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ANALYSIS AND COMPUTATION OF POWER SYSTEM TRANSIENTS IN FREQUENCY DOMAIN

BY

RAM BABU DAHAL ©

A thesis
submitted to the faculty of graduate studies and research
in partial fulfillment of the requirements for the degree of
Master of Science

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled Analysis and Computation of Power System Transients in Frequency Domain submitted by Ram Babu Dahal in partial fulfillment of the requirements for the degree of Master of Science.

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Abstract

The first part of this thesis presents a method to compute switching transients in the power network in frequency domain. The method is based on the use of the impedance response of the power system network and the switching current. The impedance response is found by forming the admittance matrix as a function of frequency. The switching current is obtained by use of superposition method to model switch closure.

The second part of the thesis presents the key frequency concept to get quick but fairly accurate result for the purpose of eliminating insignificant frequencies from the transient spectrum. Several options of picking key frequencies are explained depending on the degree of accuracy desired. The key frequency selection quantifies the nature of the transients through the dominant frequencies. One point to note here, however, is that the transients described by the key frequency spectrum can not be used for the construction of time domain representation of the waveform.

The last part of the thesis deals with the analysis of the result obtained by the frequency domain method by proposing the ranking technique to determine the worst buses of the network. In the first case, the ranking of the buses is performed according to the peak index of the transients. In the second case, the buses are ranked by the energy index.

Acknowledgement

I would like to express my sincere gratitude and appreciation to my research supervisor Dr. Wilsun Xu for his guidance and encouragement. I would also like to thank my co-supervisor Dr. Xian Liu for taking time to painstakingly going through my thesis to correct errors. In addition, I would like to thank all my colleagues and fellow students at the department for creating a productive environment.

At the end, I would like to mention my wife Manju and my daughter Melanie for their support and love.

Ram Babu Dahal

Analysis and Computation of Power System Transients in Frequency Domain

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List of Symbols

$EMTP$	Electromagnetic Transient Program
L	Inductance
C	Capacitance
V	Voltage
ω	Frequency in radian
I	Current
N	Number of points
n	Number of points
Z	Impedance
Z_{ii}	Transfer impedance at bus i
R	Resistance
$p.u.$	Per Unit
t	Time
$i(t)$	Current as function of time
$V_C(0)$	Initial capacitor voltage
V_m	Peak voltage magnitude
ϕ	Phase angle of the waveform
$I_L(0)$	Initial inductor current
$I(j\omega)$	Current as a function of frequency
$V_C(j\omega)$	Capacitor voltage as a function of frequency
X_C	Capacitance in ohm
X_L	Inductance in ohm
$V_{cf}(t)$	Steady state capacitor voltage as a function of time
$V_{cn}(t)$	Capacitor transient voltage as a function of time
$V_c(t)$	Capacitor voltage as a function of time

K	Constant
f	Frequency in Hz
G	Conductance
$V_S(t)$	Source voltage as a function of time
$G(S)$	Transfer function (Laplace model)
$Y(j\omega)$	Admittance as a function of frequency
$Z_{ij}(j\omega)$	Transfer impedance of bus j, switching at bus i in frequency domain
$V_j(j\omega)$	Transient voltage at bus j
$V_{switch}(j\omega)$	Steady state voltage at switch location prior to switch closure
V_{tk}^{peak}	Transient peak voltage at bus k in time domain
V_{tk}	Total voltage at bus k in time domain
V_{tk}^{SS}	Steady state voltage at bus k in time domain
V_{ik}	Voltage magnitudes at frequency i at bus k
V_{fk}^{peak}	Correlated transient peak voltage at bus k in frequency domain
E	Energy of the transient
T	Transient period
V_{fk}^{P}	Largest magnitude of transient voltage spectrum at bus k
V_{fk}^{base}	Threshold voltage
V_{jfk}	Voltage magnitudes at frequencies j larger than threshold voltage
V_{fk}^{sum}	Sum of voltage magnitudes at all frequencies at bus k

Chapter 1

Introduction

Electric power quality is an area of study that includes methods or devices designed to maintain a near sinusoidal voltage waveform, at rated voltage magnitude and frequency for power systems at all times. In this chapter the concept of switching transients and methods for the computation and analysis of switching transients are presented to facilitate the better understanding of transients and ways to reduce or remove transients from the power system network to maintain the quality of power. The chapter ends with a statement of thesis objective and the outline of how the objective will be achieved.

1.0 Power Quality

Ideally, power should be supplied without interruptions at constant frequency, in North America at 60Hz, constant voltage magnitude with perfectly sinusoidal waveform and, in the case of three-phase, symmetrical waveforms. However, due to the complex network between utilities and the end-user with the presence of a multitude of non-linear elements, the ideal case can not be realized. The specific objective of power quality is then focused on "*pureness*" of the supply including voltage variations and waveform distortion. Deviation from the sinusoidal voltage supply can be due to transient phenomena or due to the presence of non-linear components.

Power Quality (PQ) refers to the characteristics of the power supply required for the electrical equipment to operate correctly. Taking the lead of [1] a power quality problem is defined from the customer prospective as: "Any power problem *manifested in voltage, current, or frequency deviations that result in failure or mis-operation of customer equipment."*

There are many different types and sources of power quality disturbances. It is common practice in industries for disturbances to be classified according to the electrical characteristics of the voltage experienced by the customer equipment. The characteristics include waveforms, RMS values and phase voltage balances. According to the recent international efforts to standardize the definitions of power quality terms, the common power quality disturbances are classified as [1]:

- Transients
  Transients are disturbances that last less than three cycles and they have many possible origins, for example, capacitor switching, lightning strikes etc. Transients can also be classified as impulsive and oscillatory types. Impulsive transients are characterized by having sharp rise and fall edges.
- Short duration voltage variations
  These include voltage sags, swells and momentary interruptions. These disturbances cause abnormalities in the voltage periods of 0.5 cycles to 1 minutes. Fault in the system or the connection or the disconnection of the large equipment or loads could cause short duration voltage variations.
- Long duration voltage variations
  These are steady state over-voltages, under voltages and sustained interruptions. These disturbances have duration in excess of 1 min. In these type of voltage variations, the rms voltage goes outside of the contract service voltage band such as CSA standard of 110~128 V. The causes could be poor system design and/or operation or excessive loads.
- Waveform distortions
  This type of disturbance is characterized by steady state distortions of the 60 Hz sinusoidal waveform. Examples of distortions are harmonics, voltage notching,

DC offset and broadband noise. The causes could be non-linear loads such as power-electronic loads.

- Voltage unbalance

  These are steady state disturbances where there is unbalance of the voltages among the three-phase power supply. The causes could be unbalanced load or unbalanced system.
- Voltage fluctuations

  Repetitive voltage sags and swells appear as voltage fluctuations. A typical spectral content of voltage fluctuation is less than 25Hz. Causes could be repeated motor starting, industry processes such as arc furnace etc.
- Power frequency variations

  This type of disturbance is defined as the deviation of the power system fundamental frequency from its specified nominal value. The typical duration of the frequency variation of interest is less than 10 seconds.

Both electrical utilities and the end users of electrical power are becoming increasingly concerned about the quality of electric power. The growing concerns for the power quality is due to many factors such as:

- Newer and more advanced load equipment is more sensitive to power quality than equipment used in the past.
- The increasing emphasis on overall power system efficiency has resulted in a continued growth in the application of devices such as high efficiency drives and shunt capacitors for power factor correction to reduce losses as well as wide spread use of power electronics. This is causing increase in harmonic levels in the power system.
- Manufacturer wants faster, more productive, more efficient machinery. Interestingly often the equipment installed to increase the productivity is also the equipment that suffers the most from common power disruptions.

The proliferation of power quality sensitive loads in recent years has made power quality one of the major concerns for utility companies, manufacturers and customers [2]. Interest in power quality was initially concentrated on the survey of power quality conditions and the improvement of monitoring techniques. Over the years, the increase in the general awareness on the subject with the increasing concerns over productivity and efficiency (as mentioned above) have made development and application of technologies for power quality disturbance analysis and mitigation a new area of power quality research [3]. Many techniques and applications such as transients-analyzers and suppression methods have been developed and tested for power system network. However, there still a need for improvement to meet the industry expectation to better utilize our resources and manpower.

1.1 Switching Transients

Transient over-voltage is one of the main concerns when it comes to power quality issues. Transients can severely damage end user equipment as well as supplier's equipment, which can be very costly to repair or replace. Transients can also disrupt sensitive industrial processes such as chip fabrication. Therefore study and analysis of transients in power system have been receiving considerable attention from both power consumers and suppliers. Transients in power system can occur in many ways of which there are two main sources of transient over-voltages on utility systems: Capacitor switching and lightning. These are also sources of transient over voltages within the end user facilities as well as myriad of other switching phenomena.

Capacitor switching is one of the most common switching events in utility systems. Capacitors are used to provide reactive power (vars.) to correct the power factor, to reduce losses and to support the voltage in the system [4]. One drawback of capacitors is that they can interact with the inductance of the power system to yield oscillatory transients when switched.

The goal of switching transients is to develop methods for transient prediction and mitigation. Reducing or totally removing switching transient will have tremendous financial and economical benefits, as the power system will be more reliable, stable and efficient. Voltage and current transients can be deadly to the proper function of other devices as:

- Many modern power supply based devices require a clean supply current to determine correct firing angle. The high current spikes can cause device to malfunction by damaging semiconductor chips.
- Transient over voltage can reach as high as 2.0 p.u. that is capable of melting the sensitive insulation.
- The utility transformer can fail due to sudden surge of current.
- The sudden high impulse transients can easily damage the end user equipment.

Recently much research and effort have been directed towards the study of the origin, propagation and the mitigation of transients in the power system. The special concerns have also been focused towards switching transients due to the fact that the capacitor banks are a necessity to provide reactive power support in the network.

1.2 Analysis methods for Switching Transients

A number of methods have been applied in the past to study switching transients. Most of them have been focused on analytical and the time domain simulation methods with emphasis on developing transfer function models of network elements such as transmissions lines, transformer etc [5, 6]. In some cases, Transients analyzers have been used reasonably effectively in the past, but they are inevitably special purpose devices while pressure has been increasing to make use of general-purpose device such as digital computer to analyze transients related disturbances. For the past decade or so, time domain transient simulation program called EMTP[1] that runs in general-purpose digital computers has also been used widely.

Analytical methods consist of options such as developing a transfer function of the power system network and using Fourier transformation to compute transient solution. The method works fine for the simple systems but it is almost impossible to use for the large and complex power systems. A number of methods have also been developed for modeling distribution or transmission networks, transformers, and machines etc. that can be used to compute switching transients in the power systems [5, 6, 7].

The EMTP program can perform transient analysis on the power system network in the time domain with the input data of network parameters such as bus voltages, bus impedance, transformer models etc. The output of EMTP result, however, still needs to be processed for proper understanding of transient disturbance and its effects in the power system such as energy and frequency content of the transients. Time domain result, obtained by EMTP, by itself is insufficient to draw any conclusion other than proof of the fact that the transients exist in the system.

1.3 Objective and Scope

The study of switching transients is important for reliability, and to prevent economic and financial losses. The more we know about the transient disturbance in power system, the more likely we will be able to mitigate its harmful effects to the equipment and the network itself. With ever-increasing complex power network, analysis of the whole system or just knowing the presence of transients becomes unrealistic and of very little value. It is, therefore, important to have a fast and

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[1] EMTP - Electromagnetic Transient Program. First developed by H. W. Dommel at the Bonneville Power Administration, Portland, U.S. A.

efficient transient analysis method that not only gives most information about transients but also can be applied for localized calculation.

This thesis proposes a method to analyze and calculate transients that have practical uses and be very fast in terms of computer and engineer's time, and at the same time give adequate result. Calculation can be performed using existing tools. The only required result can be printed avoiding unnecessary information and calculation. It is simple to use and understand. The proposed method focuses on minimizing numerical and calculation error as well as aims at avoiding the need for expensive and sophisticated hardware and software.

The proposed method calculates power system transients in the frequency domain. It can be applied to the real life power networks. With this method, selective study of the transients can be performed among the buses in the power network. A real case example involving the power system of Southern Alberta is presented as a test case. This thesis will try to demonstrate the flexibility and the simplicity of the method over conventional methods.

In the final chapter, a practical method is proposed to determine the worst buses (the buses that will most likely to have higher transients and high-energy content) of the power network. A technique is proposed for the ranking of the buses of the network according to the transient indices (peak index and the energy index). Again, the real case scenario is used as an example to prove the validity of the method. Keeping the above objective in perspective, the scope of this thesis can be summarized as:

- Propose a frequency domain based method to calculate switching transients in the power network in frequency domain. Any random buses can be selectively monitored for the transients. The indices that characterize the transient such as peak and the energy contents will be computed and used for further analysis.

- Determine the worst buses due to transients by ranking the network buses using key indices. The ranking of the bus by the peak and the energy contents are critical to limit harmful effects on the power network as it enables us to identify the problem buses.
- Demonstrate the applicability of the proposed method to the real case of the Southern Alberta Power Network.
- Compare the results for efficiency and accuracy with the existing time-domain and the proposed frequency-domain methods wherever possible.

The proposed method is however limited to calculating switching transients and will not touch upon other modes of transients such as the transients caused by lightning, which is a whole new research subject.

1.4 Outline of the Thesis

Present transient analysis methods mostly utilize time domain method. The results obtained through these methods have to be processed again to know certain parameters such as frequency contents, dominant frequencies and the duration of the transient etc. Other available methods employ very expensive and sophisticated analyzers that are not economical to every potential user. Therefore, it has become a necessity to improve present methods of transient analysis while keeping the cost lower and increasing the efficiency and the usefulness. If the required data can be obtained through one calculation, it will have vast usefulness to the power industry. To this end, and to achieve that goal this thesis is conducted as follows.

Chapter 2 presents the problem of capacitor-switching transients. Analytical solution for a single cap-switching transient problem is used to demonstrate the complexity of the calculation involved, as the network becomes larger. Large case scenario is also simulated using the existing time domain simulation program (EMTP) and try to evaluate both the analytical and the EMTP methods noting the specific problem areas. This chapter also states the general outline of the previous work in transient analysis in frequency domain.

Frequency domain analysis of switching transient is presented in chapter 3. The concept of the method is described using a simple example. Chapter 3 also details the proposed method of computing capacitor-switching transients from impedance response of the network and the switching current. The impedance response of the network is computed by forming the admittance matrix as a function of frequency. The switching current is computed by using the superposition method. The chapter ends with two case studies. (1) Simple case; (2) the large system case of Southern Alberta and the results are compared with the time domain results.

Chapter 4 tries to simplify even more the proposed method by proposing the *key frequency* concept. This concept is based on the fact that number of frequencies from the transient frequency spectrum can be effectively discarded with out losing the accuracy in the computation of the indices. Using the key frequency concept, the transient can be quantified by only the dominant frequencies. The method reduces the calculation involved and can be used more effectively for genral purpose work.

Chapter 5 details the idea of determination of worst buses, i.e. the buses that are more susceptible to transients and more likely to be affected by it. Buses will be ranked by two indices of transients—*the peak and the energy* contents. The ranking of the buses will be a valuable tool for the power system management. An example case will be presented to show the buses in the system that have the transients with highest peak as well as higher energy contents.

Finally in chapter 6, conclusions about the transient analysis method investigated in this thesis are drawn and the possible steps for future development and research are suggested.

Chapter 2

Capacitor Switching Transients in Power System

2.0 Introduction

When the switch is closed the transients in the form of over-voltage may be observed up-line from the capacitor. The capacitor switch contact generally closes at a none-zero voltage between the contacts. However, the voltage across the capacitor at this instant is zero. Since the voltage across the capacitor cannot change instantaneously, the system voltage at the capacitor location is briefly pulled to zero and rises as the capacitor begins to charge toward the system voltage. As is typical of capacitors in inductive power systems, the capacitor voltage overshoots and rings at the natural frequency of the system. The overshoot will generate a transient between 1.0 to 2.0 per-unit depending on the system damping. The utility capacitor switching transients are generally in the 1.3 to 1.4 per unit range but have also been observed nearer the theoretical maximum. The transient present during switching propagates into the local power system and generally passes through distribution transformer into customer load facilities by an amount in proportion to the turns-ratio of the transformer. While transients of up to 2.0 per unit are not generally damaging to the system insulation, the occurrence of such transients can often cause misoperation of electronic power conversion devices. The transient may effect gating of thyrsistors for proper operation. The analysis of transients therefore becomes one of the important tasks in power quality management.

In this chapter, different methods for computation of capacitor switching transients as well as some of the indices that we look for in the transient analysis are explained. Capacitor switching transients can be calculated using analytical, time domain simulation, numerical or frequency domain methods. The indices that play an important role to describe transients are peak, frequency spectrum, and energy content of the transients.

2.1 Analytical Example

The transients can be computed using analytical method. Consider the RLC network with a simple switch shown in figure 2.1. The analytical computation will result in the combined output functions of transients and the steady state. The example below will demonstrate analytically the presence of transients in the circuit. It is supplied from the source of sinusoidal voltage of the form ***V*** $V_m \cdot \sin(\omega * T + \phi)$, where V_m is peak magnitude of the source voltage, ω is frequency in radian per second and ϕ is phase angle in radian. ***R*** is the resistance of the circuit, ***L*** is the inductance, and ***C*** is the capacitor to be switched.

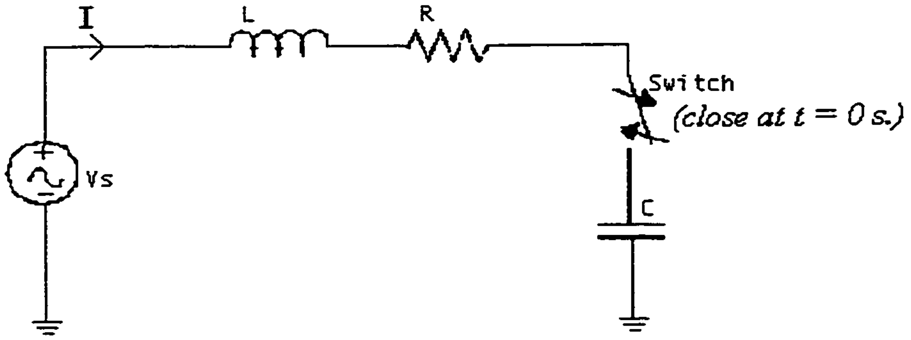


Figure 2.1 RLC circuit

The circuit can be described by the equation in the time domain for $t > 0$ s as:

(Switch close at $t = 0$ s, $\phi = 0$, initial capacitor voltage = 0.)

$$V_m \sin(\omega t) = R * i(t) + L * \frac{di(t)}{dt} + \frac{1}{C}\int_0 i(\tau)d\tau + V_C(0) \tag{2.1}$$

and in frequency domain (Laplace model) as:

$$\frac{V_m * \omega}{S^2 + \omega^2} = R * I(S) + S * L * I(S) - L * i_L(0^-) + \frac{I(S)}{SC} + \frac{V_C(0)}{S} \tag{2.2}$$

Where $V_c(0)$ is the initial capacitor voltage at $t = 0$ s.

$i_L(0^-)$ is the initial current through the inductor.

Analytical method basically involves solving the equations 2.1 or 2.2 that describe the circuit. However, solving the above equations requires some standard steps to follow. For our case, initial capacitor voltage and initial inductor currents both are equal to zero. Therefore, we can write separate equations for capacitor voltage after the switch is closed in simpler form.

$$V_C(S) = \frac{1/SC}{R + SL + 1/SC} V(S) = \frac{1}{1 + RCS + LCS^2} V(S) \qquad (2.3)$$

where,

$$V(S) = \frac{V_m * \omega}{S^2 + \omega^2}.$$

From the equation 2.3, the characteristic equation that governs the transient response of circuits containing capacitors, inductors, and resistors can be written as:

$$S^2 + \frac{R}{L}S + \frac{1}{LC} = 0. \qquad (2.4)$$

We solve for S of the equation 2.4 by the use of quadratic formula. Let us use actual numbers from a typical power system data to compute capacitor voltages of the figure 2.1. Consider a 34.5 kV system with short-circuit current $I_{sc} = 25\ kA$ and the capacitor size of 18 MVA. Then the normal capacitor current is given by:

$$\sqrt{3} * V * I = 18MVA$$

$$I = \frac{18MVA}{\sqrt{3} * 34.5kV} = 301.2A.$$

Therefore, the capacitance is:

$$X_C = \frac{V/\sqrt{3}}{I} = \frac{34500}{\sqrt{3} * 301} = 66.13\Omega$$
$$\therefore C = 40.1\mu F.$$

Then, the source reactance is:

$$I_{SC} = \frac{V/\sqrt{3}}{X_L} \Rightarrow X_L = \frac{34500}{\sqrt{3} * 25000} = 0.797\Omega$$
$$\therefore L = 0.0021H.$$

The value of R is

$$R = 0.40\ \Omega.$$

As the switch is initially open, the initial capacitor voltage and the inductor current are both equal to 0. The total response of the capacitor voltage is calculated for $t > 0$ sec.

The steady state component is obtained by the phasor method. Using the voltage-divider method:

$$V_{Cf} = \frac{(0 - j66.13)(34500 + j0)}{(0.40 - j65.3)} = 34938\angle -0.35^\circ V.$$

The corresponding function is

$$V_{Cf}(t) = 49410\sin(\omega t - 0.35^\circ)V. \tag{2.5}$$

To obtain the transient response, we substitute the values of R, L, and C in equation 2.4 and obtain, for the characteristic equation

$$S^2 + 190S + 11875074 = 0. \tag{2.6}$$

The solution of quadratic equation 2.6 yields two equal negative values for S_1 and S_2:

$$S_1 = -95 + j3445,$$
$$S_2 = -95 - j3445.$$

The time constant associated with this response are equal and their value is 1/95 s = .0105 s. One of the options for the solution for the transient component of the capacitor voltage is of the form:

$$V_{Cn}(t) = \operatorname{Re} Ke^{St}. \tag{2.7}$$

This form is preferable to one employing two arbitrary constants because of the computational ease with which K can be determined.

For the total response, we have thus far

$$V_C(t) = 49410\sin(\omega t - 0.35^\circ) + \operatorname{Re}[Ke^{St}] \qquad t > 0\ \text{s} \tag{2.8}$$

and

$$\frac{dV_C}{dt} = 49410\omega\cos(\omega t - 0.35^\circ) + \operatorname{Re}[(SKe^{St})].$$

At $t = 0_+$

$$V_C(0_+) = 0 = 49410\sin(0 - 0.35^\circ) + \operatorname{Re}[K].$$

Let $K = a + jb$; evaluating the equation at $t = 0_+$ gives

$$0 = -302 + a,$$

thus

$$\operatorname{Re}[K] = 302.$$

Next using the expression for the derivative of the capacitor voltage together with its initial conditions, the value of S and the numerical values of the cosine term and of $\omega = 2(3.14)(f) = 377$ rad/s., we obtain at $t = 0_+$

$$\frac{dV_C}{dt} = 0 = 49410(377)(0.99) + \mathrm{Re}[(-95 + j3445)(302 + jb)].$$

Taking the real part of the quantity with in the square brackets, we have

$$\mathrm{Re}[(-95 + j3445)(302 + jb)] = -28690 - 3445b.$$

Substituting this into the expression for the time derivative of the capacitor voltage and evaluating it at $t = 0_+$

$$0 = 18441294 - 28690 - 3445b,$$

solving for b gives

$$b = 5344.$$

Hence

$$\mathrm{K} = 302 + \mathrm{j}5344 = 5352 \angle 86.7.$$

Entering this value into our expression for the $V_C(t)$, we finally have

$$V_C(t) = 49410\sin(\omega t - 0.35^\circ) + 5352e^{-95t}\cos(3445t + 86.7^\circ)V. \qquad t > 0 \text{ s} \qquad (2.9)$$

The transient component is

$$V_{Cn}(t) = 5352\ e^{-95t}\cos(3445\ t + 86.7^\circ)V. \qquad t > 0 \text{ s} \qquad (2.10)$$

Figure 2.2 shows the capacitor voltage and the input voltage as well as the transient component of the capacitor voltage obtained by using the equations 2.9 and 2.10.

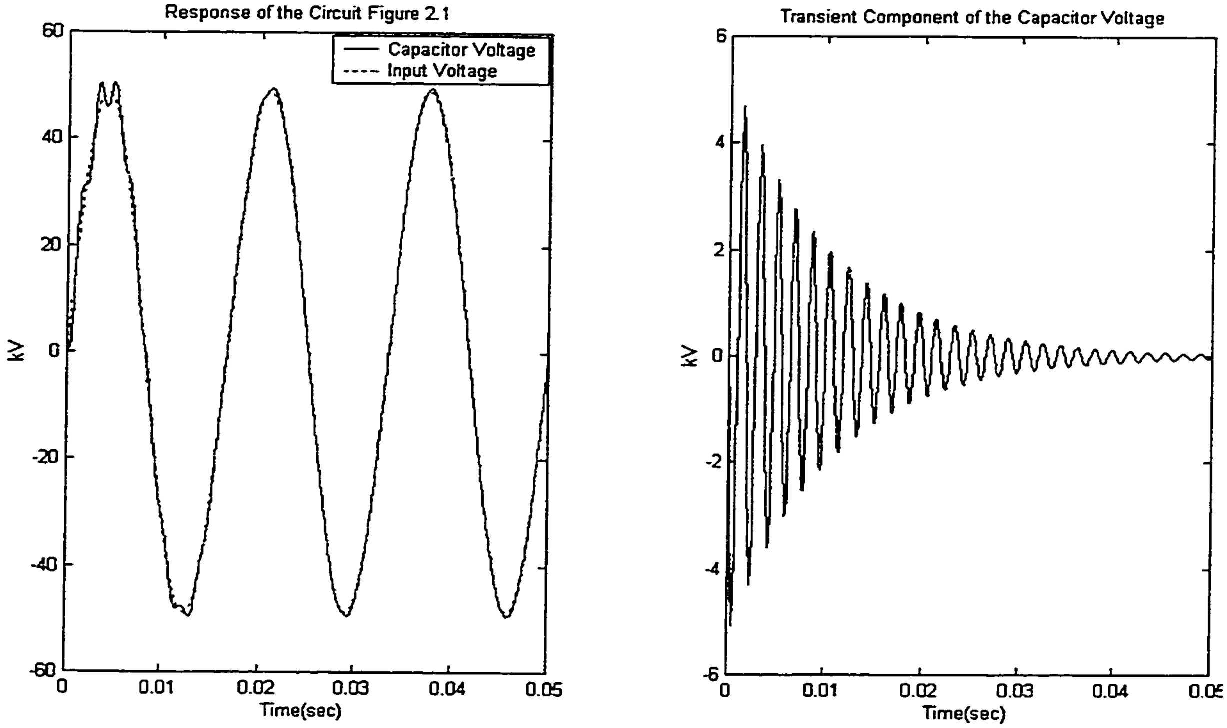


Figure 2.2: Capacitor Voltage of the Circuit Shown in Figure 2.1
(Plotted from Equations 2.9 & 2.10)

2.1.1 Transient Indices

Equation 2.9 is the capacitor voltage of the circuit shown in figure 2.1 for $t > 0$ s and equation 2.10 is the transient component of the capacitor voltage. From these equations, information needs to be extracted to understand transient behavior. It is seen from the plot of the transient voltage that the transient oscillation frequency is much higher than the fundamental frequency. The oscillation frequency is

$$\omega_0 = 3445 rad/\sec \Rightarrow f_{osc} = \frac{3445}{2 * \pi} = 548 Hz.$$

Transients are considered to be effectively non-existent after the transient magnitude reaches the 10% of the peak. With that consideration, it can be seen that the transient duration is 0.026 s. or 1.55 cycles.

The peak of the capacitor voltage can be computed from the equation 2.9 and is found to be $54000 V$ or 110% of the steady state voltage. In some cases, the peak voltage can reach up to twice the steady state voltage. The other index that is important is the energy of the transient. The area under the curve of the transient represents the energy of the transient.

2.1.2 Analytical Method Summary

The analytical process of evaluating the voltage response in the network can be summarized as follows:

1) The characteristic equation of the network is determined.
2) The roots of the characteristic equations are evaluated.
3) Steady state response is determined by the phasor method.
4) The transient component of the network is evaluated by using the roots of the characteristic equations.
5) The constants are evaluated by using the initial conditions and the steady state response.
6) Finally, the voltage or current response equation can be obtained. These equations are further manipulated or plotted to get the desired result such as peak, energy, and duration of the transient.

The main difficulty in analyzing transients by this method for general networks, described by higher order differential equations, consists of the need of calculating the arbitrary constants and the roots of the characteristic equation. It is seen from the example that as soon as there is a presence of frequency dependent elements such as C and L in the circuit, there would be a presence of transients. As the number of RLC-branch increases in the circuit, the "order of the equation[1]" increases. The higher the order of the equation, the more difficult it becomes to find the solution.

The case shown above is just a simple example of analytical method. It only has simple RLC parameters and one source. However, in real case there would be thousands of RLC branches and number of sources in one system. There would be more complicated interconnections and not to mention the presence of transformers, machines, and other non-linear elements in the system. It will be virtually impossible to have all the parameters and solve analytically for the transients in the real case. Analytical method, therefore, is limited to research work as it will prove to be too complex for all practical purpose.

2.2 Time—Domain Simulation Methods

As shown in the previous section, an analytical method of solution for the transients in the power system is not practical for practical purposes. Other methods to compute transients are necessary. One of the methods is the time-domain simulation of the network. Computers and computer programs are used to predict the transient voltages and current in the power network. As the name itself signifies, voltage and current magnitudes are plotted in time domain and the plots can be analyzed further for the desired result. There are a number of different techniques for time domain evaluation of the power system network. The most prevalent method is solving network equations by numerical method. The differential circuit equations are written in the form

---

[1] In the function $f(S) = \frac{Z(S)}{P(S)}$, the power of "S" in the denominator determines the order of the equation. Higher the power of "S", the more complex the solution of $f(S)$ becomes.

$$[\dot{X}] = [A][X] + [B][U] \tag{2.11}$$
$$[X(0)] = [X_0]$$

Where $[X]$ is the state variable such as V and I. $[A]$ is a constant square matrix. Second part of the right hand side of the equation 2.11 is a vector of known forcing functions such as voltage and current sources. For example, network equation can be set up for figure 2.1 as:

$$\begin{bmatrix} di/dt \\ dVc/dt \end{bmatrix} = \begin{bmatrix} -R/L & -1/L \\ 1/C & 0 \end{bmatrix} \begin{bmatrix} i \\ Vc \end{bmatrix} + \begin{bmatrix} (1/L)\,V(t) \\ 0 \end{bmatrix} \tag{2.12}$$

A number of different computer programs exists that perform time domain simulation of the power network by solving network equations. EMTP (Electro-Magnetic Transient Program) is one of the most popular and widely used in the power-engineering field. There is an ATP (Alternate Transient Program) that evolved from EMTP. ATP is shareware while EMTP requires commercial license to use. EMTP uses trapezoidal numerical method to solve the network equation such as equation 2.11. However, the numerical solution is used at component level using the component model. An example can be seen below:

Inductor model:

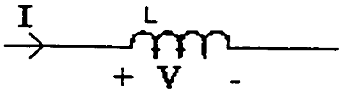


Figure 2.3: Inductor

We have,

$$V = L\frac{di}{dt} \Rightarrow Vdt = Ldi.$$

Assume at $t = t_k$, V and i are known. It is needed to find the V and i at $t = t_{k+1} = t_k + \Delta t$.

Also,

$$\int_{t_k}^{t_{k+1}} Vdt = \int_{t_k}^{t_{k+1}} Ldi.$$

Therefore,

Right hand side = $L(i_{k+1} - i_k)$.

Left hand side = $((V_k + V_{k+1})/2)*\Delta t$.

We have

$$V_k + V_{k+1} = (2L/\Delta t)\,(i_{k+1} - i_k).$$

So

$$V_{k+1} = R_L * i_{k+1} - E_k \qquad (2.13)$$

$$i_{k+1} = G_L * V_{k+1} + i_k.$$

Where,

$R_L = (2L/\Delta t)$ and $E_k = R_L * i_k + V_k$ = known.

$i_k = G_L * V_k + i_k$.

$G_L = (1/R_L)$.

Similarly,

The capacitor model can be written as:

$$V_{k+1} = R_C * i_{k+1} - E_k, \qquad (2.14)$$

$$i_{k+1} = G_C * V_{k+1} + i_k$$

$[E_k = -R_C * i_k - V_k$ = known; $i_k = -G_C * V_k - i_k]$.

The resistor model is

$$R = R_R. \tag{2.15}$$

Using the above models, the numerical circuit can be set up. Starting from time '0' and known initial values such as V, I; next values for V, I can be computed for $t_1 = 0 + \Delta t$ and similarly $t_2 = t_1 + \Delta t$ and so on. Equations 2.13, 2.14, and 2.15 are used in the program EMTP to solve for the network equations. In this thesis, EMTP is used as a tool for time domain calculation and comparison. EMTP simulation of the actual power system network is taken as an example below for the computation of transients using time domain solution methods.

To demonstrate the time domain method, a sample network is taken from the Southern Alberta Power Transmission and Distribution Network. Appendix A has the complete electrical parameters of the network of the Southern Alberta in EMTP format. The system is rated at 138kV. Network has 14 electrical sources or power generators. There are 332 inter-connected buses rated at various voltage levels. There are number of capacitors in the network that are kept on at all times. In this section, the transient voltage occurring due to the closure of a 54 MVar capacitor switching at substation 42S, bus-number 42S-202 is considered. The system is simulated using EMTP computer program to determine transients at the switching bus and also at one of the non-switching bus in the network. Figure 2.4 in the next page shows the general interconnection network of the Southern Alberta Power System. This figure will give a general idea about the network layout. The other bus (non-switching bus) that is monitored for transients is at substation 44S, the bus number 44S-184. This bus was also picked at random for analysis. However, the bus number 44S-184 is also one of the major distribution bus in the network and it is of considerable distance from the substation 42S, bus number 42S-202. One point is to be noted here that this network is also used as a test case for the proposed method.

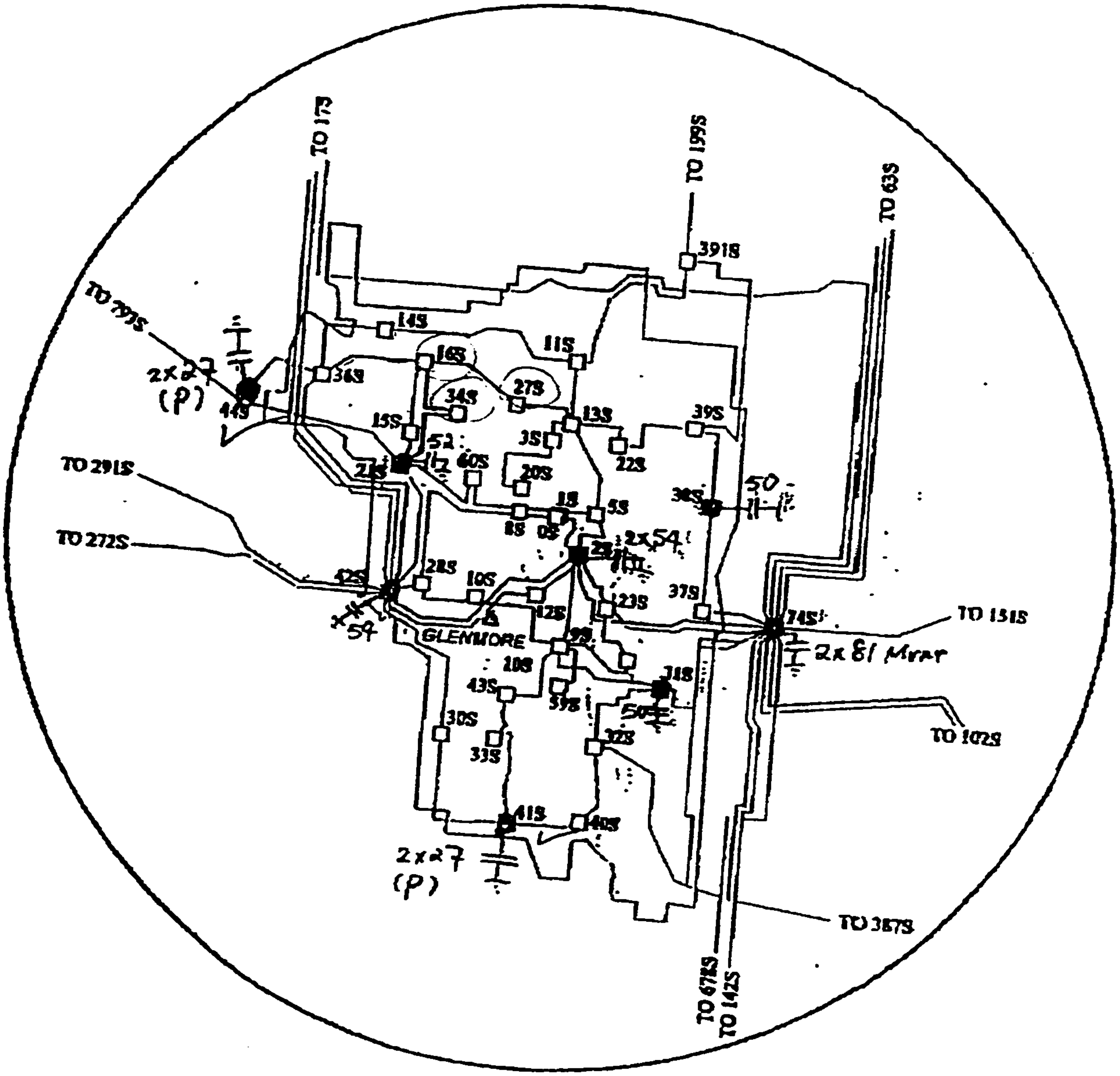


Figure 2.4: Southern Alberta Power Transmission and Distribution Network

The capacitor switch at 42S-202 is initially open and switch closes at the peak at .0671 sec and remains closed during the duration of simulation. The time step is taken at 41 microseconds. The time step should be small enough to "catch" the transients in the circuit. However, very small time step should be avoided to reduce computational burden. Forty-one (41) microseconds was arrived by trial and error and also by engineering judgement as it has been noticed that the simulation with time-step of 50 microseconds or equivalent have no change in result. Figure 2.5 below shows the transients phenomena at the switching bus (42S-202).

