_1$ is negative and the sign of $Signal_2$ is positive. Therefore $Point_1$ is the minimum point of the curve in that region [18].

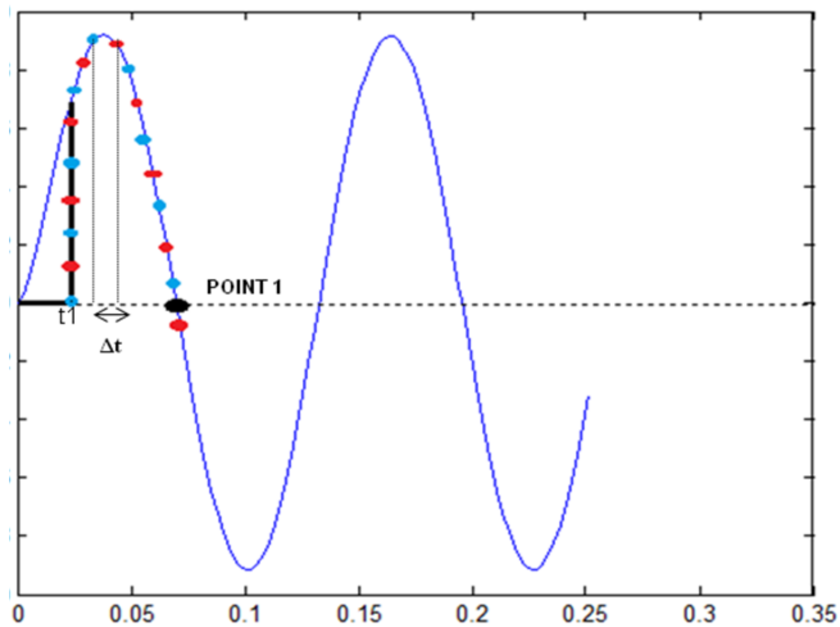


Figure 4.6. Switching During the Positive Half Cycle (t_1)

4.3.4 Maximum Tracking for Negative Half Cycle. Switching in the negative half cycle when the switching event falls in the negative half cycle and is shown in Figure 4.7. When the switch is closed at t_2, the maximum value of the signal corresponds to the point where signal1 is positive and signal2 is negative. The single point that hast his characteristic in the negative cycle is indicated as point2 on Figure 4.6. At this point, the voltage signal has zero value and no energy [18]. The same delay will apply to $Signal_2$ in this case as determined in equation 4.10. This minimum/maximum tracking method will be used in the control design to help eliminate the transient analysis provoked my capacitor switching and single phase faults.

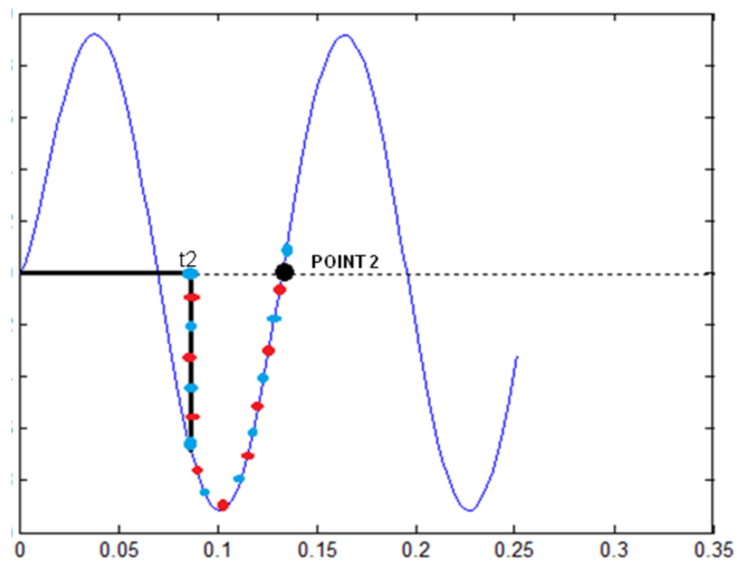


Figure 4.7. Switching During the Negative Half Cycle (*t_2*)

CHAPTER 5

POWER SYSTEMS TRANSIENTS CONTROLLER (*PSTC*)

5.1 Overview of *PSTC*

The *PSTC* interfaces power system elements, the *ATP-EMTP*, and *TACS* components. This coupling is shown in Figure 5.1.

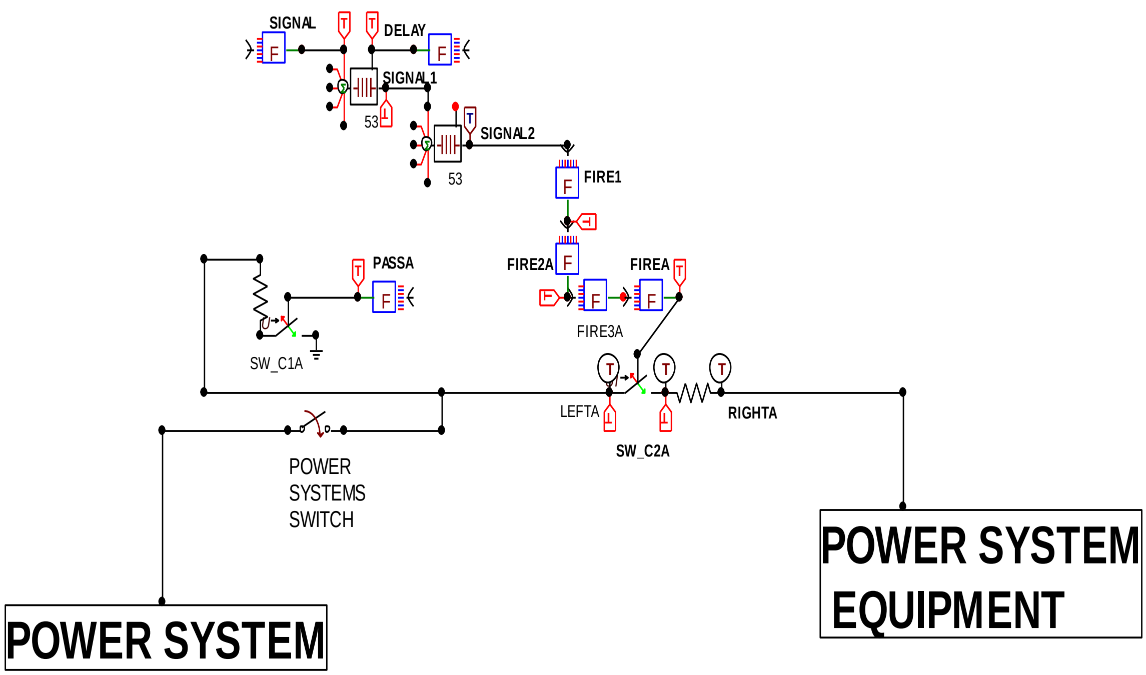


Figure 5.1. Schematic of *PSTC*

5.2 *TACS* Components

The control scheme of the *PSTC* was implemented using *TACS* components available in the *ATP-EMTP* and then interfacing the control scheme to the power system. The *TACS* components used to implement the control scheme are:

- Transport Delay devices
- *FORTRAN* expressions (algebraic and logical) and
- *TACS* controlled switch, type 13
- *TACS* circuit couplings

5.2.1 Transport Delay Device. The Transport Delay Device, Device-53, is designed to delay the input signal by a fixed value or any other variable already that is defined *TACS.* This device is shown in Figure 5.2. The delay of the device can be defined as the output of other *TACS* blocks where the delay is calculated. The input signal enters the delay box and creates an output signal with a delay of *T*. The input-output relationship at any time *t* is given by equation 5.1, where *T* is the delay in seconds [15].

$$output = input(t - T) \tag{5.1}$$

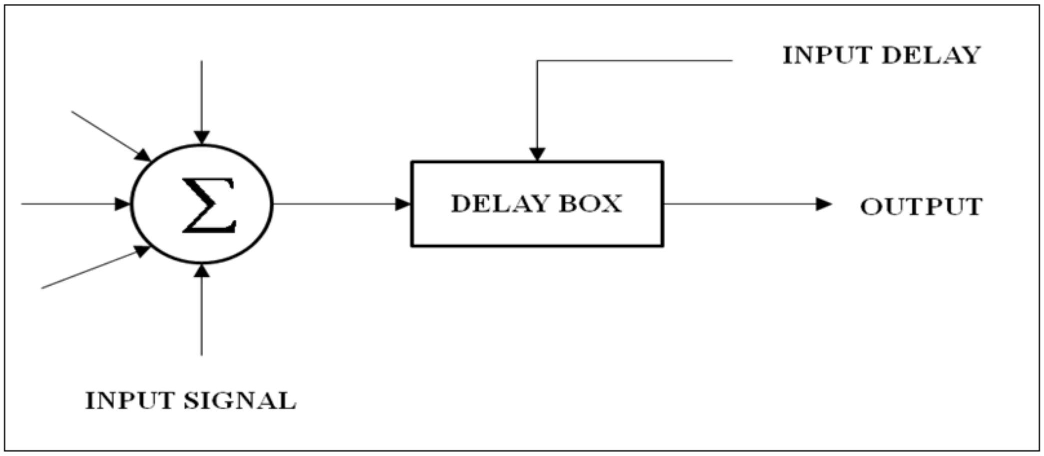


Figure 5.2. Transport Delay Device in *TACS*

5.2.2 *FORTRAN* Expression. The *FORTRAN* general statements use the *FORTRAN* languages and can be as general as the language allows. Algebraic operations (+,-,*,etc), relational operations (<, >, =,etc), *FORTRAN* intrinsic functions (SIN, COS, etc) and special functions can be used within *TACS* [13]. Table 5.1 shows several of these functions used in the control scheme. The output of all logical statements used in *PSTC* is Boolean (1, 0 or -1).

Table 5.1. Logical Statements used in *PSTC*

Logical Function	**Function**
AND(arg.)	Returns T only if arg. is T
OR(arg.)	Returns T if one arg. is T
NOT(arg.)	Returns T if arg. is F
SIGN(arg.)	Arg. > 0 output= 1
	Arg. < 0 output= 0
	Arg. = 0 output= -1

5.2.3 *TACS* Controlled Switch Type 13. The *TACS* controlled switch is controlled by any given *TACS* variable and is shown in Figure 5.3. The variables once assigned or calculated are passed to the signal node of the switch. The *Open/Close* operation of the signal is defined in Tables 5.2 and 5.3 [15].