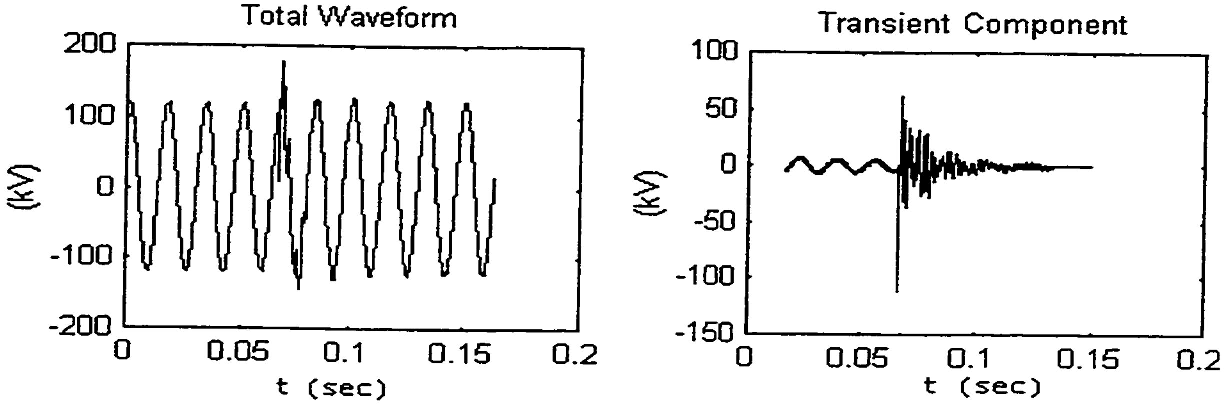


Figure 2.5: Transient Voltage waveforms at switching bus (Bus no 42S-202)

It can be seen that the voltage overshoot is quite sharp and reaches to 180kV. Matlab program can be used as an analysis tool to further understand the result obtained through EMTP program. Using MATLAB, when the 60HZ component is filtered from the total waveform, only the transient component can be seen in the figure 2.5 (right).

Frequency content of the waveform can be seen using the FFT[2]. However, it is not the standard part of the time-domain methods. Another tool needs to be used if the

---

[2] fft - Fast Fourier Transform. For the fft the basic assumptions used are:

a) Sampling frequency is equal to the number of samples multiplied by the fundamental frequency.

b) The sampling frequency theorem is satisfied by choosing the sampling frequency to be at least twice the highest frequency in the waveform.

c) The frequency contents of the waveform are the integral multiple of the fundamental frequency.

frequency spectrum of the transients is to be required. MATLAB's fft function can be used for this purpose. The sampling frequency of 18kHz is used for the process as the maximum frequency content of the transients waveform is expected to be about 5000Hz. Figure 2.6 shows the frequency content of the waveform as detected at the switching bus 42S-202.

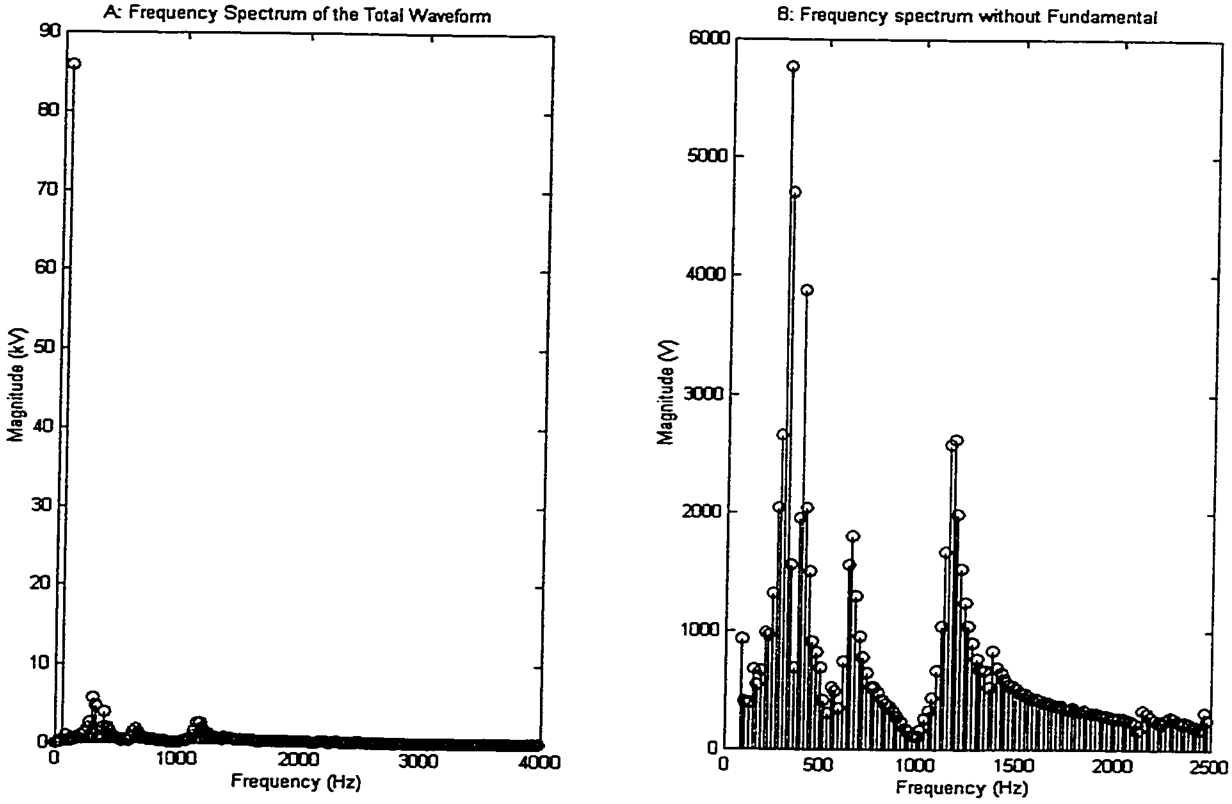


Figure 2.6: Frequency Spectrum of the Voltage at Switching bus (42S-202)

The figure 2.6A shows the total frequency spectrum. The large value is fundamental at 60HZ. When the fundamental is taken out from the plot, the transient's frequency values are clearer in the figure 2.6B. Again it is to be noted that different tools than the time-domain simulation program are required to obtain frequency spectrum of the transients. Another point is that the transients usually die out quickly. In the above example the total duration of the transient was .0065 seconds, which is approximately one third of the cycle. The duration of transient is calculated by the taking the peak of the transient and the time it takes to reduce to the 10% of the peak value.

The effect of transient voltage at non-switching bus due to the capacitor switching in the system can also be monitored. Figure 2.7 shows the transients at bus 44S-184 due to switch closing at bus 42S-202.

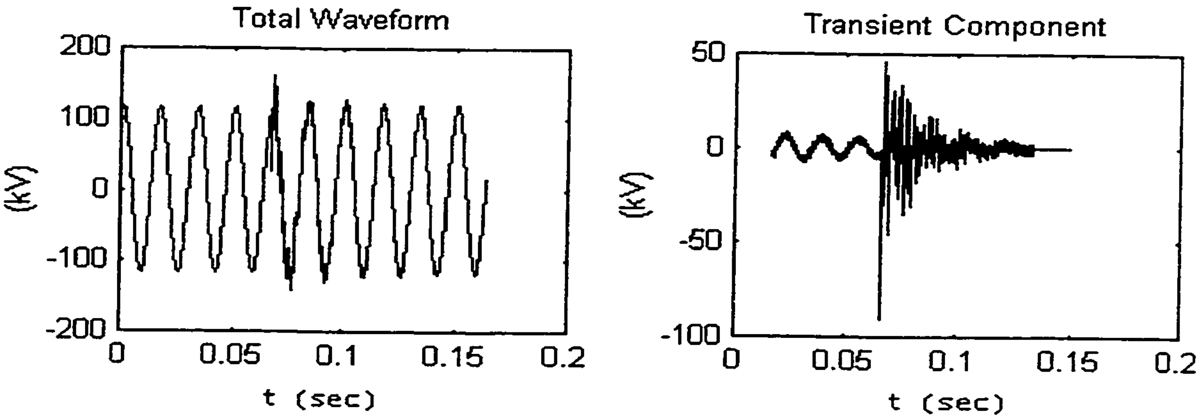


Figure 2.7: Transient voltage at non-switching bus (Bus no 44S-184) due to switching at 42S-202

The peak of the transients reaches up to the 160 kV. That is 1.5 times the nominal voltage. The peak is slightly lower at the non-switching bus than at the switching bus, which can be expected as the energy of the transient decreases, as it propagates further away from the switching bus. However, if resonance condition exists this may not be the case. The duration of the transient is also different from the switching bus and it is .0287 seconds. Again the duration is computed by taking the peak of the transient and the time it takes to reduce to the 10% of the peak value.

As in the previous case the frequency content of the transients can also be quantified using MATLAB's fft function. Figure 2.8 shows the frequency spectrum of the transient voltages. In this case there is a significant voltage at 3500Hz as well.

These results will be revisited in chapter three, when the comparison is made between the proposed method and the time-domain method using EMTP.

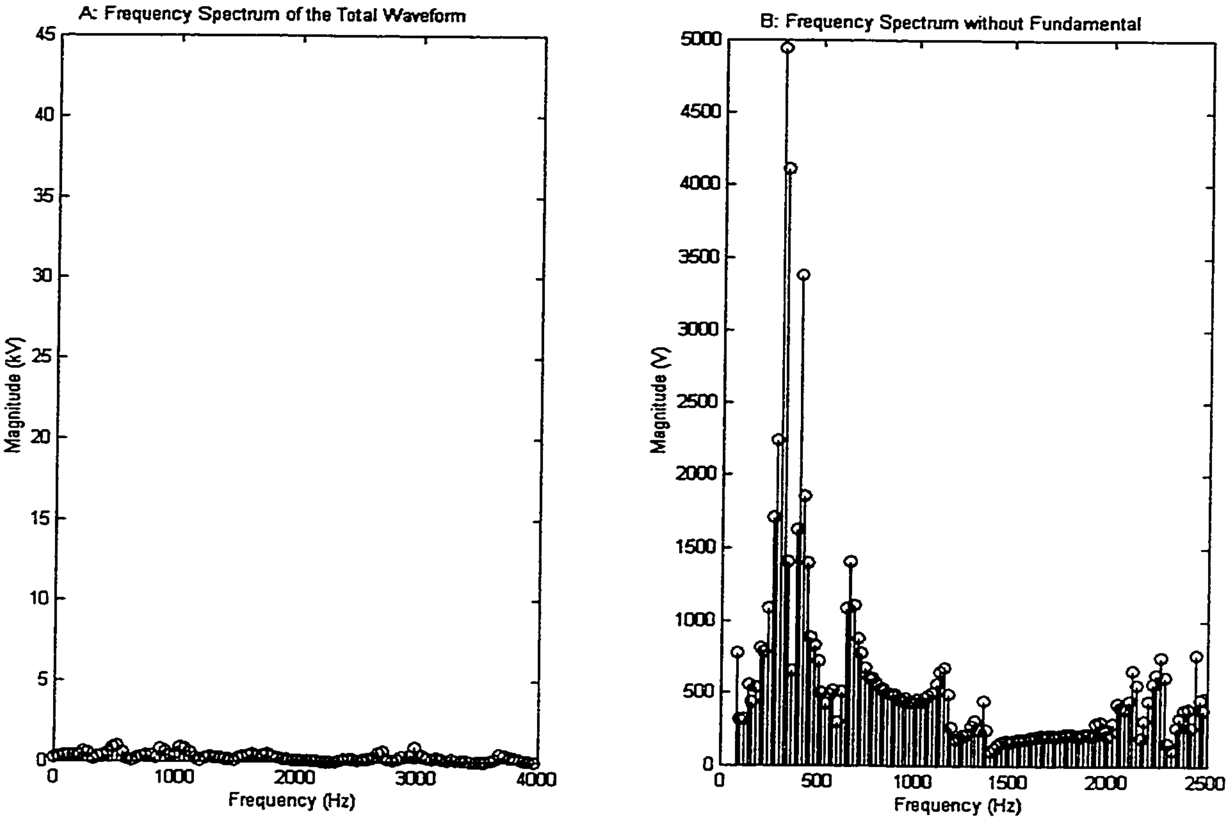


Figure 2.8: Frequency Spectrum of the Voltage at the non-switching bus (44S-184)

2.3 Problems of Existing Approach

In the examples given above, two methods of transient analysis as presented have their own constraints. Analytical approach in frequency domain tends to be mathematically too complex where as the time-domain simulation method does not give out the result that we want outright, and further computations are always required. As an example, to determine the buses with the highest transient, all buses have to be analyzed. Following points summarizes why the two methods as presented above are not the most efficient methods in certain aspects and why there is a need for an improved technique.

- One of the most important reasons for transient analysis is to be able to determine worst buses. Worst bus can be defined as a bus or buses in the network that exhibit the highest transients in terms of peak, energy, or the duration. Therefore, it is important for the analysis tool to be able to perform selection of buses according to the transient effects at individual buses. For this purpose all the waveforms needs to by analyzed. Computing analytical solution for each individual bus is not an option. The desired result can be obtained eventually by time domain solution methods. However, the work requires use of different tools and monitoring all the buses in the network.
- Analytical method has several hurdles to be efficiently used outside classroom and research labs. In real case scenario there will be multiple sources and hundreds of nodes, along with increasing number of sophisticated electronics. It will be almost impossible to find true capacitive, resistive and inductive characteristic of the network for proper analysis. Models have to be built and even model will fall short of defining all scenarios.
- Analytical method is mathematically too complex for everyday use. High degree of mathematical concept is required for the solution of higher order differential equation and for the interpretation of the results.
- Power system network is a dynamic system. Even if the system is solved analytically, as soon as the system's parameters (consumer load etc.) change, it has to be solved again, as the change in load etc. will change the system characteristic equation.
- Time-domain simulation method such as EMTP is one of the best options available for transient study today. However, it has its own limitations. As the name implies, it gives solution in time domain associated with the plots. No quantitative conclusion can be drawn from the plot along. We cannot derive the transient characteristics, frequency contents, etc. with out further calculation using other tools such as Matlab.

- Quantitative information about transients is the single most important factor for implementation of measures to reduce or remove transients from the power network. For example, knowledge of frequency content can help implement certain filter to absorb the high impact frequency signals from the system. However, EMTP falls short of providing all the information for transient study.

2.4 Frequency Domain Analysis

Frequency domain analysis of the transients has been of interest to many scientist and researchers for a long time. Even though frequency domain analysis has been mostly applied to control system, there has always been interest to use it for power system transient analysis.

In a book [8] published by Solodovnikov, V. V. (1958), extensive study of the computation of the transient response using frequency response has been performed for use in the control system. The author has arrived into the different set of equations depending on the properties of the transfer function of the given system to be used to compute the systems transient response with the help of its frequency response. His work has given a foundation for many authors to try to apply similar approach in the power system transient analysis. In the power system transient analysis, impedance response of the network becomes same as the frequency response of the network described by the transfer function.

Frequency domain technique has been used to compute the impedance characteristic [6] of the power system network. This author has used the approach to find equivalent network models.

Mathematical models for the transient analysis of poly-phase transmission lines using the modified Fourier Transform (Frequency domain technique) has been presented in detail in several papers [5, 9]. These work have been mostly devoted to modeling particular part of the power system network

All the work described above suggests that the numerical frequency domain technique can be taken as one of the major options for transient analysis. As seen in the previous section, time-domain simulation result do not provide much information outright with regards to the nature of the transients in certain aspects such as the dominant frequencies and the maximum frequency range. Other tools have to be used to extract such information. In frequency domain analysis method, most of the desired information for analysis of the transients can be obtained directly. It is this author's belief that the focus of transient analysis is extracting the information and making it useful for practical purposes rather than just computing the transients. Extracting information for ranking of the worst buses in the network can be done in number of ways that already exists. However, this thesis will explore the better ways to extract information and define the methods suitable for ranking of the buses with respect to the transient peak and the transient energy.

Chapter 3

Frequency Domain Analysis of Switching Transients

3.0 Introduction

Frequency domain method investigated in this thesis uses numerical computation to determine capacitor-switching transients in the power system network. However, all numerical computation is performed in frequency domain. Superposition method is proposed to simulate the switch closure. Software tools such as MATLAB and EMTP are used through out the thesis for computation.

Apart from the simplification of calculations involved in the derivation of transient responses, the superposition method that is described in this chapter has the important merit in that it may be used when the differential equations of the system is unknown and the starting data for the calculation of the transient responses consists of impedance response of the system.

In this chapter the superposition method to determine the transient response of the system is described using a simple example. After the validity of the method has been established, it will be used to compute transient response of the larger case of Southern Alberta Power Network to demonstrate the practical use of the proposed method. The result will also be compared with the time-domain simulation result as obtained by EMTP. Time-domain results are taken as a reference to measure the validity of the proposed method as EMTP has been proved to be reliable and correct for transient calculation for the number of years. The transient response obtained by the superposition method will be in frequency domain and will be used for the determination of the worst buses.

3.1 Basic Concepts

The impedance of the system can be determined as the function of frequency. One way is that voltage and the current can be measured at different frequencies to estimate the impedance as a function of the frequency and can be effectively termed as the impedance response of the system.

To define the concept involved in the frequency domain computation of the transient, let us look at a single input, single output (SISO), system with input *Y(t)* and the output *X(t)* is shown in figure 3.1

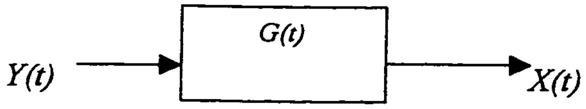


Figure3.1: Single Input-Single Output System

This system has a impulse response function, *G(t)*, that relates the input and the output as

$$X(\tau) = \int_0^\tau G(t)Y(\tau - t)dt \qquad (3.1)$$

Which is the convolution integral of the system impulse response, *G(t)*. The frequency domain transform of the integral yields

$$X(j\omega) = G(j\omega)Y(j\omega) \qquad (3.2)$$

Where *G(jω)* is the frequency response of the system shown in figure 3.1. The first term in the equation 3.2 is the effect of the input signal and the second the effect of the initial conditions. The equation 3.2 forms the basis for all the computation. It is to be noted that the transfer function is defined with zero-state conditions. A numerical example is used to show the basic concept of the proposed method. Consider a simple LRC circuit of the chapter 2, page 12.

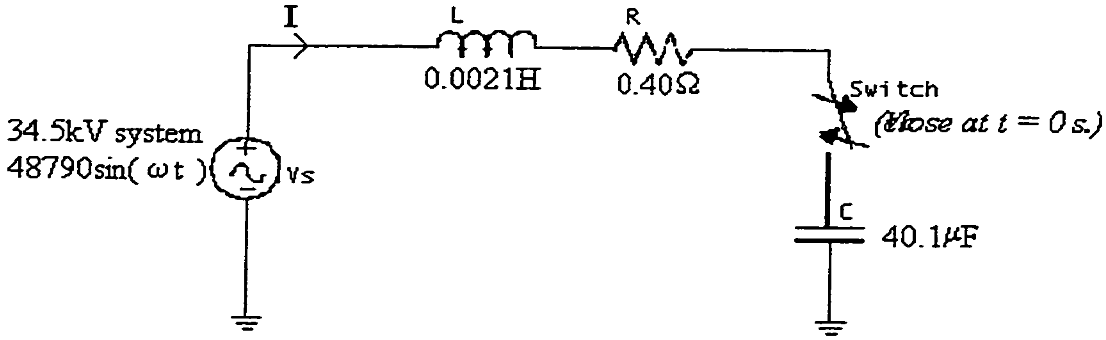


Figure 3.2: A simple RLC Circuit

We have,

$$R = 0.40\Omega; C = 40.1\mu F; L = 0.0021H,$$
$$Vs = 34.5kV; \theta = 0^\circ; V_C(0_-) = 0V.$$

Therefore, in time domain the input becomes

$$V_s(t) = \sqrt{2} * 34500\sin(\omega t + 0^\circ) = 48790\sin(\omega t). \tag{3.3}$$

It is needed to find the voltage across the capacitor V_c.

The transfer function $G(j\omega)$ of the circuit shown above when the switch is at closed position with the output is considered to be V_c can be written. The transfer function $G(j\omega)$ of the circuit is:

$$G(j\omega) = \frac{1}{1 - \omega^2 LC + j\omega RC}. \tag{3.4}$$

Then applying the equation 3.2, the capacitor voltage will be

$$V_c(j\omega) = V_s(j\omega)G(j\omega) \tag{3.5}$$

as the initial values are all zeros before the switch is closed. It must be noted that equations 3.4 and 3.5 are determined numerically, not analytically, by the proposed method.

The above derivation is programmed in Matlab. The complete program in attached in the appendix B. To be able to use the equation 3.2 numerically in the frequency domain, a window of input is selected and transformed to frequency domain. Three complete cycles of the input are taken into account for the process. The time step is taken to be .00002 seconds for the input function as shown in figure 3.3.

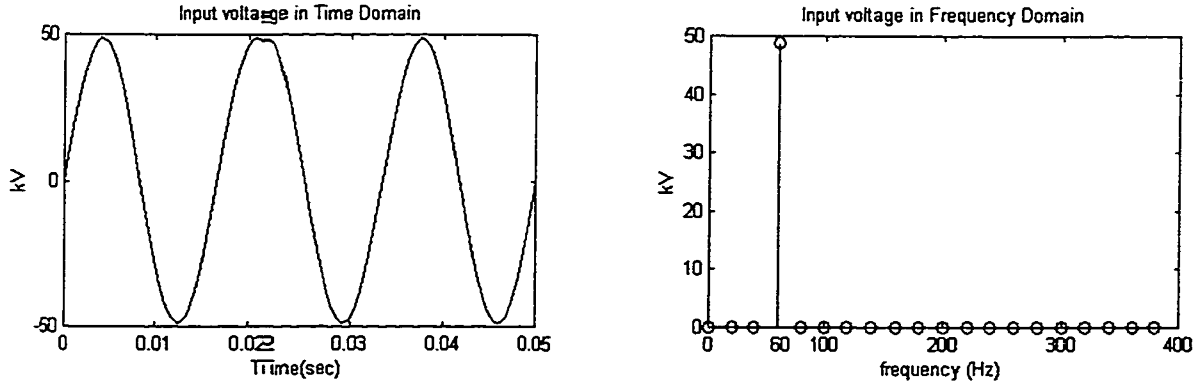


Figure 3.3: Input Voltage

Figure 3.4 shows the frequency response ($G(j\omega)$) of the circuit in figure 3.2. The frequency response plot shows that the center frequency is around 548 *Hz*, which is the oscillation frequency as shown by the analytical computation in chapter 2.

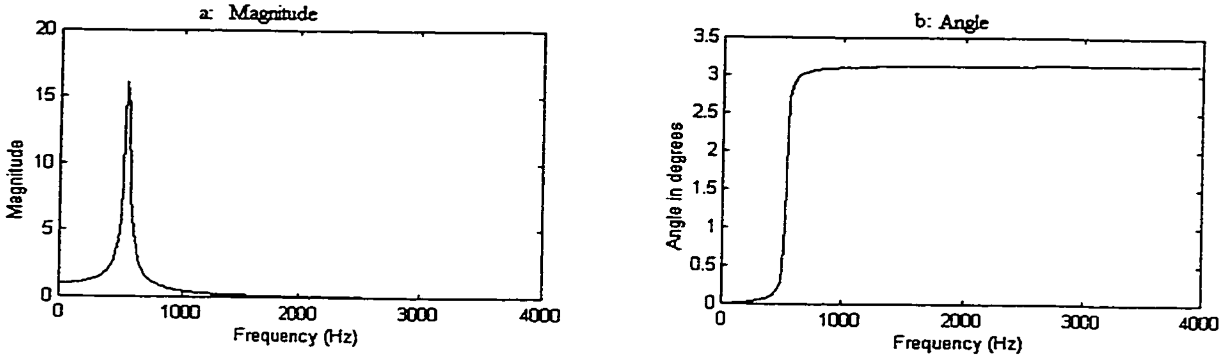


Figure 3.4: Frequency Response of the Circuit of Figure 3.2

This response multiplied by $V(j\omega)$ numerically gives the capacitor voltage response $V_C(j\omega)$ in frequency domain as shown in figure 3.5. Note that the fundamental frequency has been excluded in the figure so that the transient component can be seen

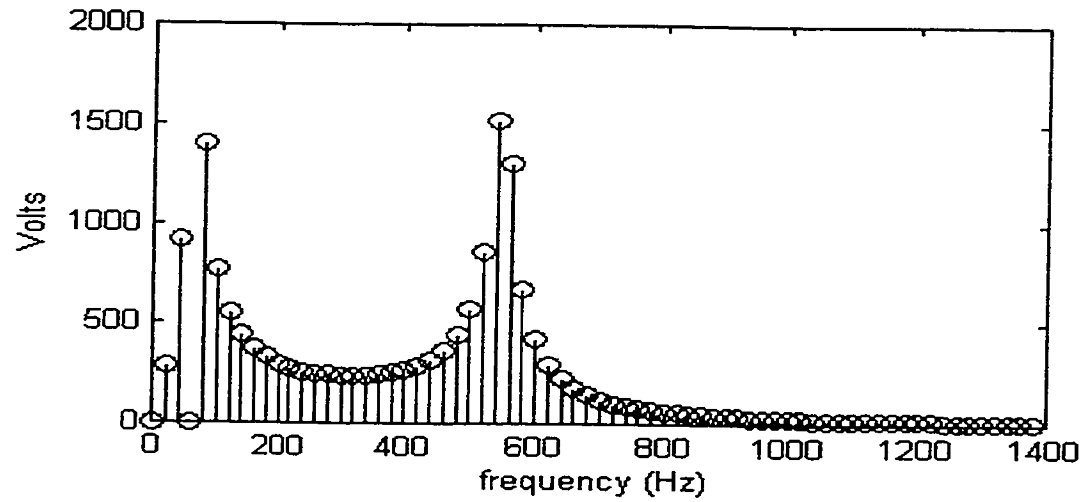


Figure 3.5: Capacitor Voltage $V_C(j\omega)$ with out Fundamental in Frequency Domain

more clearly. When the inverse fft is applied to $V_C(j\omega)$, the result is then the time domain waveform. In the figure 3.6, the capacitor voltage is obtained by time domain method and plotted side by side with the time domain result from inverse fft of $V_C(j\omega)$. The results are almost identical.

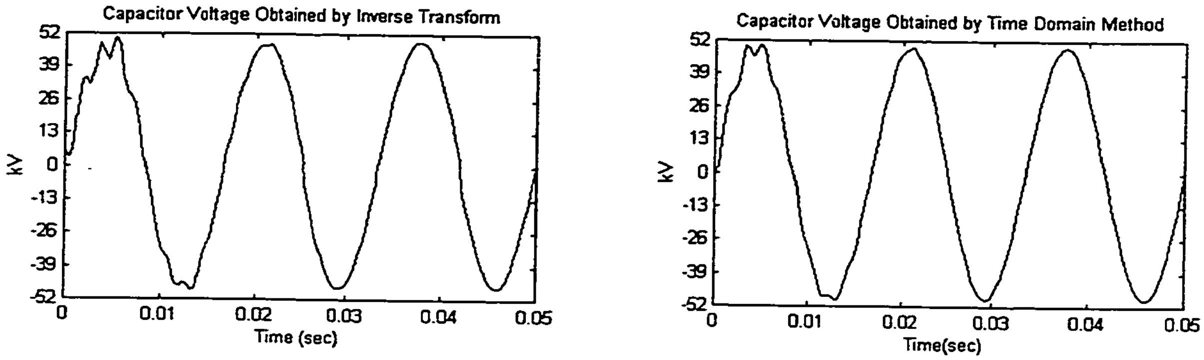


Figure 3.6: Capacitor Voltage in Time Domain

3.2 Sensitivity Study of the Basic Case

As mentioned earlier, the proposed method relies heavily on the Fast Fourier Transform for frequency domain analysis. It is therefore important to further examine the relationship of the accuracy of the result with the variation in some parameters such as number of points considered, sampling frequency, and the frequency steps. If the concept is found to be relatively sturdy or if the best numbers can be found for most accurate result with the mathematics involved then it will help in determining more accurate result from the proposed method. It would be necessary to have the mathematics very accurate for the proposed method, then if any errors are encountered in the method, we can be certain that the errors are not occurring due to mathematical error. It should be noted that the case used for basic concept is only provided for determination of mathematical accuracy, it does not address the switch or the switching scenarios, which is provided in the proposed method.

3.2.1 Data Window Size

As mentioned earlier data window size is taken as the integral multiple of the complete cycle. It is the periodic nature of the Fourier transform that the complete cycle of the waveform has to be considered to accurately represent the frequency content of the waveform. In the above example, three complete cycles of the input is taken for calculation with the assumption that in real case transients will completely die out with in three cycles. It is common for transient to become insignificant or completely gone with in one cycle. However, three cycles is considered to accommodate even the longer lasting transients. Question that is needed to be answered is if the use of larger data window size will make the result any different. Our objective is to be able to represent the transient in frequency domain as accurately as possible. If the transient only last for one or two cycles, then the data window sizes of three cycles guarantees the total representation of the transient.

Figure 3.7 below shows the capacitor voltage for the same example (figure 3.2). However in this case four cycles of the input is considered for the calculation. It must be noted that the waveforms of figure 3.5 can not be directly compared with the waveforms of figure 3.7 that uses four cycles because of the discrete nature of the fft involved. There is an indirect way of comparing the results of two different data window sizes by converting the frequency domain into time domain.

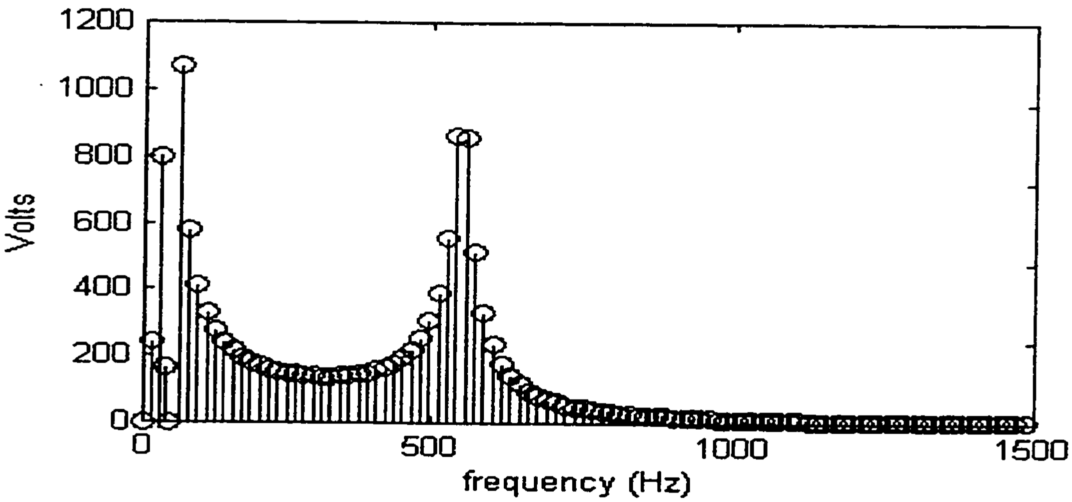


Figure 3.7: Capacitor Voltage $V_C(j\omega)$ with Four Cycles of Input without Fundamental

The time domain capacitor voltage waveform obtained with four-cycles of input is shown in the figure 3.8. When it is compared with the figure 3.6, it is seen that the use of three cycles is better than using four-cycles of input. It can be logically argued because of the periodic nature of the fft involved that the optimal data window size is the one that just accommodates the required only part of the waveform, i.e., in our case the complete transients.

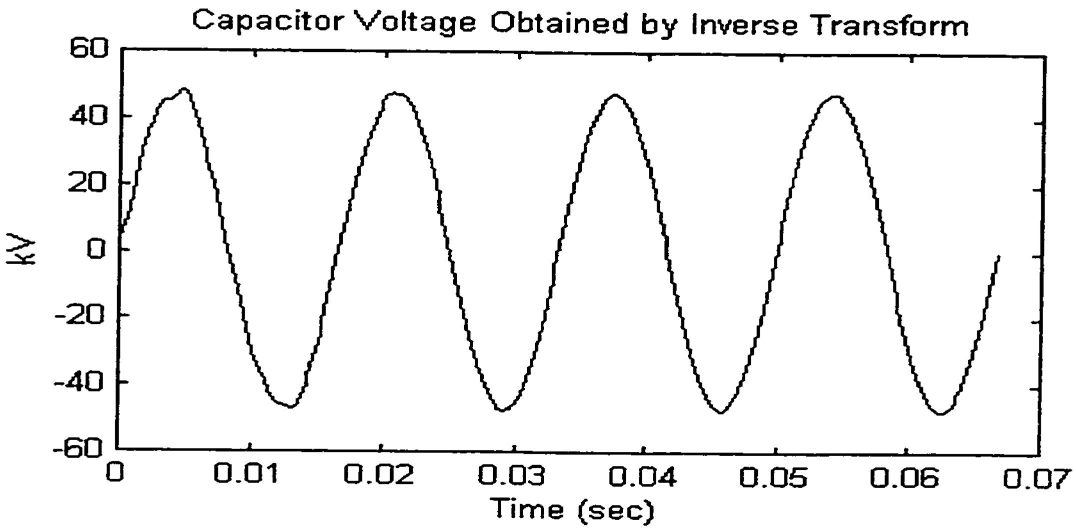


Figure 3.8: Capacitor Voltage Obtained by Inverse Transform with Four Cycles of Input

It is therefore concluded that for general-purpose use to our proposed method, we will be using three cycles of the waveform. Three cycles of waveform will cover all major switching transients. There would be some exception cases when the dominant transients is the oscillatory transients where the oscillation may last more than three cycles, but such cases are rare and becomes a whole new specialized research.

3.2.2 Sampling Frequency

Sampling frequency for the fft is equal to the number of samples multiplied by the fundamental frequency. Nyquist theorem states that the sampling frequency have to be at least twice the maximum frequency of the waveform for accurate result. For the example of figure 3.2, we knew from the analytical solution that the center frequency was 548 Hz. Therefore to satisfy the Nyquist theorem, the example in the previous sections have been computed with the sampling frequency of 3000 Hz. It is explored in this section whether the result will get any better by increasing the sampling frequency. In the complex power system network, maximum frequency can reach as high as 5000 Hz. It is not the goal of this section to find fixed sampling frequency for all computation. However, the main purpose is to explore, if the sampling frequency of slightly higher than twice the maximum expected frequency of the waveform would be sufficient for the accurate representation or the sampling frequency have to be significantly higher than the minimum requirement of double of the expected maximum. For this purpose, the capacitor voltage of figure 3.2 is computed using sampling frequency of 6 kHz, which is double the sampling frequency used in the previous section and significantly higher than the Nyquist requirement. Figure 3.9

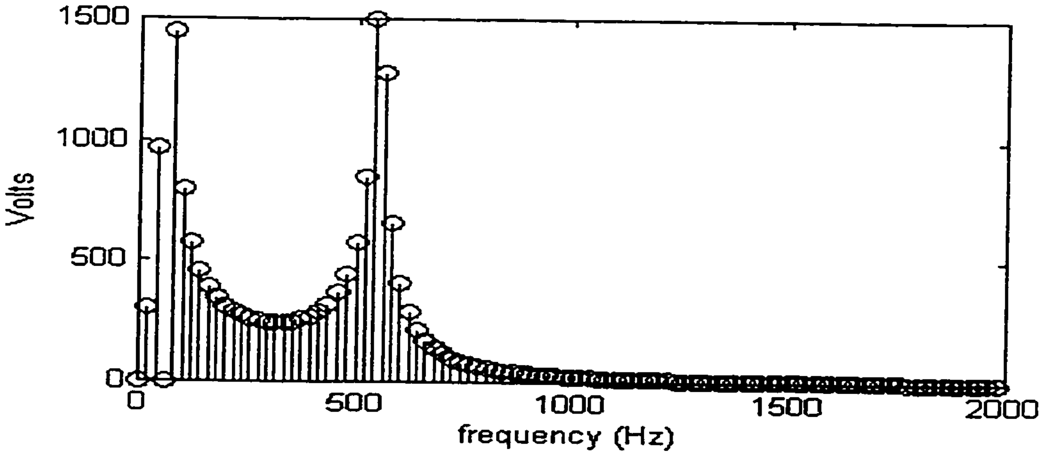


Figure 3.9: Capacitor Voltage with sampling frequency of 6kHz without Fundamental

shows the capacitor voltage that is computed with the sampling frequency of 6 kHz. Just by looking at the magnitude plot of figure 3.9, it is difficult to see the difference between this plot and the earlier figure 3.5 computed with sampling frequency of 3kHz. Figure 3.10 shows the capacitor voltages computed at two different sampling frequencies together. As always fundamental is excluded from the plot to magnify the transients. The magnitudes of the voltages at different frequencies are very close. It shows that high sampling frequency does not necessarily give the better result. It can therefore be concluded that the just right sampling frequency (that will satisfy the Nyquist requirement) will probably give the best result. Not having the need to use very high sampling frequency will reduce the computation time and probably even reduce some numerical errors that may arise due to large number computations. As the real case, switching transients will have maximum frequency in the range of 5kHz, using sampling frequency of about 12 to 15 kHz seems appropriate.

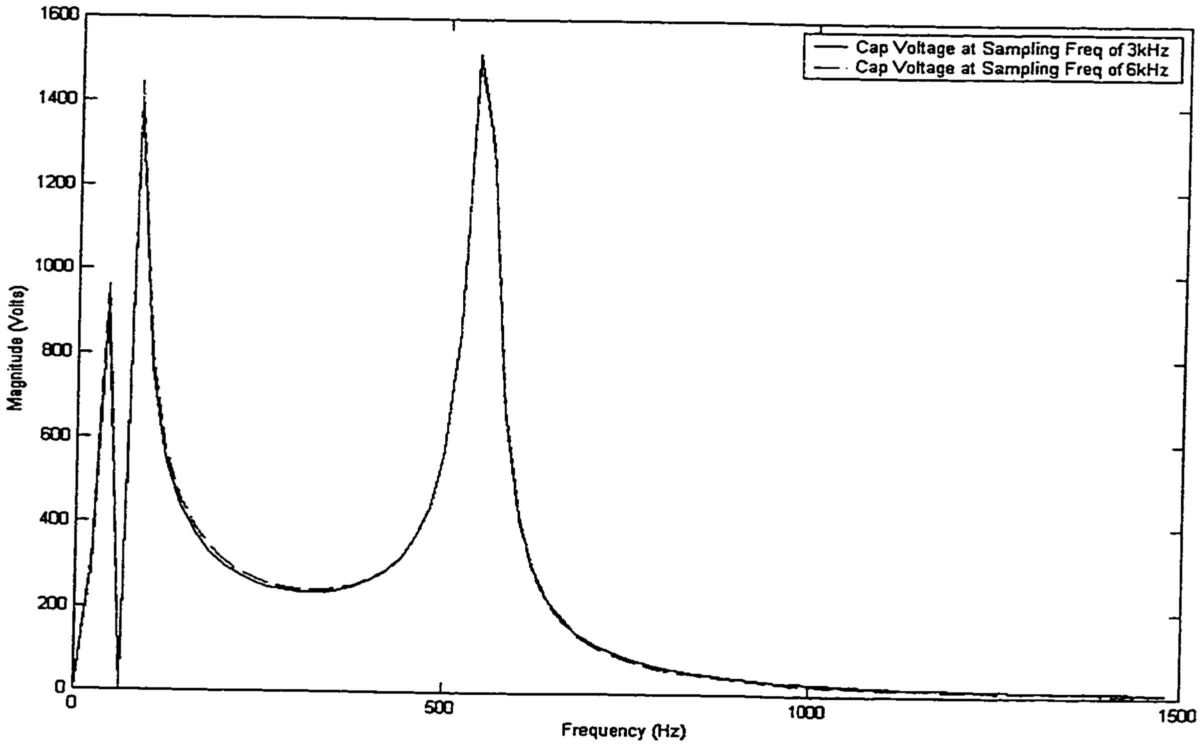


Figure 3.10: Voltage Magnitudes at Different Frequencies when Sampling Frequencies are 3KHz and 6KHz

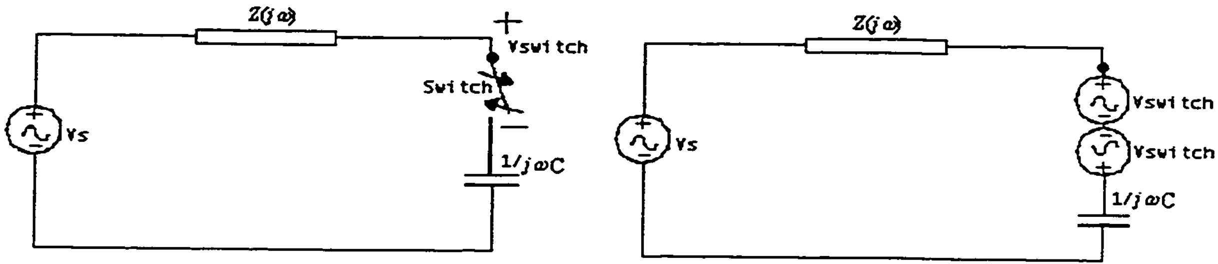
3.3 Superposition Method

The concept of frequency domain analysis described above is applied in the power system for the transient computation. In the example shown above there was no significance of having a switch as the circuit was energized at time zero and the whole circuit started at zero state. However, in the power system when the switch is closed, switch will not be at zero voltage and the power network will not be at zero state. Therefore a procedure is needed to obtain switch current and the voltages taking in consideration the switch closure time. Also, the transfer function concept has to be modified to be able to use in a numerical method.

3.3.1 Calculation of Capacitor Switching Current

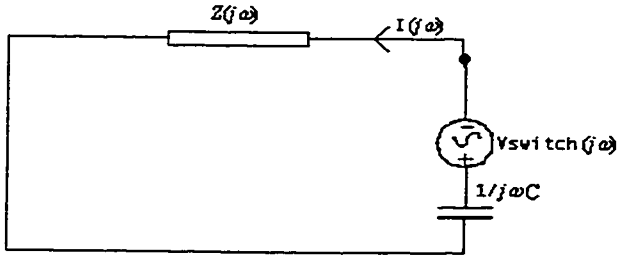
To calculate capacitor-switching transients, a key step is to obtain switching current. This is done by superposition procedure proposed in this thesis. The principle of superposition is based on the fact that considering the case of the switch to close, the voltage that exist prior to switch closure is the system steady-state voltage and to simulate switch closure it is necessary to inject across the switch terminals a voltage equal and opposite to this so that the resultant voltage across the switch terminal is zero, i.e. switch closure.

The above stated fact can be seen in picture as shown in the figure 3.11 a, b, c. In the figure 3.11a, V_{switch} is the steady state voltage that existed prior to the switch closure. The current transient can be determined by injecting a voltage that is equal but opposite in magnitude of the steady state switch voltage prior to the switch closure as shown in figure 3.11c with the supply voltage source disconnected. $Z(j\omega)$ is the impedance response of the network as a function of frequency.



a: Simple Circuit with a Switch Open

b: Circuit with Switch Closure Model



c: Model to find Switch Current (I(jω))

Figure 3.11: Principle of Superposition to find Switching Current

It should be noted that the initial capacitor voltage is considered to be zero for computation. For example if the V_{switch} (in time domain) is as shown in figure 3.12A and the switch to be closed at the peak of the voltage, then the $-V_{\text{switch}}$ will be seen as shown as the figure 3.12B (again in time domain). Finally, the current response due to this injected voltage ($-V_{\text{switch}}$) is determined which will be the required switch current $I(j\omega)$ of the system. It is to be noted that switch voltage needs to be converted to frequency domain prior to the computation.

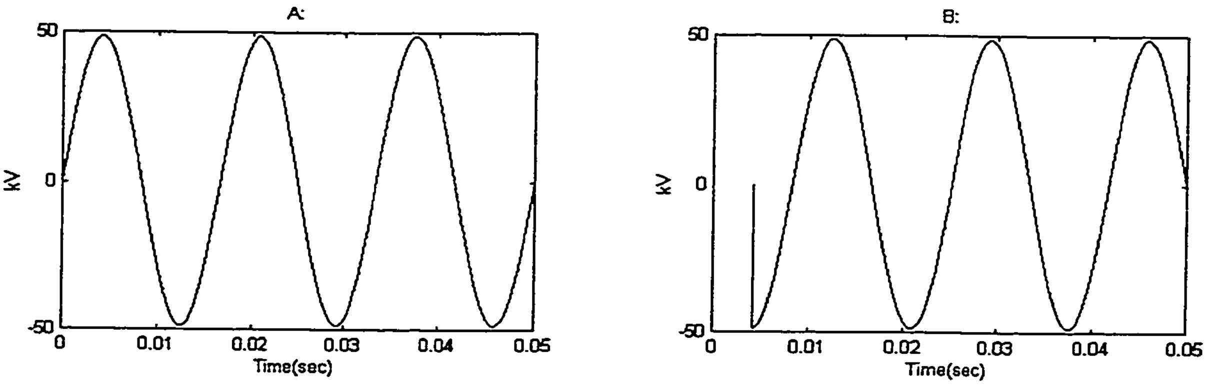


Figure 3.12: A: Steady State Switch Voltage Prior to Switch Closure (V_{switch}). B: -V_{switch} when Switch is Considered to be Closed at the First Peak.

3.3.2 Calculation of Transient Voltages at other Buses

Once the switch current $I(j\omega)$ is computed by the superposition method, the impedance response of the individual buses along with the $I(j\omega)$ can be used to compute capacitor voltages at any buses. For example, if the voltage at bus '*j*' is to be computed and the capacitor is switched at the bus '*i*', then we have

$$V_j(j\omega) = Z_{ij}(j\omega).I(j\omega). \tag{3.6}$$

Where $Z_{ij}(j\omega)$ is the impedance response of the bus '*j*' with the capacitor switched at bus '*i*'.

3.3.3 Determination of System Impedance Response

As seen in the previous two sections, impedance response of the circuit $Z_{ij}(j\omega)$ is required to compute voltages at the individual buses where subscript '*i*' stands for the switching bus and '*j*' stands for the non-switching buses.

The impedance response is determined by performing frequency response calculation on the steady-state network. The network is modeled as a frequency dependent admittance matrix as follows:

$$[Y(j\omega)][V(j\omega)] = [I(j\omega)]. \tag{3.7}$$

Where $[I(j\omega)]$ would be 0 for all the buses except 1 at switching bus, and $Y(j\omega)$ is a square matrix.

$$I(f) = [0,0.....,1,0,0,0,............]^T$$

then we have,

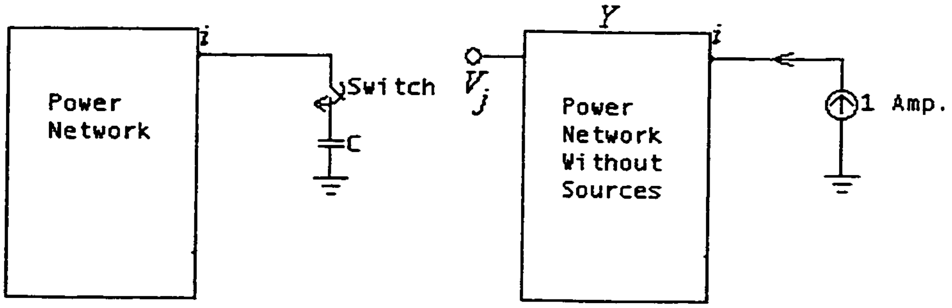
$$[V(j\omega)] = [Y(j\omega)]^{-1}[I(j\omega)]. \tag{3.8}$$

The equation 3.8 will give

$$[V(j\omega)] = [Z(j\omega)]. \tag{3.9}$$

From equation 3.9, we can obtain $Z_{ij}(j\omega)$ which is the impedance response of the bus j when the switching bus is i. Equation 3.9 is possible because $I(j\omega)$ is 1 ampere, and the inverse of $Y(j\omega)$ is $Z(j\omega)$ by definition.

A number of programs can be used to compute impedance response of the circuit by use of equation 3.8. For example, if we have a network as in the figure 3.13A, then 1 amp current at variable frequency is injected as shown in the figure 3.13B. At each frequency, the voltage response at individual buses is recorded. The resultant array of voltages at different frequencies at each bus will be the impedance response $Z_{ij}(j\omega)$ of the bus j with current injection at bus i by virtue of equation 3.9.



A: Power Network with Cap located at node i.

B: Power Network with sources disconnected and switch replaced by 1 Amp. current source.

Figure 3.13: Current injection in Power Network

3.3.4 Case1: Simple System

We can use the superposition method to compute the switching transients of the circuit described in the previous chapters. Consider a same RLC network from figure 3.2 that is shown again in figure 3.14 with the slight modification that this time the switch will be closed at the peak of the input voltage.

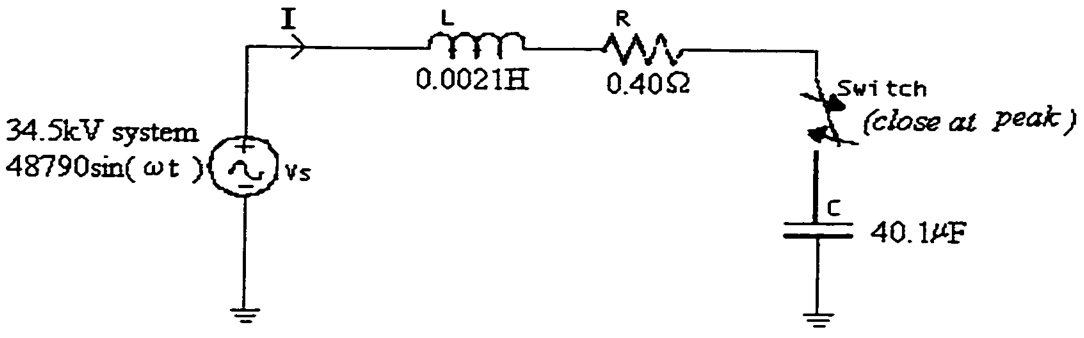


Figure 3.14: RLC network for Case 1

An ideal switch is used to switch an RLC circuit on an AC source (60 Hz). The switch, which is initially open, is closed at the peak of the input voltage. As in the previous sections, *L=0.0021H, R=0.40Ω* and *C=40.1µF*. The objective is to determine capacitor switching transient voltage using the proposed method.

The [*Y*] matrix is formed to obtain the *Z(jω)* as discussed previously. The impedance response of the circuit is shown in the figure 3.15. In this case, the state equation is simple and will lead to:

*Z(jω) = R + j*2*π*f*L, where f goes from 0 to 3000 Hz with an increment of 20Hz.*

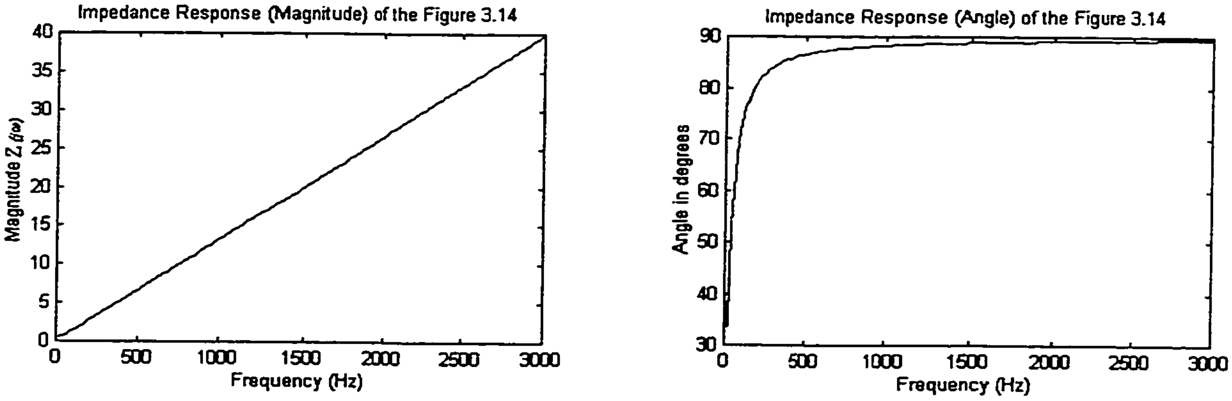


Figure 3.15: Impedance Response of the Circuit Shown in Figure 3.14

Next is to use superposition method to find switching current $I(j\omega)$. The switch voltage prior to the closure of the switch can be found (since it is the steady state voltage that exists prior to the switch closure as described in the previous section.) which will be the open circuit voltage at the location of the switch. Figure 3.16 shows the circuit configuration to find switching current by the use of principle of superposition.

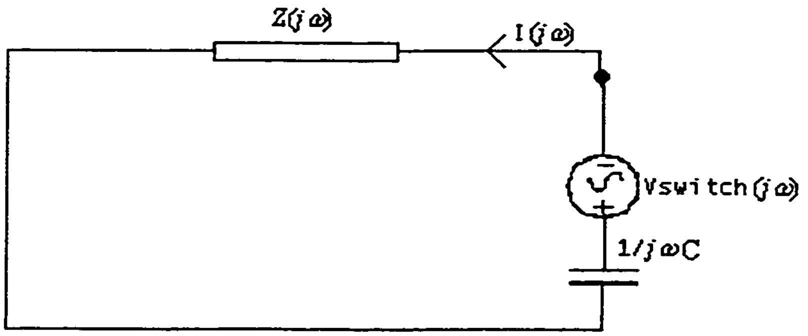


Figure 3.16: Circuit Configuration to Find Switching Current

The switch voltage ($-V_{\text{switch}}(j\omega)$) is the frequency domain values obtained by transformation (fft) of the time domain voltage values ($-V_{\text{switch}}$) as shown in the figure 3.17.

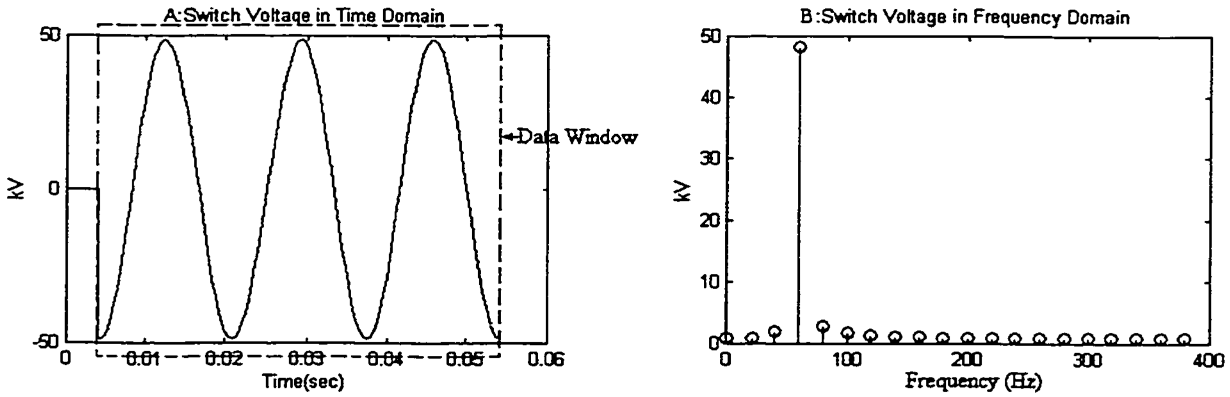


Figure 3.17: Switch Voltage

It is seen that the switch voltage is not pure sinusoidal because at the instant the switch closes, the voltage at the contact point rises from zero to the peak. The switching current obtained by using the superposition method (figure 3.16) is shown in the figure 3.18.

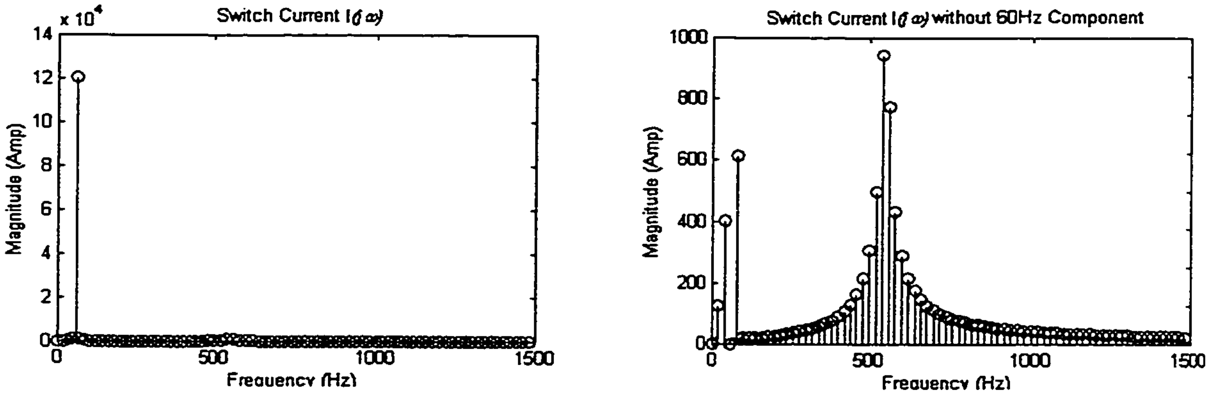


Figure 3.18: Switching Current *I(jω)* in Frequency Domain

Therefore the transient capacitor voltage due to the switching in the circuit is computed by multiplying impedance response of the switching bus with switching current by the use of equation 3.6. The resulting transient voltage is plotted in figure 3.19.

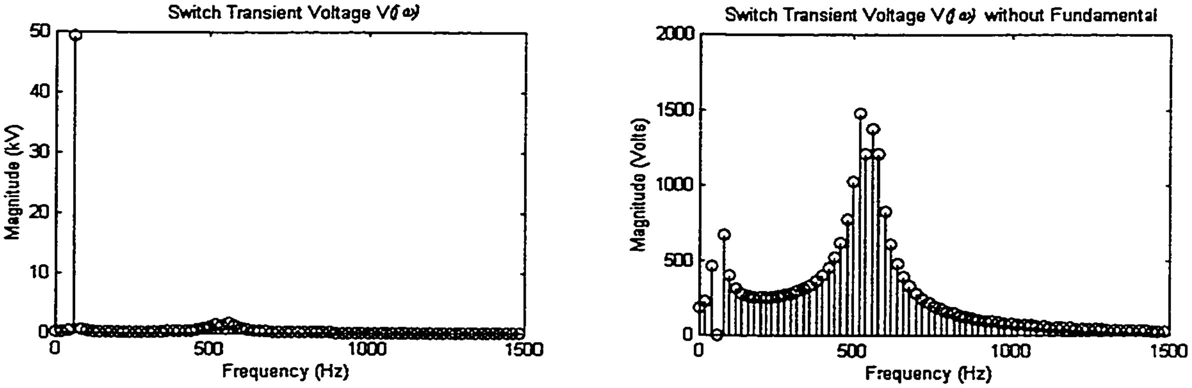


Figure 3.19: Switching Transient Voltage Frequency Spectrum

It should be noted that in this computation the switch was modeled to be closed at the peak of the waveform and the initial capacitor voltage was zero.

3.3.5 Comparison with the Time Domain Results

EMTP program is used to simulate the transient voltage in time domain. The switching voltage in the time domain for the circuit shown in the figure 3.14 as obtained with EMTP is shown in figure 3.20. The time domain plot of figure 3.20a is transformed into frequency domain using fft function and the data window of three cycles starting from the instant the switch closes (at the peak).

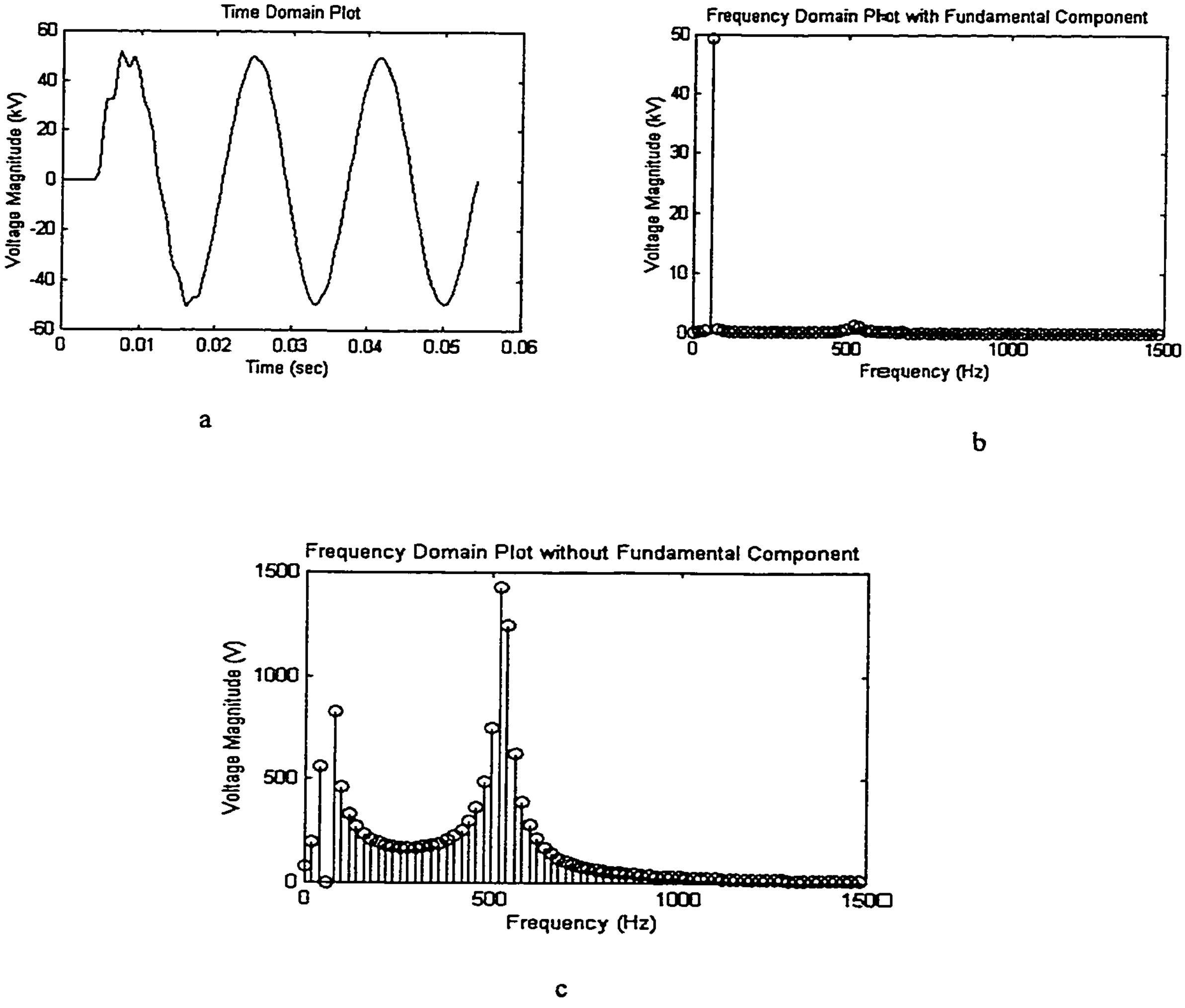


Figure 3.20: Switching Transient Voltage as obtained by Time Domain Method (Using EMTP Program)

The capacitor transient voltage obtained by the method of superposition in the frequency domain can be compared with the result obtained by the time domain method by plotting both the voltage spectrums in one plot with same number of points and the frequency steps. Figure 3.21 shows the capacitor voltage obtained by both methods, and it is seen that the result is very similar.

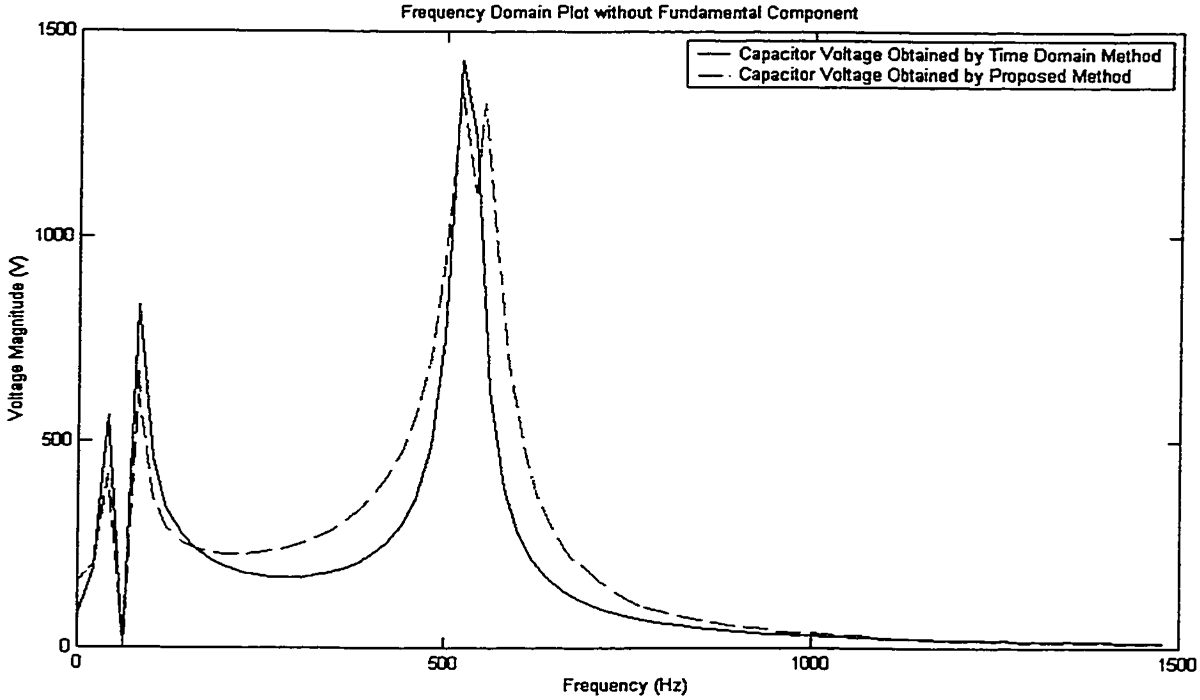
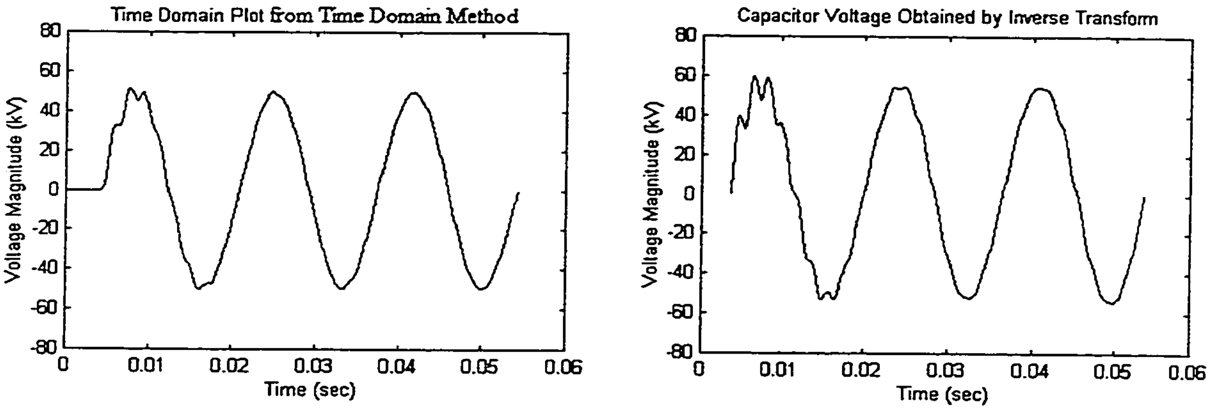


Figure 3.21: Voltage Magnitudes Obtained by Superposition Method and the Time Domain Method (EMTP) in Frequency Domain.

It is seen that the magnitudes for some frequencies are slightly higher in the result obtained by the proposed method. However, the peak, the trend and the dominant frequencies are same for both results.

Another way of comparing the two methods is by using inverse transform to change the frequency domain result into time domain and compare the voltages in the time domain. The transient voltage waveforms in time domain are seen in the figure 3.22.


Time Domain Plot from Time Domain Method

Capacitor Voltage Obtained by Inverse Transform

Figure 3.22: Time Domain Plots of the Switching Transient Voltages

In the frequency domain, before the switch is closed there are no values. To plot, the time domain values obtained from the inverse transform in the similar scale as the result obtained by the time domain method, time-shift was used to make the waveform starting point at 0.00416s. Switch closure can be modeled at the peak of the waveform but time can be shifted wherever it is appropriate in the frequency domain method. The plot shows that the two waveforms are closely matched. Again the author would like to point out that the emphasis here is at the frequency domain result and the frequency domain analysis. Occasional time domain results are used for the comparison purposes only.

3.4 Analysis of Large System

The main purpose of this thesis is to develop a method to compute and analyze power system transients in the real case with efficiency and accuracy and be able to use the result data for practical purposes. It is therefore necessary to use the method in the real system as an example to demonstrate the application of the proposed frequency domain method. In this section a method to compute switching transients from impedance response and the superposition method, as described in the previous sections, is used to compute transients of real case network.

Unlike small network, large system network will have considerably higher transients and with higher number of harmonic contents. It will be demonstrated that the frequency response method will be very suitable for the actual power system network to compute transients in frequency domain. The large system is part of city of Calgary and Southern Alberta transmission and distribution network. City of Calgary has six substations with capacitor banks at 138kV level. Southern Alberta has six substations with capacitor banks also at 138kV level. The total simulated system have 332 three-phase buses (332*3 individual buses) at various voltage levels. The system buses and the corresponding voltage levels are shown in the appendix C. The system network block diagram can be found in chapter-two figure 2.5. When the capacitor is switched on any location of the network, transients can occur in that switching bus as well as it will propagate to other buses. As the network is mostly high voltage distribution, transients can have a significant effect in the normal operation.

In this section, superposition and the system impedance response method is used to compute transients at the switching bus and as well as a non-switching bus in the frequency domain and the results are compared with the time domain solution obtained by EMTP. The knowledge of the harmonic contents of the transient and the peak magnitude will help determine whether any mitigation methods are needed to curb the transient effects or that it can simply be neglected. Chapters 4 and 5 look into the details how to use the result obtained in this section for ranking of the buses so that the worst buses can be determined. The problem to be investigated here involves the closure of capacitor switch at the substation 42S bus number 202, which has a 54MVAR capacitor. The transient at the switching bus as well as the other bus (non-switching bus) at substation 44S, bus 44S-184 is monitored. These buses were picked at random for analysis. However, bus 44S-184 is one of the major distribution bus in the network and it is of considerable distance from the substation 42S, bus number 42S-202. The distance between two buses gives the rough extent of transient propagation in the network. The capacitor switch at 42S-202 is closed at the peak of the waveform.

3.4.1 Determination of System Impedance Response

The procedure for obtaining the system frequency response for the large case is the same as for the smaller network described earlier. In this case, since large numbers of buses are involved, equation 3.7 is solved by using the frequency response feature of the EMTP program (input data is attached in appendix A). The voltage sources of the network were disconnected (Nodes were grounded). The capacitor bank at the substation "42-S bus number 202" was turned on and one ampere current source was placed in between capacitor bank and the bus-202A (where the capacitor switch was located) for current injection into the network. A frequency step of 20Hz is used and the response up to 8000Hz is computed.

The magnitude and angle response of the impedance of the network is then plotted which can be seen in the figure 3.23. It is the $Z_{ii}(j\omega)$ (without the capacitor) of the network where i is the switching bus which is 42S-202 in this case. It can be seen from the figure 3.23 that unlike the simple case the impedance response does not follow any order. The impedance magnitude for some frequencies is very high while for other frequencies it is considerably low. The angle of the network also varies in the low frequency range.

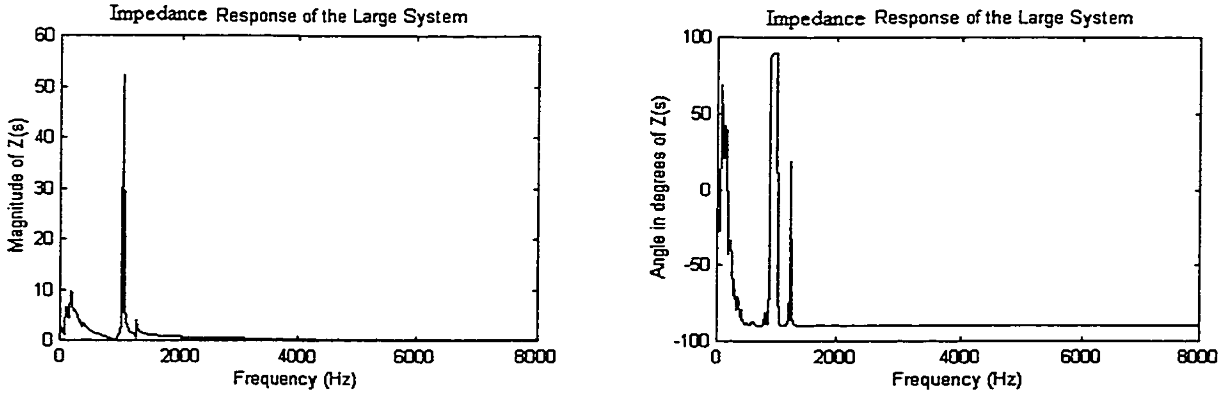


Figure 3.23: Impedance Response of the Large System

The substation 44-S-bus-number-184 is also monitored for the transfer impedance response $Z_{202,184}(j\omega)$, where 202 is the switching bus, as an example to obtain voltage at other buses. The figure 3.24 shows the impedance response of the bus 184 when the capacitor is switched at bus 202.

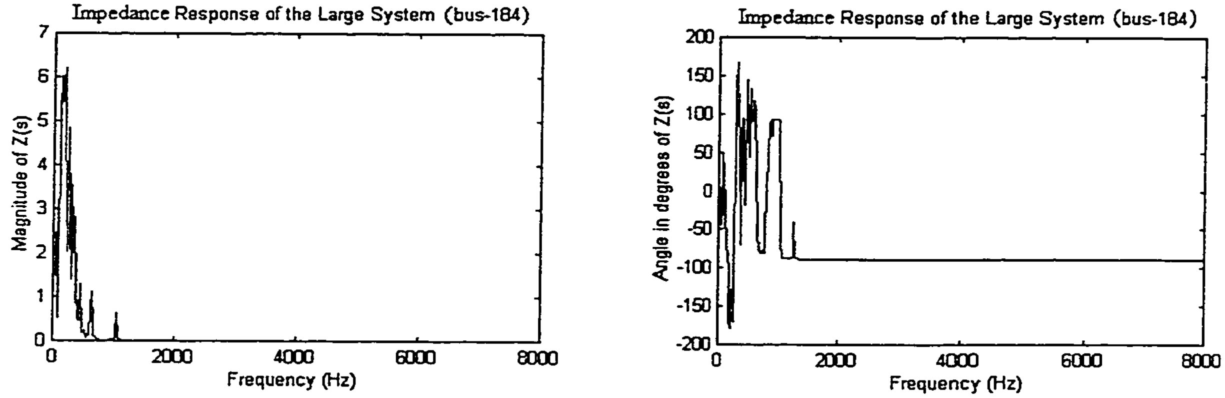


Figure 3.24: Impedance Response at Bus 184 when Capacitor is Switched at Bus 202

We know that the resulting impedance response of the bus is the transfer impedance of that bus. Therefore, the transient voltage at any bus such as bus 184 is given by the equation 3.6, which is the product of switching current and the impedance of the given bus. Switching current is computed by the method of superposition.