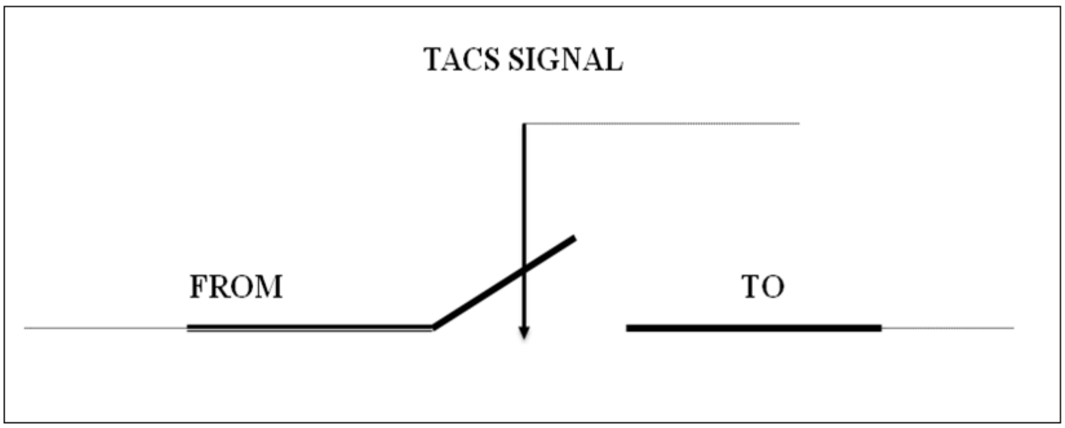


Figure 5.3. Switch Type-13 in *TACS*

Table 5.2. Switching Operation for Switch Type 13 on OPEN Status

SWITCH OPEN (INITIAL)	
SIGNAL	**STATUS SWITCH**
> 0	CLOSE
≤ 0	OPEN

Table 5.3. Switching Operation for Switch Type 13 on CLOSED Status

SWITCH closed (INITIAL)	
SIGNAL	**STATUS SWITCH**
> 0	OPEN
≤ 0	CLOSED

5.2.4 *TACS* Coupling to Circuit. *TACS* coupling to circuit, or *EMTP_OUT*, is the probe that passes *ATP-EMTP* information to *TACS*. These devices act as a source in *TACS* and there are four types available in the *ATP-EMTP*. The *PSTC* will use only two of the devices; type 90 (node voltage) and type 93 (switch status). The type 90 component measures the voltages with respect to ground in the power systems connected to *TACS* and then sends the information to *TACS*. Type 93 sends information regarding the switch status in the power system to *TACS*, sending a 1 if the switch is open and a zero otherwise.

5.3 Control Design

As discussed in chapter 4, there are two possible switching scenarios that can occur. Switching can occur during the positive half cycle of the signal or during the negative half cycle. The *PSTC* is programmed to automatically control switching regardless of the when switching occurs.

The idea as presented in chapter 4, is to close the switch coupling the *PSTC* to the power system at a time when the voltage, energy and power is 0 and reduce the transient signals to acceptable ranges. The responsibility of the *PSTC* is to automatically find the zero crossing point for the voltage across the load bus and then send a signal commanding SW_2 to open or close. This process must occur regardless of the timing at which the switch closes.

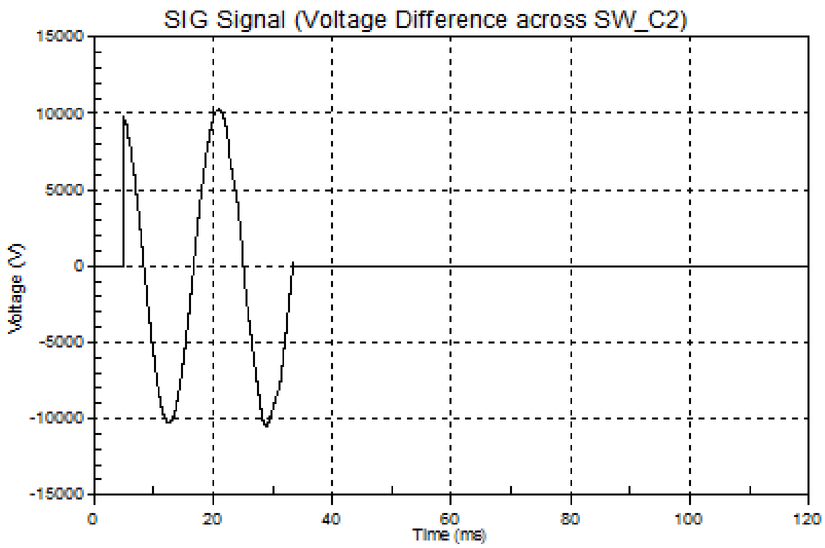
At $t=t_1$, SW_4 is closed, SW_C_1 is closed and SW_C_2 is opened. In order for the minimum energy point to be determined, two signals are needed to be compared. These two signals will be derived from the voltage across SW_C_2 and are called SIG_1 and SIG_2. After switch one closes, the two type-90 components across SW_C_2, *LEFT* and *RIGHT* will read the voltages at these two nodes. The *FORTRAN* expression will calculate this difference and output a signal called *SIG* (Equation 5.2). This *SIG* signal is shown in Figure 5.4a and then again with respect to the voltage at the left side of the switch connected to the main capacitor bus in Figure 5.4b.

$$SIG = (LEFT - RIGHT) \tag{5.2}$$

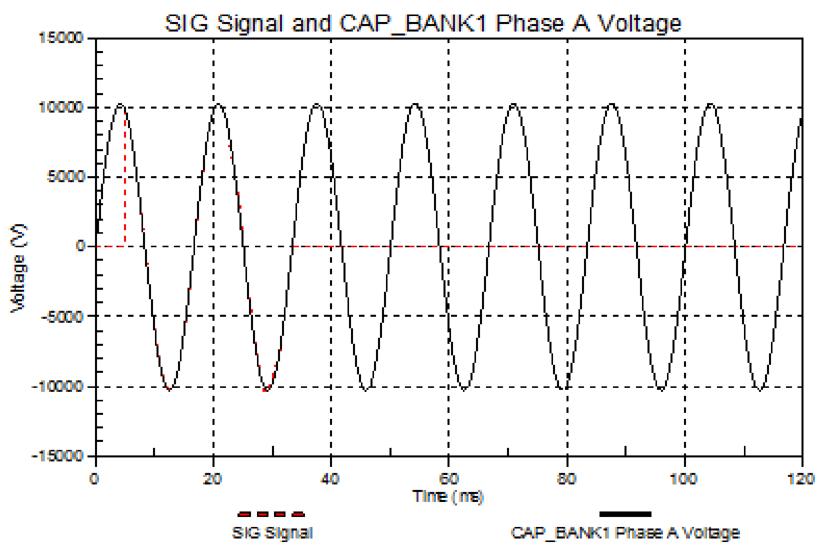
This *SIG* signal will be the input to the first transport delay device. The device will delay this signal by:

$$delay = \frac{1}{f} * n \tag{5.3}$$

The output signal of the first transport delay device (SIG_1) is given by equation 5.4.



(a)



(b)

Figure 5.4. (a) *SIG* Signal (Voltage difference across SW_C_2), (b) *SIG* Signal and *CAP_BANK1*

SIG_1 is the first signal that will be used to determine the minimum point.

$$SIG_1 = SIG\left[t_1 - \left(\frac{1}{f} * n\right)\right] \qquad (5.4)$$

Where,

f- system frequency in hertz

n- number of cycles to be delayed

t1- time SW_1 closes, and

SUB- output signal.

In chapter 2, it was seen that oscillatory transients that often occur after switching can be classified according to predominant frequency and its duration. The classification of these transients, their frequency, duration and optimal number of cycles is shown in Table 5.4.

Table 5.4. Transients Classification

CATEGORY	TYPICAL FREQUENCY	TYPICAL DURATION	*N*
Low	< 5 kHz	0.3 – 50ms	3
Medium	5 – 500 kHz	20μs	1
High	0.5 – 5 MHz	5μs	1

Choosing the value of $n=1$, causes the SIG_1 signal to be delayed by *16.6667 ms* and is shown in Figure 5.5. The second signal used to determine the minimum point will now be generated.

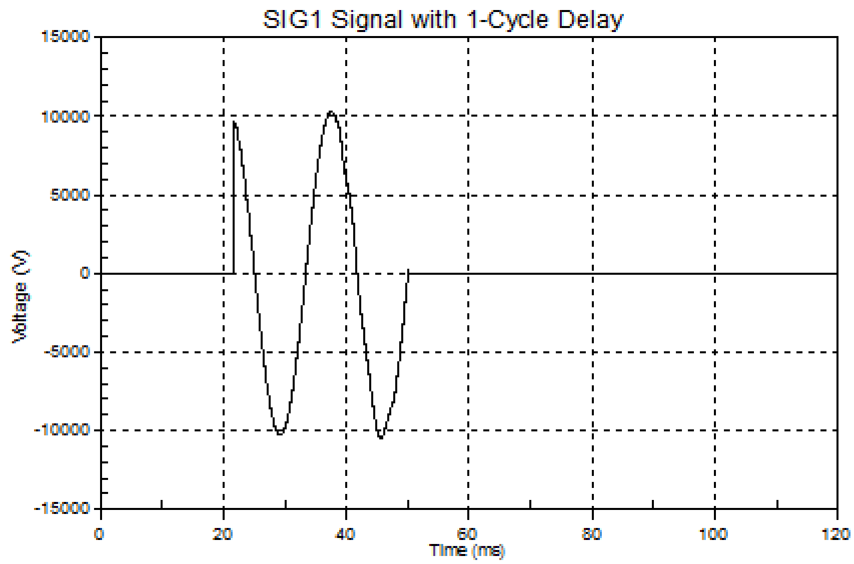


Figure 5.5. SIG_1 Signal with 1-Cycle Delay

The delayed SIG_1 signal is now the input to the second transport delay device. The output signal (SIG_2) is the second signal used to determine the minimum energy point of the voltage across the capacitor and is given by:

$$SIG_2 = SIG_1(t_{11} - \Delta t) \tag{5.5}$$

$$t_{11} = t_1 - \left(\frac{1}{f} * n \right) \tag{5.6}$$

Where,

Δt- size of time step delay (≈ 2e-5 s)

SIG_2- output signal of second Transport Delay Device

The two signals to be compared have been generated and are shown in Figure 5.6. Logical statements must be assigned in order for the *PSTC* to perform the switching procedure automatically.

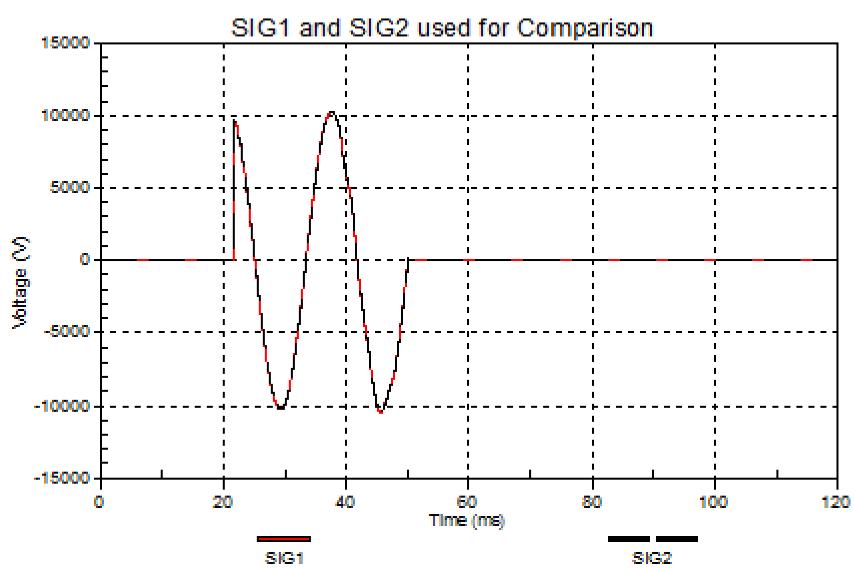


Figure 5.6. *SIG_1* and *SIG_2* used to find Zero Crossing

Recalling from chapter 4, minimum point in the positive half cycle would occur when the sign of the first signal is negative and the sign of the second signal is positive and vice versa for switching in the negative half cycle. The *FORTRAN* expression for $FIRE_1$ will only activate at the point in time in the positive region when these conditions are satisfied and the logical expression is given by:

$$FIRE_1 = SIGN(SIG1).NE.SIGN(SIG2) \tag{5.7}$$

$FIRE_2$ will find the zero point in the negative region and the logical expression is given by:

$$FIRE_2 = SIGN(SIG1).EQ.UNITY.AND.SIGN(SIG2).EQ.MINUS1 \tag{5.8}$$

This expression says that $FIRE_2$ will only activate when the value of SIG_1 is positive and the value of SIG_2 is negative. SW_4 can close at any time along the voltage signal and so both equations 5.7 and 5.8 would need to be satisfied to ensure that the *PSTC* is automatic. Thus using the logical *AND* statement gives $FIRE_3$ in equation 5.9.

$$FIRE_3 = FIRE_1.AND.FIRE_2 \tag{5.9}$$

If the value of $FIRE_3$ becomes 1 then, the signal has reached $Point_1$ and $Point_2$ respectively. Figure 5.7 shows that if switching is done in the first positive half cycle, the

PSTC will ignore the first zero crossing and look for the second zero crossing, $FIRE_1$, and then $FIRE_2$ while if switching occurs in the negative first half cycle, *PSTC* will find the first zero crossing , $FIRE_2$ and then $FIRE_1$. The signal that activates SW_C_2 is *FIRE*. SW_C_2 should close only when $FIRE_3$ becomes 1. Once the switch is closed it should remain closed. The logical *OR* statement must be used to guarantee this and the statement is given in equation 5.10, where $RIGHT_2$ is the status of SW_C_2 is read by the type 93 component.

$$FIRE = FIRE_3.OR.RIGHT_2 \tag{5.10}$$

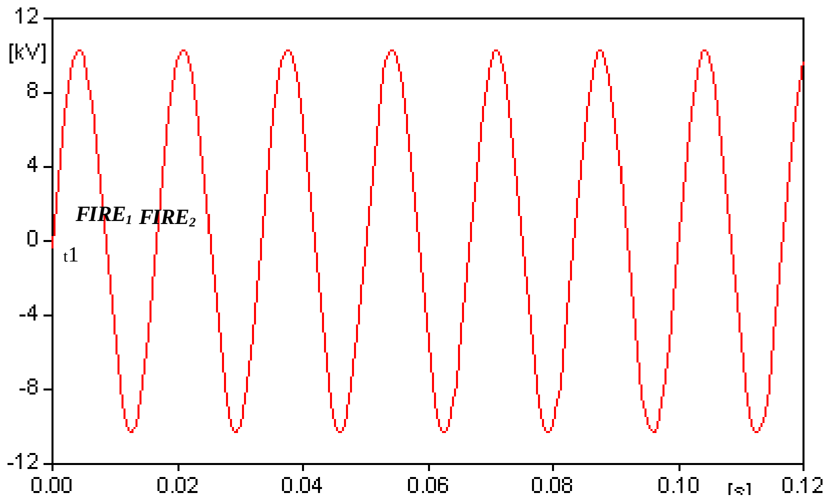


Figure 5.7. $FIRE_1$ and $FIRE_2$ Location on the Voltage Signal

The value of *FIRE (*Figure 5.8) will remain 0 until $FIRE_3$ becomes 1 (*PSTC* finds $Point_1$ and $Point_2$), and once this occurs, SW_C_2 that connects the sensitive power system equipment and load to the main power system will remain closed . While SW_C_2 is open, SW_C_1 is initially closed and diverts and discharges most of the transient signal through the large resistor into the ground. There must be no delay between the closing of *SW2* and the opening of SW_3. To achieve this, the logical *NOT* is used in the *FORTRAN* expression *PASS* (Figure 5.9) controlling SW_C_1 (Equation 5.11).

$$PASS = .NOT.FIRE \tag{5.11}$$

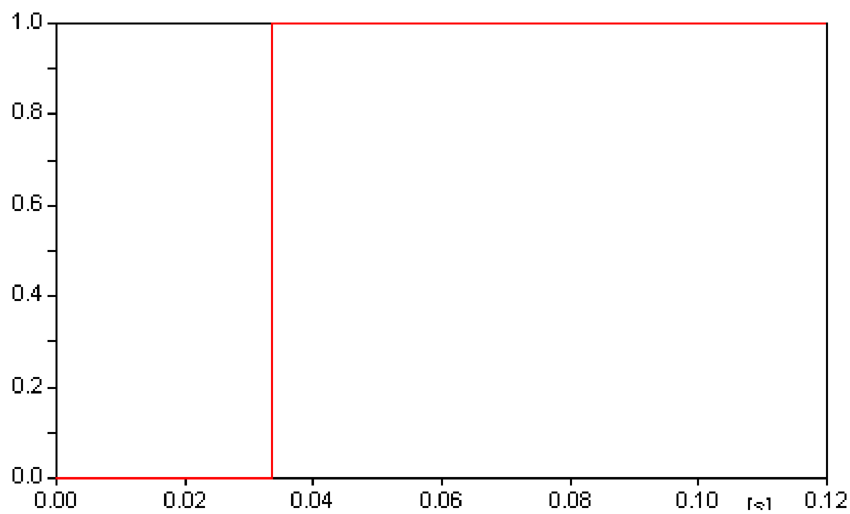


Figure 5.8. *FIRE* Signal to Activate SW_C_2

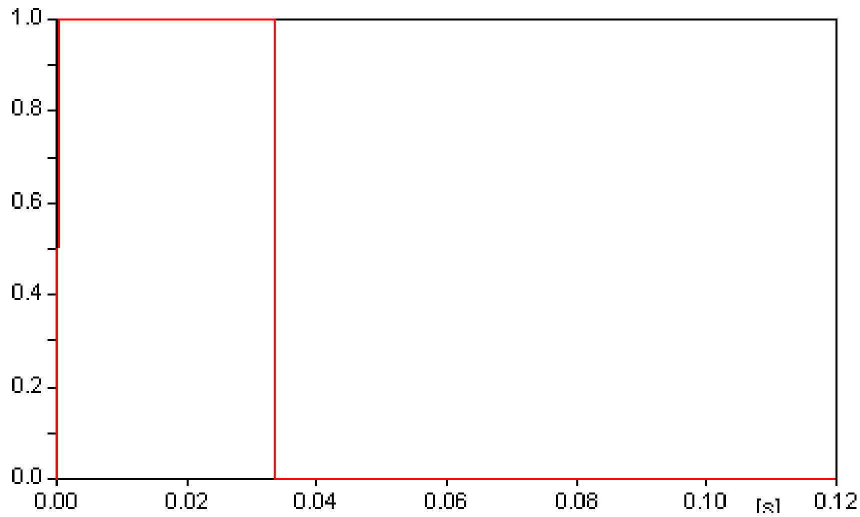


Figure 5.9. ***PASS* Signal to Activate SW_C_1**

Observing the *PASS* and *FIRE* signals, it is seen that *FIRE* signal turns on at the same time the *PASS* signal turns off, *t2*. Any power system equipment connected at the load bus would begin energizing at this time.

CHAPTER 6

RESULTS AND DISCUSSION

6.1 3 Phase Capacitor Switching

Figure 6.1 shows a one line diagram of the 3φ capacitor switching network. The corresponding 3φ diagram of the system is illustrated in Figure 6.2.

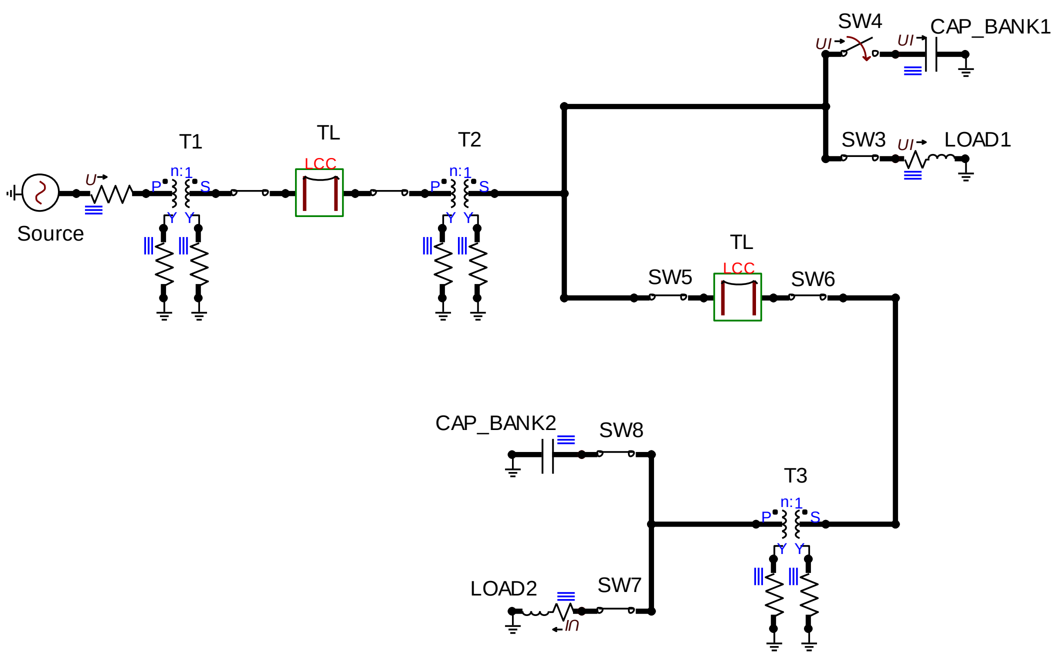


Figure 6.1. One-line Diagram of 3Φ Capacitor Switching Circuit

The power system components used are tabulated in Table 6.1.

Table 6.1. Circuit Parameters

COMPONENT	PARAMETER
Voltage Source	187 kV
Transformer 1	230/115 kV
Transformer 2	115/13.8 kV
Transformer 3	13.8/0.48 kV
Transmission Line 1	150 Miles Parallel Line
Transmission Line 2	100 Miles Flat Line
Load 1	6.475 + j4.013Ω
Load 2	0.1958 + j0.1214Ω
Capacitor Bank 1	139.3 μF
Capacitor Bank 2	5756 μF

6.1.1 Capacitor Switching without *PSTC* in Positive Half Cycle. The capacitor in Figure 6.1 is switched on at *t=4ms*. By observing the voltage across the capacitor, the transients that are provoked as a result of the switching operation can be observed. The graph in Figure 6.2 depicts phase 'a' of the 3-phase signal. The initial transient surge is approximately 18.3kV, almost twice that of the steady state voltage of 10.33kV. The capacitor inrush current in Figure 6.4 surges at over 7000 A (≈ 7300A) before it settles to close to 600A in the steady state condition. These exorbitant values can cause severe damage to the capacitor banks.

Not only does the switching operation cause dangerous transients to be experienced by the capacitor bank, the load connected to the bus with the capacitor bank is adversely affected. Figure 6.4 shows the 3 phases of the load voltage and Figures 6.5 and 6.6 show the phase ‘a’ load voltage and current after the switch closes.

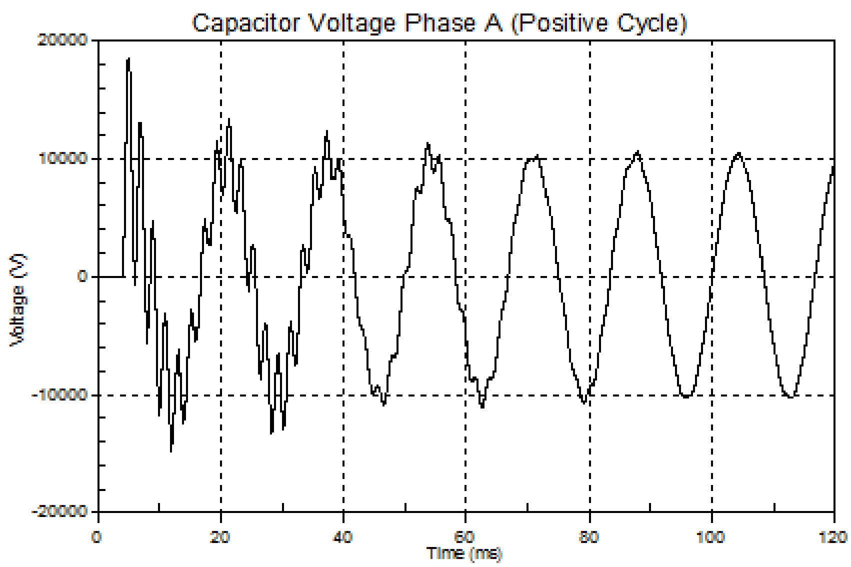


Figure 6.2. Capacitor Voltage Phase A (Positive Cycle)

The transient surges of the load voltage (≈18.4 kV) are almost twice the size of the steady state load voltage (≈10.5 kV) and the load current (≈1590A) exceeds the steady state condition (1340A) by almost 300 A. Figure 6.6 shows the load voltage for all three phases without *PSTC* implemented.