3.4.2 Case Study Results

To find the actual voltage at the bus 44S-184 or at the switching bus itself (bus 202), as explained in the previous section, switching current is needed. Switching current is computed by the superposition method described in section 3.1.1 using the steady state switch voltage and the impedance response of the network (figure 3.24) including the capacitor. Then by applying the equation 3.6, the voltage at (any) bus 184 will be $Z(j\omega)$ (i.e. the impedance response) of bus 184 multiplied by the switching current in frequency domain. The switch voltage (required to compute the switching current) represents the negative of the steady state voltage of the network prior to the switch closure in frequency domain. The steady state voltage prior to the switch closure can be measured or computed from the network data. In this case the steady state voltage was computed from the network data and the resulting switch voltage is shown in the figure 3.25 (with the switch is modeled to be closed at the peak of the waveform). The data window is shown in the figure 3.25 that covers the complete three cycles of the switch voltage for conversion to the frequency domain.

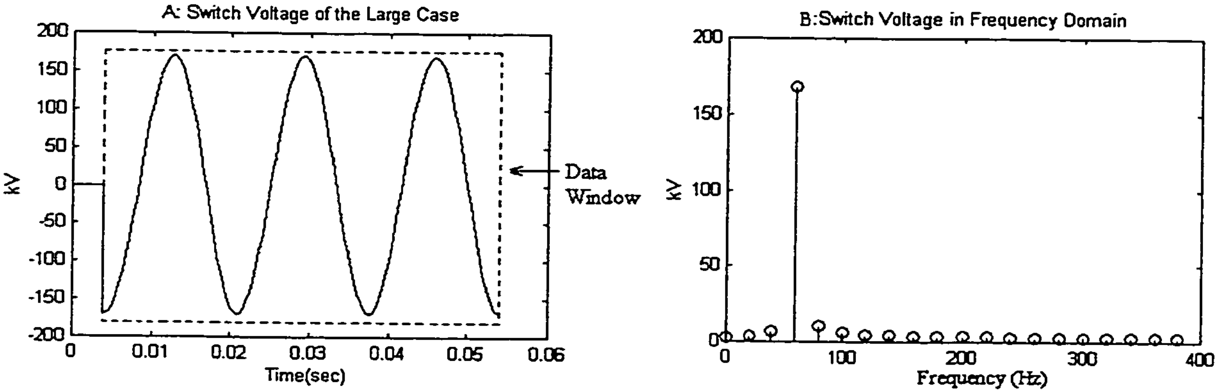


Figure 3.25: Switch Voltage of the Large Case

Finally, the switching current is obtained and shown in the figure 3.26.

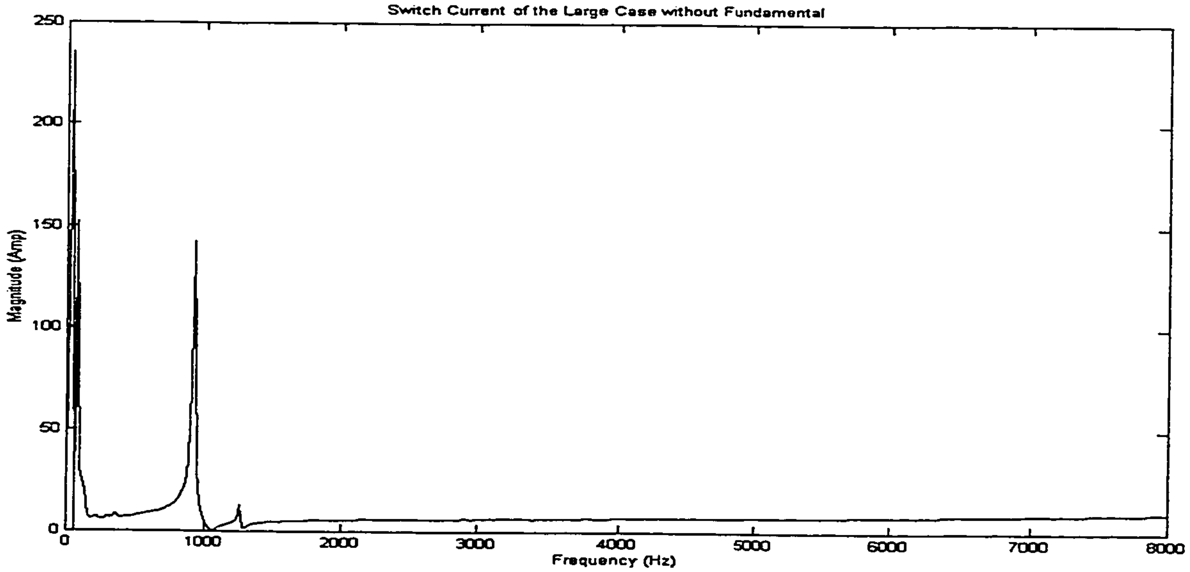


Figure 3.26: Switching Current $I(j\omega)$ of the Large Case

The switching transient voltages at the switch location (bus 42S-202) are $I(j\omega)*Z_{ij}(j\omega)$ *(where i and j are equal to bus 202)*, computed from the impedance response method are shown in the figure 3.27. The voltage magnitudes at certain frequencies are relatively high and can not be ignored for optimum performance of the network. The peak of the transient at 300Hz reaches up to 5900V.

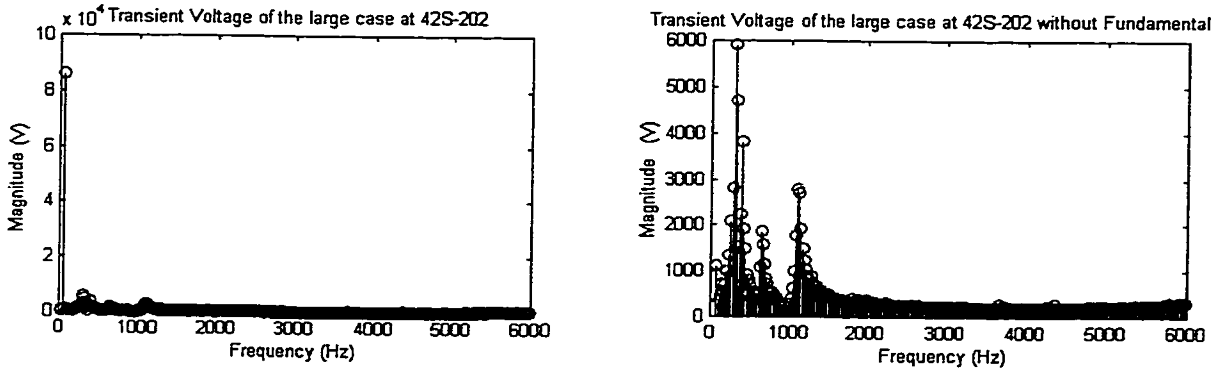


Figure 3.27: Switching Transient Voltage Obtained by Impedance Response Method

Similarly, the voltage at the bus 44S-184 can be computed by using impedance response of bus 44S-184 and the $I(j\omega)$. The transient voltage at the bus 44S-184 can be seen in the figure 3.28.

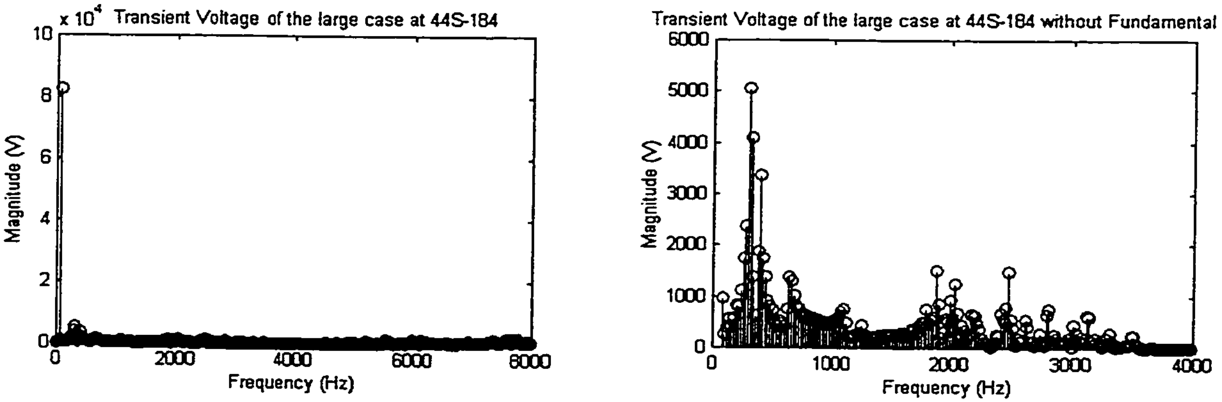


Figure 3.28: Transient Voltage Obtained from Impedance Response at Bus 44S-184

The non-fundamental peak of the transient occurs at 300Hz at peak is about 5100V. The other significant transient occurs at 1860Hz and 2460Hz.

3.4.3 Comparison with Time Domain Simulations Result

The EMTP result for the transient voltage at bus 42S-202 and at bus 44S-184 is shown in figure 3.29.

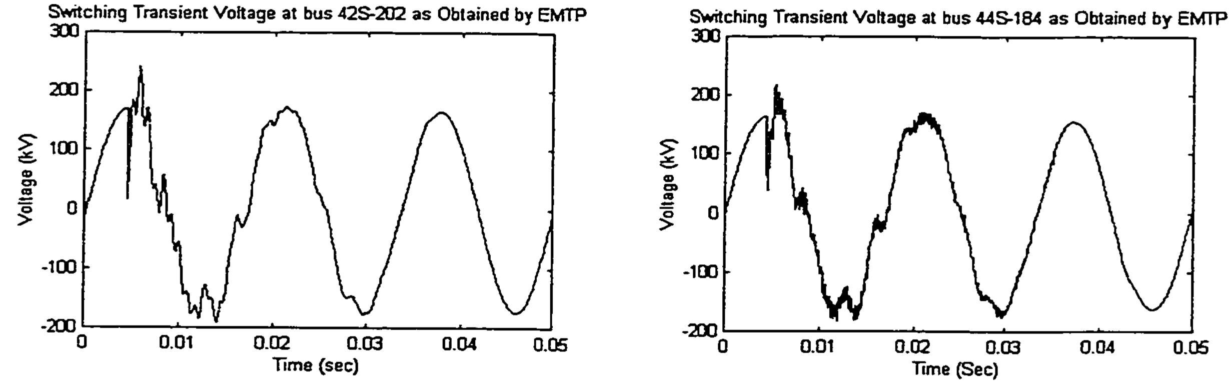
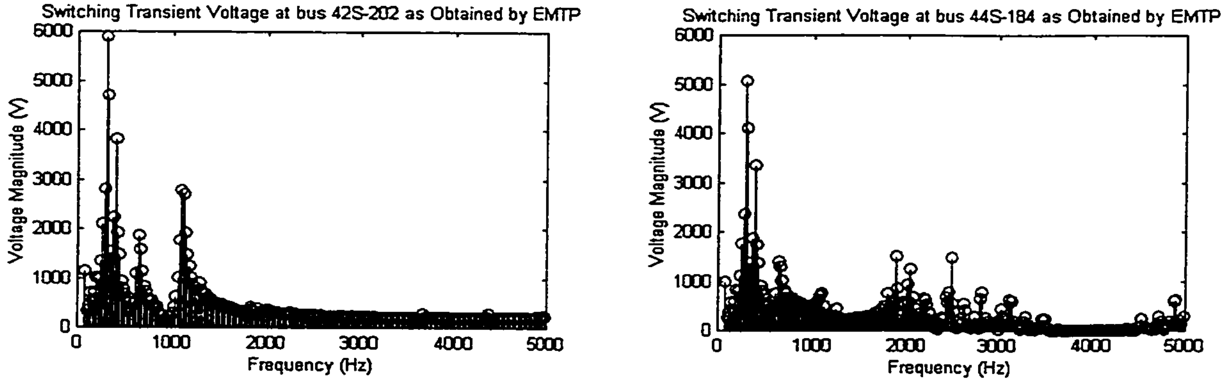


Figure 3.29: Time Domain Plots of the Transient Voltage at Bus 202 and Bus 184

To make the comparison easier, the time domain results are converted to frequency domain by taking exactly same data window and number of points as used in the impedance response method for the transient voltage computation and using the fft function in the Matlab. The resulting frequency domain transient voltages at the bus 202 and bus 184 are shown in the figure 3.30.



(a) (b)

Figure 3.30: Switching Transient Voltages as Obtained by EMTP

(Plot is shown without Fundamental)

The time domain result is converted to frequency domain result because the main focus of the thesis is based on the analysis of transient in frequency domain. We want to prove that the frequency domain result obtained by the proposed method in this thesis is correct and does provide the similar result as the existing programs that work in time domain.

One way to see the extent of difference in the result between the time domain method and the frequency domain method proposed in this thesis is to plot the discrete voltages in one plot to see the deviation of results from one another at different frequencies. The figure 3.31 shows the transient voltages obtained from both methods in one figure for both buses (bus 202 and bus 184).

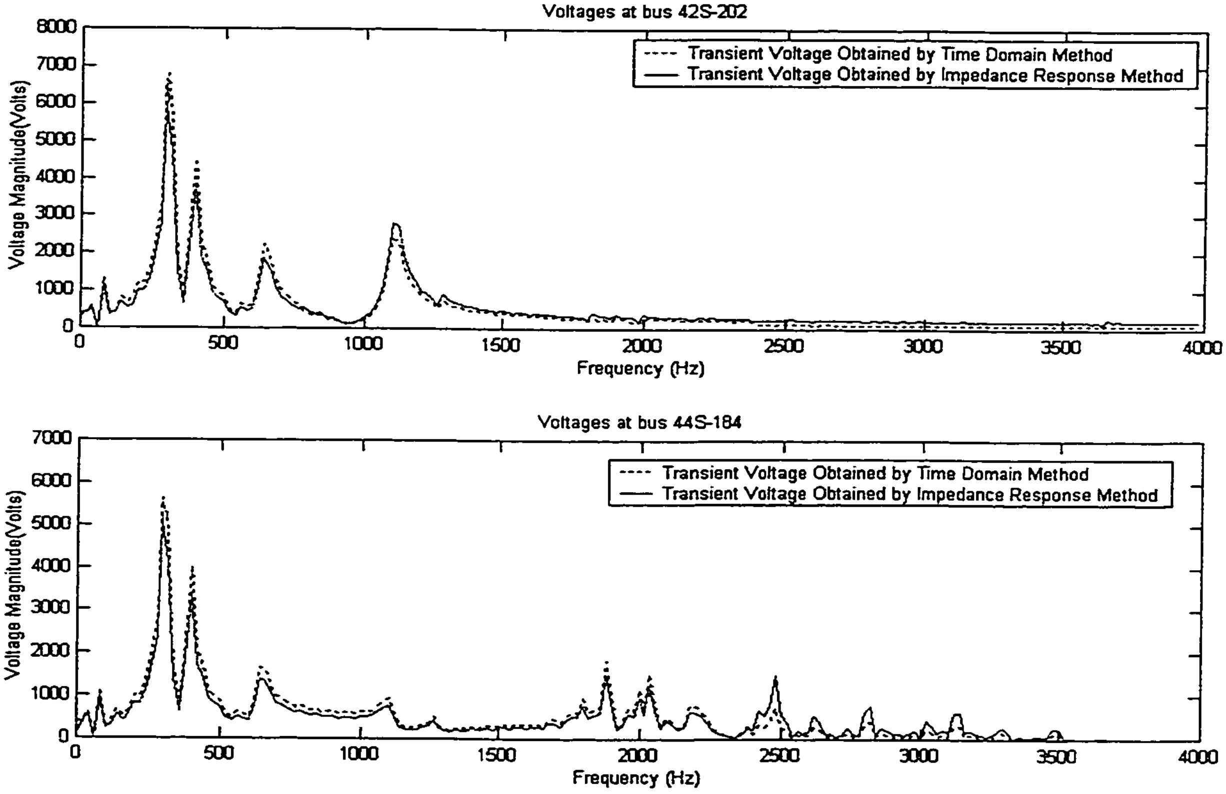
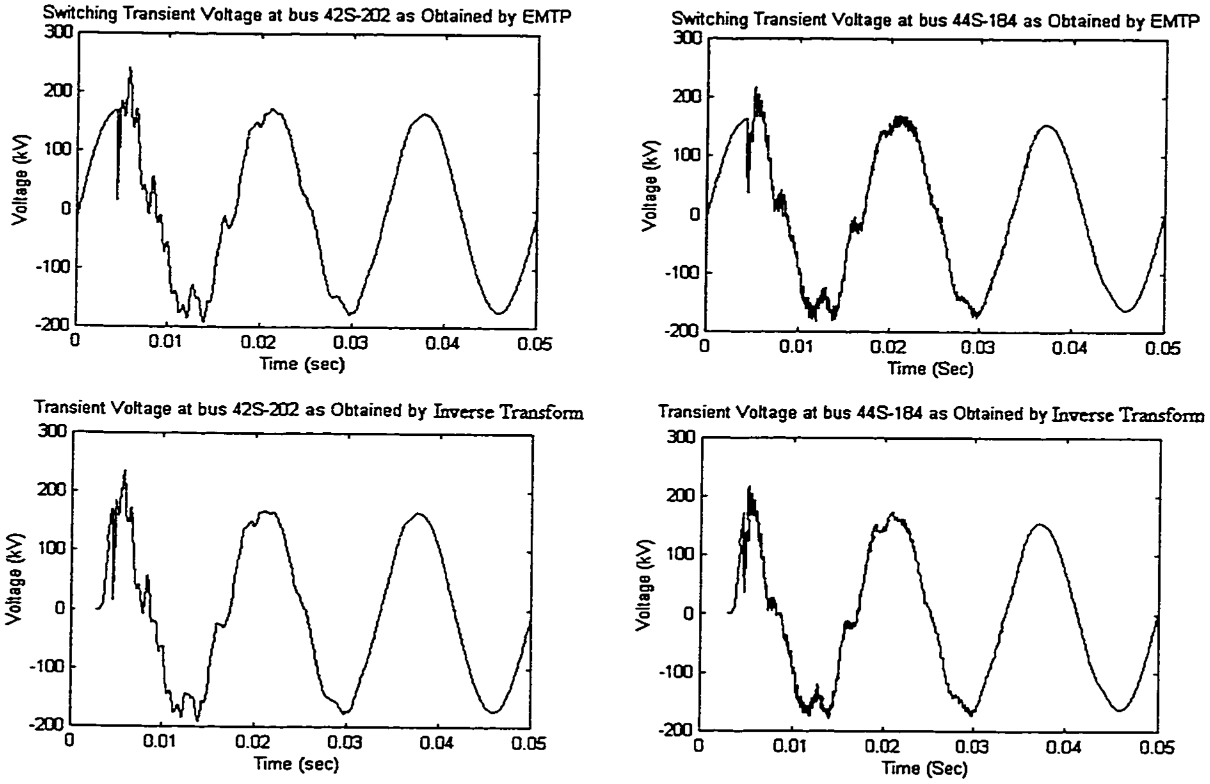


Figure 3.31: Transient Voltages in Frequency Domain without Fundamental

As mentioned earlier, the another approach of comparison between two results is to keep the time domain result as it is and transforming the frequency domain result into time domain using the inverse transform, thereby comparing the waveform in the time domain. However, the time domain plots are for quick comparison. Main goal is to show that the waveforms obtained by the both methods have the similar shapes. The figure 3.32 shows the time domain plots for bus 202 and bus 184 obtained by both methods (time domain method—figure 3.29 and the frequency domain method converted to time domain by using inverse transform).


Switching Transient Voltage at bus 42S-202 as Obtained by EMTP

Switching Transient Voltage at bus 44S-184 as Obtained by EMTP

Transient Voltage at bus 42S-202 as Obtained by Inverse Transform

Transient Voltage at bus 44S-184 as Obtained by Inverse Transform

Figure 3.32: Time Domain Plots of the Transient Voltages at Bus 202 and bus 184 Obtained by Time Domain Method (Top) and Impedance Response Method (Bottom)

It can be concluded from the figure 3.22 that the results obtained from the both methods are very similar to one another. The dominant transients have less obvious differences, while the majority of the differences seem to be in the middle section of the waveform. The results obtained by impedance response methods are more straightforward and can be directly read for any individual frequencies. It minimizes complexity and provides more information about the nature of the transients than by the EMTP results alone. Of course, EMTP results can also be further processed to arrive at same data, but the whole purpose of developing impedance response method is to avoid extra time and manpower as much as possible.

3.5 Summary of the Proposed Method

The basic flow chart of the procedure to obtain switching transients using the frequency response method is shown in the figure 3.33. The method needs the impedance response data of the power network in frequency domain and the steady state open circuit voltage at the switch node prior to switch closure.

Certain procedures are followed in this thesis to obtain frequency response of the system and the switch current. The detail flow chart, which summarizes all the procedure that is followed in this thesis to obtain the transient voltage using frequency response method, is shown in the figure 3.34.

It should be noted that the specific procedure that is used in this thesis is not the one and only way to obtain the desired result. User can follow different program or procedure. The focus is the method. It is proved that the proposed method to obtain switching transient voltage in frequency domain works with very good accuracy and provides lot of information about switching transients with respect to frequency contents, magnitudes etc.

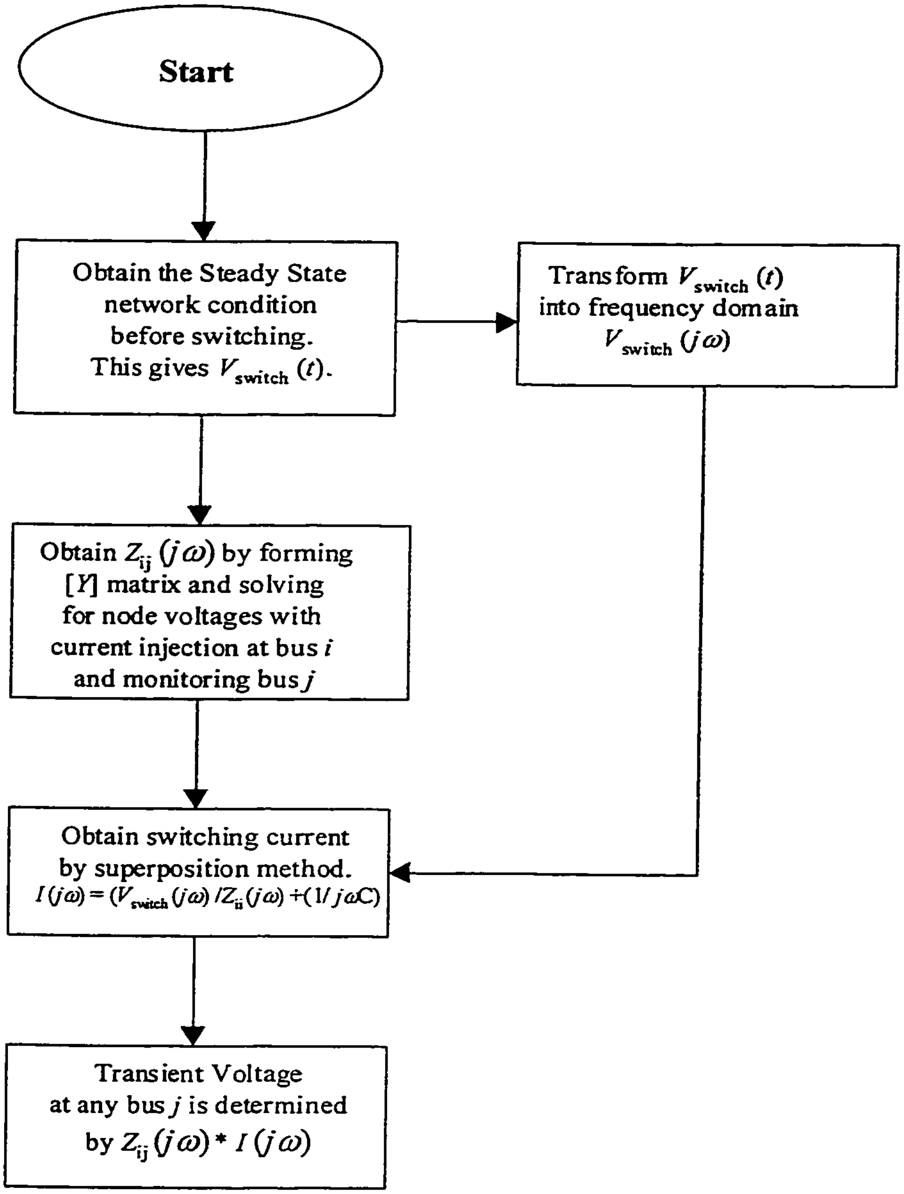


Figure 3.33: Flow Chart to Obtain Switching Transients Using Impedance Response Method in the Power Network

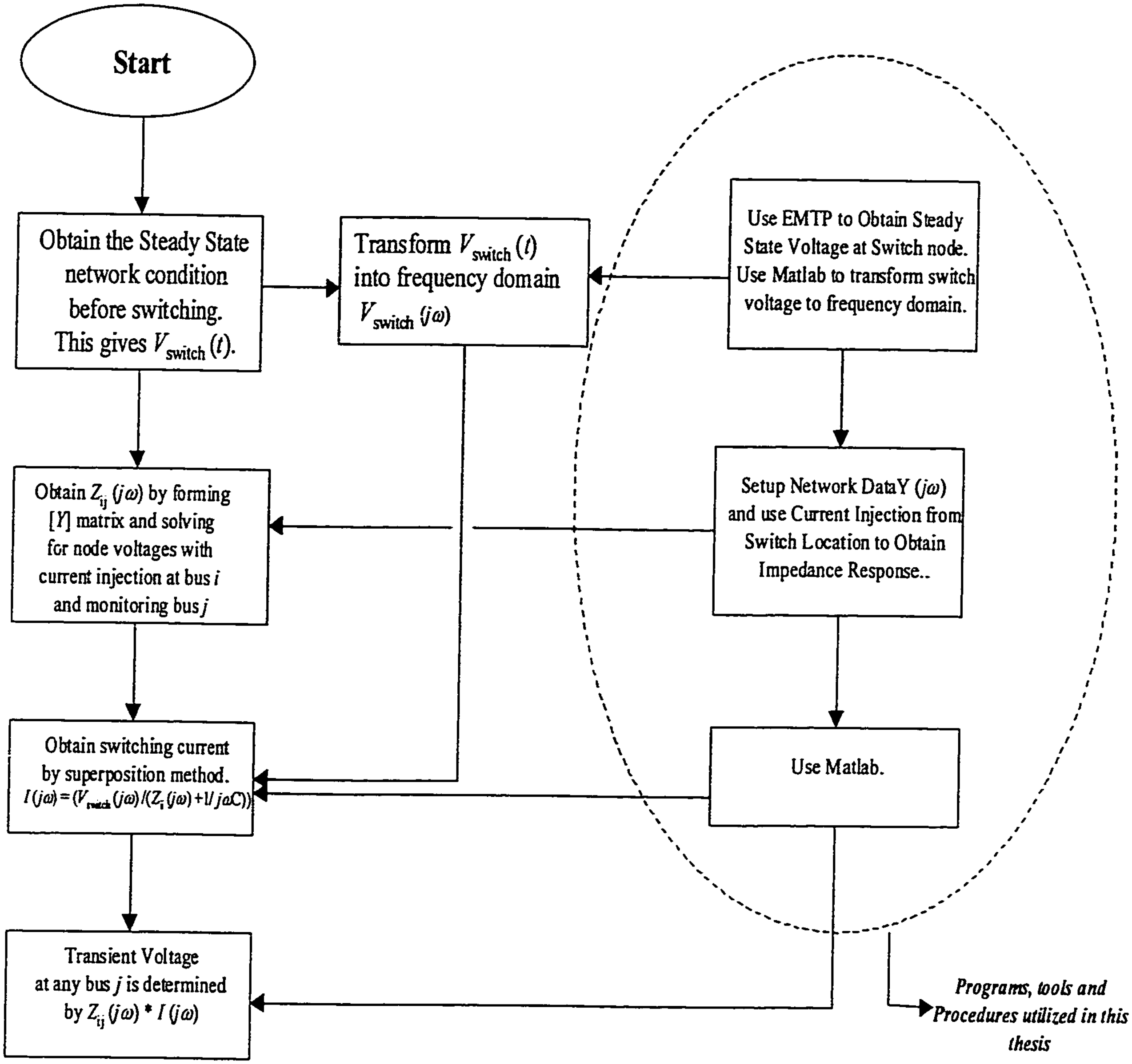


Figure 3.34: Detail Flowchart of the Methods used in this Thesis to Obtain Switching Transients in the Power System.

Chapter 4

Simplified Analysis of Switching Transients

4.0 Introduction

It can be seen from the results in chapter 3 that only some frequencies are dominant in the frequency spectrum. There is, therefore, the possibility to conduct approximate calculation by considering the dominant component only. Selective study can drastically reduce the cost and improve efficiency, as it will be possible to eliminate large portions of the frequency spectrum of the network by just looking at the rough estimate.

One of the main reasons of transient analysis is to be able to extract information that will have a practical use. For example, ranking of the buses in terms of the transient peak from highest to the lowest will provide the tools for the engineers to look for mitigation method. Similarly, buses can also be categorized in terms of transient energy. To develop this type of analytical tools, concept of key frequency plays an important role. In this and next chapter, key frequency concept and the buses rankings with regard to peak and the energy of the transient will be explored.

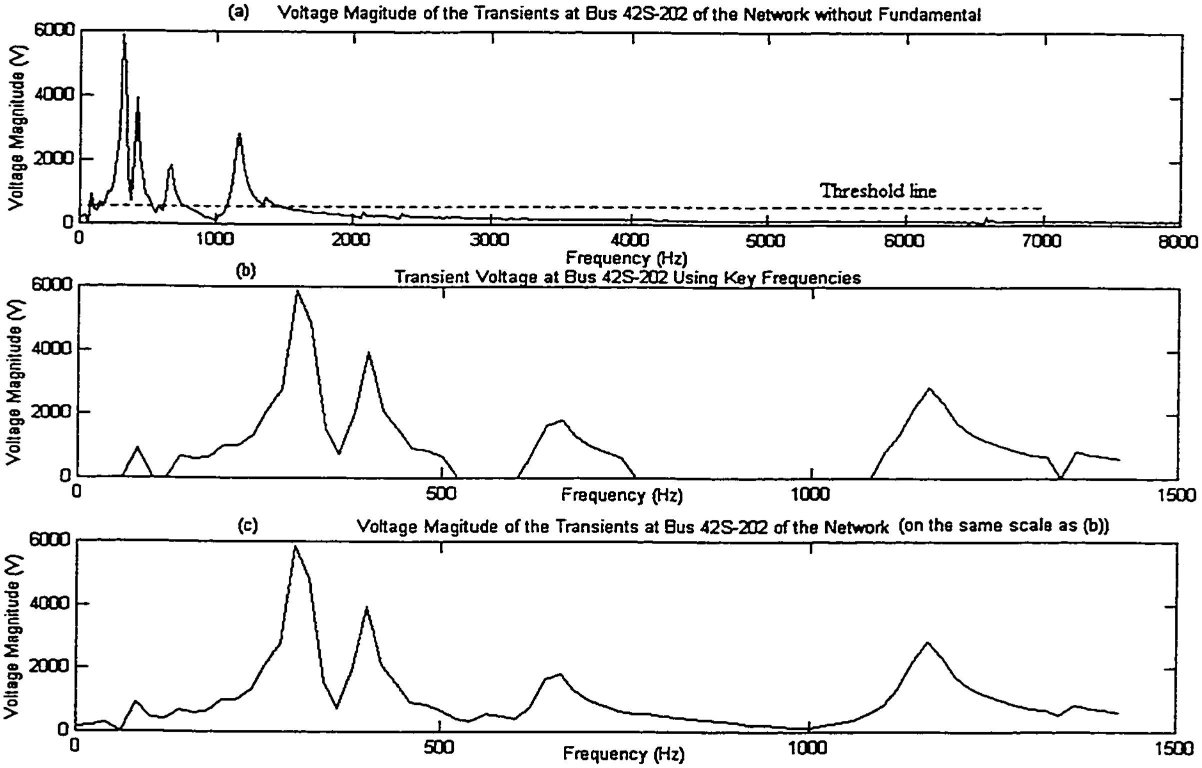
The simplified analysis of switching transients will use similar procedures as used in chapter three but the difference lies in the fact that it only uses key frequencies for further study or for determination of the impact of transients in the network. The key frequencies can be obtained by simply setting the threshold voltage. The mathematical basis for this method is that the bus-voltage is computed by taking the product of switch current and the transfer impedance of the corresponding bus in the network. Key frequencies picked will cover both voltage and current that have higher magnitudes. This will also ensure that even though we have higher current at one frequency, and the impedance is very small at that same frequency, the product of the two will still be considerably high that it can be taken into account. As mentioned earlier, as this method is for the purpose of quick analysis of the network, and as there is very small chance that few dominant frequencies can be ignored, the method has the practical applications in the power industries.

For the purpose of demonstration, same data (of Southern Alberta Power Network) from the previous chapter is used. In chapter five these key frequencies spectrum is used to determine the transient indices that will help in determination of the worst buses in the network. Another advantage of this simplification is that once the key frequencies for the particular power network are known, only those frequencies could be monitored for future references. Any type of method can be applied to obtain the key frequencies of the network. As it should be noted that it is more difficult to obtain complete spectrum than just few key frequencies.

4.1 Use of Key Frequencies of the Transient Voltage

From the previous chapter, the plots can be obtained for the transient voltages. The key frequency assumes that not all frequencies are dominant or not all frequency can cause harm to the network. It is wise to remove the frequencies that do not play any role in damaging the quality of power and can be termed negligible in terms of the its existence in the power system. Therefore, the key frequencies can be defined as those frequencies in the voltage spectrum that show the properties of having enough magnitudes or oscillation that can or may likely cause disturbance in the power network affecting the quality of the power supplied to the consumers.

For demonstration, numbers of buses are taken into account from the large case presented in the previous chapter for frequency spectrum plots after the key frequencies are picked. As it is a capacitor-switching transient, the characteristic can be generalized without losing the significance for the purpose of picking up key frequencies. Taking into account the factors such as; (a) peaks, (b) number of peaks, (c) energy of the transients and (d) using the logical judgement (based on the prior experience with the power system network), the threshold voltage magnitude is taken as the 10% of the highest peak of the transients. (Fundamental is ignored as always in these calculations). The key frequency spectrum of the voltage transient at bus 42S-202 taking into account the threshold margin then becomes as shown in the figure 4.1. The frequencies now become distinct and countable. The calculation is greatly simplified. Figure 4.1 gives a some perspectives of using key frequencies. First of all Figure 4.1 (a) shows the total spectrum of transient voltage at bus 42S-202.


(a) Voltage Magitude of the Transients at Bus 42S-202 of the Network without Fundamental

(b) Transient Voltage at Bus 42S-202 Using Key Frequencies

(c) Voltage Magitude of the Transients at Bus 42S-202 of the Network (on the same scale as (b))

Figure 4.1: Transient Voltage Magnitudes at Bus 42S-202. (a) Full spectrum. (b) Spectrum using key frequencies. (c) Full spectrum plotted on the same scale as (b).

In figure 4.1 (b), the key frequencies are picked and plotted using only the selected frequencies and rest of the spectrum is rejected. Figure 4.1 (c) shows the full spectrum data plotted in the same scale as the plot using only the key frequencies.

Use of key frequencies also allows plotting only the discrete values as shown in the figure 4.2 that will greatly increase the readability of the plot in terms of dominant frequency composition and corresponding magnitudes.

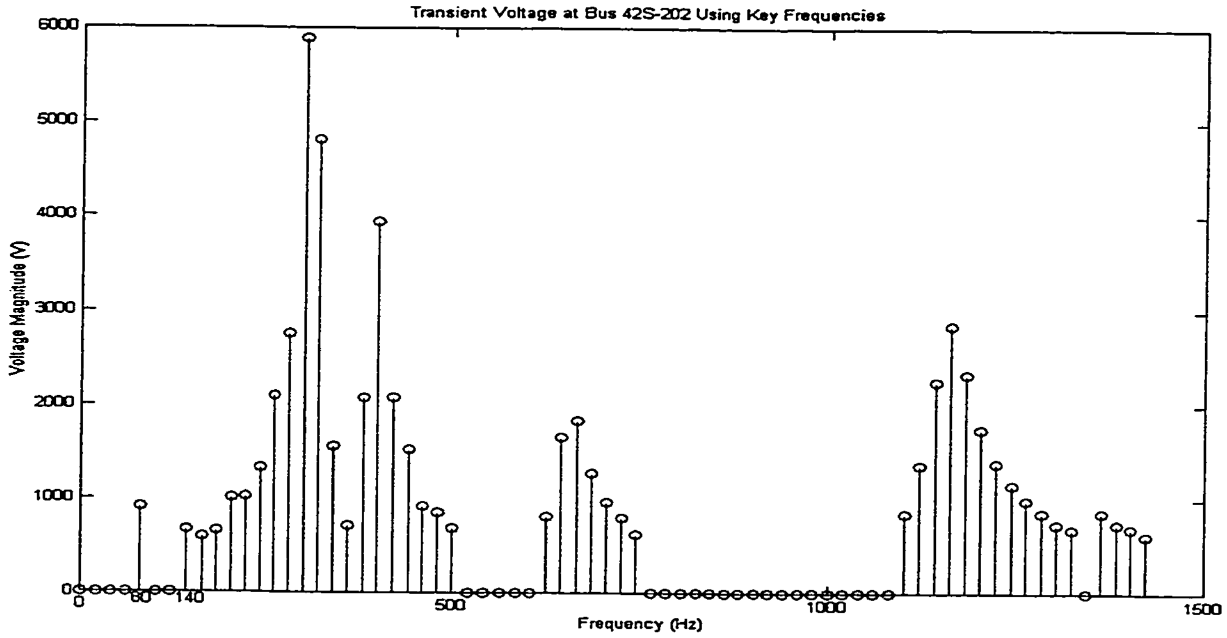


Figure 4.2: Transient Voltage at Bus 42S-202 Using Key Frequency.

4.2 Comparison with Exact Result

Key frequencies are picked after the transient voltages have been computed through the whole spectrum of the frequencies considered to be significant (8000Hz). Key-frequency technique removes frequencies with small or negligible magnitudes but it is always guaranteed to pick up major frequencies. Therefore, from the analytical point of view use of key frequencies is as correct as any actual result. For example, we can look at voltage waveform at the bus-551 of the network. The detail transient waveform can be seen in the figure 4.3. From figure 4.3, it can be seen that transient voltage is significantly higher at some higher frequencies while middle range is almost negligible. When performing analysis of the transients in this bus, middle range is not a factor and would be over looked in any case.