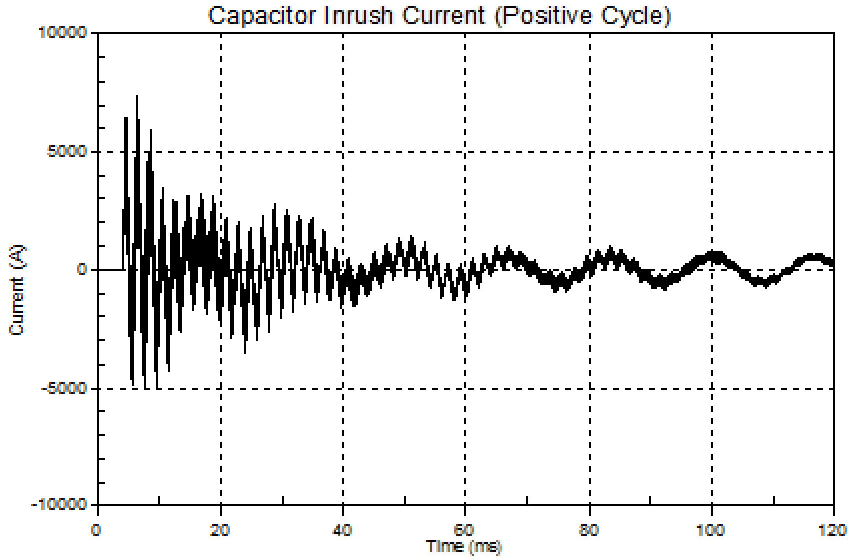


Figure 6.3. Capacitor Inrush Current (Positive Cycle)

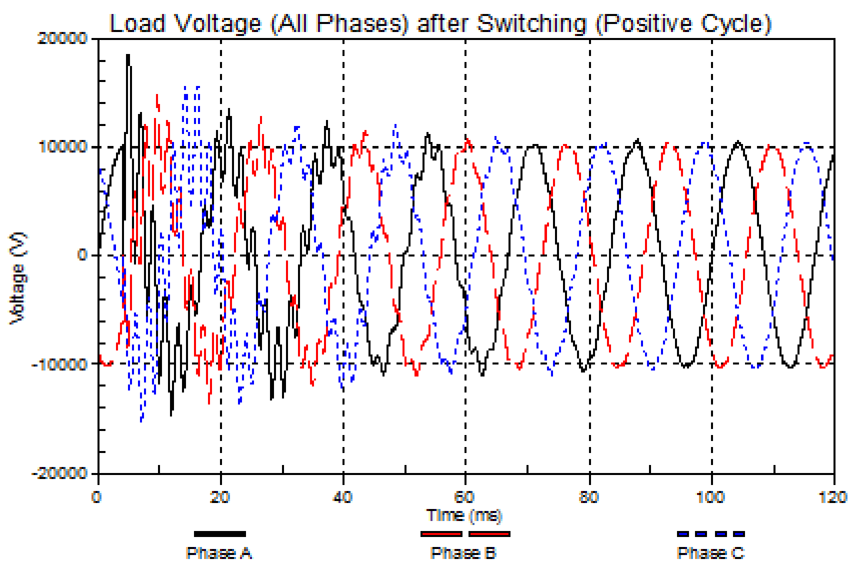


Figure 6.4. Load Voltage (All Phases) after Switching (Positive Cycle)

6.1.2 Capacitor Switching with *PSTC* in Positive Half Cycle. The system designed is supported by a balanced 3φ voltage source. The phases are called phase 'a', phase 'b' and phase 'c'. Each source is 120° out of phase with each other, but the magnitude and frequency of the generated voltage is the same. Although, the voltages are out of phase with each other (Figure 6.4), each phase experiences transient spikes. The *PSTC* developed is designed to control switching for a single phase voltage and thus. The switching times determined by *TACS* will be different for each phase and so this control scheme must be repeated across each phase.

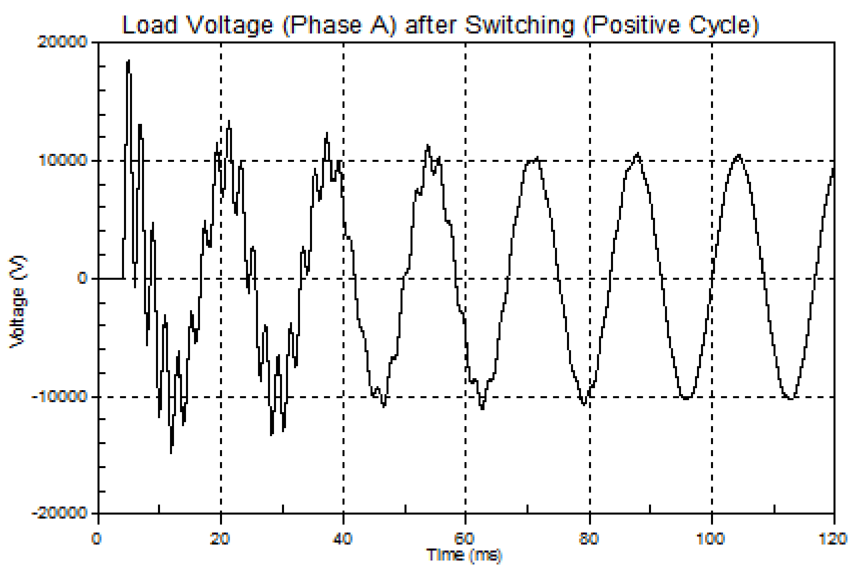


Figure 6.5. Load Voltage (Phase A) after Switching (Positive Cycle)

Figure 6.7 gives the circuit schematic for the power system network and the *PSTC* implemented on each phase. The switch energizing the capacitor has been replaced with three individual switches. The capacitor bank is also spliced into three individual quantities. SW_4 is controlled by the power system network and is where the signal to close comes from.

When the SW_{4a}, SW_{4b} and SW_{4c} close simultaneously, each controller must find the zero crossing point across its switches and then sends the signal to the respective *TACS* type 13 switches. The voltage across the capacitor phase 'a' is shown in Figure 6.8. The *PSTCs'* function is to find the zero crossing of the voltage across the switches in each phase.

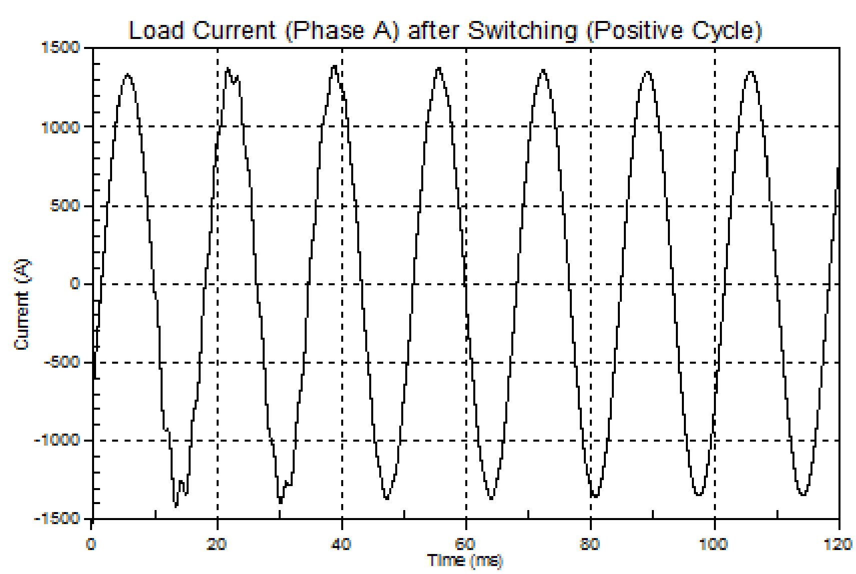


Figure 6.6. Load Current (Phase A) after Switching (Positive Cycle)

While waiting to find the corresponding zero crossing points, the *PSTC* on each phase, diverts the unwanted transient signal to ground through the large resistor connected to SW_3. Once the zero crossing points are found for each phase SW_2 is closed and the voltage across the capacitor bank for each phase is shown in Figure 6.9. The voltage across the capacitor no longer experiences surging at almost 18.3kV. The *PSTC* diverted the transients to ground and the maximum voltage experienced by the capacitor bank is approximately 10.3kV.

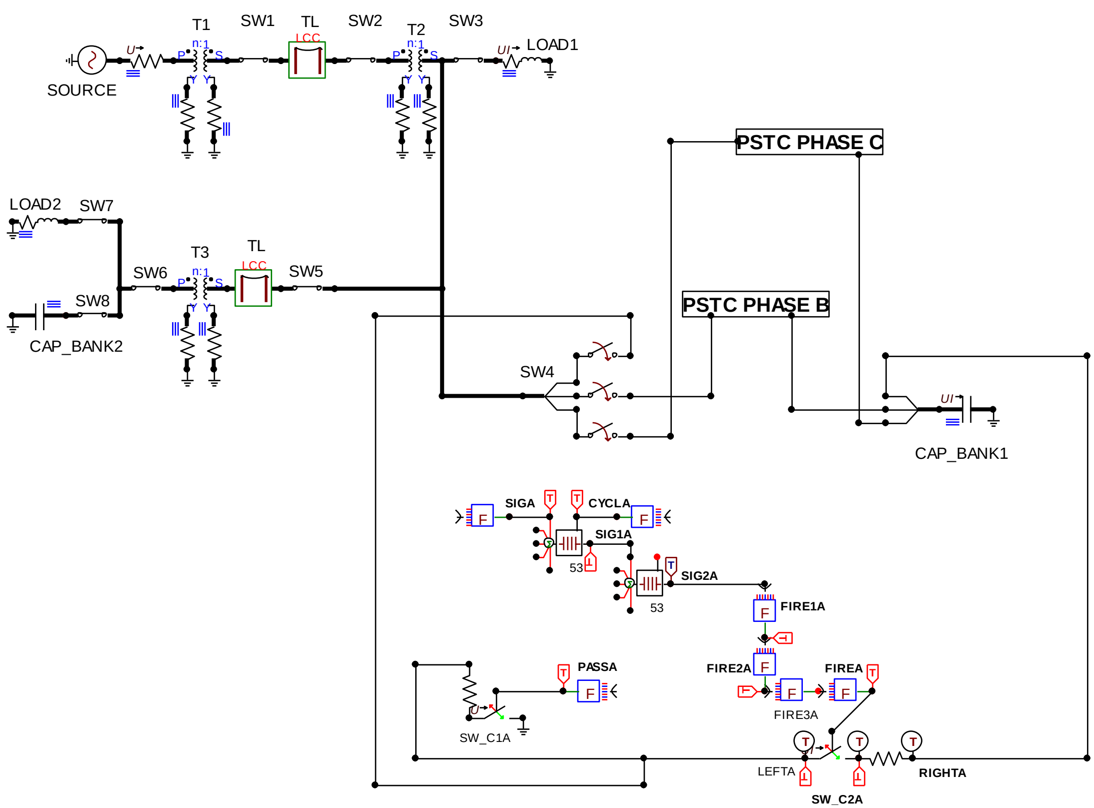


Figure 6.7. 3Φ Capacitor Switching Circuit Implementing *PSTC* (Phase A)

Figure 6.9 verifies the fact that due to the phase relationship of the voltages of the power system, the voltage across each phase begins at three different times. The load voltages and currents for each phase are also affected by the *PSTC*. Figure 6.10 shows the capacitor inrush current when *PSTC* is implements. Figure 6.11 shows that load 1 is no longer threatened by transient surges almost twice that of the voltage in steady state. The voltage across the load after the delay is now near 10.5 kV, much closer to the steady state voltage and less dangerous to the load.

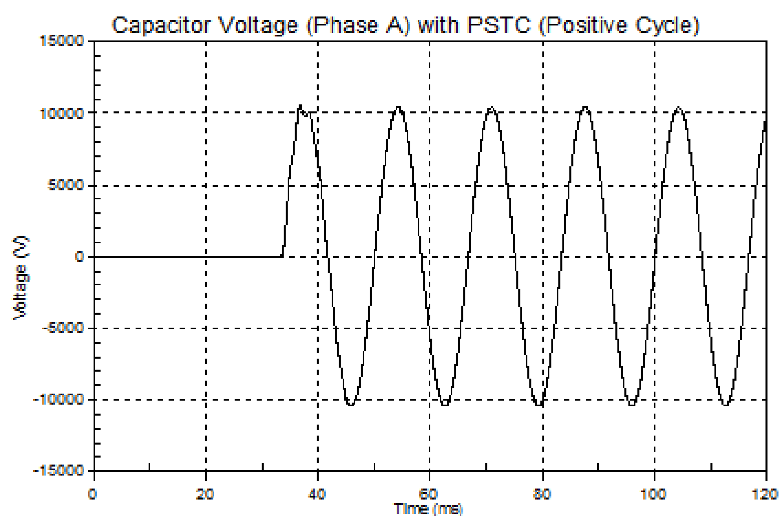


Figure 6.8. Capacitor Voltage (Phase A) with *PSTC* (Positive Cycle)

Figure 6.12 illustrates all three phases of the load voltage and the respective times each capacitor was switched in by the *PSTC*. Again, the load voltage is highest at this point, however, the surges are at tolerable levels.

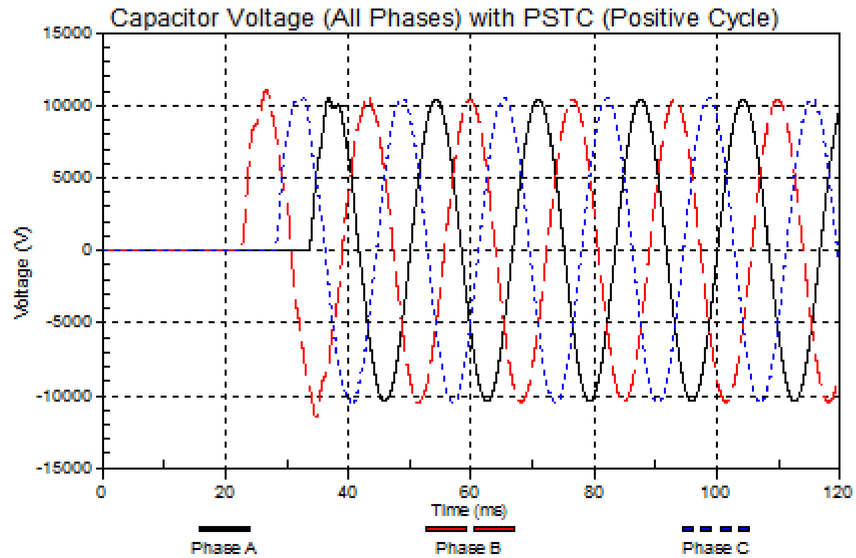


Figure 6.9. Capacitor Voltage (All Phases) with *PSTC* (Positive Cycle)

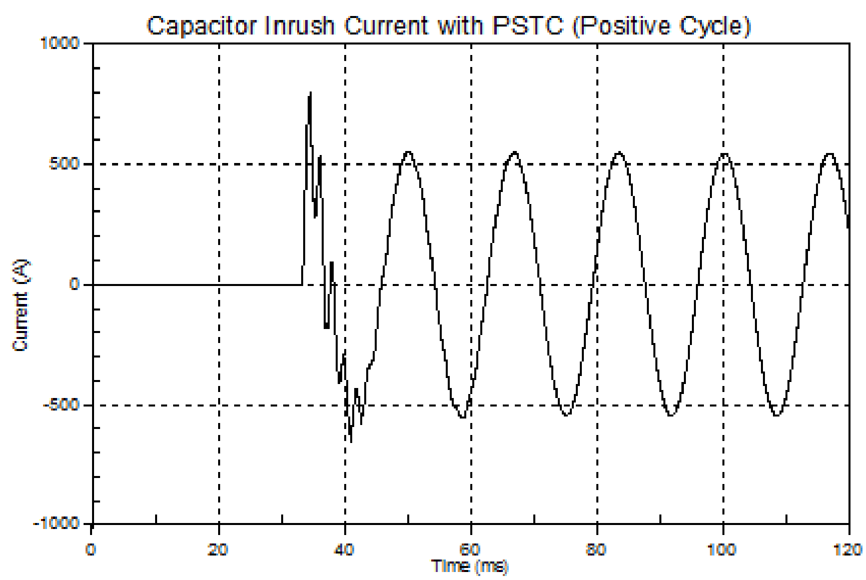


Figure 6.10. Capacitor Inrush Current with *PSTC* (Positive Cycle)

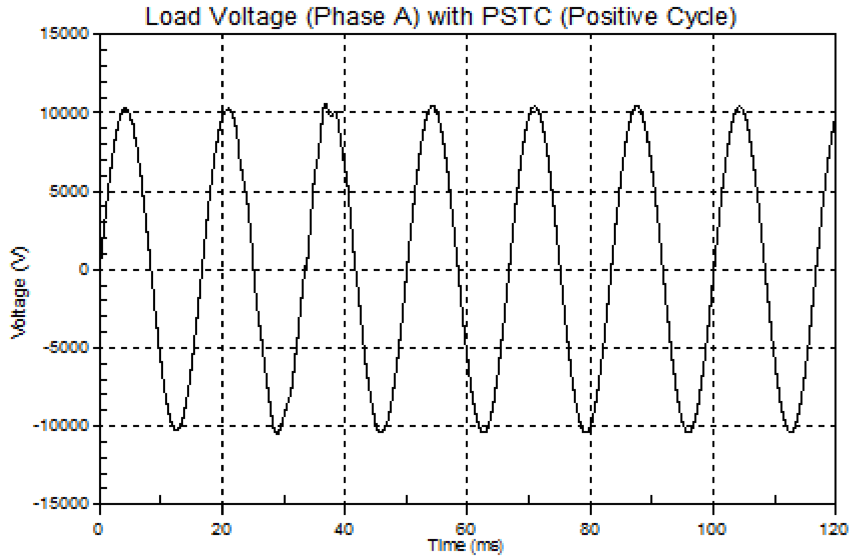


Figure 6.11. Load Voltage (Phase A) with *PSTC* (Positive Cycle)

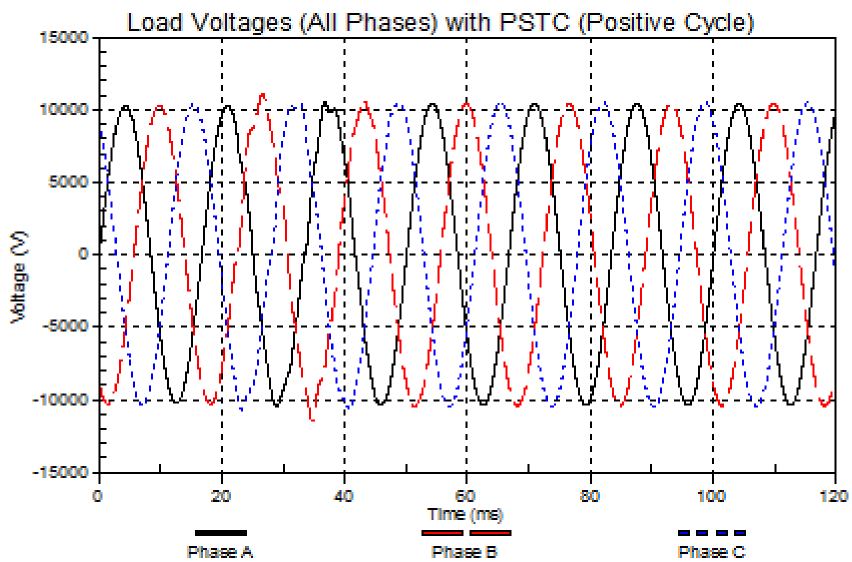


Figure 6.12. Load Voltages (All Phases) with *PSTC* (Positive Cycle)

6.1.3 Capacitor Switching without *PSTC* in Negative Cycle. SW_4 of Figure 6.1 is closed at $t=10ms$; the negative half cycle. The resulting voltage across and inrush current through the capacitor are shown in Figures 6.13 and 6.14. Since the switching is done in the negative half cycle, the initial transient surge across the capacitor is in the negative half cycle and is approximately -14.46kv is comparison to the -10.3 kV with currents peaking at near -5000A and settling to nearly 600A.

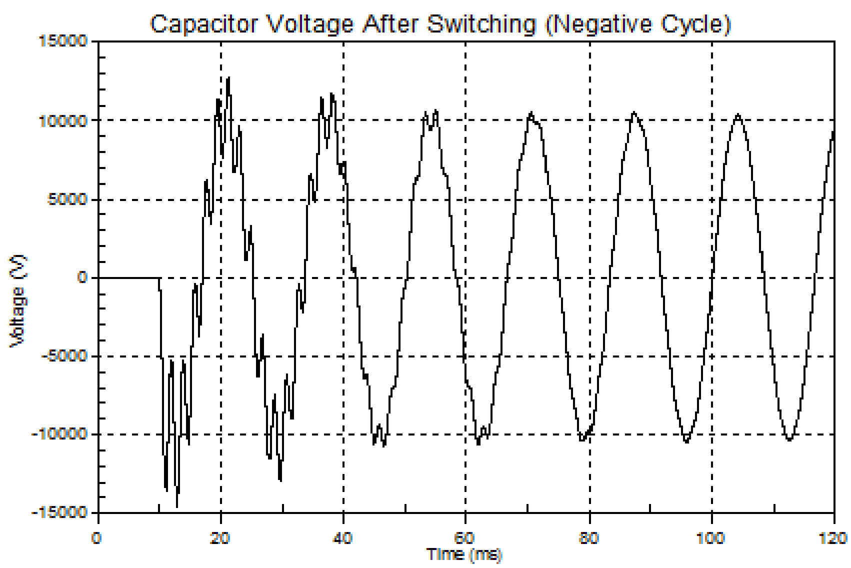


Figure 6.13. Capacitor Voltage after Switching (Negative Cycle)

Even though the initial transients occur in the negative half cycle, these transients can cause abnormalities load 1 connected to the capacitor bank. Figure 6.15 shows the phase ‘a’ load voltage.