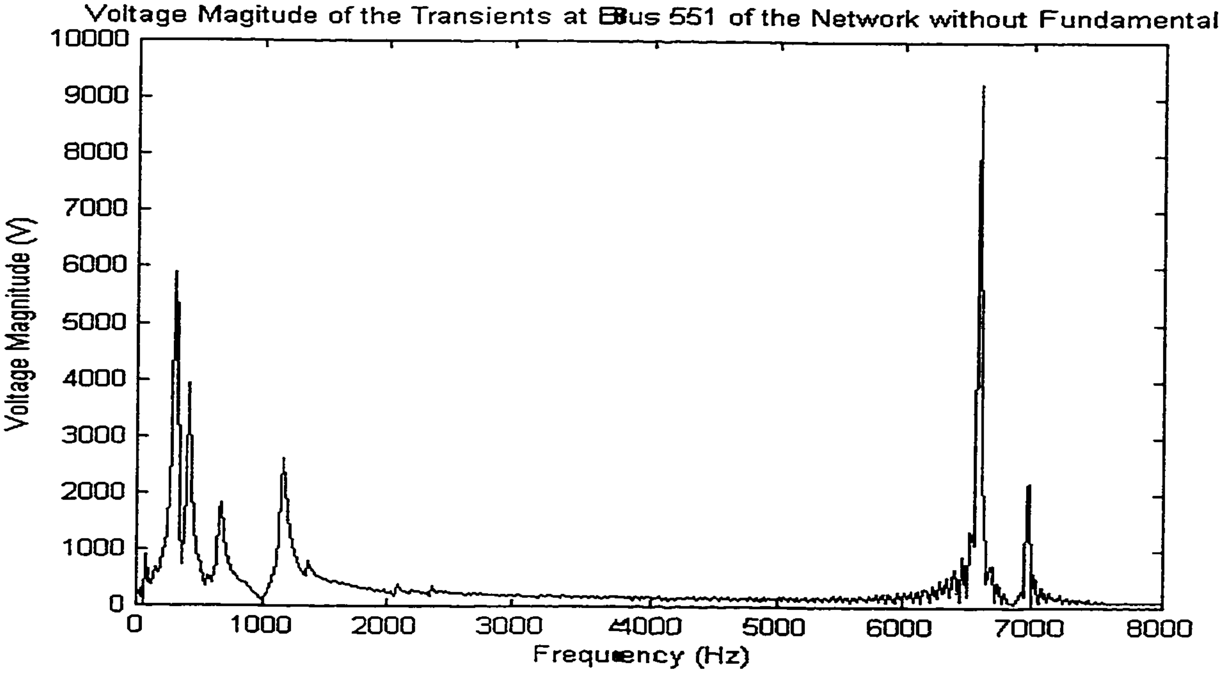
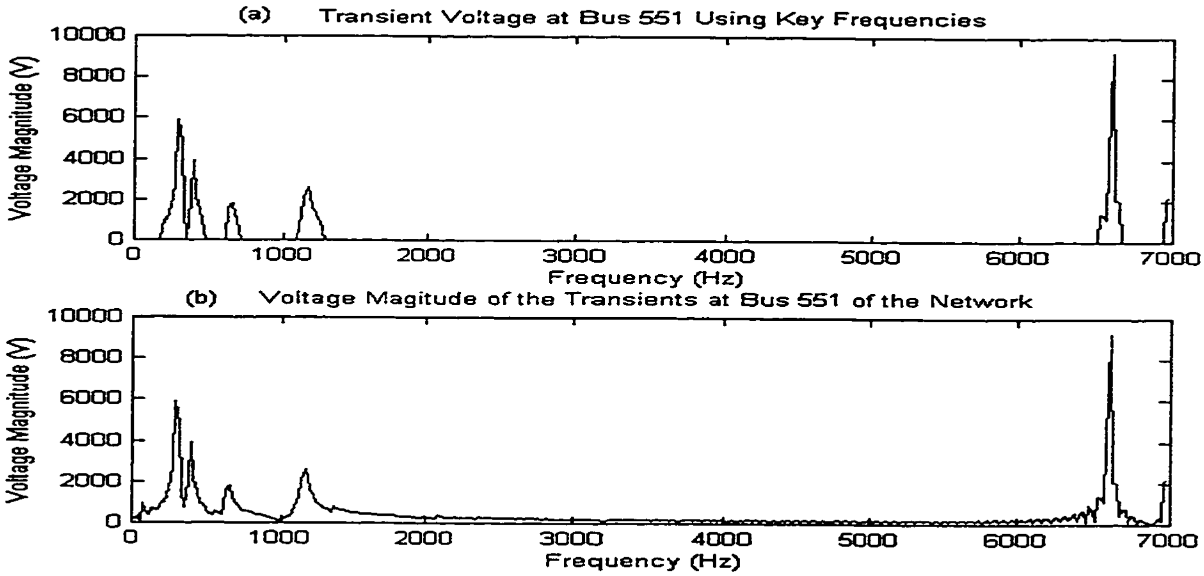


Figure 4.3: Transient Voltage at Bus 551 without Fundamental

Using the key frequency, it will neglect all the insignificant frequencies in the middle range between 2000~5800 Hz while keeping the significant frequencies as can be seen in the figure 4.4 (a). Figure 4.4 (b) shows the total spectrum of the same waveform for comparison. Figure 4.4 (b), when compared with the figure 4.4 (a), it is seen that the frequency range of 1500Hz to 6400Hz was neglected for further analysis.


(a) Transient Voltage at Bus 551 Using Key Frequencies

(b) Voltage Magitude of the Transients at Bus 551 of the Network

Figure 4.4: Transient Voltage at Bus 551. (a) Using Key Frequencies (b) Whole spectrum of the Voltage on the same scale.

When using the key frequency concept, the question will arise whether the waveform can be reconstructed in time domain using the key frequency spectrum. The exact reconstruction of the time domain waveform cannot be possible from the key frequency concept due to the theories involved in transformation methods beyond the scope of this thesis. However, for demonstration purpose, we can use the inverse transformation on the key frequency spectrum (with zeros at the neglected frequencies) of the bus-551 of the figure 4.4 to see the output in the time domain. The figure 4.5 shows the corresponding time domain plot.

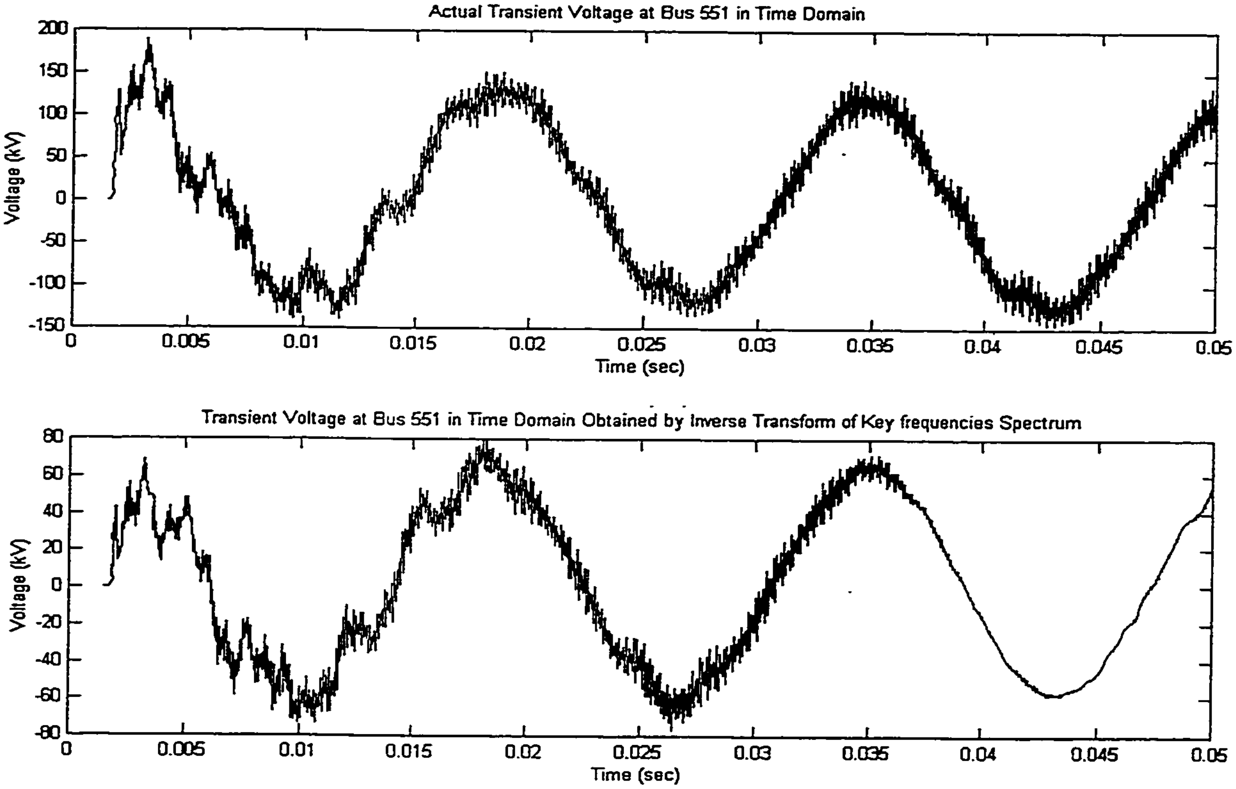


Figure 4.5: Time Domain Plots of Voltage at Bus 551. Top: Actual Time Domain Voltage Plot. Bottom: Time Domain Plot Obtained by the Key Frequencies Spectrum.

As seen in the figure, key frequency concept can not be used in the voltage reconstruction in the time domain (both the magnitude and the shape of the waveforms are different from the actual waveform). However, selection of the key frequencies is a concept to reduce the complexity of the problem by simplifying the data needed for certain aspect of transient analysis. It is therefore not relevant whether the key frequencies can be used for time domain waveform reconstruction as long as the selected frequencies reasonably represent the actual transient waveform for analytical purposes in frequency domain.

On further note, besides using transient voltage to pick the key frequencies, there are other possibilities available for the key frequency selection. One of the other possibilities that stand out the most is the selection of the key frequency from the impedance response spectrum before multiplying with the switch current to obtain the transient voltage. If this possibility gives relatively accurate result, one advantage it will have is that whole spectrum of the switch current need not be calculated but only the frequencies that are selected from the impedance response of the network can be used. Example can be used to demonstrate the selection of key frequencies from the network impedance response data. Selection of key frequencies is performed using the same criteria as above when key frequencies are picked from the transient voltage itself. All frequencies with magnitude in the range of 10% of the peak magnitudes are retained and rests are discarded. With this criteria the impedance response of the Bus 551 becomes as shown in the figure 4.6.

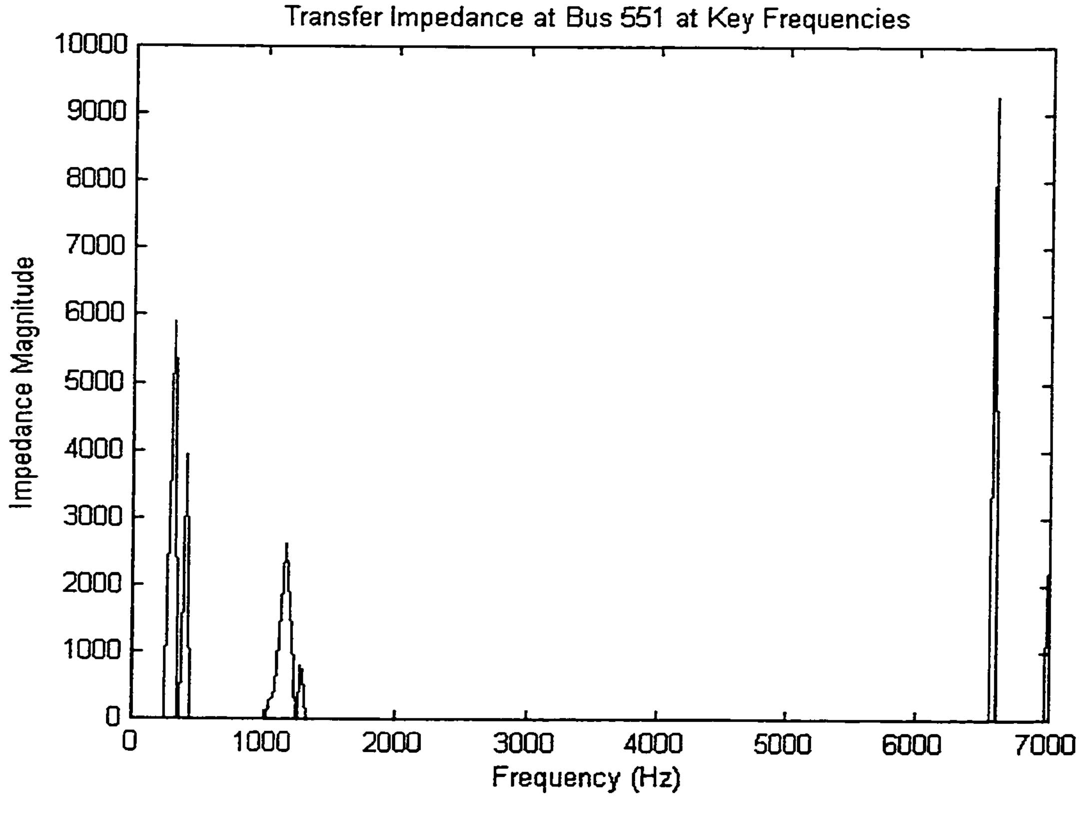
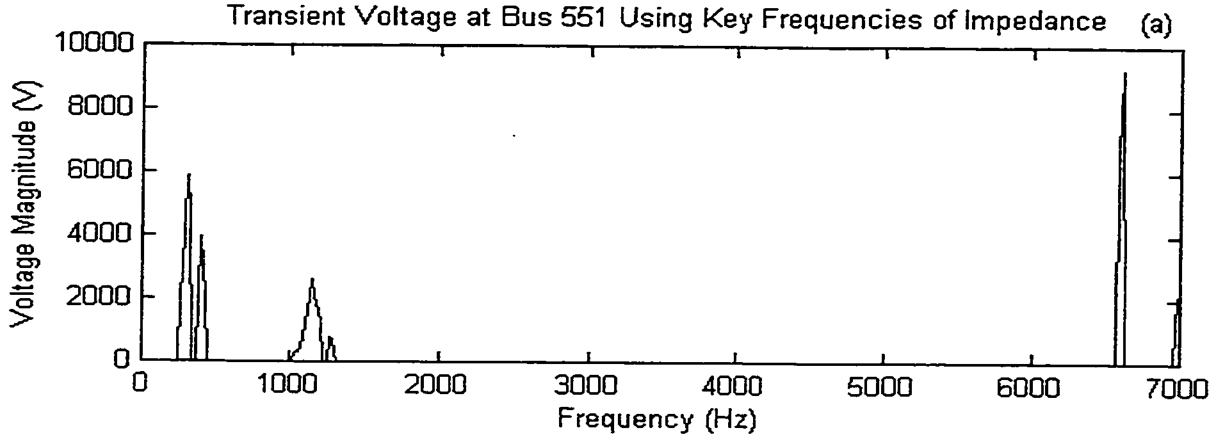


Figure 4.6: Impedance Response of the Network at Bus551 at Key Frequencies.

The switch current at the corresponding frequencies are taken from the earlier results and multiplied to obtain the transient voltage at bus 551 using the key frequencies of the impedance of the network. The plot of the transient voltage obtained through the use of key frequencies is shown in the figure 4.7 (a), compared with the actual transient voltage in figure 4.7 (b).



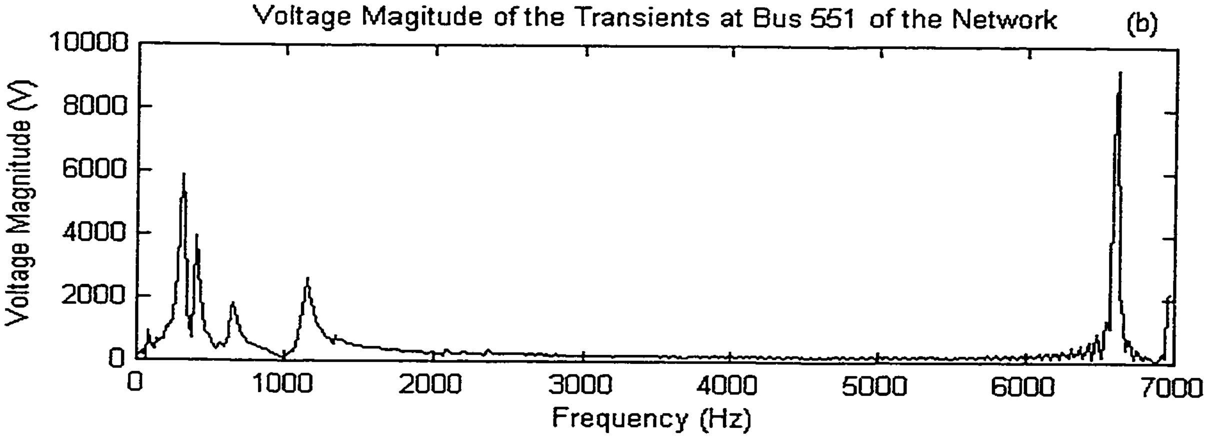


Figure 4.7: Transient Voltage at Bus 551. (a) Using key frequencies of the impedance. (b) Using the full spectrum but on the same scale as (a).

As it is clear that the using the key frequencies of the impedance data to obtain transient voltage did miss few peaks even though the peak was relatively small in magnitude. Figure 4.8 compares the transient voltage obtained using key frequencies for both cases. (a) When the key frequencies are picked using the transient voltage spectrum, (b) when the key frequencies are picked using the frequency response of the network before multiplying with the switch current to obtain the transient voltage. Figure 4.8 shows that picking key frequencies from the voltage spectrum clearly give more accurate result than the result obtained by picking key frequencies using the impedance data. However, the result does not differ on most dominant frequencies. Therefore, it will be up to the user to choose which method to use depending on how much accuracy is required. Picking key frequencies from the impedance spectrum does simplify the technique even more with slight loss of accuracy. However, the author recommends using the transient voltage spectrum to pick key frequencies for further analysis.

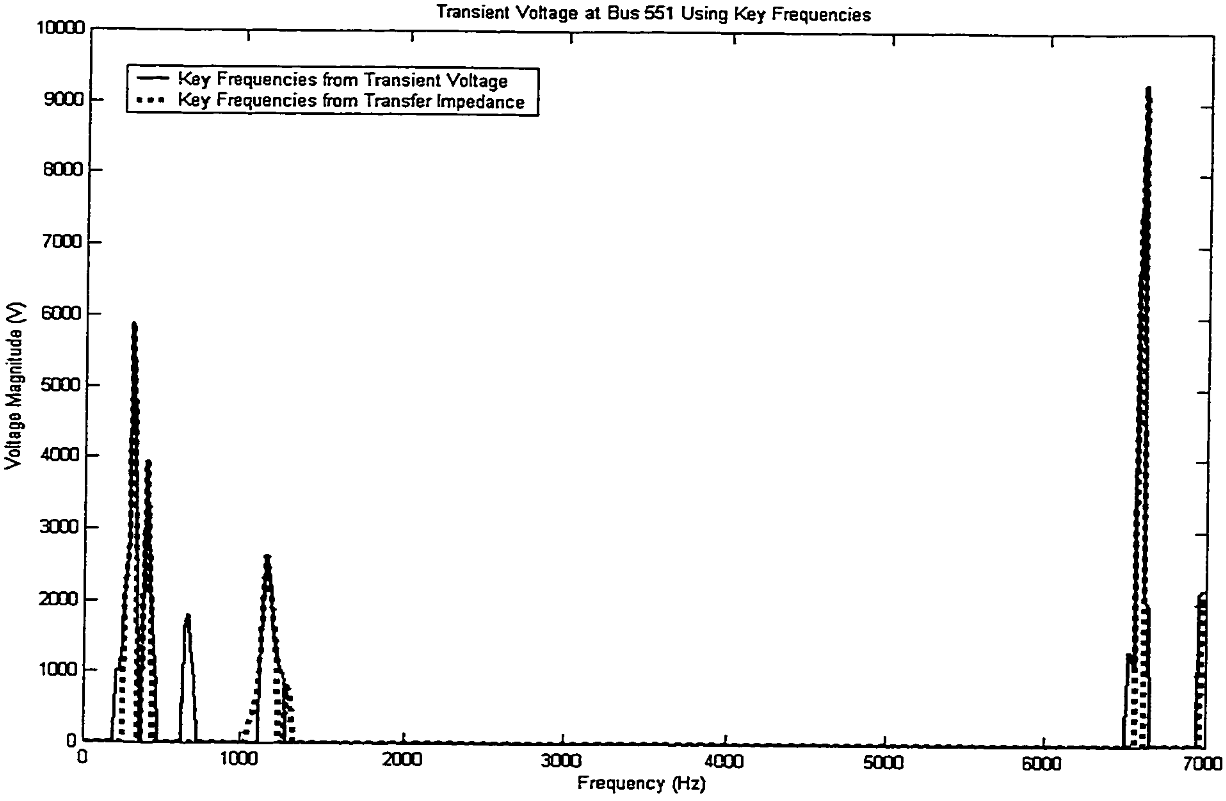


Figure 4.8: Comparison of Transient Voltages when Key Frequencies are Picked from Transient Voltage Spectrum and from the Transfer Impedance Spectrum.

It is seen that only one peak is missed when the key frequency is picked from the impedance of the network. It is also possible to accommodate that peak by lowering the cut off threshold. One should however be wary of lowering threshold too much as the whole purpose of this simplification will be lost if after picking the key frequencies, waveform still have too many frequencies to deal with.

4.3 Summary and Conclusion

Simplified technique is explained to facilitate quick methods for engineers so that they would be able to create a perspective of the networks and the problems they might face and there would be relatively smaller amount of data for further analysis. It provides more manageable numbers and disregards insignificant part of the transient which will become more obvious in chapter 5 when we explore the idea of worst bus determination.

Two methods of picking key frequency are described in this chapter. (a) Key frequency from transient voltage spectrum. (b) Key frequencies from impedance response spectrum. The comparison of the waveform obtained from both methods showed that the method (a) is slightly accurate than the method (b) with the fact that method (b) would require even less computation than the method (a). We have seen, key frequency spectrum can not be used for the time domain reconstruction of the waveform. It is a form of convenience in the analytical process in frequency domain. It is therefore an individual preference to which method shall be used depending on the level of accuracy desired from the result obtained through the use of key frequency spectrum.

Key frequency technique would provide a foundation for next chapter in determining the worst buses in the network and we will use method (a) for key frequency selections.

Chapter 5

Determination of Worst Buses

5.0 Introduction

An ideal power network will have all the buses at the voltage level of 1p.u[1]. In reality, it would be impossible to achieve all this. However, the magnitude and frequency contents of the bus voltages at all times must be within the limit for normal operation. During the transient condition, the voltage and current spectrum greatly changes from the normal operation. The transients usually die out in short time. However, even in that short duration the abnormal voltage or current waveform may likely cause disruption in the normal operation.

Transients due to switching or the faults at the distribution network served by the distribution substation propagate to every part of the network [10]. A study using mathematical models and actual measurements shows that different parts of the network have different responses. Also dispersed through out the network are many energy storage devices such as inductance and capacitors. Therefore the transient responses at different locations of a network are different for a given switching event.

Therefore, it is necessary to determine the transient level of each bus to ascertain if any bus is operating in abnormal condition. However, voltage levels only give the partial information to accurately predict the effects of the transients. It is important to quantitatively determine the buses that would be affected by the transients the most. Determination of buses that have the worst effect will help to understand

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[1] p.u.: Per Unit system, the numerical per unit value of any quantity is its ratio to a chosen base quantity of the same dimension.

characteristics of distribution network as well as to indicate what cautionary action to take. This type of study in determining the worst buses are performed in the power system planning, operational planning, and operation control to maintain the normal operating conditions in terms of stability and the efficiency of the power transmission and distribution. The following are some of the reason justifying the need to determine bus experiencing highest transients:

- Determination of worst buses would give prior knowledge of which bus would likely have problem voltages.
- There may exist some branches that have excessive losses or heat dissipation.
- Prior knowledge of such issues would permit to take cautionary actions to prevent any system failures.

5.1 Basic Idea of Worst Bus Determination

Worst bus determination is the ranking of the buses in the power network by certain indices that will provide the qualitative properties of the buses. When analyzing the effects of the switching transients, the following two indices are considered to be the most significant and are expected to provide the most information. They are:

(a) Frequency Domain Transient Peak

It correlates with actual transient peaks computed from time domain waveforms.

(b) Energy of the Transient.

It also correlates with energy of the transients in the time domain.

As we know during transient, voltage peak can reach very high values and that very high voltage level can be devastating to power system components. This is the most common effect of transients and almost everyone involved in the power system study is aware of the Peak Index. However, less common but can be equally harmful effect of a transient is its energy dissipation in the system networks or components. The energy contents of the transients can determine how much energy is being dissipated in the bus. This becomes the second index of the transient.

Worst bus depends on the ranking of all the buses in the network according to the specific index. Of all the buses, the buses that have the highest transient peak will be categorized as the worst bus according to the peak index. Transient peak in time domain can be computed by taking the maximum of the waveforms and subtracting the steady-state peak value from it. For example:

$$\begin{aligned} &V_{tk}^{Peak} = \max \mid (V_{tk}) - V_{tk}^{SS} \mid \\ &\vdots \\ &\vdots \\ &V_{tm}^{Peak} = \max \mid (V_{tm}) - V_{tm}^{SS} \mid . \end{aligned} \qquad (5.1)$$

Where,

$V_{tk}^{Peak}, \cdots, V_{tm}^{Peak}$ = Transient peak voltages at buses k...m in time domain.

$V_{tk}, \cdots, V_{tm}$ = Total voltage waveforms at buses k...m in time domain.

$V_{tk}^{SS}, \cdots, V_{tm}^{SS}$ = Steady-state voltages at buses k...m in time domain.

Figure 5.1 shows the example of steady state peak value and the total peak value of the voltage waveform as used in the equation 5.1.

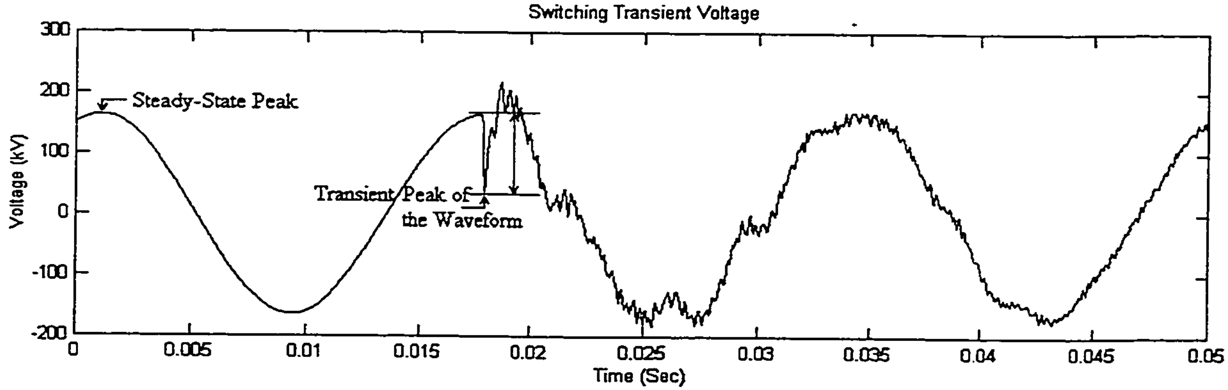

Figure 5.1: Graphical Picture of Transient Peak in Time Domain

To get a better picture of transient peak and understand the equation 5.1, we can plot the absolute value of the transient component of the figure 5.1 in time domain by removing the 60Hz component from the waveform. Figure 5.2 shows the absolute value of transient component of the waveform of figure 5.1 where the peak can be clearly seen. The peak shown in the figure 5.2 is the peak calculated by the equation 5.1. The peak value is taken from the steady state waveform considering the switching could be done at the peak of the waveform. Then the ranking is performed according to the highest transient peak voltages. The worst bus in the network is the one with the highest value.

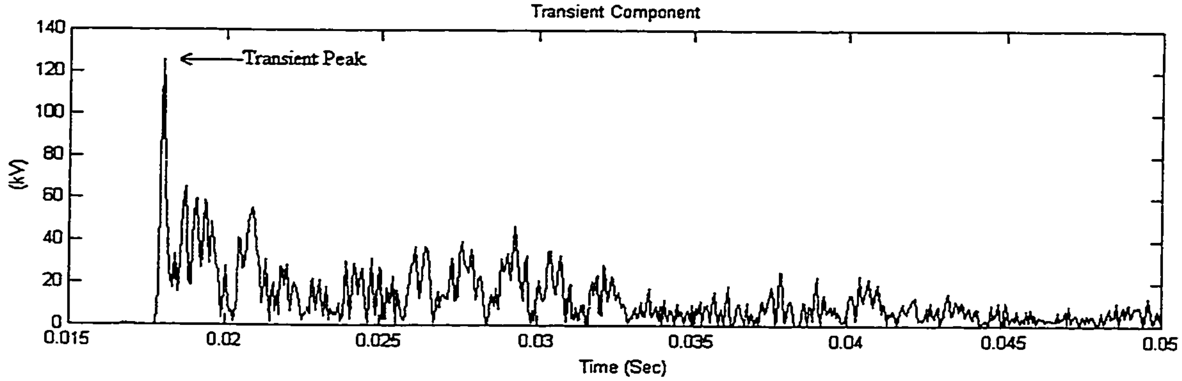

Figure 5.2: Absolute Values of Transient Component of the Waveform of Figure 5.1

The main focus of this thesis is the computation and analysis of transients in frequency domain. Time domain methods are used only for correlation and demonstration purposes. Therefore, in frequency domain, the worst bus ranking by the peak index is performed with the following method.

Let V_{ik} be the voltage magnitudes at frequencies "*i*" of the bus "*k*". It should be noted that fundamental is excluded from all the calculation unless otherwise specified. Then, we have,

$$V_{fk}^{Peak} = \sqrt{\sum_{i=0}^{n} V_{ik}^2}. \qquad (5.2)$$

Where

V_{fk}^{Peak} = Transient peak voltage Magnitude at bus k in Frequency Domain
V_{ik} = Transient Component Voltage Magnitude at Frequency i at Bus k.
n = Maximum Frequency Range.

And i is the frequency step. In this thesis, frequency step of 20Hz is used for all the examples.

Similarly, transient energy in time domain is defined by assuming the voltage applied to the fictitious 1—ohm resistor [12]. Then if the transient component of the voltage as a function of time is represented as $V^t(t)$, then the average energy of the transient is given by

$$E = \frac{1}{T}\int_0^T (V^t)^2\,dt \tag{5.3}$$

Where T is the transient duration computed by taking the time it takes for the transient to drop from the peak to the 5% of the steady state peak voltage. The equation 5.6 can be solved numerically using the trapezoidal method.

Using the Parseval's theorem [12] for the aperiodic, real $V^t(t)$ with finite energy content, the time domain definition of energy of equation can be converted to frequency domain as:

$$E = \frac{1}{\pi}\int_0^\infty |V(\omega)|^2\,d\omega \tag{5.4}$$

From equation 5.3 and 5.4, it is possible to obtain energy of the transients in time domain and in frequency domain of the individual buses. The upper-limit (infinity) of the integral in the equation 5.4 will be approximated to the maximum expected frequency in the waveform. The worst affected bus will be the one with the highest average energy. The calculation to determine the worst bus is performed by removing fundamental from the transient voltage.

5.2 Application to Real Case

The Southern Alberta Power Network is taken for the study of the worst bus determination. Altogether 15 buses are monitored for the transient voltages. Out of the 15 buses, some buses are adjacent to the switching bus while some are some distant away from the switching bus. In this example the buses will be ranked according to the two indices—first by peak index and second by the energy content index. The bus with the highest index will be ranked as the worst bus in the network. The frequency domain indices are then correlated with the time domain indices.

5.2.1 Determination of Worst Buses by Peak Index

The transient voltages at the different buses are computed using the method described in the chapter 3. The plots of the voltages at different frequencies are shown in the figure 5.3 for fifteen sampled buses of the network. The fundamental is omitted from the plot because it is the transient component of the voltages that we need. However, just by looking at the plot, it can not be determined which bus has the highest peak. As we know some frequencies may cancel out due to phase angle differences. As mentioned earlier, by the use of equation 5.2, the square root of the sum of the square of the magnitudes of the dominant frequencies can be taken to correlate the peak of the transient voltages in frequency domain. It is compared with the time domain result to check if the consistent ranking is obtained.

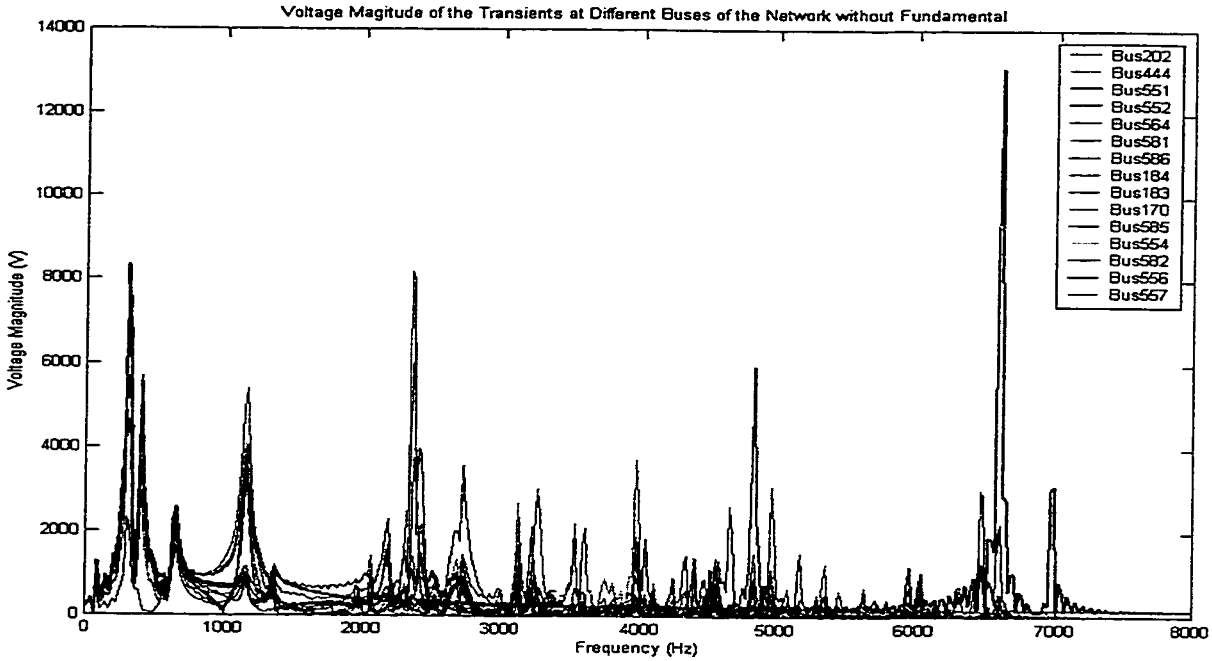

Figure 5.3: Transient Voltages at Different Buses in Frequency Domain

The rms values of the harmonics of the transient are not the actual peak of the transient but, it is considered that the higher rms values signifies higher peak of the transients. The plot of the ranking of the buses can be seen in the figure 5.4.

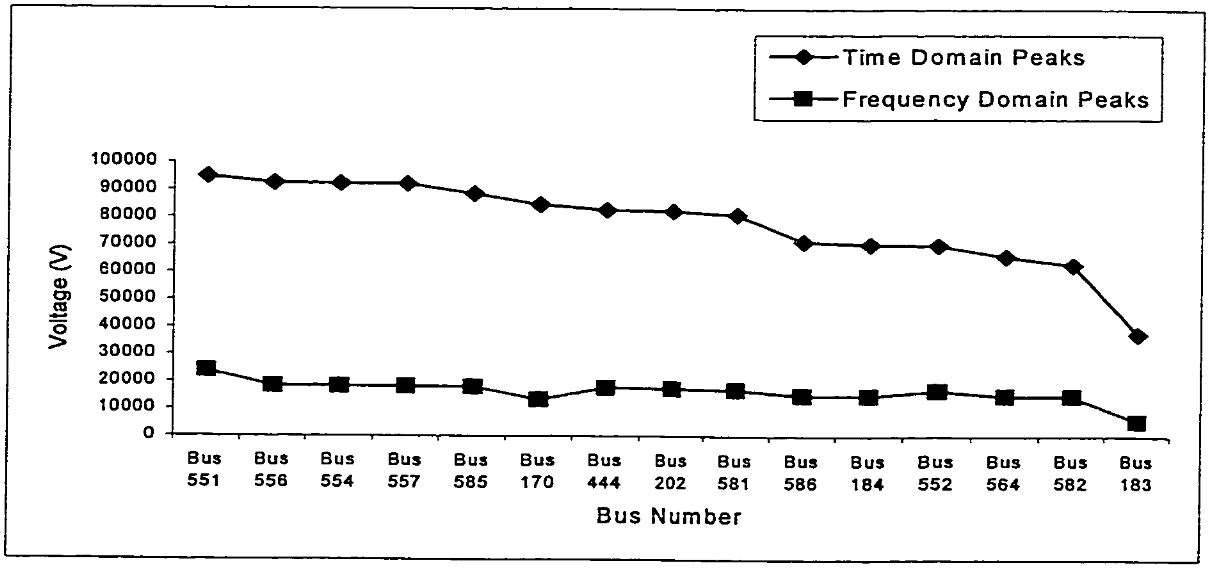

Figure 5.4: Ranking of the Buses by Peak Index

The ranking by the time domain method is taken as a reference and it is also shown in the figure 5.4. It is shown that the frequency domain method indeed is able to rank the buses in correct order for the purpose of worst bus determination. Time domain solution has the worst bus as bus 551 with the highest peak and the same bus was pointed by the frequency domain solution as the worst bus. It is the case with the least affected bus, by both method of computation, it is found to be the bus 183.