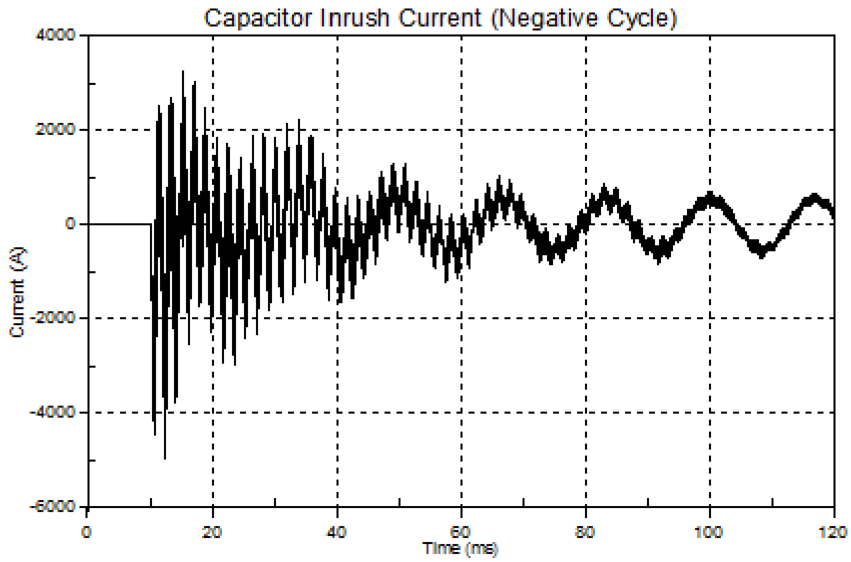


Figure 6.14. Capacitor Inrush Current (Negative Cycle)

6.1.4 Capacitor Switching with *PSTC* in Negative Cycle. The *PSTC* is designed to be able to automatically control switching no matter which half cycle the switch is closed during. So, with no adjustments made to the *PSTC* parameters, the circuit in Figure 6.7 was implemented with SW_3 closing at $t=10ms$.

Again, it is seen that with the *PSTC* in place, there was significant decrease in the transient voltage surges across the capacitor bank and inrush capacitor currents. These effects are shown in Figures 6.16 and 6.17.

Load 1 also is affected by the *PSTC* implementation and the Voltage across the load is shown in Figure 6.18.

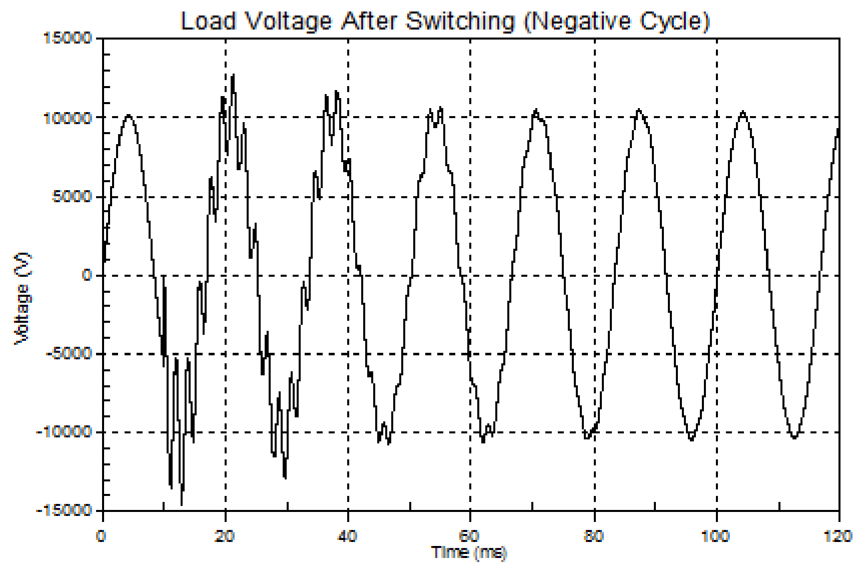


Figure 6.15. Load Voltage after Switching (Negative Cycle)

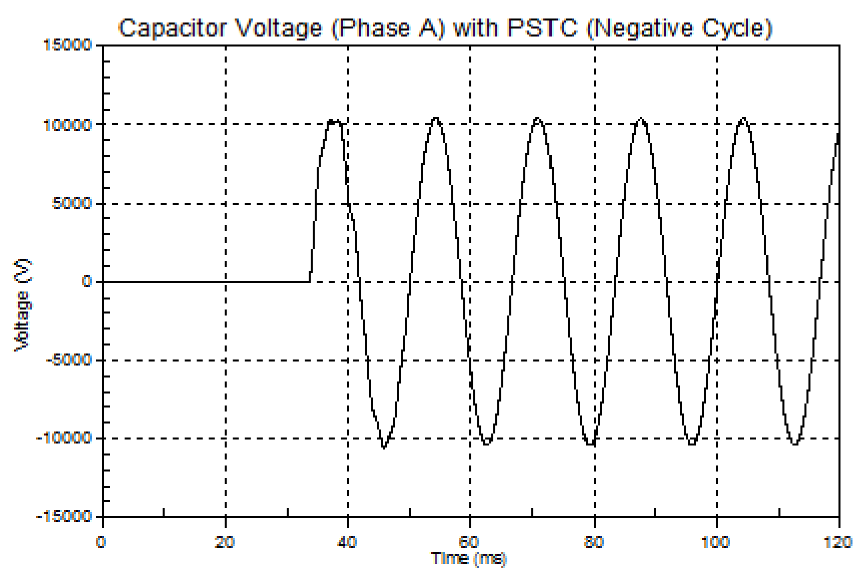


Figure 6.16. Capacitor Voltage (Phase A) with *PSTC* (Negative Cycle)

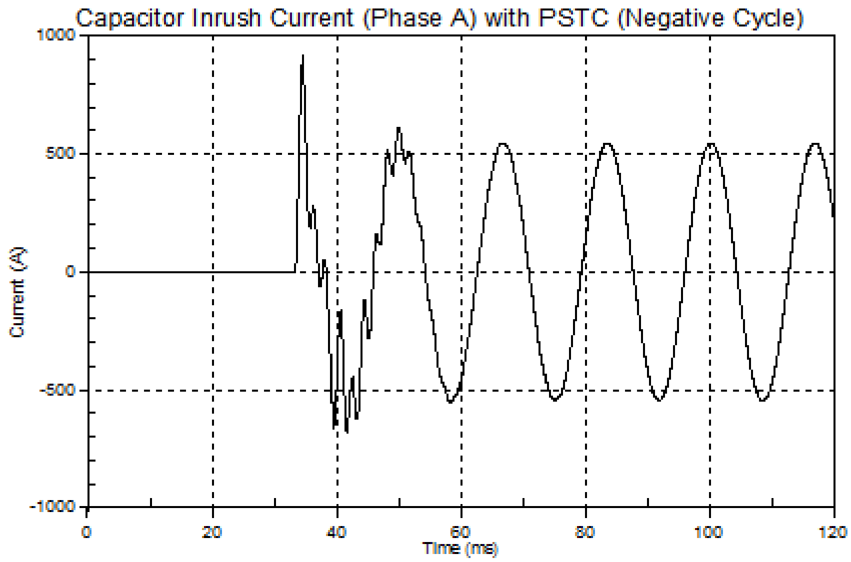


Figure 6.17. Capacitor Inrush Current (Phase A) with *PSTC* (Negative Cycle)

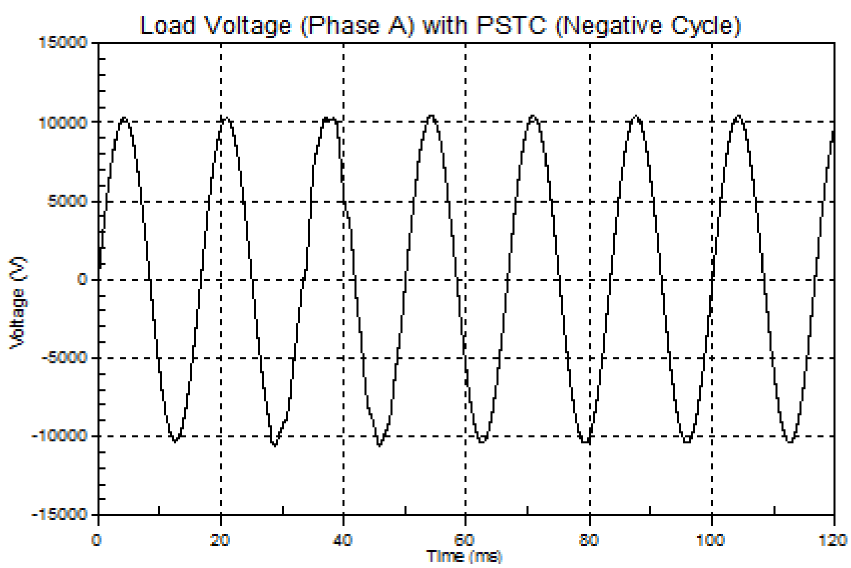


Figure 6.18. Load Voltage (Phase A) with *PSTC* (Negative Cycle)

6.2 Single Phase-to-Ground Fault

As previously discussed, single phase-to-ground faults are the most frequent on the power system. Figure 6.19 shows the one-line diagram of a 3φ two bus system with a single-phase to ground fault in phase ‘c’.

6.2.1 Single Phase-to-Ground Fault without *PSTC*. The switch in Figure 6.19 closes at *t=5ms*. Line to ground faults are often permanent and cannot be addressed be reclosing. Although the fault occurs only on the ‘c’ phase, the fault causes transients to be experienced on phase ‘a’ and ‘b’ as well. The voltage across the load and capacitor are the same since they are connected in parallel and no switching is occurring at this time.

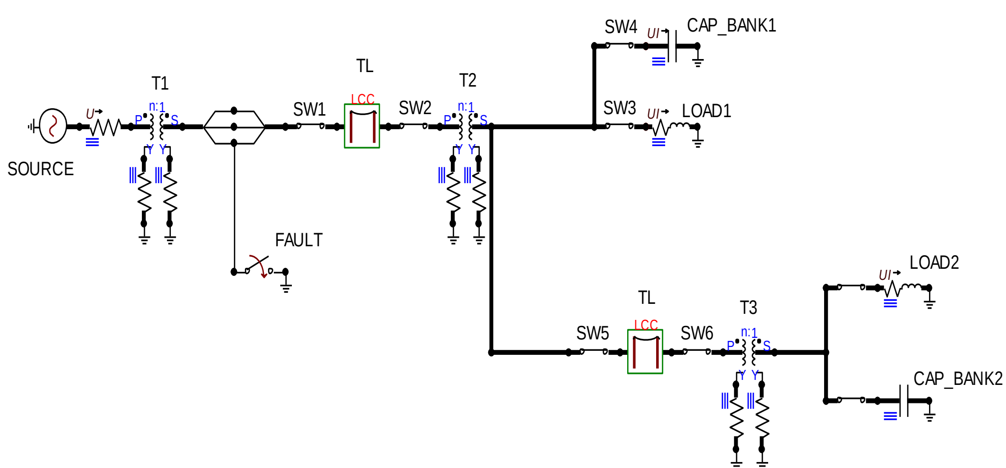


Figure 6.19 One-line Diagram of 3Φ Single Phase-to-Ground Fault Circuit

The voltage in phase 'a' and 'c' after the fault occurs across the capacitor and the load is shown in Figure 6.20 and 21. The transient surge after the fault for the voltage is almost 17.0 kV while the steady state voltage settles at almost 1.5kV less than this value. Although this surge may not seem excessive in value, sensitive load equipment cannot handle voltage spikes of this magnitude frequently and could face damage.

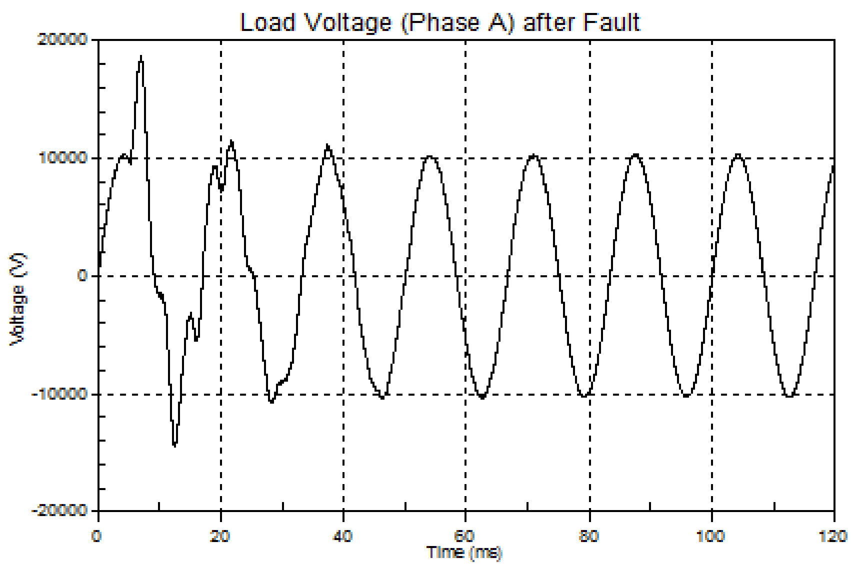


Figure 6.20. Capacitor and Load Voltage (Phase A) after Fault

6.2.2 Single Phase-to-Ground Fault with *PSTC*. As seen with capacitor switching, the *PSTC* diverts certain cycles of an unwanted signal to ground eliminating the negative effects of any transients on sensitive load equipment (Figure 6.22).

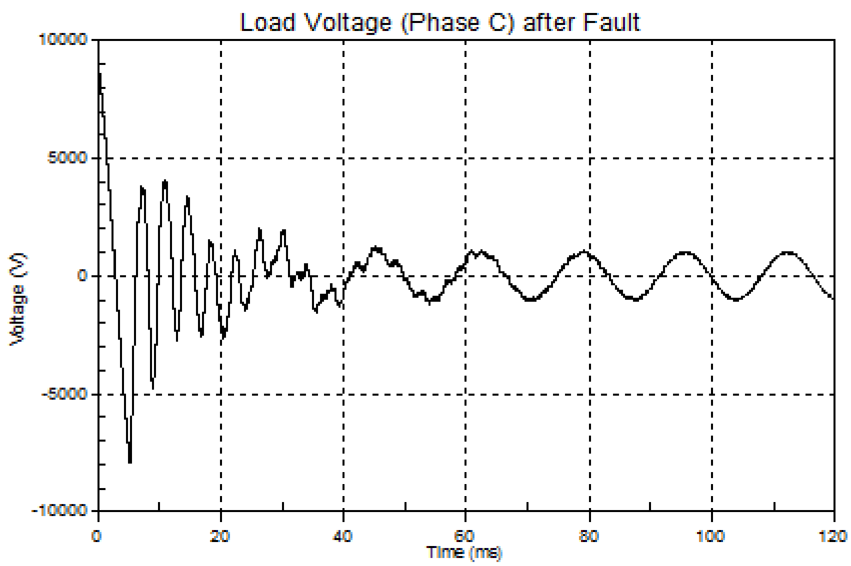


Figure 6.21. Capacitor and Load Voltage (Phase C) after Fault

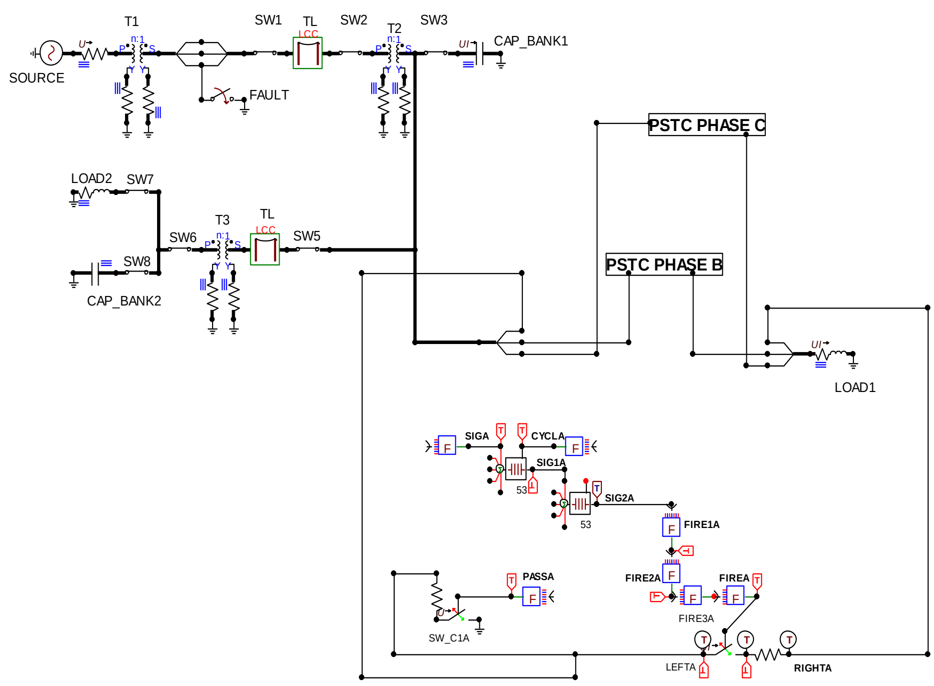


Figure 6.22. ***PSTC*** **Implemented for Single Phase-to-Ground Fault**

Simulation of the fault without *PSTC* showed us that the capacitor and load1 voltage would be equal as they are connected in parallel. The *PSTC* will now use the minimum/maximum tracking method to find when to allow voltage across the load after the fault.

Initially the *PSTC* will block the transient voltage signal from the load for only the first cycle. The delayed voltage across the phase 'a' load is shown in Figure 6.23.

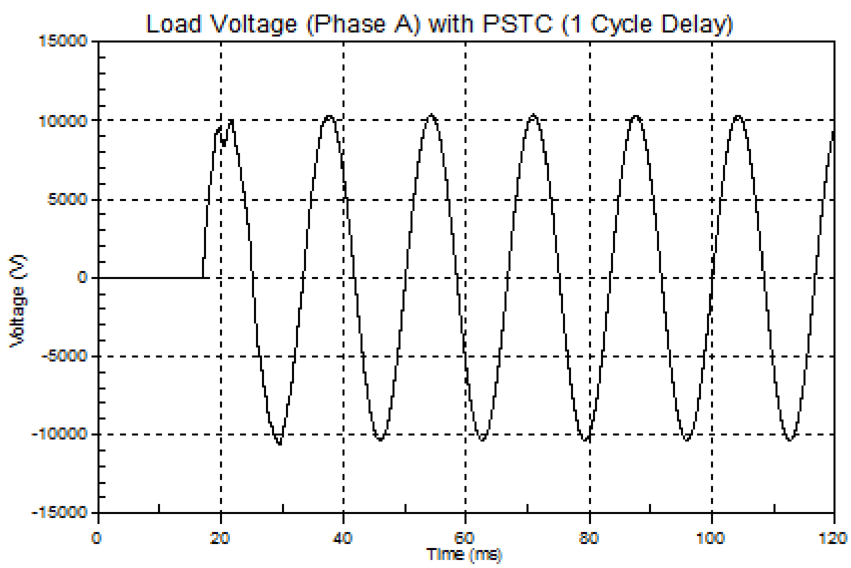


Figure 6.23. Load Voltage (Phase A) with *PSTC* (1-Cycle Delay)

Due to the fault occuring on phase 'c' the system is no longer balance. To better see the affects of the contoller on system, the load voltage of phase 'a' is graphed with respect to the capacitor voltage (Figure 6.24) since they should be the same as they are connected in parallel.

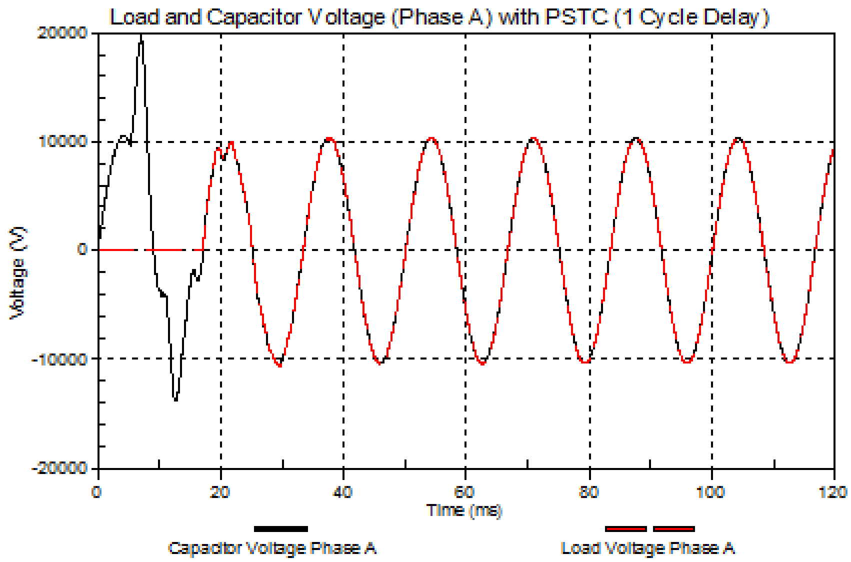


Figure 6.24. Load and Capacitor Voltage (Phase A) with *PSTC* (1-Cycle Delay)

The number of cycles the signal can be delayed can be adjusted as desired by simply adjusting the input delay to the first transport delay device. The voltage across the load can be improved by adding more time delays or diverting more of the transient signal to ground. Figure 6.25 shows the load phase ‘a’ voltage with a three cycle delay and Figure 6.26 shows the capacitor and load voltage for the perspective phases with this three cycle delay.

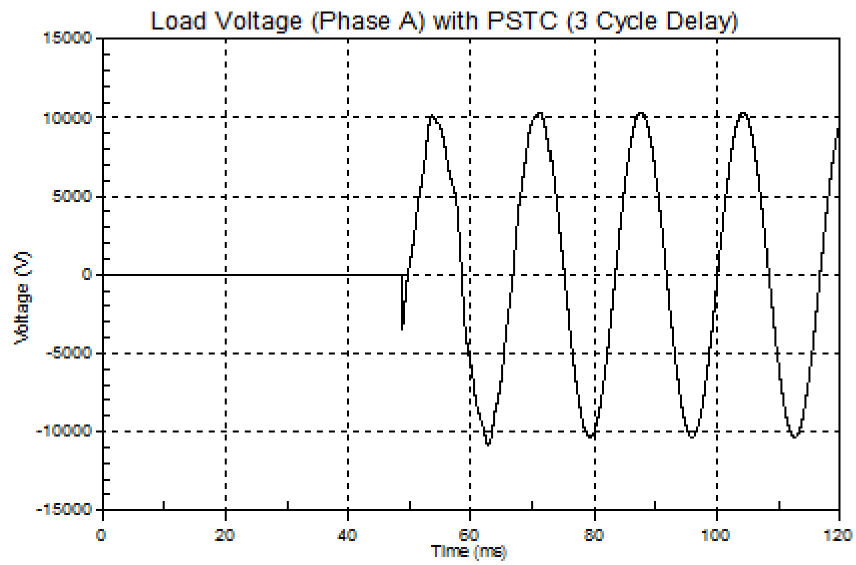


Figure 6.25. Load Voltage (Phase A) with *PSTC* (3-Cycle Delay)