5.2.1.1 Estimation of Transient Peak in Frequency Domain

First of all, the method to estimate the transient peak in frequency domain that is described in this section has been arrived purely by trail and error. Further research is required to determine the theoretical basis for the method. Also, it is possible that the method described here may not work as desired for the different case (network).

It is seen from the previous section that the network buses can be ranked in frequency domain according to the transient peak voltages from worst to least affected buses. In time domain, actual peak can be determined with computation of the waveforms, so the question arises whether the actual peak can be estimated in the frequency domain. There are number of logical starting point in the process to predict the transient peak in the frequency domain. It is best to start with picking key frequencies that are likely to contribute to the transient peak. Key frequencies are picked by the method explained in chapter 4. The maximum value of the magnitude spectrum is taken as a reference and 10% of the maximum is taken as the base value. The frequencies with the magnitudes greater than the base value are considered the key frequencies and picked for the computation. Then the algorithm for computing the transient peak from the frequency spectrum data is as follows:

1: Find maximum of the magnitudes of the given spectrum.

2: Take ten percent of the maximum value as the base or threshold values for the peak computation.

3: Add all the magnitudes that have values more than base value. This will be the total sum.

4: Take root mean square of the all values that are greater than the base value. This will be the correction factor.

5: Subtract the correction factor from the total sum to get the peak of the transient.

In symbolic form, it can be written as:

If V_{ifk} is the voltage magnitudes at "*i*" frequencies of the bus "*k*", then

$$V_{fk}^{P} = \max(V_{ifk}).$$

Then the base value is:

$$V_{fk}^{base} = 0.10 * V_{fk}^{P}.$$

The set of voltage magnitude data that are greater than the base value is:

$$V_{jfk} = \{V_{ifk}\} > V_{fk}^{base} .$$

The sum of the voltage magnitudes at key frequency j is:

$$V_{fk}^{sum} = \sum_{j\min}^{j\max} V_{jfk}.$$

The correction factor is:

$$V_{fk}^{corr} = \sqrt{(\sum_{j\min}^{j\max} V_{jfk}^{2})}.$$

Finally the estimated transient peak in the frequency domain is given by:

$$V_{fk}^{Peak} = V_{fk}^{sum} - V_{fk}^{corr} \tag{5.5}$$

Using the equation 5.5, the transient peak voltage for all 15 buses are plotted along with the transient peak voltage obtained through time domain computation using the equation 5.1. The figure 5.5 shows the remarkable similarity and accuracy with in acceptable range.

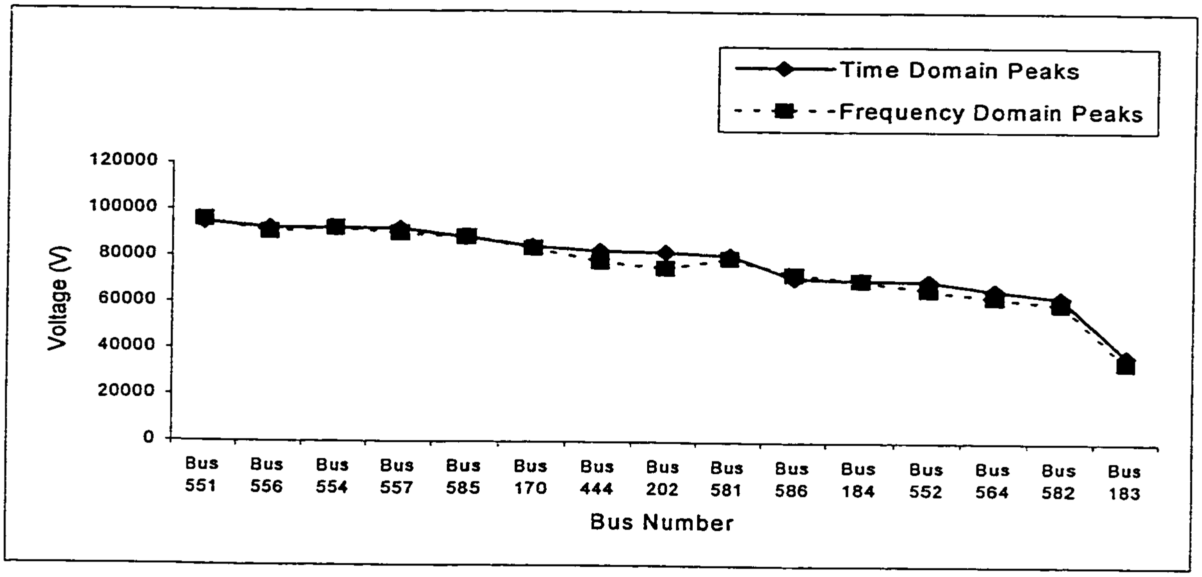

Figure 5.5: Peak of the Transient Voltages at Different Buses

The above algorithm works for all the buses. After extensive testing, it is found that there is one case where the algorithm fails to accurately predict the correct result. The exception occurs if there is a sustained oscillation in the bus. Such oscillation is caused by the numerical characteristics of the simulation program and it is not a real phenomenon.

5.2.2 Determination of Worst Buses by Transient Energy Index

As with the peak determination, energy index can be used to rank the buses in the power network in frequency domain. The energy index concept exploits the fact that other than the 60Hz (fundamental) waveform, any other waveforms have no usefulness. Equations 5.3 and 5.4 are used to determine the energy of the transient for the individual buses. Equation 5.3 is solved numerically to determine the energy from the time-domain transient-voltage waveform and equation 5.4 is solved to determine the energy from the frequency domain transient-voltage spectrum for 15 different buses in the network. According to the energy magnitudes, buses are ranked to determine the worst bus. Figure 5.6 shows the correlation of the buses starting from the worst bus to the least affected bus by average energy index obtained by both time domain and the frequency domain method.

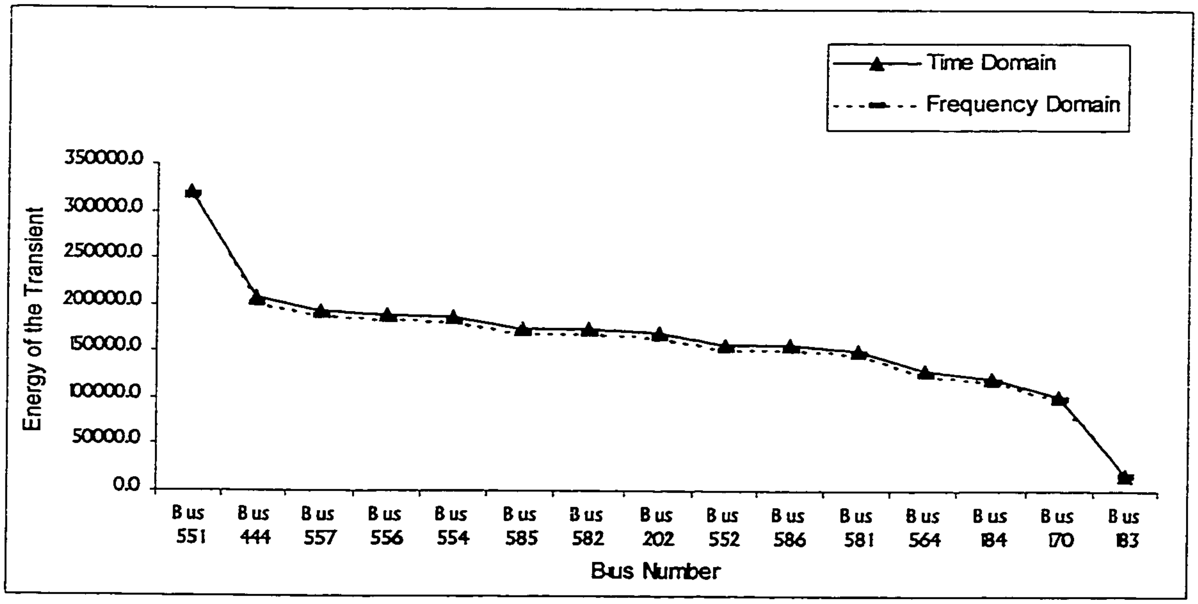

Figure 5.6: Worst Bus Ranking by Average Energy index

The time domain solution of the transients for the determination of the worst buses is the accepted solution. From the figure 5.6, it can be seen that the energy index in frequency domain is almost exactly the same as the time domain solution. In both cases, the units of the average energy is same--*(volt)*^{2}*/ohm* and therefore the identical result should be no surprise. The slightly higher values obtained by time domain method, therefore, is due to the numerical computation and approximation used in the process.

5.3 Summary

The ranking of the network buses by the peak index and the energy contents of the transients are valuable to analyze the switching transients. It will help identify the culprit buses so that the method can easily be devised to reduce the transient effects. As we have seen that not all the buses in the network are equally affected by the switching transients, isolating only the worst affected bus is a very powerful tool for engineers. The two indices show the nature of transients present in the power network comparatively. This chapter tries to put an emphasis on organization and presentation of results in proper way so that they will provide maximum information. Emphasis is given in the ranking than the actual values of the indices. The reason is that the transient will be present in the power network, whenever the capacitor switching occurs. The option is to find ways to reduce such transient effect in the network since there is no possible solution to remove the transients from the entire network altogether. Therefore, it is only logical to find the buses that are most likely to have higher transients so that the efforts can be made in those buses to reduce the transients.

Furthermore, the estimation of the actual peak in frequency domain is purely speculative work and is not the main objective of this thesis. It is mentioned in the thesis on a secondary note. The method seems to work very well for the case described. Only logical explanation that can be given for the accuracy of the result is that when the sum of the magnitudes of the harmonicas is taken to determine the peak of the transients, we know the peak will be higher than the actual peak. In real case, some of the magnitudes will cancel out due to difference in phase angle. In this scenario, all the magnitude that cancels out due to difference in phase angle happen to be equal to the root mean square of the sum of the harmonics. In the end it may be a coincidence or that there may exist a correlation between the root mean square sum of the harmonics and the magnitudes that cancels out due to difference in phase angle in the transient spectrum. Whatever the case, further study is required before the method can be used for general purposes in determination of transient peak in frequency domain.

There is no such issue for the energy index because in both time domain method and in frequency domain method, actual average energy of the transient is computed for the bus ranking. One further observation to be noted is that the worst bus out of the sampled buses was found to be bus-551 by both peak and energy index ranking in the case example presented in the previous section. Also the least affected bus was found to be bus-183 by both indices. It does not necessarily mean that worst bus determined by peak index always have to be same as the worst bus determined by energy index, even though as the example shows such possibilities exist.

Chapter 6

Conclusions and Recommendations

The goal of this work is to present a method of computation and analysis of capacitor switching transients in a way that can be best utilized by the Utility Companies for improvement of power system network. The goal was achieved through series of steps with details of computation methods to the development of network buses ranking technique using transient characteristic indices. First a detail method to obtain transients in frequency domain was explained. This method computes transients in frequency domain through use of network impedance and the switching current. Capacitor switching current was obtained by superposition method while the network impedance response was obtained by creating the network admittance matrix as a function of frequency. These methods are used for the computation of transients in frequency domain because the certain aspects of transients are best described in frequency domain such as (a) frequency content, (b) dominant frequency, and (c) elimination of unnecessary conversion procedures from time domain. Existing analytical method and time domain simulation method of computation of transients were also presented in the thesis to demonstrate their disadvantages over the proposed frequency domain method to achieve our final goal. Our goal that the results needs to be presented in a manner that will provide comparative and complete information about the power network with regards to the transient.

The second step was the introduction of the *key frequency* concept. This concept is based on the fact that the frequency spectrum of the transients contains number of frequencies that can be effectively neglected without losing the accuracy of the desired result. The key frequency concept leads to less computation and more manageable numbers. As an intermediate result, with the key frequency selection, one can quantify the switching transients in terms of dominant frequency. The main use of the key frequency concepts is seen in the determination of the worst buses of the power network with regards to transient. It was, however, demonstrated that the transients characterized by the key frequency spectrum could not be used to construct time domain representation of the transients. The key frequency spectrum is useful only in the frequency domain analysis.

The third step was the *determination of worst buses*. Switching transients in the power network is not limited to switching bus; it is transmitted to entire network. However, the transient behavior is different at the different buses. The characteristics of transients can be defined by its indices. Two transient indices, peak index and the energy index were explained in this thesis to characterize the behavior of transients. The method was presented to rank the buses in the power network according to these indices. The bus in the network with highest peak and the highest energy were the worst bus in the network. The findings of these bus or buses are expected to greatly facilitate the utility companies to apply appropriate mitigation method to reduce the transient effect.

Time domain comparison was done wherever possible through out the thesis to show that the proposed method was consistent with the existing time domain results. Matlab and EMTP programs were used as a tool for computation and comparisons of the result. The result obtained through the proposed method is found to be accurate as compared with the time domain solution.

It is to be noted however that the proposed method can be used for specific purposes only that is computing switching transients of the power network. On the other hand, the program such as EMTP can perform wide varieties of tasks related to power systems. While EMTP can solve non-linear time variant system, the proposed method can only work on linear time invariant system. Therefore, the proposed method should not be taken as a substitute for existing method such as EMTP but rather as an addition to such programs to increase efficiency and practicability.

Future work may be done to write a standalone program for this method, with the input being the admittance matrix of the network and the output of values such as ranking plots, dominant frequencies, etc. Author believes that such a program (software) would be very useful in the power industry.

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Appendix A

Large Test Case System Data

Below are the complete electrical parameters of the Southern Alberta Power Transmission and Distribution Network in EMTP (Electromagnetic Transient Program) format. The left two columns are the connection bus numbers.

```
BEGIN NEW DATA CASE
C   Model Alberta
C   1    2    3    4    5    6    7    8
C
01234567890123456789012345678901234567890123456789012345678901234567890123456789
0
C      bus2)(bus3)(bus4)( R )( L )( C )( R )( L )( C )( R )( L )( C )
C      0.0    0.1    60.  60.
.000041 .1666   60.0    60.0
              1    1
-1152A 160A       16.83 61.93 990.8 1.0
-2152B 160B       3.196 18.47 1819. 1.0
-3152C 160C
-1152A 160A       16.40 62.26 966.6 1.
-2152B 160B       3.194 18.46 1818. 1.
-3152C 160C
-1155A 160A       16.83 61.93 990.8 1.
-2155B 160B       3.196 18.47 1819. 1.
-3155C 160C
-1155A 160A       16.40 62.26 966.6 1.
-2155B 160B       3.194 18.46 1818. 1.
-3155C 160C
 1159A 160A        .77  4.62 159.1
 2159B 160B        .52  1.85 -25.4   .77  4.62 159.1
 3159C 160C        .52  1.85 -25.4   .52  1.85 -25.4   .77  4.62 159.1
 1159A 160A        .77  4.62 159.3
 2159B 160B        .52  1.85 -25.2   .77  4.62 159.3
 3159C 160C        .52  1.85 -25.2   .52  1.85 -25.2   .77  4.62 159.3
 1160A 162A        .55  3.10 102.7
 2160B 162B        .33  1.24 -15.6   .55  3.10 102.7
```

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-1160A 165A       18.50 71.22 1273. 1.
-2160B 165B       3.706 20.74 2058. 1.
-3160C 165C
-1160A 988A       5.923 22.69 349.9 1.
-2160B 988B       .9941 7.233 608.3 1.
-3160C 988C
 1161A 162A        .62  3.19 103.8
 2161B 162B        .34  1.27 -14.8   .62  3.19 103.8
 3161C 162C        .34  1.27 -14.8   .34  1.27 -14.8   .62  3.19 103.8
 1170A 184A       5.50 14.71  51.7
 2170B 184B       1.79  6.38  -7.5  5.50 14.71  51.7
 3170C 184C       1.79  6.38  -7.5  1.79  6.38  -7.5  5.50 14.71  51.7
 1177A 198A       4.57 13.40  45.5
 2177B 198B       1.27  6.08  -7.6  4.57 13.40  45.5
 3177C 198C       1.27  6.08  -7.6  1.27  6.08  -7.6  4.57 13.40  45.5
 1184A 552A       3.13  8.66  28.5
 2184B 552B        .96  3.26  -2.8  3.13  8.66  28.5
 3184C 552C        .96  3.26  -2.8   .96  3.26  -2.8  3.13  8.66  28.5
 1184A 564A        .62  2.83  10.4
 2184B 564B        .19  1.34  -1.4   .62  2.83  10.4
 3184C 564C        .19  1.34  -1.4   .19  1.34  -1.4   .62  2.83  10.4
 1198A 561A       1.99  8.94  44.2
 2198B 561B       1.08  4.43  -7.0  1.99  8.94  44.2
 3198C 561C       1.08  4.43  -7.0  1.08  4.43  -7.0  1.99  8.94  44.2
 1198A 572A       2.06 10.11  58.1
 2198B 572B       1.11  5.55 -12.9  2.06 10.11  58.1
 3198C 572C       1.11  5.55 -12.9  1.11  5.55 -12.9  2.06 10.11  58.1
 1202A 444A       6.56 20.55  68.9
 2202B 444B       1.98  8.92 -11.0  6.56 20.55  68.9
```

Appendix A Large Test Case System Data

```
3202C 444C   1.98 8.92 -11.0 1.98 8.92 -11.0 6.56 20.55 68.9
1202A 551A   .03 .29 1.8
2202B 551B   .03 .16 -.2 .03 .29 1.8
3202C 551C   .03 .16 -.2 .03 .16 -.2 .03 .29 1.8
1202A 552A   .68 4.13 15.1
2202B 552B   .29 1.89 -2.0 .68 4.13 15.1
3202C 552C   .29 1.89 -2.0 .29 1.89 -2.0 .68 4.13 15.1
1202A 564A   1.40 12.04 50.2
2202B 564B   .83 6.44 -12.3 1.40 12.04 50.2
3202C 564C   .83 6.44 -12.3 .83 6.44 -12.3 1.40 12.04 50.2
1202A 581A   1.37 7.04 25.0
2202B 581B   .74 2.80 -3.6 1.37 7.04 25.0
3202C 581C   .74 2.80 -3.6 .74 2.80 -3.6 1.37 7.04 25.0
1202A 586A   1.44 6.77 24.4
2202B 586B   .46 3.13 -3.3 1.44 6.77 24.4
3202C 586C   .46 3.13 -3.3 .46 3.13 -3.3 1.44 6.77 24.4
1202A 900A   5.94 28.20 106.2
2202B 900B   3.41 11.34 -12.4 5.94 28.20 106.2
3202C 900C   3.41 11.34 -12.4 3.41 11.34 -12.4 5.94 28.20 106.2
1202A 5161A  .00 -.20 .0
2202B 5161B  .00 .00 .0 .00 -.20 .0
3202C 5161C  .00 .00 .0 .00 .00 .0 .00 -.20 .0
1207A 212A   4.32 19.24 70.9
2207B 212B   2.26 7.92 -10.7 4.32 19.24 70.9
3207C 212C   2.26 7.92 -10.7 2.26 7.92 -10.7 4.32 19.24 70.9
1207A 239A   10.29 29.21 100.5
2207B 239B   2.84 13.17 -17.1 10.29 29.21 100.5
3207C 239C   2.84 13.17 -17.1 2.84 13.17 -17.1 10.29 29.21 100.5
1207A 259A   11.71 34.46 116.3
2207B 259B   3.23 15.45 -19.0 11.71 34.46 116.3
3207C 259C   3.23 15.45 -19.0 3.23 15.45 -19.0 11.71 34.46 116.3
1207A 574A   .38 2.24 14.0
2207B 574B   .18 1.25 -1.9 .38 2.24 14.0
3207C 574C   .18 1.25 -1.9 .18 1.25 -1.9 .38 2.24 14.0
1207A 577A   .97 6.59 23.4
2207B 577B   .47 2.78 -3.1 .97 6.59 23.4
3207C 577C   .47 2.78 -3.1 .47 2.78 -3.1 .97 6.59 23.4
1207A 590A   .80 4.59 35.3
2207B 590B   .38 2.55 -4.7 .80 4.59 35.3
3207C 590C   .38 2.55 -4.7 .38 2.55 -4.7 .80 4.59 35.3
1208A 568A   .38 2.18 12.7
2208B 568B   .18 1.19 -2.4 .38 2.18 12.7
3208C 568C   .18 1.19 -2.4 .18 1.19 -2.4 .38 2.18 12.7
1208A 577A   .52 3.55 12.4
2208B 577B   .25 1.50 -1.9 .52 3.55 12.4
3208C 577C   .25 1.50 -1.9 .25 1.50 -1.9 .52 3.55 12.4
1208A 581A   .18 .93 29.9
2208B 581B   .10 .37 -4.3 .18 .93 29.9
3208C 581C   .10 .37 -4.3 .10 .37 -4.3 .18 .93 29.9
1208A 585A   .47 2.66 15.4
2208B 585B   .22 1.47 -3.2 .47 2.66 15.4
3208C 585C   .22 1.47 -3.2 .22 1.47 -3.2 .47 2.66 15.4
1208A 601A   .30 2.41 9.6
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2208B 601B   .17 1.28 -2.5 .30 2.41 9.6
3208C 601C   .17 1.28 -2.5 .17 1.28 -2.5 .30 2.41 9.6
1550A 559A   .87 3.87 13.7
2550B 559B   .27 1.85 -2.6 .87 3.87 13.7
3550C 559C   .27 1.85 -2.6 .27 1.85 -2.6 .87 3.87 13.7
1550A 572A   1.36 6.06 21.7
2550B 572B   .42 2.90 -3.8 1.36 6.06 21.7
3550C 572C   .42 2.90 -3.8 .42 2.90 -3.8 1.36 6.06 21.7
1551A 567A   1.76 9.01 162.4
2551B 567B   .64 4.02 -71.0 1.76 9.01 162.4
3551C 567C   .64 4.02 -71.0 .64 4.02 -71.0 1.76 9.01 162.4
1551A 5551A  .14 9.23 .0
2551B 5551B  .06 .00 .0 .14 9.23 .0
3551C 5551C  .06 .00 .0 .06 .00 .0 .14 9.23 .0
1552A 566A   .82 3.71 12.6
2552B 566B   .25 1.66 -1.9 .82 3.71 12.6
3552C 566C   .25 1.66 -1.9 .25 1.66 -1.9 .82 3.71 12.6
1552A 7552A  .14 8.24 .0
2552B 7552B  .06 .00 .0 .14 8.24 .0
3552C 7552C  .06 .00 .0 .06 .00 .0 .14 8.24 .0
1553A 554A   1.60 6.73 4.3
2553B 554B   .58 3.29 -1.7 1.60 6.73 4.3
3553C 554C   .58 3.29 -1.7 .58 3.29 -1.7 1.60 6.73 4.3
1553A 556A   3.95 15.75 11.9
2553B 556B   1.42 7.67 -4.9 3.95 15.75 11.9
3553C 556C   1.42 7.67 -4.9 1.42 7.67 -4.9 3.95 15.75 11.9
1554A 557A   2.79 12.68 4.6
2554B 557B   .94 6.21 -1.5 2.79 12.68 4.6
3554C 557C   .94 6.21 -1.5 .94 6.21 -1.5 2.79 12.68 4.6
1555A 561A   1.85 8.33 29.7
2555B 561B   .55 3.97 -5.4 1.85 8.33 29.7
3555C 561C   .55 3.97 -5.4 .55 3.97 -5.4 1.85 8.33 29.7
1555A 564A   1.08 4.86 17.2
2555B 564B   .32 2.31 -3.1 1.08 4.86 17.2
3555C 564C   .32 2.31 -3.1 .32 2.31 -3.1 1.08 4.86 17.2
1556A 557A   3.15 12.89 8.4
2556B 557B   1.11 6.39 -3.4 3.15 12.89 8.4
3556C 557C   1.11 6.39 -3.4 1.11 6.39 -3.4 3.15 12.89 8.4
1557A 558A   4.23 18.71 4.4
2557B 558B   1.25 9.98 -1.1 4.23 18.71 4.4
3557C 558C   1.25 9.98 -1.1 1.25 9.98 -1.1 4.23 18.71 4.4
1557A 599A   4.09 17.31 6.7
2557B 599B   1.31 8.77 -2.3 4.09 17.31 6.7
3557C 599C   1.31 8.77 -2.3 1.31 8.77 -2.3 4.09 17.31 6.7
1558A 560A   4.08 17.99 4.9
2558B 560B   1.26 9.69 -1.4 4.08 17.99 4.9
3558C 560C   1.26 9.69 -1.4 1.26 9.69 -1.4 4.08 17.99 4.9
1559A 561A   .97 4.35 15.0
2559B 561B   .29 1.97 -2.4 .97 4.35 15.0
3559C 561C   .29 1.97 -2.4 .29 1.97 -2.4 .97 4.35 15.0
1559A 569A   .53 2.52 8.7
2559B 569B   .18 1.21 -1.9 .53 2.52 8.7
3559C 569C   .18 1.21 -1.9 .18 1.21 -1.9 .53 2.52 8.7
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1559A 601A    .61 3.49 19.7
2559B 601B    .28 1.87 -3.9  .61 3.49 19.7
3559C 601C    .28 1.87 -3.9  .28 1.87 -3.9  .61 3.49 19.7
1559A 8559A   .16 8.82  .0
2559B 8559B   .06 -.35  .0  .16 8.82  .0
3559C 8559C   .06 -.35  .0  .06 -.35  .0  .16 8.82  .0
1564A 6564A   .27 12.07  .0
2564B 6564B   .09  .00  .0  .27 12.07  .0
3564C 6564C   .09  .00  .0  .09  .00  .0  .27 12.07  .0
1566A 567A    .50 2.22 141.3
2566B 567B    .17  .94 -68.4  .50 2.22 141.3
3566C 567C    .17  .94 -68.4  .17  .94 -68.4  .50 2.22 141.3
1567A 568A    .79  .74 277.3
2567B 568B    .79  .51 -37.1  .79  .74 277.3
3567C 568C    .79  .51 -37.1  .79  .51 -37.1  .79  .74 277.3
1567A 568A    .79  .74 277.3
2567B 568B    .79  .51 -37.1  .79  .74 277.3
3567C 568C    .79  .51 -37.1  .79  .51 -37.1  .79  .74 277.3
1567A 588A    .04  .22 111.7
2567B 588B    .04  .06 -14.9  .04  .22 111.7
3567C 588C    .04  .06 -14.9  .04  .06 -14.9  .04  .22 111.7
1567A 588A    .02  .14  71.2
2567B 588B    .02  .04  -9.5  .02  .14  71.2
3567C 588C    .02  .04  -9.5  .02  .04  -9.5  .02  .14  71.2
1568A 601A    .30 1.74 10.1
2568B 601B    .14  .96  -2.1  .30 1.74 10.1
3568C 601C    .14  .96  -2.1  .14  .96  -2.1  .30 1.74 10.1
1569A 588A    .21  .84 420.2
2569B 588B    .11  .23 -56.2  .21  .84 420.2
3569C 588C    .11  .23 -56.2  .11  .23 -56.2  .21  .84 420.2
1571A 585A    .48 3.24 83.1
2571B 585B    .23 1.60 -38.1  .48 3.24 83.1
3571C 585C    .23 1.60 -38.1  .23 1.60 -38.1  .48 3.24 83.1
1571A 594A    .51 2.93 81.9
2571B 594B    .30 1.52 -38.2  .51 2.93 81.9
3571C 594C    .30 1.52 -38.2  .30 1.52 -38.2  .51 2.93 81.9
1572A 573A    .61 3.47 20.9
2572B 573B    .29 1.97 -4.3  .61 3.47 20.9
3572C 573C    .29 1.97 -4.3  .29 1.97 -4.3  .61 3.47 20.9
1573A 574A    .66 3.75 21.5
2573B 574B    .31 2.07 -4.7  .66 3.75 21.5
3573C 574C    .31 2.07 -4.7  .31 2.07 -4.7  .66 3.75 21.5
1577A 4577A   .08 9.17  .0
2577B 4577B   .00  .00  .0  .08 9.17  .0
3577C 4577C   .00  .00  .0  .00  .00  .0  .08 9.17  .0
1578A 580A   6.30 32.41  8.6
2578B 580B   2.18 16.71 -2.5  6.30 32.41  8.6
3578C 580C   2.18 16.71 -2.5  2.18 16.71 -2.5  6.30 32.41  8.6
1579A 583A   1.14 4.78 19.0
2579B 583B    .39 2.70 -2.5  1.14 4.78 19.0
3579C 583C    .39 2.70 -2.5  .39 2.70 -2.5  1.14 4.78 19.0
1579A 585A    .82 4.07 24.9
2579B 585B    .41 2.11 -5.7  .82 4.07 24.9
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3579C 585C     .41 2.11 -5.7  .41 2.11 -5.7  .82 4.07 24.9
1579A 590A     .64 3.64 21.2
2579B 590B     .30 2.01 -4.2  .64 3.64 21.2
3579C 590C     .30 2.01 -4.2  .30 2.01 -4.2  .64 3.64 21.2
1580A 593A     .63 3.10  .8
2580B 593B     .20 1.54 -.2  .63 3.10  .8
3580C 593C     .20 1.54 -.2  .20 1.54 -.2  .63 3.10  .8
1582A 593A    3.30 15.20  6.5
2582B 593B     .98 7.26 -2.4  3.30 15.20  6.5
3582C 593C     .98 7.26 -2.4  .98 7.26 -2.4  3.30 15.20  6.5
1582A 597A    3.63 15.73  5.0
2582B 597B    1.14 8.05 -1.5  3.63 15.73  5.0
3582C 597C    1.14 8.05 -1.5  1.14 8.05 -1.5  3.63 15.73  5.0
1583A 590A    4.22 18.81  63.5
2583B 590B    1.29 8.68 -12.8  4.22 18.81  63.5
3583C 590C    1.29 8.68 -12.8  1.29 8.68 -12.8  4.22 18.81  63.5
1583A 591A     .87 3.91 13.9
2583B 591B     .26 1.87 -2.6  .87 3.91 13.9
3583C 591C     .26 1.87 -2.6  .26 1.87 -2.6  .87 3.91 13.9
1586A 592A    2.02 9.09 31.5
2586B 592B     .60 4.28 -6.2  2.02 9.09 31.5
3586C 592C     .60 4.28 -6.2  .60 4.28 -6.2  2.02 9.09 31.5
1591A 592A     .85 3.99 13.6
2591B 592B     .27 1.88 -3.0  .85 3.99 13.6
3591C 592C     .27 1.88 -3.0  .27 1.88 -3.0  .85 3.99 13.6
1592A 594A     .80 4.66 19.4
2592B 594B     .48 2.43 -4.1  .80 4.66 19.4
3592C 594C     .48 2.43 -4.1  .48 2.43 -4.1  .80 4.66 19.4
1593A 595A     .29  .80  .3
2593B 595B     .10  .17 -.1  .29  .80  .3
3593C 595C     .10  .17 -.1  .10  .17 -.1  .29  .80  .3
12551A 8551A  7.20 35.46  .0
22551B 8551B   .00  .00  .0  7.20 35.46  .0
32551C 8551C   .00  .00  .0  .00  .00  .0  7.20 35.46  .0
14564A 8564A  6.80 33.31  .0
24564B 8564B   .00  .00  .0  6.80 33.31  .0
34564C 8564C   .00  .00  .0  .00  .00  .0  6.80 33.31  .0
0550A 5550A   1.50130.141 .000
0550B 5550B   1.50130.141 .000
0550C 5550C   1.50130.141 .000
0550A 6550A   1.50130.141 .000
0550B 6550B   1.50130.141 .000
0550C 6550C   1.50130.141 .000
0551A 6551A    .70536.296 .000
0551B 6551B    .70536.296 .000
0551C 6551C    .70536.296 .000
0551A 7551A   3.68140.571 .000
0551B 7551B   3.68140.571 .000
0551C 7551C   3.68140.571 .000
0552A 5552A   1.26137.490 .000
0552B 5552B   1.26137.490 .000
0552C 5552C   1.26137.490 .000
0552A 6552A   1.29137.395 .000
```

Appendix A *Large Test Case System Data*

```
0552B 6552B   1.29137.395 .000
0552C 6552C   1.29137.395 .000
0554A 5554A   2.28033.801 .000
0554B 5554B   2.28033.801 .000
0554C 5554C   2.28033.801 .000
0554A 6554A   2.28033.801 .000
0554B 6554B   2.28033.801 .000
0554C 6554C   2.28033.801 .000
0555A 5555A   3.68141.575 .000
0555B 5555B   3.68141.575 .000
0555C 5555C   3.68141.575 .000
0555A 6555A   3.68141.575 .000
0555B 6555B   3.68141.575 .000
0555C 6555C   3.68141.575 .000
0555A 7555A   1.98139.625 .000
0555B 7555B   1.98139.625 .000
0555C 7555C   1.98139.625 .000
0555A 8555A   1.98139.625 .000
0555B 8555B   1.98139.625 .000
0555C 8555C   1.98139.625 .000
0556A 5556A   3.20150.080 .000
0556B 5556B   3.20150.080 .000
0556C 5556C   3.20150.080 .000
0556A 6556A   3.24151.120 .000
0556B 6556B   3.24151.120 .000
0556C 6556C   3.24151.120 .000
0556A 7556A   3.26065.260 .000
0556B 7556B   3.26065.260 .000
0556C 7556C   3.26065.260 .000
0556A 8556A   3.18063.519 .000
0556B 8556B   3.18063.519 .000
0556C 8556C   3.18063.519 .000
0557A 5557A    .38733.881 .000
0557B 5557B    .38733.881 .000
0557C 5557C    .38733.881 .000
0557A 6557A    .38733.820 .000
0557B 6557B    .38733.820 .000
0557C 6557C    .38733.820 .000
0558A 5558A   2.28033.801 .000
0558B 5558B   2.28033.801 .000
0558C 5558C   2.28033.801 .000
0558A 6558A   2.28033.801 .000
0558B 6558B   2.28033.801 .000
0558C 6558C   2.28033.801 .000
0559A 5559A   1.99038.526 .000
0559B 5559B   1.99038.526 .000
0559C 5559C   1.99038.526 .000
0559A 6559A   2.09141.735 .000
0559B 6559B   2.09141.735 .000
0559C 6559C   2.09141.735 .000
0559A 7559A   3.68141.360 .000
0559B 7559B   3.68141.360 .000
0559C 7559C   3.68141.360 .000
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0561A 5561A   1.98139.625 .000
0561B 5561B   1.98139.625 .000
0561C 5561C   1.98139.625 .000
0561A 6561A   2.00039.650 .000
0561B 6561B   2.00039.650 .000
0561C 6561C   2.00039.650 .000
0561A 7561A   1.98139.625 .000
0561B 7561B   1.98139.625 .000
0561C 7561C   1.98139.625 .000
0564A 5564A   3.65142.002 .000
0564B 5564B   3.65142.002 .000
0564C 5564C   3.65142.002 .000
0564A 7564A   3.65142.002 .000
0564B 7564B   3.65142.002 .000
0564C 7564C   3.65142.002 .000
0566A 5566A    .57124.805 .000
0566B 5566B    .57124.805 .000
0566C 5566C    .57124.805 .000
0566A 6566A    .57524.805 .000
0566B 6566B    .57524.805 .000
0566C 6566C    .57524.805 .000
0567A 5567A    .74516.995 .000
0567B 5567B    .74516.995 .000
0567C 5567C    .74516.995 .000
0567A 6567A    .74516.945 .000
0567B 6567B    .74516.945 .000
0567C 6567C    .74516.945 .000
0567A 7567A    .73516.945 .000
0567B 7567B    .73516.945 .000
0567C 7567C    .73516.945 .000
0567A 8567A    .74117.410 .000
0567B 8567B    .74117.410 .000
0567C 8567C    .74117.410 .000
0568A 5568A   1.27040.200 .000
0568B 5568B   1.27040.200 .000
0568C 5568C   1.27040.200 .000
0568A 5570A   1.23624.626 .000
0568B 5570B   1.23624.626 .000
0568C 5570C   1.23624.626 .000
0568A 6568A   1.27039.570 .000
0568B 6568B   1.27039.570 .000
0568C 6568C   1.27039.570 .000
0568A 6570A   1.23624.710 .000
0568B 6570B   1.23624.710 .000
0568C 6570C   1.23624.710 .000
0568A 7568A   1.27039.766 .000
0568B 7568B   1.27039.766 .000
0568C 7568C   1.27039.766 .000
0568A 8568A   1.27039.861 .000
0568B 8568B   1.27039.861 .000
0568C 8568C   1.27039.861 .000
0569A 5569A   1.97939.625 .000
0569B 5569B   1.97939.625 .000
```

0569C	5569C	1.97939.625	.000
0569A	6569A	1.97939.625	.000
0569B	6569B	1.97939.625	.000
0569C	6569C	1.97939.625	.000
0571A	5571A	1.90138.056	.000
0571B	5571B	1.90138.056	.000
0571C	5571C	1.90138.056	.000
0571A	6571A	1.90138.056	.000
0571B	6571B	1.90138.056	.000
0571C	6571C	1.90138.056	.000
0572A	5572A	3.68141.206	.000
0572B	5572B	3.68141.206	.000
0572C	5572C	3.68141.206	.000
0572A	6572A	3.68141.206	.000
0572B	6572B	3.68141.206	.000
0572C	6572C	3.68141.206	.000
0572A	7572A	1.98139.625	.000
0572B	7572B	1.98139.625	.000
0572C	7572C	1.98139.625	.000
0572A	8572A	1.98139.625	.000
0572B	8572B	1.98139.625	.000
0572C	8572C	1.98139.625	.000
0573A	5573A	3.68142.740	.000
0573B	5573B	3.68142.740	.000
0573C	5573C	3.68142.740	.000
0573A	6573A	3.68142.636	.000
0573B	6573B	3.68142.636	.000
0573C	6573C	3.68142.636	.000
0573A	7573A	3.40139.526	.000
0573B	7573B	3.40139.526	.000
0573C	7573C	3.40139.526	.000
0574A	5574A	1.98139.625	.000
0574B	5574B	1.98139.625	.000
0574C	5574C	1.98139.625	.000
0574A	6574A	3.68142.000	.000
0574B	6574B	3.68142.000	.000
0574C	6574C	3.68142.000	.000
0578A	5578A	4.39963.264	.000
0578B	5578B	4.39963.264	.000
0578C	5578C	4.39963.264	.000
0578A	6578A	4.87563.855	.000
0578B	6578B	4.87563.855	.000
0578C	6578C	4.87563.855	.000
0578A	7578A	2.37933.841	.000
0578B	7578B	2.37933.841	.000
0578C	7578C	2.37933.841	.000
0578A	8578A	2.38133.841	.000
0578B	8578B	2.38133.841	.000
0578C	8578C	2.38133.841	.000
0579A	5579A	1.98139.625	.000
0579B	5579B	1.98139.625	.000
0579C	5579C	1.98139.625	.000
0579A	6579A	1.98139.625	.000
0579B	6579B	1.98139.625	.000
0579C	6579C	1.98139.625	.000
0579A	7579A	3.68142.070	.000
0579B	7579B	3.68142.070	.000
0579C	7579C	3.68142.070	.000
0581A	5581A	1.98139.625	.000
0581B	5581B	1.98139.625	.000
0581C	5581C	1.98139.625	.000
0581A	6581A	1.98139.625	.000
0581B	6581B	1.98139.625	.000
0581C	6581C	1.98139.625	.000
0582A	5582A	2.30133.561	.000
0582B	5582B	2.30133.561	.000
0582C	5582C	2.30133.561	.000
0582A	6582A	1.70133.841	.000
0582B	6582B	1.70133.841	.000
0582C	6582C	1.70133.841	.000
0582A	7582A	3.60171.741	.000
0582B	7582B	3.60171.741	.000
0582C	7582C	3.60171.741	.000
0582A	8582A	2.80163.540	.000
0582B	8582B	2.80163.540	.000
0582C	8582C	2.80163.540	.000
0583A	5583A	2.19638.661	.000
0583B	5583B	2.19638.661	.000
0583C	5583C	2.19638.661	.000
0583A	6583A	3.68142.000	.000
0583B	6583B	3.68142.000	.000
0583C	6583C	3.68142.000	.000
0585A	5585A	1.79041.636	.000
0585B	5585B	1.79041.636	.000
0585C	5585C	1.79041.636	.000
0585A	6585A	1.79041.956	.000
0585B	6585B	1.79041.956	.000
0585C	6585C	1.79041.956	.000
0585A	7585A	3.74041.356	.000
0585B	7585B	3.74041.356	.000
0585C	7585C	3.74041.356	.000
0586A	6586A	3.68137.671	.000
0586B	6586B	3.68137.671	.000
0586C	6586C	3.68137.671	.000
0586A	7586A	3.68140.571	.000
0586B	7586B	3.68140.571	.000
0586C	7586C	3.68140.571	.000
0588A	5588A	1.38127.600	.000
0588B	5588B	1.38127.600	.000
0588C	5588C	1.38127.600	.000
0588A	6588A	1.38127.600	.000
0588B	6588B	1.38127.600	.000
0588C	6588C	1.38127.600	.000
0588A	7588A	1.20524.070	.000
0588B	7588B	1.20524.070	.000
0588C	7588C	1.20524.070	.000

Appendix A *Large Test Case System Data*

0588A 8588A	1.20524.070	.000	
0588B 8588B	1.20524.070	.000	
0588C 8588C	1.20524.070	.000	
0588A 9588A	1.38127.600	.000	
0588B 9588B	1.38127.600	.000	
0588C 9588C	1.38127.600	.000	
0591A 5591A	3.68142.000	.000	
0591B 5591B	3.68142.000	.000	
0591C 5591C	3.68142.000	.000	
0591A 6591A	3.68142.000	.000	
0591B 6591B	3.68142.000	.000	
0591C 6591C	3.68142.000	.000	
0592A 5592A	3.68142.000	.000	
0592B 5592B	3.68142.000	.000	
0592C 5592C	3.68142.000	.000	
0592A 6592A	1.79642.221	.000	
0592B 6592B	1.79642.221	.000	
0592C 6592C	1.79642.221	.000	
0594A 5594A	1.98139.625	.000	
0594B 5594B	1.98139.625	.000	
0594C 5594C	1.98139.625	.000	
0594A 6594A	1.98139.625	.000	
0594B 6594B	1.98139.625	.000	
0594C 6594C	1.98139.625	.000	
0208A 5208A	3.68141.895	.000	
0208B 5208B	3.68141.895	.000	
0208C 5208C	3.68141.895	.000	
0208A 6208A	3.68141.895	.000	
0208B 6208B	3.68141.895	.000	
0208C 6208C	3.68141.895	.000	
0208A 7208A	2.23038.170	.000	
0208B 7208B	2.23038.170	.000	
0208C 7208C	2.23038.170	.000	
0208A 8208A	2.20038.170	.000	
0208B 8208B	2.20038.170	.000	
0208C 8208C	2.20038.170	.000	
1184A 183A	8.87223.44		
2184B 183B	7.66192.97	8.87223.44	
3184C 183C	7.66192.97	7.66192.97	8.87223.44
1203A 5161A	1.75110.43		
2203B 5161B	1.51 95.37	1.75110.43	
3203C 5161C	1.51 95.37	1.51 95.37	1.75110.43
1160A 207A	.88 49.10		
2160B 207B	.76 42.41	.88 49.10	
3160C 207C	.76 42.41	.76 42.41	.88 49.10
1160A 207A	.88 49.10		
2160B 207B	.76 42.41	.88 49.10	
3160C 207C	.76 42.41	.76 42.41	.88 49.10
1161A 202A	.74 47.26		
2161B 202B	.64 40.82	.74 47.26	
3161C 202C	.64 40.82	.64 40.82	.74 47.26
1161A 5161A	.77 48.71		
2161B 5161B	.66 42.07	.77 48.71	

3161C 5161C	.66 42.07	.66 42.07	.77 48.71
1162A 208A	1.02 58.28		
2162B 208B	.88 50.33	1.02 58.28	
3162C 208C	.88 50.33	.88 50.33	1.02 58.28
14183A 183A	33.59774.36		
24183B 183B	29.01668.77	33.59774.36	
34183C 183C	29.01668.77	29.01668.77	33.59774.36
14198A 198A	36.05677.89		
24198B 198B	31.13585.45	36.05677.89	
34198C 198C	31.13585.45	31.13585.45	36.05677.89
1553A 7552A	.61 60.43		
2553B 7552B	.53 52.19	.61 60.43	
3553C 7552C	.53 52.19	.53 52.19	.61 60.43
1560A 8559A	.68 67.24		
2560B 8559B	.59 58.07	.68 67.24	
3560C 8559C	.59 58.07	.59 58.07	.68 67.24
1578A 4577A	.60 67.24		
2578B 4577B	.52 58.07	.60 67.24	
3578C 4577C	.52 58.07	.52 58.07	.60 67.24
1597A 5551A	.63 67.69		
2597B 5551B	.54 58.46	.63 67.69	
3597C 5551C	.54 58.46	.54 58.46	.63 67.69
1599A 6564A	1.33 88.51		
2599B 6564B	1.15 76.44	1.33 88.51	
3599C 6564C	1.15 76.44	1.15 76.44	1.33 88.51
17208A 2208A	16.35279.91		
27208B 2208B	14.12241.74	16.35279.91	
37208C 2208C	14.12241.74	14.12241.74	16.35279.91
15550A 2550A	22.00442.05		
25550B 2550B	19.00381.77	22.00442.05	
35550C 2550C	19.00381.77	19.00381.77	22.00442.05
17551A 2551A	27.00297.52		
27551B 2551B	23.31256.95	27.00297.52	
37551C 2551C	23.31256.95	23.31256.95	27.00297.52
17555A 2555A	14.52290.58		
27555B 2555B	12.54250.96	14.52290.58	
37555C 2555C	12.54250.96	12.54250.96	14.52290.58
17556A 2556A	23.91478.57		
27556B 2556B	20.65413.31	23.91478.57	
37556C 2556C	20.65413.31	20.65413.31	23.91478.57
17559A 2559A	27.00303.30		
27559B 2559B	23.31261.95	27.00303.30	
37559C 2559C	23.31261.95	23.31261.95	27.00303.30
17561A 2561A	14.52290.58		
27561B 2561B	12.54250.96	14.52290.58	
37561C 2561C	12.54250.96	12.54250.96	14.52290.58
17564A 2564A	26.77308.01		
27564B 2564B	23.12266.01	26.77308.01	
37564C 2564C	23.12266.01	23.12266.01	26.77308.01
17567A 2567A	5.39124.27		
27567B 2567B	4.66107.32	5.39124.27	
37567C 2567C	4.66107.32	4.66107.32	5.39124.27
18568A 2568A	9.32292.31		

28568B 2568B	8.04252.45	9.32292.31	
38568C 2568C	8.04252.45	8.04252.45	9.32292.31
15571A 2571A	27.86558.14		
25571B 2571B	24.06482.03	27.86558.14	
35571C 2571C	24.06482.03	24.06482.03	27.86558.14
17572A 2572A	14.52290.58		
27572B 2572B	12.54250.96	14.52290.58	
37572C 2572C	12.54250.96	12.54250.96	14.52290.58
17573A 2573A	24.94289.86		
27573B 2573B	21.54250.33	24.94289.86	
37573C 2573C	21.54250.33	21.54250.33	24.94289.86
18578A 2578A	17.46248.17		
28578B 2578B	15.08214.33	17.46248.17	
38578C 2578C	15.08214.33	15.08214.33	17.46248.17
17579A 2579A	27.00308.51		
27579B 2579B	23.31266.44	27.00308.51	
37579C 2579C	23.31266.44	23.31266.44	27.00308.51
17582A 2582A	26.41526.10		
27582B 2582B	22.81454.36	26.41526.10	
37582C 2582C	22.81454.36	22.81454.36	26.41526.10
17585A 2585A	27.43303.28		
27585B 2585B	23.69261.92	27.43303.28	
37585C 2585C	23.69261.92	23.69261.92	27.43303.28
17588A 2588A	8.84176.51		
27588B 2588B	7.63152.44	8.84176.51	
37588C 2588C	7.63152.44	7.63152.44	8.84176.51
17578A 2598A	17.44248.17		
27578B 2598B	15.06214.33	17.44248.17	
37578C 2598C	15.06214.33	15.06214.33	17.44248.17
16208A 3208A	27.00307.23		
26208B 3208B	23.31265.33	27.00307.23	
36208C 3208C	23.31265.33	23.31265.33	27.00307.23
16550A 3550A	22.00442.05		
26550B 3550B	19.00381.77	22.00442.05	
36550C 3550C	19.00381.77	19.00381.77	22.00442.05
16551A 3551A	5.17266.17		
26551B 3551B	4.46229.87	5.17266.17	
36551C 3551C	4.46229.87	4.46229.87	5.17266.17
16552A 3552A	9.47274.23		
26552B 3552B	8.18236.83	9.47274.23	
36552C 3552C	8.18236.83	8.18236.83	9.47274.23
16554A 3554A	16.72247.88		
26554B 3554B	14.44214.07	16.72247.88	
36554C 3554C	14.44214.07	14.44214.07	16.72247.88
16555A 3555A	27.00304.88		
26555B 3555B	23.31263.31	27.00304.88	
36555C 3555C	23.31263.31	23.31263.31	27.00304.88
16556A 3556A	23.77374.88		
26556B 3556B	20.53323.76	23.77374.88	
36556C 3556C	20.53323.76	20.53323.76	23.77374.88
16557A 3557A	2.84248.02		
26557B 3557B	2.45214.19	2.84248.02	
36557C 3557C	2.45214.19	2.45214.19	2.84248.02
16558A 3558A	16.72247.88		
26558B 3558B	14.44214.07	16.72247.88	
36558C 3558C	14.44214.07	14.44214.07	16.72247.88
16559A 3559A	15.33306.06		
26559B 3559B	13.24264.32	15.33306.06	
36559C 3559C	13.24264.32	13.24264.32	15.33306.06
16561A 3561A	14.66290.76		
26561B 3561B	12.66251.11	14.66290.76	
36561C 3561C	12.66251.11	12.66251.11	14.66290.76
13564A 8564A	49.86244.30		
23564B 8564B	43.06210.99	49.86244.30	
33564C 8564C	43.06210.99	43.06210.99	49.86244.30
16566A 3566A	4.22181.90		
26566B 3566B	3.64157.10	4.22181.90	
36566C 3566C	3.64157.10	3.64157.10	4.22181.90
16567A 3567A	5.46124.27		
26567B 3567B	4.72107.32	5.46124.27	
36567C 3567C	4.72107.32	4.72107.32	5.46124.27
17568A 3568A	9.32291.62		
27568B 3568B	8.04251.85	9.32291.62	
37568C 3568C	8.04251.85	8.04251.85	9.32291.62
16569A 3569A	14.51290.58		
26569B 3569B	12.53250.96	14.51290.58	
36569C 3569C	12.53250.96	12.53250.96	14.51290.58
16570A 3570A	9.06181.20		
26570B 3570B	7.83156.49	9.06181.20	
36570C 3570C	7.83156.49	7.83156.49	9.06181.20
16571A 3571A	27.86558.14		
26571B 3571B	24.06482.03	27.86558.14	
36571C 3571C	24.06482.03	24.06482.03	27.86558.14
16572A 3572A	27.00302.17		
26572B 3572B	23.31260.97	27.00302.17	
36572C 3572C	23.31260.97	23.31260.97	27.00302.17
16573A 3573A	27.00312.66		
26573B 3573B	23.31270.03	27.00312.66	
36573C 3573C	23.31270.03	23.31270.03	27.00312.66
16574A 3574A	27.00308.00		
26574B 3574B	23.31266.00	27.00308.00	
36574C 3574C	23.31266.00	23.31266.00	27.00308.00
16578A 3578A	35.75468.27		
26578B 3578B	30.88404.41	35.75468.27	
36578C 3578C	30.88404.41	30.88404.41	35.75468.27
16579A 3579A	14.52290.58		
26579B 3579B	12.54250.96	14.52290.58	
36579C 3579C	12.54250.96	12.54250.96	14.52290.58
16581A 3581A	14.52290.58		
26581B 3581B	12.54250.96	14.52290.58	
36581C 3581C	12.54250.96	12.54250.96	14.52290.58
16582A 3582A	12.47248.17		
26582B 3582B	10.77214.33	12.47248.17	
36582C 3582C	10.77214.33	10.77214.33	12.47248.17
16583A 3583A	27.00308.00		
26583B 3583B	23.31266.00	27.00308.00	

Large Test Case System Data

36583C 3583C	23,31266.00	23,31266,00	27,00308,00
16585A 3585A	13.13307.68		
26585B 3585B	11,34265,72	13.13307,68	
36585C 3585C	11,34265,72	11,34265,72	13,13307,68
17586A 3586A	27,00297,52		
27586B 3586B	23,31256,95	27,00297,52	
37586C 3586C	23,31256,95	23,31256,95	27,00297,52
16588A 3588A	10,13202,40		
26588B 3588B	8,74174,80	10,13202,40	
36588C 3588C	8,74174,80	8,74174,80	10,13202,40
16591A 3591A	27,00308,00		
26591B 3591B	23,31266,00	27,00308,00	
36591C 3591C	23,31266,00	23,31266,00	27,00308,00
16592A 3592A	13,17309,62		
26592B 3592B	11,37267,40	13,17309,62	
36592C 3592C	11,37267,40	11,37267,40	13,17309,62
16594A 3594A	14,52290,58		
26594B 3594B	12,54250,96	14,52290,58	
36594C 3594C	12,54250,96	12,54250,96	14,52290,58
15208A 4208A	27,00307,23		
25208B 4208B	23,31265,33	27,00307,23	
35208C 4208C	23,31265,33	23,31265,33	27,00307,23
15550A 4550A	22,00442,05		
25550B 4550B	19,00381,77	22,00442,05	
35550C 4550C	19,00381,77	19,00381,77	22,00442,05
18551A 4551A	52,80260,04		
28551B 4551B	45,60224,58	52,80260,04	
38551C 4551C	45,60224,58	45,60224,58	52,80260,04
15552A 4552A	9,25274,93		
25552B 4552B	7,98237,44	9,25274,93	
35552C 4552C	7,98237,44	7,98237,44	9,25274,93
15554A 4554A	16,72247,88		
25554B 4554B	14,44214,07	16,72247,88	
35554C 4554C	14,44214,07	14,44214,07	16,72247,88
15555A 4555A	27,00304,88		
25555B 4555B	23,31263,31	27,00304,88	
35555C 4555C	23,31263,31	23,31263,31	27,00304,88
15556A 4556A	23,48367,25		
25556B 4556B	20,27317,17	23,48367,25	
35556C 4556C	20,27317,17	20,27317,17	23,48367,25
15557A 4557A	2,84248,46		
25557B 4557B	2,45214,58	2,84248,46	
35557C 4557C	2,45214,58	2,45214,58	2,84248,46
15558A 4558A	16,72247,75		
25558B 4558B	14,44213,97	16,72247,75	
35558C 4558C	14,44213,97	14,44213,97	16,72247,75
15559A 4559A	14,59282,52		
25559B 4559B	12,60244,00	14,59282,52	
35559C 4559C	12,60244,00	12,60244,00	14,59282,52
15561A 4561A	14,52290,58		
25561B 4561B	12,54250,96	14,52290,58	
35561C 4561C	12,54250,96	12,54250,96	14,52290,58
15564A 4564A	26,77308,01		
25564B 4564B	23,12266,01	26,77308,01	
35564C 4564C	23,12266,01	23,12266,01	26,77308,01
15566A 4566A	4,19181,90		
25566B 4566B	3,62157,10	4,19181,90	
35566C 4566C	3,62157,10	3,62157,10	4,19181,90
15567A 4567A	5,46124,63		
25567B 4567B	4,72107,63	5,46124,63	
35567C 4567C	4,72107,63	4,72107,63	5,46124,63
15568A 4568A	9,32294,80		
25568B 4568B	8,04254,60	9,32294,80	
35568C 4568C	8,04254,60	8,04254,60	9,32294,80
15569A 4569A	14,51290,58		
25569B 4569B	12,53250,96	14,51290,58	
35569C 4569C	12,53250,96	12,53250,96	14,51290,58
15570A 4570A	9,06180,59		
25570B 4570B	7,83155,96	9,06180,59	
35570C 4570C	7,83155,96	7,83155,96	9,06180,59
15571A 4571A	27,86558,14		
25571B 4571B	24,06482,03	27,86558,14	
35571C 4571C	24,06482,03	24,06482,03	27,86558,14
15572A 4572A	27,00302,17		
25572B 4572B	23,31260,97	27,00302,17	
35572C 4572C	23,31260,97	23,31260,97	27,00302,17
15573A 4573A	27,00313,43		
25573B 4573B	23,31270,69	27,00313,43	
35573C 4573C	23,31270,69	23,31270,69	27,00313,43
15574A 4574A	14,52290,58		
25574B 4574B	12,54250,96	14,52290,58	
35574C 4574C	12,54250,96	12,54250,96	14,52290,58
15578A 4578A	32,26463,94		
25578B 4578B	27,86400,67	32,26463,94	
35578C 4578C	27,86400,67	27,86400,67	32,26463,94
15579A 4579A	14,52290,58		
25579B 4579B	12,54250,96	14,52290,58	
35579C 4579C	12,54250,96	12,54250,96	14,52290,58
15581A 4581A	14,52290,58		
25581B 4581B	12,54250,96	14,52290,58	
35581C 4581C	12,54250,96	12,54250,96	14,52290,58
15582A 4582A	16,87246,12		
25582B 4582B	14,57212,55	16,87246,12	
35582C 4582C	14,57212,55	14,57212,55	16,87246,12
15583A 4583A	16,10283,52		
25583B 4583B	13,91244,85	16,10283,52	
35583C 4583C	13,91244,85	13,91244,85	16,10283,52
15585A 4585A	13,13305,32		
25585B 4585B	11,34263,68	13,13305,32	
35585C 4585C	11,34263,68	11,34263,68	13,13305,32
16586A 4586A	27,00276,25		
26586B 4586B	23,31238,58	27,00276,25	
36586C 4586C	23,31238,58	23,31238,58	27,00276,25
15588A 4588A	10,13202,40		
25588B 4588B	8,74174,80	10,13202,40	
35588C 4588C	8,74174,80	8,74174,80	10,13202,40

Appendix A   *Large Test Case System Data*

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15591A 4591A    27,00308,00
25591B 4591B    23,31266,00   27,00308,00
35591C 4591C    23,31266,00   23,31266,00   27,00308,00
15592A 4592A    27,00308,00
25592B 4592B    23,31266,00   27,00308,00
35592C 4592C    23,31266,00   23,31266,00   27,00308,00
15594A 4594A    14,52290,58
25594B 4594B    12,54250,96   14,52290,58
35594C 4594C    12,54250,96   12,54250,96   14,52290,58
19588A 4888A    10,13202,40
29588B 4888B    8,74174,80    10,13202,40
39588C 4888C    8,74174,80    8,74174,80    10,13202,40
18588A 4990A    8,84176,51
28588B 4990B    7,63152,44    8,84176,51
38588C 4990C    7,63152,44    7,63152,44    8,84176,51
18582A 4991A    20,54465,96
28582B 4991B    17,74402,42   20,54465,96
38582C 4991C    17,74402,42   17,74402,42   20,54465,96
18567A 4992A    5,43127,67
28567B 4992B    4.69110.26    5,43127,67
38567C 4992C    4.69110.26    4.69110.26    5,43127,67
18572A 4993A    14,52290,58
28572B 4993B    12,54250,96   14,52290,58
38572C 4993C    12,54250,96   12,54250,96   14,52290,58
18555A 4994A    14,52290,58
28555B 4994B    12,54250,96   14,52290,58
38555C 4994C    12,54250,96   12,54250,96   14,52290,58
18208A 4995A    16,13279,91
28208B 4995B    13,93241,74   16,13279,91
38208C 4995C    13,93241,74   13,93241,74   16,13279,91
16550A 9550A    22,00442,05
26550B 9550B    19,00381,77   22,00442,05
36550C 9550C    19,00381,77   19,00381,77   22,00442,05
16568A 9568A    9,32290,18
26568B 9568B    8,04250,61    9,32290,18
36568C 9568C    8,04250,61    8.04250.61    9,32290,18
16571A 9571A    27,86558,14
26571B 9571B    24,06482,03   27,86558,14
36571C 9571C    24,06482,03   24,06482,03   27,86558,14
18556A 9556A    23,32465,75
28556B 9556B    20,14402,24   23,32465,75
38556C 9556C    20,14402,24   20,14402,24   23,32465,75
0159A             5192,6
0159B             5192,6
0159C             5192,6
0183A          13785, 4595,
0183B          13785, 4595,
0183C          13785, 4595,
0595A          40774, 8272,
0595B          40774, 8272,
0595C          40774, 8272,
02208A          1495,  304,
02208B          1495,  304,

02208C         1495,  304,
02550A         1013,  206,
02550B         1013,  206,
02550C         1013,  206,
02551A         1639,  333,
02551B         1639,  333,
02551C         1639,  333,
02555A         1591,  323,
02555B         1591,  323,
02555C         1591,  323,
02556A         3788,  769,
02556B         3788,  769,
02556C         3788,  769,
02559A         1806,  367,
02559B         1806,  367,
02559C         1806,  367,
02561A         1486,  302,
02561B         1486,  302,
02561C         1486,  302,
02564A         2852,  579,
02564B         2852,  579,
02564C         2852,  579,
02567A          527,  107,
02567B          527,  107,
02567C          527,  107,
02568A         1827,  371,
02568B         1827,  371,
02568C         1827,  371,
02571A         3317,  674,
02571B         3317,  674,
02571C         3317,  674,
02573A         2579,  524,
02573B         2579,  524,
02573C         2579,  524,
02578A         2553,  518,
02578B         2553,  518,
02578C         2553,  518,
02579A         4550,  924,
02579B         4550,  924,
02579C         4550,  924,
02582A         5492, 1116,
02582B         5492, 1116,
02582C         5492, 1116,
02588A          916,  186,
02588B          916,  186,
02588C          916,  186,
02598A         1875,  381,
02598B         1875,  381,
02598C         1875,  381,
03208A         1896,  385,
03208B         1896,  385,
03208C         1896,  385,
03550A         1558,  316,
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03550B	1558.	316.
03550C	1558.	316.
03551A	1975.	401.
03551B	1975.	401.
03551C	1975.	401.
03552A	1889.	383.
03552B	1889.	383.
03552C	1889.	383.
03554A	1712.	347.
03554B	1712.	347.
03554C	1712.	347.
03555A	3664.	744.
03555B	3664.	744.
03555C	3664.	744.
03556A	2002.	406.
03556B	2002.	406.
03556C	2002.	406.
03557A	2892.	587.
03557B	2892.	587.
03557C	2892.	587.
03558A	3416.	694.
03558B	3416.	694.
03558C	3416.	694.
03559A	2068.	420.
03559B	2068.	420.
03559C	2068.	420.
03561A	1469.	298.
03561B	1469.	298.
03561C	1469.	298.
03566A	966.	196.
03566B	966.	196.
03566C	966.	196.
03567A	615.	125.
03567B	615.	125.
03567C	615.	125.
03568A	1828.	371.
03568B	1828.	371.
03568C	1828.	371.
03569A	2304.	468.
03569B	2304.	468.
03569C	2304.	468.
03570A	609.	124.
03570B	609.	124.
03570C	609.	124.
03571A	1462.	297.
03571B	1462.	297.
03571C	1462.	297.
03572A	2897.	588.
03572B	2897.	588.
03572C	2897.	588.
03573A	1798.	365.
03573B	1798.	365.
03573C	1798.	365.
03574A	1597.	324.
03574B	1597.	324.
03574C	1597.	324.
03578A	4687.	952.
03578B	4687.	952.
03578C	4687.	952.
03579A	572.	116.
03579B	572.	116.
03579C	572.	116.
03581A	2016.	409.
03581B	2016.	409.
03581C	2016.	409.
03582A	3398.	690.
03582B	3398.	690.
03582C	3398.	690.
03583A	5563.	1130.
03583B	5563.	1130.
03583C	5563.	1130.
03585A	797.	162.
03585B	797.	162.
03585C	797.	162.
03586A	1766.	359.
03586B	1766.	359.
03586C	1766.	359.
03588A	1173.	238.
03588B	1173.	238.
03588C	1173.	238.
03591A	2481.	504.
03591B	2481.	504.
03591C	2481.	504.
03592A	3011.	612.
03592B	3011.	612.
03592C	3011.	612.
03594A	1284.	261.
03594B	1284.	261.
03594C	1284.	261.
04183A	14451.	4817.
04183B	14451.	4817.
04183C	14451.	4817.
04198A	2884.	961.
04198B	2884.	961.
04198C	2884.	961.
04208A	1508.	306.
04208B	1508.	306.
04208C	1508.	306.
04550A	770.	156.
04550B	770.	156.
04550C	770.	156.
04552A	2780.	564.
04552B	2780.	564.
04552C	2780.	564.
04554A	3633.	737.
04554B	3633.	737.

04554C	3633, 737,
04555A	11994, 2434,
04555B	11994, 2434,
04555C	11994, 2434,
04556A	1379, 280,
04556B	1379, 280,
04556C	1379, 280,
04557A	2856, 580,
04557B	2856, 580,
04557C	2856, 580,
04558A	2463, 500,
04558B	2463, 500,
04558C	2463, 500,
04559A	1199, 244,
04559B	1199, 244,
04559C	1199, 244,
04561A	1258, 256,
04561B	1258, 256,
04561C	1258, 256,
04564A	1774, 360,
04564B	1774, 360,
04564C	1774, 360,
04566A	1005, 204,
04566B	1005, 204,
04566C	1005, 204,
04568A	2427, 493,
04568B	2427, 493,
04568C	2427, 493,
04569A	925, 188,
04569B	925, 188,
04569C	925, 188,
04570A	1186, 241,
04570B	1186, 241,
04570C	1186, 241,
04571A	2206, 448,
04571B	2206, 448,
04571C	2206, 448,
04572A	2081, 423,
04572B	2081, 423,
04572C	2081, 423,
04573A	2049, 416,
04573B	2049, 416,
04573C	2049, 416,
04574A	1354, 275,
04574B	1354, 275,
04574C	1354, 275,
04578A	5393, 1096,
04578B	5393, 1096,
04578C	5393, 1096,
04579A	1118, 227,
04579B	1118, 227,
04579C	1118, 227,
04581A	1048, 213,

04581B	1048, 213,
04581C	1048, 213,
04582A	4530, 919,
04582B	4530, 919,
04582C	4530, 919,
04583A	3238, 658,
04583B	3238, 658,
04583C	3238, 658,
04585A	767, 156,
04585B	767, 156,
04585C	767, 156,
04586A	4291, 871,
04586B	4291, 871,
04586C	4291, 871,
04588A	1173, 238,
04588B	1173, 238,
04588C	1173, 238,
04591A	1964, 399,
04591B	1964, 399,
04591C	1964, 399,
04592A	1965, 399,
04592B	1965, 399,
04592C	1965, 399,
04594A	1164, 236,
04594B	1164, 236,
04594C	1164, 236,
04888A	1685, 342,
04888B	1685, 342,
04888C	1685, 342,
04990A	556, 113,
04990B	556, 113,
04990C	556, 113,
04991A	3946, 801,
04991B	3946, 801,
04991C	3946, 801,
04992A	721, 146,
04992B	721, 146,
04992C	721, 146,
04993A	1394, 283,
04993B	1394, 283,
04993C	1394, 283,
04994A	3227, 655,
04994B	3227, 655,
04994C	3227, 655,
04995A	1402, 285,
04995B	1402, 285,
04995C	1402, 285,
09550A	1671, 339,
09550B	1671, 339,
09550C	1671, 339,
09568A	2428, 493,
09568B	2428, 493,
09568C	2428, 493,

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09571A          3250. 660.
09571B          3250. 660.
09571C          3250. 660.
1900A 900X      5.542423.551
2900B 900Y       -0.1972.2218   5.542423.551
3900C 900Z       -0.1972.2218  -0.1972.2218   5.542423.551
1444A 444X        13.72649.405
2444B 444Y       -0.4919.7347   13.72649.405
3444C 444Z       -0.4919.7347  -0.4919.7347   13.72649.405
1170A 170X       8.300631.558
2170B 170Y       0.34985.3209   8.300631.558
3170C 170Z       0.34985.3209  0.34985.3209   8.300631.558
1155A 155X       1.18205.2669
2155B 155Y       0.47171.8866   1.18205.2669
3155C 155Z       0.47171.8866  0.47171.8866   1.18205.2669
1177A 177X       11.74749.669
2177B 177Y       0.899512.012   11.74749.669
3177C 177Z       0.899512.012  0.899512.012   11.74749.669
1183A 183X       0.253943.610
2183B 183Y       -0.127-11.61  0.253943.610
3183C 183Z       -0.127-11.61  -0.127-11.61  0.253943.610
1152A 152X       1.21255.3253
2152B 152Y       0.29071.6612   1.21255.3253
3152C 152Z       0.29071.6612  0.29071.6612   1.21255.3253
1988A 988X       4.262020.893
2988B 988Y       1.11606.1360   4.262020.893
3988C 988Z       1.11606.1360  1.11606.1360   4.262020.893
1259A 259X       29.62178.292
2259B 259Y       -2.15821.331   29.62178.292
3259C 259Z       -2.15821.331  -2.15821.331   29.62178.292
1159A 159X       1.01707.3700
2159B 159Y       -0.390-1.339   1.01707.3700
3159C 159Z       -0.390-1.339  -0.390-1.339   1.01707.3700
1212A 212X       22.86658.067
2212B 212Y       -4.7807.9566   22.86658.067
3212C 212Z       -4.7807.9566  -4.7807.9566   22.86658.067
1165A 165X       7.241832.182
2165B 165Y       -0.6922.6864   7.241832.182
3165C 165Z       -0.6922.6864  -0.6922.6864   7.241832.182
1239A 239X       24.87650.724
2239B 239Y       -8.6620.2361   24.87650.724
3239C 239Z       -8.6620.2361  -8.6620.2361   24.87650.724
0202AA                  2835.5
BLANK card ending branch cards
0202A 202AA  .0671   10
BLANK card ending switch cards
14152X   .9470E+05 .6000E+02 .3925E+02              -1.
14152Y   .9470E+05 .6000E+02-.8075E+02              -1.
14152Z   .9470E+05 .6000E+02-.2008E+03              -1.
14155X   .1019E+06 .6000E+02-.3611E+02              -1.
14155Y   .1019E+06 .6000E+02-.1561E+03              -1.
14155Z   .1019E+06 .6000E+02-.2761E+03              -1.
14159X   .1734E+06 .6000E+02-.1639E+02              -1.
14159Y   .1734E+06 .6000E+02-.1364E+03              -1.
14159Z   .1734E+06 .6000E+02-.2564E+03              -1.
14159X   .9262E+05 .6000E+02-.1556E+02              -1.
14159Y   .9262E+05 .6000E+02-.1356E+03              -1.
14159Z   .9262E+05 .6000E+02-.2556E+03              -1.
14165X   .9454E+05 .6000E+02 .2456E+02              -1.
14165Y   .9454E+05 .6000E+02-.9544E+02              -1.
14165Z   .9454E+05 .6000E+02-.2154E+03              -1.
14170X   .8107E+05 .6000E+02 .6730E+01              -1.
14170Y   .8107E+05 .6000E+02-.1133E+03              -1.
14170Z   .8107E+05 .6000E+02-.2333E+03              -1.
14177X   .1119E+06 .6000E+02-.3851E+02              -1.
14177Y   .1119E+06 .6000E+02-.1585E+03              -1.
14177Z   .1119E+06 .6000E+02-.2785E+03              -1.
14183X   .1186E+06 .6000E+02-.4618E+02              -1.
14183Y   .1186E+06 .6000E+02-.1662E+03              -1.
14183Z   .1186E+06 .6000E+02-.2862E+03              -1.
14212X   .1112E+06 .6000E+02-.4494E+02              -1.
14212Y   .1112E+06 .6000E+02-.1649E+03              -1.
14212Z   .1112E+06 .6000E+02-.2849E+03              -1.
14239X   .8551E+05 .6000E+02-.2315E+02              -1.
14239Y   .8551E+05 .6000E+02-.1431E+03              -1.
14239Z   .8551E+05 .6000E+02-.2631E+03              -1.
14259X   .1156E+06 .6000E+02-.4590E+02              -1.
14259Y   .1156E+06 .6000E+02-.1659E+03              -1.
14259Z   .1156E+06 .6000E+02-.2859E+03              -1.
14444X   .1073E+06 .6000E+02-.3945E+02              -1.
14444Y   .1073E+06 .6000E+02-.1595E+03              -1.
14444Z   .1073E+06 .6000E+02-.2795E+03              -1.
14900X   .1124E+06 .6000E+02-.4245E+02              -1.
14900Y   .1124E+06 .6000E+02-.1624E+03              -1.
14900Z   .1124E+06 .6000E+02-.2824E+03              -1.
14988X   .8994E+05 .6000E+02-.2219E+02              -1.
14988Y   .8994E+05 .6000E+02-.1422E+03              -1.
14988Z   .8994E+05 .6000E+02-.2622E+03              -1.
BLANK card ending source cards
 184A  202A
BLANK card terminating output specifications (node voltages only, here)
```

Appendix B

Matlab Scripts

Following Matlab scripts are used to calculate and generate data in the thesis.

1. Matlab Scripts 1

Following scripts are used in chapter 2 to plot the analytical solution.

```
clf;
f=60;                   % Frequency
W=2*3.14*f;             % Frequency in radian per second
t=0:.000125:.05;           % Time step
t=t';
angle=0.35;             % angle
phi=angle*3.14/180;
phi1=86.7*3.14/180;

% Capacitor voltage waveform
Vt=49410*sin(W*t-phi)+5352*exp(-95*t).*cos(3445*t+phi1);

% Source voltage waveform
Vt1=48790*sin(W*t);

% Capacitor transient voltage component
V=5352*exp(-95*t).*cos(3445*t+phi1);

% Plot commands
subplot(1,2,1);
plot(t,Vt/1000,t,Vt1/1000);
title('Response of the Circuit Figure 2.1')
xlabel('Time(sec)')
ylabel('kV');
subplot(1,2,2);
plot(t,V/1000);   % Plot voltage waveform
title('Transient Component of the Capacitor Voltage')
xlabel('Time(sec)')
ylabel('kV');
% ***********************************************
```

2. Matlab Scripts 2

Following scripts are used in chapter 3.