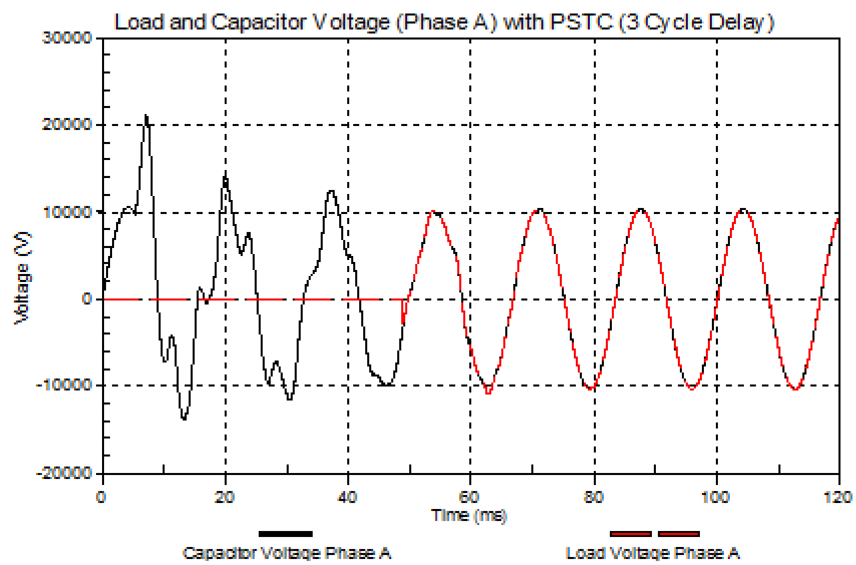


Figure 6.26. Load and Capacitor Voltage (Phase A) with *PSTC* (3-Cycle Delay)

CHAPTER 7

CONCLUSION

7.1 Summary

Delivering reliable electricity efficiently is of paramount importance to electric utilities. Of equal importance to these utilities is the generation of power in the most economical way possible. Shunt capacitors banks are used in the power system to improve the power factor and help maintain the systems voltage security. These capacitor banks if switched into the power system can induce transients that can be potentially dangerous to the capacitor banks and end use loads. Faults are any occurrences that may cause an abnormality in the flow of current and in addition to capacitor switching, induce transients on the power system. Single phase-to-ground faults are most common and induce transients on unaffected phases. Transient disturbances on the power system affect the reliability, safety and costs of power delivery.

This research presents a controller using Transient Analysis of Control System (*TACS*) in the *ATP-EMTP* software. The Power System Transients Controller (*PSTC*) was developed using the minimum/maximum signal tracking method. If capacitor voltage is zero, both the instantaneous power of the capacitor and energy of the capacitor will be zero. If the switching can occur at these specific instances in time, the transient signals otherwise provoked by switching events can be considerable reduced and even eliminated. For sinusoidal signals, switching can occur in the positive half cycle or negative half cycle. The *PSTC* is designed to automatically switch no matter what cycle switching is done.

In the instances of a fault, the *PSTC* is designed to block the transient signal from being seen by the load. The number of cycles the load voltage can be delayed can be adjusted as desired. The longer the delay, however, increases the length of time the load is not energized which affects system reliability.

7.2 Future Work

The future of the *PSTC* lies in moving from a simulated environment and making the device hardware to be implemented in the power system. In addition the controller can be enhanced from a single phase controller, to operate as a 3Φ controller. This would require robust switching control expressions that are time and phase sensitive.

As the utility industry advances toward a smart gird, the *PSTC* can be implemented into this new era of system development by improving the control switching to perform automatic fault-isolation switching operations and feeder re-routing after faults.

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APPENDIX

ATP-EMTP SAMPLE PROGRAM

The following presents a sample *ATP-EMTP* program used to generate the results for capacitor switching in the positive half cycle.

ATP-EMTP Code for Capacitor Switching in Positive Half Cycle With *PSTC*

```
C -----------------------------------------------------
C Generated by ATPDRAW  October, Thursday 14, 2010
C A Bonneville Power Administration program
C by H. K. Høidalen at SEfAS/NTNU - NORWAY 1994-2009
C -----------------------------------------------------
POWER FREQUENCY                  60.
$DUMMY, XYZ000
C  dT  >< Tmax >< Xopt >< Copt >
  2.E-5    .12
    500      1      1      1      1      0      0      1      0
/TACS
TACS HYBRID
98DIF1A   =LEFTA-CAPA
98FIRE3A  =FIRE1A.AND.FIRE2A
```

```
98CYCLA   =1/FREQHZ
98FIRE2A  =SIGN(DIFA).EQ.UNITY.AND.SIGN(PREVA).EQ.MINUS1
98FIRE1A  =SIGN(DIFA).NE.SIGN(PREVA)
98FIREA   =FIRE3A.OR.RIGHTA
98PASSA   =.NOT.FIREA
98DIFA  53+DIF1A                                  CYCLA
98PREVA 53+DIFA                                   DELTAT
98FIRE2B  =SIGN(DIFB).EQ.UNITY.AND.SIGN(PREVB).EQ.MINUS1
98DIF1B   =LEFTB-CAPB
98FIREB   =FIRE3B.OR.RIGHTB
98PASSB   =.NOT.FIREB
98FIRE1B  =SIGN(DIFB).NE.SIGN(PREVB)
98FIRE3B  =FIRE1B.AND.FIRE2B
98CYCLB   =1/FREQHZ
98DIFB  53+DIF1B                                  CYCLB
98PREVB 53+DIFB                                   DELTAT
98FIRE2C  =SIGN(DIFC).EQ.UNITY.AND.SIGN(PREVC).EQ.MINUS1
98FIRE1C  =SIGN(DIFC).NE.SIGN(PREVC)
98PASSC   =.NOT.FIREC
98FIREC   =FIRE3C.OR.RIGHTC
98FIRE3C  =FIRE1C.AND.FIRE2C
98DIF1C   =LEFTC-CAPC
```

98CYCLC =1/FREQHZ	
98PREVC 53+DIFC	DELTAT
98DIFC 53+DIF1C	CYCLC
90LEFTA	10.
93RIGHTA	10.
90CAPA	10.
90LEFTB	10.
93RIGHTB	10.
90CAPB	10.
93RIGHTC	10.
90CAPC	10.
90LEFTC	10.
33DIF1C	
33FIRE1C	
33PREVC	
33FIRE2C	
33LEFTC	
33RIGHTC	
33CYCLC	
33DIFB	
33FIRE1B	
33LEFTB	

33PREVB

33CYCLB

33FIRE2B

33DIF1B

33RIGHTB

33DIFC

33CYCLA

33DIF1A

33DIFA

33FIRE1A

33PREVA

33FIRE2A

33LEFTA

33RIGHTA

33PASSA

33FIREA

33FIREB

33PASSB

33FIREC

33PASSC

C 1 2 3 4 5 6 7 8

C

```
34567890123456789012345678901234567890123456789012345678901234567890123456789012345
567890
/BRANCH
C < n1 >< n2 ><ref1><ref2>< R  >< L  >< C  >
C < n1 >< n2 ><ref1><ref2>< R  >< A  >< B  ><Leng><><>0
  X0002AX0005A           1.E-6                                    2
  X0002BX0005B           1.E-6                                    2
  X0002CX0005C           1.E-6                                    2
  LOAD1A               6.475 4.013                                3
  LOAD1B               6.475 4.013                                3
  LOAD1C               6.475 4.013                                3
  CAP2A                      5756.                                0
  CAP2B                      5756.                                0
  CAP2C                      5756.                                0
  X0011A              1.E-6                                       0
  X0011B              1.E-6                                       0
  X0011C              1.E-6                                       0
  X0015A              1.E-6                                       0
  X0015B              1.E-6                                       0
  X0015C              1.E-6                                       0
  X0017A              1.E-6                                       0
  X0017B              1.E-6                                       0
```

X0017C	1.E-6	0
X0010A	1.E-6	0
X0010B	1.E-6	0
X0010C	1.E-6	0
CAPA	139.3	3
CAPB	139.3	3
CAPC	139.3	3
LEFTA XX0028	350.	0
RIGHTACAPA	1.E-6	0
RIGHTBCAPB	1.E-6	0
LEFTB XX0037	350.	0
RIGHTCCAPC	1.E-6	0
LEFTC XX0046	350.	0
X0008A	1.E-6	0
X0008B	1.E-6	0
X0008C	1.E-6	0
X0006A	1.E-6	0
X0006B	1.E-6	0
X0006C	1.E-6	0
X0018A	.1958 .1214	0
X0018B	.1958 .1214	0
X0018C	.1958 .1214	0

```
$INCLUDE, C:\ATP-EMTP\bin\LINE1.lib, X0013A, X0013B, X0013C, X0019A,
     X0019B
$$  , X0019C
$INCLUDE, C:\ATP-EMTP\bin\LINE1.lib, X0016A, X0016B, X0016C, X0012A,
     X0012B
$$, X0012C
/SWITCH
C < n 1>< n 2>< Tclose ><Top/Tde ><   Ie   ><Vf/CLOP ><  type  >
  X0012AX0001A        -1.      10.                                  0
  X0012BX0001B        -1.      10.                                  0
  X0012CX0001C        -1.      10.                                  0
  X0001ALOAD1A        -1.      10.                                  0
  X0001BLOAD1B        -1.      10.                                  0
  X0001CLOAD1C        -1.      10.                                  0
  X0007AX0013A        -1.      10.                                  0
  X0007BX0013B        -1.      10.                                  0
  X0007CX0013C      -1.      10.                                    0
  X0047AX0014A      -1.      10.                                    0
  X0047BX0014B      -1.      10.                                    0
  X0047CX0014C      -1.      10.                                    0
  X0018AX0047A      -1.      10.                                    0
  X0018BX0047B      -1.      10.                                    0
```

```
  X0018CX0047C      -1.      10.                                0
  X0019AX0009A      -1.      10.                                0
  X0019BX0009B      -1.      10.                                0
  X0019CX0009C      -1.      10.                                0
  X0001ALEFTA      .004      10.                                0
  X0047ACAP2A       -1.     1.E3                                0
  X0047BCAP2B       -1.     1.E3                                0
  X0047CCAP2C       -1.     1.E3                                0
  X0001CLEFTC      .004      10.                                0
  X0001BLEFTB      .004      10.                                0
13XX0028                              CLOSED      PASSA   2
13LEFTA RIGHTA                                   FIREA   3
13XX0037                              CLOSED      PASSB   2
13LEFTB RIGHTB                                   FIREB   3
13LEFTC RIGHTC                                   FIREC   3
13XX0046                              CLOSED      PASSC   2
/SOURCE
C < n 1><>< Ampl.  >< Freq.  ><Phase/T0><   A1   ><   T1   >< TSTART >< TSTOP  >
14X0002A    187794.      60.     -90.                     -1.       1.
14X0002B    187794.      60.    -210.                     -1.       1.
14X0002C    187794.      60.      30.                     -1.       1.
14X0005A      1.E-20     60.                              -1.      10.
```

```
18X0006A         2.X0007AX0008A
14X0005B     1.E-20      60.                                          -1.       10.
18X0006A         2.X0007BX0008A
14X0005C     1.E-20      60.                                         -1.       10.
18X0006A         2.X0007CX0008A
14X0009A     1.E-20      60.                                        -1.       10.
18X0010A         9.X0001AX0011A
14X0009B     1.E-20      60.                                         -1.       10.
18X0010A         9.X0001BX0011A
14X0009C     1.E-20      60.                                        -1.       10.
18X0010A         9.X0001CX0011A
14X0014A     1.E-20      60.                                        -1.       10.
18X0015A        29.X0016AX0017A
14X0014B     1.E-20      60.                                       -1.       10.
18X0015A        29.X0016BX0017A
14X0014C     1.E-20      60.                                       -1.       10.
18X0015A        29.X0016CX0017A
/OUTPUT
BLANK TACS
BLANK BRANCH
BLANK SWITCH
BLANK SOURCE
```

BLANK OUTPUT

BLANK PLOT

BEGIN NEW DATA CASE

BLANK