2.1 Basic Concept Calculation

```
%Example program to demonstrate the basic concept
%of the frequency domain calculation.

%****************************************************


ff =60;                 % Fundamental frequency
W=2*pi*ff;
t=0:.0002:.05;       % Time step
t=t';

% Input voltage waveform
Vt=48790*sin(W*t);
figure(1);
subplot(2,2,1);
plot(t,Vt/1000);  % Plot voltage waveform
title('Input voltage in Time Domain')
xlabel('Time(sec)')
ylabel('kV');
% ***********************************************

% FFT the input voltage
N=length(t); % Number of points to be considered for the fft.
Vs=fft(Vt, N); % FFT (!!Actually it is DFT)
f=(0:N-1)*20;  % Symmetry since three cycle of waveform is taken.
f=f';
Vm=((2)/N)*abs(Vs); % The Amplitude at different frequencies
Subplot (2,2,2);
% Selectively plot just the first 20 harmonics of the waveform.
stem(f(1:20),Vm(1:20)/1000);
title('Input voltage in Frequency Domain')
xlabel('frequency (Hz)')
ylabel('kV');

% **************************************************
% Circuit Transfer Function

s=-j*2*pi*f; % Define 's'
% Circuit parameters
L=0.0021;
C=40.1e-6;
R=0.4;

% Transfer function
y=(L*C*s).*s;
```

```
y1=R*C*s;
Gs=1./(y+y1+1);
Gsm=abs(Gs);
angl=angle(Gs);

% Frequency response plots

figure(2);
Subplot (2,2,1);
plot(f(1:200),Gsm(1:200));
ylabel(' Magnitude G(s)');
xlabel('Frequency (Hz)')

Subplot (2,2,2);
plot(f(1:200),angl(1:200));
ylabel(' Angle in degrees G(s)');
xlabel('Frequency (Hz)')

%****************************************************
% Capacitor voltage computation
Vcs=Gs.*Vs;
% The capacitor voltage amplitude at different frequencies
Vcm=((2)/N)*abs(Vcs);

% Plot commands
figure(3);
Subplot (2,2,1);
stem(f(1:100),Vcm(1:100));
title('Capacitor voltage in Frequency Domain')
xlabel('frequency (Hz)')
ylabel('Volts');

Vcm1=[Vcm(1:3);0;Vcm(5:100)];
Subplot (2,2,2);
stem(f(1:100),Vcm1);
title('Frequency Content of the Capacitor Voltage without
Fundamental')
xlabel('frequency (Hz)')
ylabel('Volts');
```

2.2 Case 1 and Superposition Method Calculations

```
%****************************************************
%clear
clf
%Error Curve
%-----------------
% Load impedance response data from three cycles of input
% computed by another program
load case1imp.txt
%************************
%Impedance Response
```

```
f=caselimp(:,2); % Frequency
% Extract magnitude and angles of the response
Zs=caselimp(:,3);
angl=caselimp(:,4);

figure(1);
%Plot commands
subplot(2,2,1);
plot(f,Zs);
title('Impedance Response (Magnitude) of the Figure 3.14 ')
ylabel(' Magnitude Z(s)');
xlabel('Frequency (Hz)')

subplot(2,2,2);
plot(f,angle);
title('Impedance Response (Angle) of the Figure 3.14 ')
ylabel(' Angle in degrees');
xlabel('Frequency (Hz)')

%**************************************************
% Switch Voltage

ff=60;
W=2*pi*ff;
t=0:.0004:.054167;
t=t';

Vt=48790*sin(W*t); %Voltage waveform
N=length(t);

% Voltage is such that the switch is closed at the peak
Vtsw=[zeros(size(Vt(1:10)));Vt(11:N)];

figure(2);
% Plot command
subplot(2,2,1);
plot(t,-Vtsw/1000);  % Plot voltage waveform
title('A:Switch Voltage in Time Domain')
xlabel('Time(sec)')
ylabel('kV');

% Change switch voltage into frequency domain
N1=length(Vtsw(10:N));
Vtsw=-Vtsw;
Vts=fft(Vtsw(10:N),N1);
Vtsm=(2/N1)*abs(Vts);

subplot(2,2,2);
stem(f(1:20),Vtsm(1:20)/1000);   % Plot voltage waveform
title('A:Switch Voltage in Frequency Domain')
xlabel('Time(sec)')
ylabel('kV');

%*******************************************************
```

```
% Switching current computation

Zsr=Zs.*cos(angl*3.1415/180);
Zsi=j*Zs.*sin(angl*3.1415/180);
Zst=Zsr+Zsi;
s=-j*2*3.1415*f;
C=40.1e-6;
Cs=1./((s+10e-6)*C);
len=length(Zst);
Zstt=Zst+Cs(1:len);
Is=(Vts)./Zstt;
% Switching current magnitude
Ism=(2/N1)*abs(Is);
% Switching current magnitude without fundamental
Ism1=[Ism(1:3);0;Ism(5:151)];

% Plot commands
figure(3);
subplot(2,2,1);
stem(f(1:75),Ism(1:75));
xlabel('Frequency (Hz)');
ylabel('Magnitude (Amp)');
title('Switching Current I(s)');

subplot(2,2,2);
stem(f(1:75),Ism1(1:75));
xlabel('Frequency (Hz)');
ylabel('Magnitude (Amp)');
title('Switching Current I(s) without 60Hz Component');

%*******************************************
%Capacitor voltage computation

Vcs=Zst.*Is;
% Magnitude
Vcsm=(2/N1)*abs(Vcs);
%Plot commands
figure(4);
plot(f(1:75),(Vcsm(1:75));
title('Capacitor Voltage')
ylabel('Voltage Magnitude (V)');
xlabel('Frequency (Hz)')
```

2.3 Large Case and Superposition Method Calculations

```
%clear
clf
%------------------
% Steady state voltage at the switch node prior to the switch
closure
load vswitch1.txt
%***********************
```

```
t=vswitchl(:,2);
N=length(t);
Vswith=sqrt(2)*vswitchl(:,3); %Peak
% Assume switch closes at the first peak of the waveform
Vswith=-[zeros(size(Vswith(1:9)));Vswith(10:N)];

%plot command
figure(1);
subplot(2,2,1);
plot(t,Vswith/1000);
xlabel('Time (sec)');
ylabel('Volts (kV)');
title('A: Switch Voltage of the Large Case');

%Convert to frequency domain taking the data window of three cycles
N1=length(Vswith(9:N));
Vts=fft(Vswith(9:N),N1);
f=(0:N1-1)*20; %symmetry (taking three cycles as a period)
Vtsm=(2/N1)*abs(Vts);

subplot(2,2,2);
stem(f(1:20),Vtsm(1:20)/1000);   % Plot voltage waveform
title('B: Switch Voltage in Frequency Domain')
xlabel('Frequency (Hz)')
ylabel('kV');

%*******************************************************
% Load impedance response computed by another program

load fscan.txt %load data file for the impedance response of the
network
load fscanone.txt %load impedance response of the bus 184
Zs=fscan(:,3);
angl=fscan(:,4);
Zs1=fscanone(:,3);
angl1=fscanone(:,4);

%Network impedance response from bus 202
Zsr=Zs.*cos(angl*3.1415/180);
Zsi=j*Zs.*sin(angl*3.1415/180);
Zst=Zsr+Zsi;

%Impedance response of bus 184 from bus 202
Zsr1=Zs1.*cos(angl1*3.1415/180);
Zsi1=j*Zs1.*sin(angl1*3.1415/180);
Zst1=Zsr1+Zsi1;

%Plot commands
figure(2);

subplot(2,2,1);
plot(f,Zs);
title('Impedance Response of the Large System ')
ylabel(' Magnitude of Z(s)');
```

```
xlabel('Frequency (Hz)')

subplot(2,2,2);
plot(f,angl);
title('Impedance Response of the Large System ')
ylabel(' Angle in degrees of Z(s)');
xlabel('Frequency (Hz)')

subplot(2,2,3);
plot(f,Zs1);
title('Impedance Response of the Large System bus-184 ')
ylabel(' Magnitude of Z(s)');
xlabel('Frequency (Hz)')

subplot(2,2,4);
plot(f,angl1);
title('Impedance Response of the Large System bus-184')
ylabel(' Angle in degrees of Z(s)');
xlabel('Frequency (Hz)')

%************************************************************
%Compute switching current

s=-j*2*3.1415*f;
C=7.52e-6;
Cs=1./(s*C+1e-6);
Zstt=Zst+Cs;
Is=(Vts)./Zstt;

Ism=(2/N)*abs(Is);          %The Amplitude at different frequencies
Ism1=[Ism(1:3);0;Ism(5:401)]; % Remove fundamental

% Plot commands
figure(3);
subplot(2,2,1);
plot(f,Ism);
xlabel('Frequency (Hz)');
ylabel('Magnitude (Amp)');
title(' Switching Current I(s) of the Large Case');

subplot(2,2,2);
plot(f,Ism1);
xlabel('Frequency (Hz)');
ylabel('Magnitude (Amp)');
title(' Switching Current I(s) of the Large Case without
Fundamental');

%*******************************************************
%Compute transient voltages

% At switching bus (bus 202)
Vts=Zst.*Is;
Vst=(2/N)*abs(Vts);        %The Amplitude at different frequencies
```

```
% At bus 184
Vts1=Zst1.*Is;
Vst1=(2/N)*abs(Vts1);       %The Amplitude at different frequencies

% Plot commands

figure(4);
subplot(2,2,1);
stem(f(1:300), Vst(1:300));
xlabel('Frequency (Hz)');
ylabel('Magnitude (V)');
title('Transient Voltage V(s) of the large case at 42S-202');

subplot(2,2,2);
stem(f(1:300), Vst1(1:300));
xlabel('Frequency (Hz)');
ylabel('Magnitude (V)');
title('Transient Voltage V(s) of the large case at 184');

%end
```

3. Matlab Scripts 3

Following scripts are used in chapter 4.

3.1 Selection of Key Frequencies from Voltage Spectrum

```
%clear
clf
%------------------

%Load voltage data computed earlier in chapter 3
load chfive.txt;

V551=chfive(:,5);
f=chfive(:,2);

%*****************************************
%Compute magnitudes at key frequencies

% Bus 551
PeakH=max(V551); %Find the maximum values among the magnitudes
Min_reqd=0.10*PeakH; % Calculate the ten percent of the peak of all
the magnitudes

n=length(V551);  %find the total number of points

fnew=0;
Ismnew=0;
```

```
j=1;
for i=1:1:n

if   (V551(i)>=Min_reqd)
      V551new(j)=V551(i);
      fnew(j)= f(i);
end

j=i+1;

end

V551new=V551new';
fnew=fnew';

% Plot commands
figure(1);
subplot(2,1,1);
plot(f(1:350),V551new(1:350));
xlabel('Frequency (Hz)');
ylabel('Voltage Magnitude (V)');
title(' Transient Voltage at Bus 551 Using Key Frequencies');

subplot(2,1,2);
plot(f(1:350),V551fm(1:350));
title('Actual Voltage Magitude at Bus 551 of the Network')
ylabel('Voltage Magnitude (V)');
xlabel('Frequency (Hz)')
```

3.2 Selection of Key Frequencies from Transfer Impedance

```
%clear
clf
%------------------

%Load impedance response Data
load fscan1.txt;
load Iswitch.txt;
% Extract Column values from the data table
Z551fm=fscan1(:,3);
angl551=fscan1(:,4);
f=fscan1(:,2);
Is=Iswitch(:,3);
%---------------------------------------
%Determination of key frequencies

%Find the Peak of the transient component
PeakH=max(Z551fm);
% Calculate the threshold values
Min_reqd=0.10*PeakH;

n=length(Z551fm);  %find the total number of points
```

```
fnew=0;
j=1;
Z551new=0;

for i=1:1:n

if    (Z551fm(i)>=Min_reqd)
       Z551new(j)=Z551fm(i);
       fnew(j)= f(i);
end

j=i+1;

end

Z551new=Z551new';
fnew=fnew';



figure(1);
subplot(2,2,1);
plot(f(1:350),Z551new(1:350));
xlabel('Frequency (Hz)');
ylabel('Impedance Magnitude');
title(' Transfer Impedance at Bus 551 at Key Frequencies');

%Compute voltage by key frequencies
V551fma=Z551new.*Is;

subplot(2,2,2);
plot(f(1:350),V551fma(1:350));
xlabel('Frequency (Hz)');
ylabel('Voltage Magnitude (V)');
title(' Transient Voltage at Bus 551 Using Key Frequencies of
Impedance');
%*********************************************************************
```

4. Matlab Scripts 4

Following scripts are used to generate figures found in chapter 5.

4.1 Time Domain Calculations to Determine Peak of the Transient:

```
%clear
clf
%------------------
```

```
load chfive.txt;          %Load Data
load chfivea.txt;         %Load Data


%---------------------------------------

V202=chfive(:,3);
V444=chfive(:,4);
V551=chfive(:,5);
V552=chfive(:,6);
V564=chfive(:,7);
V581=chfive(:,8);
V586=chfive(:,9);

V184=chfivea(:,3);
V183=chfivea(:,4);
V170=chfivea(:,5);
V585=chfivea(:,6);
V554=chfivea(:,7);
V582=chfivea(:,8);
V556=chfivea(:,9);
V557=chfivea(:,10);

%*****************************************
%Find Steady State Peak Value

V202s=max((V202(50:200)));
V444s=max((V444(50:200)));
V551s=max((V551(50:200)));
V552s=max((V552(50:200)));
V564s=max((V564(50:200)));
V581s=max((V581(50:200)));
V586s=max((V586(50:200)));

V184s=max((V184(50:200)));
V183s=max((V183(50:200)));
V170s=max((V170(50:200)));
V585s=max((V585(50:200)));
V554s=max((V554(50:200)));
V582s=max((V582(50:200)));
V556s=max((V556(50:200)));
V557s=max((V557(50:200)));


%*****************************************
%Find total peak Value

V202t=max(abs(V202));
V444t=max(abs(V444));
V551t=max(abs(V551));
V552t=max(abs(V552));
V564t=max(abs(V564));
```

```
V581t=max(abs(V581));
V586t=max(abs(V586));


V184t=max(abs(V184));
V183t=max(abs(V183));
V170t=max(abs(V170));
V585t=max(abs(V585));
V554t=max(abs(V554));
V582t=max(abs(V582));
V556t=max(abs(V556));
V557t=max(abs(V557));

%*******************************************
%Find the Transient Peak

   V202tt=V202t-V202s;
   V444tt=V444t-V444s;
   V551tt=V551t-V551s;
   V552tt=V552t-V552s;
   V564tt=V564t-V564s;
   V581tt=V581t-V581s;
   V586tt=V586t-V586s;

   V184tt=V184t-V184s;
   V183tt=V183t-V183s;
   V170tt=V170t-V170s;
   V585tt=V585t-V585s;
   V554tt=V554t-V554s;
   V582tt=V582t-V582s;
   V556tt=V556t-V556s;
   V557tt=V557t-V557s;

%Time Domain Transient Peaks:

VT=[V202tt,V444tt,V551tt,V552tt,V564tt,V581tt,V586tt,V184tt,V183tt,V
170tt,V585tt,V554tt,V582tt,V556tt,V557tt]';
 %
 %****************************************
 %
```

4.2 Frequency Domain Calculations to Determine Estimated Peak of the Transient:

```
%clear
clf
%-------------------
load chf.txt;                 %Load Data
load chfa.txt;                %Load Data
N=chf(:,1);
f=(0:N-1)*20';
```

```
%--------------------------------------
% Load voltage magnitudes computed from
% program used in chapter 3.
V202fm=chf(:,3);
V444fm=chf(:,4);
V551fm=chf(:,5);
V552fm=chf(:,6);
V564fm=chf(:,7);
V581fm=chf(:,8);
V586fm=chf(:,9);

V184fm=chfa(:,3);
V183fm=chfa(:,4);
V170fm=chfa(:,5);
V585fm=chfa(:,6);
V554fm=chfa(:,7);
V582fm=chfa(:,8);
V556fm=chfa(:,9);
V557fm=chfa(:,10);

%****************************************
%Find the Peak of the transient component
PeakH1=max(V202fm);
% Calculate the ten percent of the peak of all the magnitudes
Min_reqd1=0.10*PeakH1;

n1=length(V202fm);  %find the total number of points

fnew1=0;

j=1;
for i=1:1:n1

if    (V202fm(i)>=Min_reqd1)
       V202new(j)=V202fm(i);
       fnew1(j)= f(i);
      end

j=i+1;

end

V202new=V202new';
fnew1=fnew1';

Peak202=sum(V202new)-sqrt(sum(V202new.*V202new));

%*******************************************************************
%Find the Peak of the transient component
PeakH2=max(V444fm);
% Calculate the ten percent of the peak of all the magnitudes
Min_reqd2=0.10*PeakH2;

n2=length(V444fm);  %find the total number of points
```

```
  count=0;
  for k=1:1:n2
     if Min_reqd2>=V444fm(k)+100 | Min_reqd2<=V444fm(k)-100
        count=count+1;
     end
  end

  fnew2=0;

  if count>=50
     Min_reqd2=Min_reqd2+200;
  end

  j=1;
  for i=1:1:n2

  if    (V444fm(i)>=Min_reqd2)
         V444new(j)=V444fm(i);
         fnew2(j)= f(i);
     end

 j=i+1;

 end

  if (length(V444new)>100)
     Min_reqd2=Min_reqd2+150;
  end

     j=1;
     for i=1:1:n2

             if (V444fm(i)>Min_reqd2)
              V444newa(j)=V444fm(i);
              fnew2a(j)= f(i);
             end

      j=i+1;

    end

   V444new=V444newa;
   fnew2=fnew2a;

V444new=V444new';
fnew2=fnew2';

Peak444=sum(V444new)-sqrt(sum(V444new.*V444new));

%************************************************************************

PeakH3=max(V551fm);
Min_reqd3=0.10*PeakH3;
```

```
n3=length(V551fm);  %find the total number of points

fnew3=0;

j=1;
for i=1:1:n3

if   (V551fm(i)>=Min_reqd3)
      V551new(j)=V551fm(i);
      fnew3(j)= f(i);
     end

j=i+1;

end

V551new=V551new';
fnew3=fnew3';

Peak551=sum(V551new)-sqrt(sum(V551new.*V551new));

%****************************************************************************

PeakH4=max(V552fm);
Min_reqd4=0.10*PeakH4;
n4=length(V552fm);  %find the total number of points

fnew4=0;

j=1;
for i=1:1:n4

if   (V552fm(i)>=Min_reqd1)
      V552new(j)=V552fm(i);
      fnew4(j)= f(i);
     end

j=i+1;

end

V552new=V552new';
fnew4=fnew4';

Peak552=sum(V552new)-sqrt(sum(V552new.*V552new));

%****************************************************************************

PeakH5=max(V564fm);
Min_reqd5=0.10*PeakH5;

n5=length(V564fm);  %find the total number of points

fnew5=0;
```

```
j=1;
for i=1:1:n5

if    (V564fm(i)>=Min_reqd1)
       V564new(j)=V564fm(i);
       fnew5(j)= f(i);
      end

j=i+1;

end

V564new=V564new';
fnew5=fnew5';

Peak564=sum(V564new)-sqrt(sum(V564new.*V564new));

%*******************************************************************

PeakH6=max(V581fm);
Min_reqd6=0.10*PeakH6;

n6=length(V581fm);  %find the total number of points

fnew6=0;

j=1;
for i=1:1:n6

if    (V581fm(i)>=Min_reqd6)
       V581new(j)=V581fm(i);
       fnew6(j)= f(i);
      end

j=i+1;

end

V581new=V581new';
fnew6=fnew6';

Peak581=sum(V581new)-sqrt(sum(V581new.*V581new));

%*******************************************************************

PeakH7=max(V586fm);
Min_reqd7=0.10*PeakH7;

n7=length(V586fm);  %find the total number of points

fnew7=0;

j=1;
```

```
 for i=1:1:n7

 if   (V586fm(i)>=Min_reqd7)
       V586new(j)=V586fm(i);
       fnew7(j)= f(i);
      end

j=i+1;

end

V586new=V586new';
fnew7=fnew7';

Peak586=sum(V586new)-sqrt(sum(V586new.*V586new));

%*****************************************************************

PeakH9=max(V184fm);
Min_reqd9=0.10*PeakH9;
n9=length(V184fm);  %find the total number of points

fnew9=0;

j=1;
for i=1:1:n9

if   (V184fm(i)>=Min_reqd9)
      V184new(j)=V184fm(i);
      fnew9(j)= f(i);
     end

j=i+1;

end

V184new=V184new';
fnew9=fnew9';

Peak184=sum(V184new)-sqrt(sum(V184new.*V184new));

%*****************************************************************
PeakH10=max(V183fm);
Min_reqd10=0.10*PeakH10;
n10=length(V183fm);  %find the total number of points

fnew10=0;


j=1;
for i=1:1:n10

if   (V183fm(i)>=Min_reqd10)
      V183new(j)=V183fm(i);
```

```
       fnew10(j)= f(i);
      end

j=i+1;

end

V183new=V183new';
fnew10=fnew10';

Peak183=sum(V183new)-sqrt(sum(V183new.*V183new));

%*******************************************************************

PeakH11=max(V170fm);
Min_reqd11=0.10*PeakH11;
n11=length(V170fm);  %find the total number of points

fnew11=0;

j=1;
for i=1:1:n11

if   (V170fm(i)>=Min_reqd11)
       V170new(j)=V170fm(i);
       fnew11(j)= f(i);
      end

j=i+1;

end

V170new=V170new';
fnew11=fnew11';

Peak170=sum(V170new)-sqrt(sum(V170new.*V170new));

%*******************************************************************

PeakH12=max(V585fm);
Min_reqd12=0.10*PeakH12;
n12=length(V585fm);  %find the total number of points

fnew12=0;


j=1;
for i=1:1:n12

if   (V585fm(i)>=Min_reqd12)
       V585new(j)=V585fm(i);
       fnew12(j)= f(i);
      end
```

```
j=i+1;

end

V585new=V585new';
fnew12=fnew12';

Peak585=sum(V585new)-sqrt(sum(V585new.*V585new));

%*******************************************************************

PeakH13=max(V554fm);
Min_reqd13=0.10*PeakH13;
n13=length(V554fm);  %find the total number of points

fnew13=0;

j=1;
for i=1:1:n13

if    (V554fm(i)>=Min_reqd13)
       V554new(j)=V554fm(i);
       fnew13(j)= f(i);
      end

j=i+1;

end

V554new=V554new';
fnew13=fnew13';

Peak554=sum(V554new)-sqrt(sum(V554new.*V554new));

%*******************************************************************

PeakH14=max(V582fm);
Min_reqd14=0.10*PeakH14;
n14=length(V582fm);  %find the total number of points

fnew14=0;

j=1;
for i=1:1:n14

if    (V582fm(i)>=Min_reqd14+200)
       V582new(j)=V582fm(i);
       fnew14(j)= f(i);
      end

j=i+1;

end
```

```
V582new=V582new';
fnew14=fnew14';

Peak582=sum(V582new)-sqrt(sum(V582new.*V582new));

%***************************************************************

PeakH15=max(V556fm);
Min_reqd15=0.10*PeakH15;

n15=length(V556fm);  %find the total number of points

fnew15=0;

j=1;
for i=1:1:n15

if   (V556fm(i)>=Min_reqd15)
      V556new(j)=V556fm(i);
      fnew16(j)= f(i);
     end

j=i+1;

end

V556new=V556new';
fnew15=fnew15';

Peak556=sum(V556new)-sqrt(sum(V556new.*V556new));
%***************************************************************
PeakH16=max(V557fm);
Min_reqd16=0.10*PeakH16;

n16=length(V557fm);  %find the total number of points

fnew16=0;

j=1;
for i=1:1:n16

if   (V557fm(i)>=Min_reqd16)
      V557new(j)=V557fm(i);
      fnew17(j)= f(i);
     end

j=i+1;

end

V557new=V557new';
fnew16=fnew16';

Peak557=sum(V557new)-sqrt(sum(V557new.*V557new));
```

```
%**********************************************************************
%Correlated peak
Peak202r=sqrt(sum(V202new.*V202new));
Peak444r=sqrt(sum(V444new.*V444new));
Peak551r=sqrt(sum(V551new.*V551new));
Peak552r=sqrt(sum(V552new.*V552new));
Peak564r=sqrt(sum(V564new.*V564new));
Peak581r=sqrt(sum(V581new.*V581new));
Peak586r=sqrt(sum(V586new.*V586new));

Peak184r=sqrt(sum(V184new.*V184new));
Peak183r=sqrt(sum(V183new.*V183new));
Peak170r=sqrt(sum(V170new.*V170new));
Peak585r=sqrt(sum(V585new.*V585new));
Peak554r=sqrt(sum(V554new.*V554new));
Peak582r=sqrt(sum(V582new.*V582new));
Peak556r=sqrt(sum(V556new.*V556new));
Peak557r=sqrt(sum(V557new.*V557new));
%*****************************************
diary on;
%Estimated peak
Vfes=[Peak202,Peak444,Peak551,Peak552,Peak564,Peak581,Peak586,Peak18
4,Peak183,Peak170,Peak585,Peak554,Peak582,Peak556,Peak557]'
%Correlated peak
Vfcr=[Peak202r,Peak444r,Peak551r,Peak552r,Peak564r,Peak581r,Peak586r
,Peak184r,Peak183r,Peak170r,Peak585r,Peak554r,Peak582r,Peak556r,Peak
557r]'
diary off;
```

4.3 Time domain calculations to Determine Energy of the Transients:

```
%clear
clf
%—————————


load chfive.txt;          %Load voltage Data
load chfivea.txt;         %Load voltage Data
load current.txt;
t=chfive(:,2);            %Time column

%********************************************
%Load  voltages for 15 given buses

V202=chfive(:,3);
V444=chfive(:,4);
V551=chfive(:,5);
V552=chfive(:,6);
V564=chfive(:,7);
V581=chfive(:,8);
V586=chfive(:,9);

V184=chfivea(:,3);
V183=chfivea(:,4);
V170=chfivea(:,5);
V585=chfivea(:,6);
V554=chfivea(:,7);
```

```
V582=chfivea(:,8);
V556=chfivea(:,9);
V557=chfivea(:,10);

%*******************************************
% Functions to extract 60Hz component. Data files is such that the first cycle of the waveform contains the steady state 60Hz  component.

delta_t=.625e-4;                     %Time Step
Ffreq=60;                            %Fundamental Frequency in Hz
Nf=(inv(Ffreq)/delta_t);             %Number of points for one cycle of the waveform.
Nf=round(Nf);                        %Convert to interger


V60A=V202(1:Nf);                     %Extract data for one cycle of waveform from bus 202
t1=t(1:Nf);                          %Extract time column from the data file.

V60B=V444(1:Nf);                     %Extract data for one cycle of waveform from bus 444
V60C=V551(1:Nf);                     %Extract data for one cycle of waveform from bus 551
V60D=V552(1:Nf);                     %Extract data for one cycle of waveform from bus 552
V60E=V564(1:Nf);                     %Extract data for one cycle of waveform from bus 564
V60F=V581(1:Nf);                     %Extract data for one cycle of waveform from bus 581
V60G=V586(1:Nf);                     %Extract data for one cycle of waveform from bus 586
V60I=V184(1:Nf);                     %Extract data for one cycle of waveform from bus 184
V60J=V183(1:Nf);                     %Extract data for one cycle of waveform from bus 183
V60K=V170(1:Nf);                     %Extract data for one cycle of waveform from bus 170
V60L=V585(1:Nf);                     %Extract data for one cycle of waveform from bus 585
V60M=V554(1:Nf);                     %Extract data for one cycle of waveform from bus 554
V60N=V582(1:Nf);                     %Extract data for one cycle of waveform from bus 582
V60O=V556(1:Nf);                     %Extract data for one cycle of waveform from bus 556
V60P=V557(1:Nf);                     %Extract data for one cycle of waveform from bus 557

%***************************************************************
% Functions to substract 60Hz component from the total waveform (Cycle by Cycle)
% to get the transient component.

VH1=V202(1:Nf);
VH1=VH1-V60A;
VH2=V202(Nf+1:2*Nf);
VH2=VH2-V60A;
VH3=V202(2*Nf+1:3*Nf);
VH3=VH3-V60A;
VHA=[VH1;VH2;VH3];

VH1=V444(1:Nf);
VH1=VH1-V60B;
VH2=V444(Nf+1:2*Nf);
VH2=VH2-V60B;
VH3=V444(2*Nf+1:3*Nf);
VH3=VH3-V60B;
VHB=[VH1;VH2;VH3];

VH1=V551(1:Nf);
VH1=VH1-V60C;
VH2=V551(Nf+1:2*Nf);
VH2=VH2-V60C;
VH3=V551(2*Nf+1:3*Nf);
VH3=VH3-V60C;
VHC=[VH1;VH2;VH3];

VH1=V552(1:Nf);
VH1=VH1-V60D;
VH2=V552(Nf+1:2*Nf);
VH2=VH2-V60D;
VH3=V552(2*Nf+1:3*Nf);
VH3=VH3-V60D;
VHD=[VH1;VH2;VH3];

VH1=V564(1:Nf);
VH1=VH1-V60E;
VH2=V564(Nf+1:2*Nf);
VH2=VH2-V60E;
VH3=V564(2*Nf+1:3*Nf);
VH3=VH3-V60E;
VHE=[VH1;VH2;VH3];

VH1=V581(1:Nf);
```

```
VH1=VH1-V60F;
VH2=V581(Nf+1:2*Nf);
VH2=VH2-V60F;
VH3=V581(2*Nf+1:3*Nf);
VH3=VH3-V60F;
VHF=[VH1;VH2;VH3];

VH1=V586(1:Nf);
VH1=VH1-V60G;
VH2=V586(Nf+1:2*Nf);
VH2=VH2-V60G;
VH3=V586(2*Nf+1:3*Nf);
VH3=VH3-V60G;
VHG=[VH1;VH2;VH3];


VH1=V184(1:Nf);
VH1=VH1-V60I;
VH2=V184(Nf+1:2*Nf);
VH2=VH2-V60I;
VH3=V184(2*Nf+1:3*Nf);
VH3=VH3-V60I;
VHI=[VH1;VH2;VH3];

VH1=V183(1:Nf);
VH1=VH1-V60J;
VH2=V183(Nf+1:2*Nf);
VH2=VH2-V60J;
VH3=V183(2*Nf+1:3*Nf);
VH3=VH3-V60J;
VHJ=[VH1;VH2;VH3];

VH1=V170(1:Nf);
VH1=VH1-V60K;
VH2=V170(Nf+1:2*Nf);
VH2=VH2-V60K;
VH3=V170(2*Nf+1:3*Nf);
VH3=VH3-V60K;
VHK=[VH1;VH2;VH3];

VH1=V585(1:Nf);
VH1=VH1-V60L;
VH2=V585(Nf+1:2*Nf);
VH2=VH2-V60L;
VH3=V585(2*Nf+1:3*Nf);
VH3=VH3-V60L;
VHL=[VH1;VH2;VH3];

VH1=V554(1:Nf);
VH1=VH1-V60M;
VH2=V554(Nf+1:2*Nf);
VH2=VH2-V60M;
VH3=V554(2*Nf+1:3*Nf);
VH3=VH3-V60M;
VHM=[VH1;VH2;VH3];

VH1=V582(1:Nf);
VH1=VH1-V60N;
VH2=V582(Nf+1:2*Nf);
VH2=VH2-V60N;
VH3=V582(2*Nf+1:3*Nf);
VH3=VH3-V60N;
VHN=[VH1;VH2;VH3];

VH1=V556(1:Nf);
VH1=VH1-V60O;
VH2=V556(Nf+1:2*Nf);
VH2=VH2-V60O;
VH3=V556(2*Nf+1:3*Nf);
VH3=VH3-V60O;
VHO=[VH1;VH2;VH3];

VH1=V557(1:Nf);
VH1=VH1-V60P;
VH2=V557(Nf+1:2*Nf);
VH2=VH2-V60P;
```

```
VH3=V557(2*Nf+1:3*Nf);
VH3=VH3-V60P;
VHP=[VH1;VH2;VH3];


%***********************************************
% Function to integrate the transient component (Equation 5.3) by trapezoidal method

n=(length(VHA));                  %find the total number of points

x1=VHA(1:n-1).*VHA(1:n-1);        %extract points beginning from second entry to the end and square it.
x2=VHA(2:n).*VHA(2:n);             %extract points from start to one before the end and square it.
y=[(x1+x2)/2];                    %sum of the two sides of the trapezoid
AreaA=(1/n)*sum(y);               %Sum to find the final result for bus 202

x1=VHB(1:n-1).*VHB(1:n-1);
x2=VHB(2:n).*VHB(2:n);
y=[(x1+x2)/2];
AreaB=(1/n)*sum(y);               %Bus 444

x1=VHC(1:n-1).*VHC(1:n-1);
x2=VHC(2:n).*VHC(2:n);
y=[(x1+x2)/2];
AreaC=(1/n)*sum(y);               %Bus 551

x1=VHD(1:n-1).*VHD(1:n-1);
x2=VHD(2:n).*VHD(2:n);
y=[(x1+x2)/2];
AreaD=(1/n)*sum(y);               % Bus 552

x1=VHE(1:n-1).*VHE(1:n-1);
x2=VHE(2:n).*VHE(2:n);
y=[(x1+x2)/2];
AreaE=(1/n)*sum(y);               % Bus 564

x1=VHF(1:n-1).*VHF(1:n-1);
x2=VHF(2:n).*VHF(2:n);
y=[(x1+x2)/2];
AreaF=(1/n)*sum(y);               % Bus 581

x1=VHG(1:n-1).*VHG(1:n-1);
x2=VHG(2:n).*VHG(2:n);
y=[(x1+x2)/2];
AreaG=(1/n)*sum(y);               % Bus 586


x1=VHI(1:n-1).*VHI(1:n-1);
x2=VHI(2:n).*VHI(2:n);
y=[(x1+x2)/2];
AreaI=(1/n)*sum(y);               % Bus 184

x1=VHJ(1:n-1).*VHJ(1:n-1);
x2=VHJ(2:n).*VHJ(2:n);
y=[(x1+x2)/2];
AreaJ=(1/n)*sum(y);               % Bus 183

x1=VHK(1:n-1).*VHK(1:n-1);
x2=VHK(2:n).*VHK(2:n);
y=[(x1+x2)/2];
AreaK=(1/n)*sum(y);               % Bus 170

x1=VHL(1:n-1).*VHL(1:n-1);
x2=VHL(2:n).*VHL(2:n);
y=[(x1+x2)/2];
AreaL=(1/n)*sum(y);               % Bus 585

x1=VHM(1:n-1).*VHM(1:n-1);
x2=VHM(2:n).*VHM(2:n);
y=[(x1+x2)/2];
AreaM=(1/n)*sum(y);               % Bus 554

x1=VHN(1:n-1).*VHN(1:n-1);
x2=VHN(2:n).*VHN(2:n);
y=[(x1+x2)/2];
AreaN=(1/n)*sum(y);               % Bus 582
```

```
x1=VHO(1:n-1).*VHO(1:n-1);
x2=VHO(2:n).*VHO(2:n);
y=[(x1+x2)/2];
AreaO=(1/n)*sum(y);                    % Bus 556

x1=VHP(1:n-1).*VHP(1:n-1);
x2=VHP(2:n).*VHP(2:n);
y=[(x1+x2)/2];
AreaP=(1/n)*sum(y);                    % Bus 557

energy=[AreaA, AreaB, AreaC, AreaD,AreaE, AreaF, AreaG,  AreaI, AreaJ, AreaK, AreaL, AreaM, AreaN, AreaO, AreaP]';

%end
```

4.4 Frequency domain calculations to Determine Energy of the Transients:

```
%clear
clf
%-------------------

load chf.txt;                  %Load Data
load chfa.txt;                 %Load Data

f=chf(:,2);
%---------------------------------------
%Load voltage magnitudes
V202fm=chf(:,3);
V444fm=chf(:,4);
V551fm=chf(:,5);
V552fm=chf(:,6);
V564fm=chf(:,7);
V581fm=chf(:,8);
V586fm=chf(:,9);

V184fm=chfa(:,3);
V183fm=chfa(:,4);
V170fm=chfa(:,5);
V585fm=chfa(:,6);
V554fm=chfa(:,7);
V582fm=chfa(:,8);
V556fm=chfa(:,9);
V557fm=chfa(:,10);

%************************************
%Compute energy
% Function to integrate  by trapezoidal method

n=(length(V202fm));  %find the total number of points
%extract points beginning from second entry to the end and square
it.
x1=V202fm(1:n-1).*V202fm(1:n-1);
%extract points from start to one before the end and square it.
x2=V202fm(2:n).*V202fm(2:n);
y=[(x1+x2)/2]; %sum of the two sides of the trapezoid
AreaA=(1/pi)*sum(y); %Sum to find the final result for bus 202
```

```
x1=V444fm(1:n-1).*V444fm(1:n-1);
x2=V444fm(2:n).*V444fm(2:n);
y=[(x1+x2)/2];
AreaB=(1/pi)*sum(y); %Bus 444

x1=V551fm(1:n-1).*V551fm(1:n-1);
x2=V551fm(2:n).*V551fm(2:n);
y=[(x1+x2)/2];
AreaC=(1/pi)*sum(y); %Bus 551

x1=V552fm(1:n-1).*V552fm(1:n-1);
x2=V552fm(2:n).*V552fm(2:n);
y=[(x1+x2)/2];
AreaD=(1/pi)*sum(y); % Bus 552

x1=V564fm(1:n-1).*V564fm(1:n-1);
x2=V564fm(2:n).*V564fm(2:n);
y=[(x1+x2)/2];
AreaE=(1/pi)*sum(y); % Bus 564

x1=V581fm(1:n-1).*V581fm(1:n-1);
x2=V581fm(2:n).*V581fm(2:n);
y=[(x1+x2)/2];
AreaF=(1/pi)*sum(y); % Bus 581

x1=V586fm(1:n-1).*V586fm(1:n-1);
x2=V586fm(2:n).*V586fm(2:n);
y=[(x1+x2)/2];
AreaG=(1/pi)*sum(y); % Bus 586


x1=V184fm(1:n-1).*V184fm(1:n-1);
x2=V184fm(2:n).*V184fm(2:n);
y=[(x1+x2)/2];
AreaI=(1/pi)*sum(y); % Bus 184

x1=V183fm(1:n-1).*V183fm(1:n-1);
x2=V183fm(2:n).*V183fm(2:n);
y=[(x1+x2)/2];
AreaJ=(1/pi)*sum(y); % Bus 183

x1=V170fm(1:n-1).*V170fm(1:n-1);
x2=V170fm(2:n).*V170fm(2:n);
y=[(x1+x2)/2];
AreaK=(1/pi)*sum(y); % Bus 170

x1=V585fm(1:n-1).*V585fm(1:n-1);
x2=V585fm(2:n).*V585fm(2:n);
y=[(x1+x2)/2];
AreaL=(1/pi)*sum(y); % Bus 585

x1=V554fm(1:n-1).*V554fm(1:n-1);
x2=V554fm(2:n).*V554fm(2:n);
```

```
y=[(x1+x2)/2];
AreaM=(1/pi)*sum(y); % Bus 554

x1=V582fm(1:n-1).*V582fm(1:n-1);
x2=V582fm(2:n).*V582fm(2:n);
y=[(x1+x2)/2];
AreaN=(1/pi)*sum(y); % Bus 582

x1=V556fm(1:n-1).*V556fm(1:n-1);
x2=V556fm(2:n).*V556fm(2:n);
y=[(x1+x2)/2];
AreaO=(1/pi)*sum(y); % Bus 556

x1=V557fm(1:n-1).*V557fm(1:n-1);
x2=V557fm(2:n).*V557fm(2:n);
y=[(x1+x2)/2];
AreaP=(1/pi)*sum(y); % Bus 557

energy=[AreaA, AreaB, AreaC, AreaD,AreaE, AreaF, AreaG,  AreaI,
AreaJ, AreaK, AreaL, AreaM, AreaN, AreaO, AreaP]';

%end
```